LBL—1050
c.2

RECEIVED
LAWRENCE
RADIATION LABORATORY

JUN 18 1973

LIBRARY AND
DOCUMENTS SECTION

# PHYSICS
# Annual Report

July 1971 through June 1972

TWO-WEEK LOAN COPY

This is a Library Circulating Copy
which may be borrowed for two weeks.
For a personal retention copy, call
Tech. Info. Division, Ext. 5545

Lawrence Berkeley Laboratory
University of California
Berkeley, California

LBL—1050
c.2

34

## DISCLAIMER

This document was prepared as an account of work sponsored by the United States Government. While this document is believed to contain correct information, neither the United States Government nor any agency thereof, nor the Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or the Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof or the Regents of the University of California.

LBL-1050
UC-34 Physics
TID-4500 (59th Ed.)

# PHYSICS
# Annual Report

July 1971 through June 1972

W. A. Wenzel
Associate Director for Physics

Lawrence Berkeley Laboratory
University of California
Berkeley, California

## PHYSICS RESEARCH STAFF

### July 71 – June 72

G. S. Abrams
L. W. Alvarez
H. W. Baer
J. A. Baker
R. O. Bangerter
K. Bardakci
K. W. Barnham
K. H. Berkner
R. W. Birge
M. Bishari
A. Bonney
A. L. Bridgewater
R. J. Budnitz
O. Chamberlain
G. F. Chew
W. Chinowsky
W. W. Chupp
A. R. Clark
E. P. Colton
E. D. Commins
P. Concus
W. S. Cooper
F. S. Crawford
K. M. Crowe
B. Y. Daugeras
S. E. Derenzo
P. H. Eberhard
M. B. Einhorn
T. Elioff
R. P. Ely
A. Entis
R. C. Field
A. Firestone
S. M. Flatté
J. V. Franck
C. E. Friedberg
J. H. Friedman
A. B. Galtieri
M. A. Garnjost
A. A. Garren
G. Gidal
W. S. Gilbert
M. B. Goitein
G. Goldhaber
H. A. Gould
D. F. Grether
H. A. Grunder
T. Hadeishi
M. B. Halpern
W. D. Hartsough
R. J. Harvey
H. H. Heckman
J. A. Helland
A. C. Helmholz
V. P. Henri
W. R. Holley
J. D. Jackson
C. E. Johnson
R. P. Johnson
D. L. Judd
J. A. Kadyk
G. E. Kalmus
S. N. Kaplan
R. Karplus
A. N. Kaufman
D. Keefe
R. W. Kenney
L. T. Kerth
G. Knies
W. B. Kunkel
G. R. Lambertson
J. L. Laslett
J. V. Lepore
E. J. Lofgren
G. R. Lynch
S. Mandelstam
R. Marrus
T. S. Mast
L. P. Meissner
W. B. Michael
D. E. Mohl
R. G. Moorhouse
G. D. Nixon
G. C. Nooney
H. G. Oberlack
P. J. Oddone
W. P. Oliver
S. I. Parker
H. W. Patterson
M. R. Pennington
V. Perez-Mendez
W. A. Perkins
J. M. Peterson
M. H. Prior
M. Pripstein
R. V. Pyle
M. S. Rabin
R. J. Riddell
A. Rittenberg
A. H. Rosenfeld
R. R. Ross
R. C. Sah
S. G. Schmelling
L. S. Schroeder
E. Segre
A. M. Sessler
G. Shapiro
S-S. Shei
H. A. Shugart
L. Smith
F. T. Solmitz
J. M. Sperinde
J. W. Staples
H. P. Stapp
H. M. Steiner
A. W. Stetz
M. L. Stevenson
R. F. Stiening
M. Suzuki
W. J. Swiatecki
R. H. Thomas
H. K. Ticho
G. H. Trilling
R. D. Tripp
J. T. Vale
M. A. Wahlig
R. W. Wallace
K. M. Watson
B. R. Webber
W. A. Wenzel
H. S. White
C. E. Wiegand
J. D. Young

PHYSICS RESEARCH

# Contents


**BEVATRON: Lofgren**

OPERATION AND PROGRAMS . . . 1
MACHINE IMPROVEMENT AND DEVELOPMENT . . . 2
Resonant Extraction of the EPB . . . 2
Ion Electron Instability—Clearing Field Electrodes . . . 3
Cryogenic Pumping of Bevatron Vacuum Tank . . . 3
New 50-MeV Proton Linac Injector . . . 3
Computer Control of Acceleration System . . . 4
High-Intensity Kaon Beams . . . 4
Streamer Chamber Facility . . . 4
Heavy-Ion Program . . . 4
PUBLICATIONS AND PAPERS . . . 5

**184-INCH SYNCHROCYCLOTRON: Vale**

184-INCH SYNCHROCYCLOTRON . . . 7

**ACCELERATOR STUDIES: Lofgren**

ELECTRON RING ACCELERATOR . . . 9
Compressor-4 Experiments . . . 9
Compressor-5 Experiments . . . 10
Injector Facility . . . 10
SUPERCONDUCTIVITY PROGRAM . . . 10
Bevatron Transport Magnets — Nonpulsed . . . 10
Pulsed Dipoles . . . 10
Cryopumping . . . 11
Polarized Target Magnet . . . 11
PUBLICATIONS AND PAPERS . . . 11

**GROUP A EXPERIMENTAL PHYSICS: Rosenfeld**

BUBBLE CHAMBER EXPERIMENTS . . . 13
K82 Experiment . . . 13
$K^+p \rightarrow \pi^+pK^\circ$ . . . 13
$K\pi$ scattering . . . 13
Low-mass $K\pi\pi$ systems . . . 13
$K^+p \rightarrow pK^+\phi$ and $pK^+\omega$ . . . 13
$\pi$82 Experiment . . . 14
Anomaly in the $\pi^+\pi^-$ system . . . 14
$\pi\pi$ phase-shift analysis . . . 14
Energy dependence of inclusive distributions . . . 14
Quasi-two-body reactions . . . 15
Properties of the $B^+(1235)$ meson . . . 15
High-Energy Photoproduction Experiment . . . 15
Low-Energy Photoproduction . . . 16
K70 Experiment . . . 16
Antiprotons in Deuterium . . . 16

$\pi^-p$ Inelastic Reactions . . . 17
$\pi$66 Experiment . . . 18
BP66 Experiment . . . 18
Multiparticle production . . . 18
P65 Experiment . . . 18
$\pi^-$ production . . . 18
K65 Experiment . . . 18
Analysis of $K^-p \rightarrow \Lambda\pi^+\pi^-$ in the region of the $\Lambda(1520)$ . . . 19
Branching ratio of $\Sigma(1385)$ . . . 19
$\Sigma$ lifetimes and branching ratios . . . 19
$\Sigma N$ interactions . . . 19
K63 Experiment . . . 19
$K^-p$ four-prong reactions . . . 20
Resonance production . . . 20
SPARK CHAMBER AND COUNTER STUDIES . . . 20
Neutral Final States in $\pi^-p$ Interactions . . . 20
Polarization Parameter in $\pi^-p \rightarrow n\pi^0$ . . . 20
Counter Experiment at NAL . . . 20
STREAMER CHAMBER EXPERIMENTS . . . 21
COSMIC RAY EXPERIMENTS . . . 21
High Altitude Particle Physics and Cosmic Ray Experimental Facility . . . 21
SEARCH FOR MONOPOLES . . . 22
DETECTOR DEVELOPMENT . . . 22
Detectors Using Liquified Noble Gases . . . 22
Infrared Detector for Astrophysics . . . 23
DATA REDUCTION OPERATIONS . . . 23
PROGRAMMING EFFORT . . . 24
PUBLICATIONS AND PAPERS . . . 24

**LOFGREN EXPERIMENTAL PHYSICS**

SEARCH FOR $K^0_S \rightarrow \mu^+\mu^-$ . . . 29
SEARCH FOR A $\pi$-$\mu$ RESONANCE . . . 30
SEARCH FOR A NEW VECTOR MESON . . . 30
DIBOSON PRODUCTION . . . 30
$(K^+ \rightarrow e^+\nu)/(K^+ \rightarrow \mu^+\nu)$ BRANCHING RATIO . . . 30
HEAVY-ION WORK . . . 30
RANGE OF POSITIVE AND NEGATIVE MUONS 31
$K^\circ\mu_3$ POLARIZATION MEASUREMENT . . . 31
$K^\circ\mu 3$ AND $K^\circ e3$ CHARGE ASYMMETRY . . . 31
NEUTRAL PARTICLES DECAYING TO $e^+e^-$ . . . 31
NEUTRINO MASS LIMITS . . . 31
PUBLICATIONS AND PAPERS . . . 32

**GROUP R EXPERIMENTAL PHYSICS**

**1. CROWE PHYSICS GROUP**

MUON DEPOLARIZATION STUDIES . . . 33
RADIATIVE PION CAPTURE . . . 34
Results for $^6$Li . . . 34
Results for $^{14}$N . . . 35
Results for $^3$He . . . 35
$K^\circ_{\mu 3}$ CHARGE ASYMMETRY . . . 35

EXPERIMENTS AT LASL . . . . . 36
Radiative Pion Capture in Light Nuclei . . . . . 36
High-Resolution Study of the Boson Mass Region 0 . . . . . 36
PUBLICATIONS AND PAPERS . . . . . 36

II. PEREZ-MENDEZ PHYSICS GROUP

$\pi^0$ FORM FACTOR EXPERIMENT . . . . . 38
$np \rightarrow \gamma d$: TEST OF TIME REVERSAL . . . . . 38
$p+d \rightleftarrows \gamma+{}^3He$: TEST OF TIME REVERSAL . . . . . 38
pd ELASTIC SCATTERING . . . . . 38
$\pi^+$ RADIATIVE DECAY . . . . . 38
INSTRUMENTATION . . . . . 39
Neutron Radiographic Imaging . . . . . 39
Multiwire Proportional Chamber for Nuclear Medicine . . . . . 40
PUBLICATIONS AND PAPERS . . . . . 40

III. KAPLAN PHYSICS GROUP

NUCLEAR STRUCTURE STUDIES . . . . . 42
PULSE-HEIGHT ANALYZER . . . . . 42
MULTIWIRE PROPORTIONAL CHAMBERS . . . . . 42
PUBLICATIONS AND PAPERS . . . . . 43

GROUP S EXPERIMENTAL PHYSICS

I. TRILLING/GOLDHABER PHYSICS GROUP

$K^+d$ INTERACTIONS AT 12 GeV/c . . . . . 45
Coherent Production of $Q^+$ . . . . . 45
$K\pi$ System . . . . . 45
Diffractive Production of Baryons . . . . . 46
$\pi^+p$ INTERACTIONS AT 3.7 GeV/c . . . . . 46
Vector Meson Production . . . . . 46
Other Topics . . . . . 46
$\pi^+p$ INTERACTIONS AT 3.8 GeV/c . . . . . 47
$\Lambda p$ INTERACTIONS IN THE RANGE 0.5 to 8.0 GeV/c . . . . . 47
SPEAR EXPERIMENT . . . . . 47
PUBLICATIONS AND PAPERS . . . . . 47

II. BIRGE PHYSICS GROUP

$\pi^+p$ INTERACTIONS . . . . . 49
Non-Strange-Particle Final States (1.1 to 2.0 GeV/c) . . . . . 49
Non-Strange-Particle Final States (2.0 to 4.1 GeV/c) . . . . . 49
Strange-Particle Final States . . . . . 49
$\pi\pi$ Scattering by Pole Extrapolation Methods . . . . . 50
$K^-p$ INTERACTIONS (0.85 to 1.70 GeV/c) . . . . . 50
PHOTOPRODUCTION IN DEUTERIUM . . . . . 50
PERIPHERAL $\pi^-p$ INTERACTIONS . . . . . 50
CLOUD-CHAMBER QUARK SEARCH . . . . . 50
PUBLICATIONS AND PAPERS . . . . . 50

III. DATA-HANDLING GROUP

DAPR: AUTOMATIC SCANNING AND MEASURING OF BUBBLE CHAMBER EVENTS . . . . . 51
FCF: GEOMETRY, KINEMATICS, DISPLAY . . . . . 53
TRIST: SYSTEMS MONITOR . . . . . 53

FSD MONITOR . . . . . 53
QUARKS . . . . . 53
EVENT MEASUREMENTS PROCESSED . . . . . 54

IV. SPECIAL PROJECTS GROUP 51

SEGRE/CHAMBERLAIN EXPERIMENTAL PHYSICS

KAONIC ATOMS . . . . . 57
SEARCH FOR $K^+ \to \mu^+ \nu\bar{\nu}\nu$ AND $K^+ \to \pi^+ \nu\bar{\nu}$ . . . . . 57
TWO-PRONG $\bar{p}p$ ANNIHILATIONS . . . . . 58
PION PRODUCTION IN HEAVY-ION REACTIONS . . . . . 58
ASYMMETRY IN $\pi^- p \to \pi^0 n$ . . . . . 58
SPEAR . . . . . 59
PROPORTIONAL WIRE CHAMBERS . . . . . 59
POLARIZED-PROTON TARGET DEVELOPMENT . . . . . 59
PROTON-DEUTERIUM INTERACTIONS . . . . . 59
PROTON-PROTON INTERACTIONS . . . . . 60
WORLD $pp \to pp\pi^+\pi^-$ COLLABORATION . . . . . 60
PUBLICATIONS AND PAPERS . . . . . 60

THEORETICAL PHYSICS: Chew

PARTICLE THEORY . . . . . 61
Theoretical Analysis of General S-Matrix Concept . . . . . 61
Bootstrap Hypothesis . . . . . 62
Studies of the Consequences of Regge Behavior . . . . . 63
Classical S-Matrix Phenomenology . . . . . 64
Theory of Inclusive Reactions . . . . . 64
Field Theoretic Investigations . . . . . 65
Proton-Electron-Positron Colliding Beams (PEP) . . . . . 66
Other Work . . . . . 66
PARTICLE ACCELERATORS . . . . . 66
Proton-Electron-Positron Colliding Beam Facility . . . . . 66
Electron Ring Accelerator . . . . . 67
NUCLEAR PHYSICS . . . . . 68
ATOMIC PHYSICS . . . . . 69
PLASMA PHYSICS . . . . . 70
GRADUATE STUDENTS . . . . . 70
PUBLICATIONS AND PAPERS . . . . . 71

ATOMIC BEAM GROUP: Shugart

LOCAL HIDDEN-VARIABLE THEORIES . . . . . 77
LIGHT TRAPPING IN AN ATOMIC BEAM . . . . . 77
METASTABLE STATE OF CARBON MONOXIDE . . . . . 77
EFFECT OF ELECTRIC FIELD QUENCHING . . . . . 78
PRECISION SPECTROSCOPY . . . . . 78
MERCURY DETECTOR . . . . . 78
HYDROGENLIKE AND HELIUMLIKE ATOMS . . . . . 78
PRECISION MEASUREMENT OF $g_J$ ($N^{14}$, $^4S_{3/2}$) . . . . . 78
PUBLICATIONS AND PAPERS . . . . . 79

CONTROLLED THERMONUCLEAR RESEARCH AND PLASMA PHYSICS: Kunkel

RESEARCH PROGRAMS . . . . . 81
PUBLICATIONS AND PAPERS . . . . . 83

**HEALTH PHYSICS: Patterson**

ENVIRONMENTAL RADIATION MONITORING . . . . . 85
SPARK CHAMBER NEUTRON SPECTROMETER . . . . . 85
SHORT PULSE RADIATION DETECTOR . . . . . 85
THERAPY WITH HEAVY IONS . . . . . 86
GROUND WATER CONTAMINATION STUDIES . . . . . 86
SHIELDING STUDIES AT 28 GeV . . . . . 86
NEUTRON PERSONAL DOSIMETRY ABOVE 20 MeV . . . . . 87
RADIOELEMENTS AND HEAVY MINERALS . . . . . 87
NATURAL ENVIRONMENTAL RADIATION . . . . . 87
ELECTRON AND PROTON IRRADIATION OF GLASS—NASA SKYLAB PROJECT . . . . 87
RADIATION LEVELS IN COMMERCIAL AIRCRAFT . . . . . 88
COAL VS NUCLEAR POWER GENERATION . . . . . 88
ACCELERATOR HEALTH PHYSICS TRAINING PROGRAM . . . . . 88
ICRP PUBLICATION #21 . . . . . 88
THE ACTIVITIES AT RISØ, 1969-1971 . . . . . 88
PUBLICATIONS AND PAPERS . . . . . 89

**NUCLEAR EMULSION GROUP: Heckman**

BEVATRON HEAVY-ION RESEARCH . . . . . 91
COSMIC RAY HEAVY IONS . . . . . 92
MAGNETIC BREMSSTRAHLUNG . . . . . 92
MOMENTUM MEASUREMENTS IN EMULSIONS . . . . . 93
GEOMAGNETICALLY TRAPPED RADIATION . . . . . 93
RESPONSE OF TRAPPED PARTICLES TO A COLLAPSING DIPOLE MOMENT . . . . . 93
PUBLICATIONS AND PAPERS . . . . . 93

**PARTICLE DATA CENTER: Rosenfeld**

PARTICLE DATA CENTER . . . . . 95
PUBLICATIONS . . . . . 95

**MATHEMATICS AND COMPUTING: Baker**

MATHEMATICS AND COMPUTING RESEARCH . . . . . 97
Applied and Numerical Mathematics . . . . . 97
Mathematical Models in Biology . . . . . 97
Graphic Output of Digitized Pictorial Data . . . . . 98
Computerized Mapmaking . . . . . 98
APPLICATIONS PROGRAMMING . . . . . 98
Physics . . . . . 99
Medium-Energy Physics . . . . . 99
Helmholz Group . . . . . 99
Birge Group Bubble-Chamber Programming . . . . . 99
Accelerator and Magnet Design Group . . . . . 99
Nuclear Chemistry . . . . . 101
Nuclear Calculations . . . . . 101
Analytic Chemistry . . . . . 101
Field Free X-Ray Photospectrometers . . . . . 101
Environmental Simulation . . . . . 101
Biology and Medicine . . . . . 102
Small Computer Systems . . . . . 102
General Biomedical Applications . . . . . 102
Laboratory of Chemical Biodynamics . . . . . 103

General Applications . . . . . 103
Data Management Project . . . . . 104
SYSTEMS PROGRAMMING . . . . . 105
CDC-7000/6000 Computer Complex . . . . . 105
Remote Batch and Interactive Systems . . . . . 105
COM . . . . . 105
COMPUTER OPERATIONS . . . . . 105
PUBLICATIONS AND PAPERS . . . . . 106

# Accelerators

# BEVATRON

Edward J. Lofgren in charge

## OPERATION AND PROGRAMS

*Walter D. Hartsough in charge, Glenn Eckman, Don Evans, Ken Crebbin, Robert Force, Fred Lothrop, Kenow Lou, Richard Morgado, Wendell Olson, and Glenn White*

The Bevatron operation and experimental programs are centered around the flexible, multibeam capabilities of the Bevatron and its external beam system. Primary beams of protons and of heavy ions are extracted in a great variety of pulse modes using computer control and the new resonant extraction system. The external beam is divided by septum magnets for simultaneous illumination of targets in each of three backstop target areas. Eight to ten major experiments are usually set up at any given time in this facility, principally in secondary particle beams which originate at a backstop target. The versatility, the excellent performance characteristics, and the low operating cost of the Bevatron underline its importance in hadron research in the few-GeV region and in research programs using multi-baryon particles, including deuterons, alpha particles, and carbon, oxygen, and neon nuclei. Research programs include experiments in the fields of high-energy physics,astrophysics, nuclear chemistry, biophysics and biomedicine. A total of 34 laboratories and universities were involved in Bevatron experiments this year. Representing these institutions were 41 outside groups and 17 LBL groups. Outside groups accounted for about 55% of the experimental hours.

The Bevatron operated on a nominal 24-hour-per-day, 7-day-per-week basis, with one shift off per week for maintenance. A total of 5700 hours of machine operation was achieved. Integrated experimental time was 16 162 hours. This is slightly lower than last year because as experiments become more specialized and complex, multiple operation is reduced. The total also reflects belt-tightening measures that have been necessary to compensate for a steadily declining budget. During the last two weeks of June the Bevatron was shut down for budgetary reasons with much of the staff on vacation. Only a very limited program of shutdown activities was pursued.

To achieve our goal of $2 \times 10^{13}$ protons per pulse we have proceeded with the installation of the 50-MeV injector. Simultaneously, injection calculations and tests at 20 MeV have been completed. Studies of extraction channel improvements have been made and have resulted in design and installation of a Quad II correction coil, which decreases the transverse beam dimensions in the Bevatron fringe-field and thus increases the beam transmission at the extraction port. A cryogenic pumping system has also been installed in the Bevatron vacuum tank and has resulted in a significant increase in the intensities of heavy-ion beams.

A high-intensity, high-quality stopping K-beam, constructed with conventional elements (magnets and separators) but designed for the largest aperture consistent with second-order corrections, has been designed. Elements of this beam are being constructed and will be ready for installation during the next fiscal year. Higher intensity stopping K-beams with absorber separation are under investigation.

A very successful program was carried out this year to provide a heavy-ion capability for the Bevatron. The heavy-ion work represents a significant breakthrough in the field of high-energy particle acceleration and has evoked a substantial and enthusiastic response in the research community, particularly among those who are pursuing studies of high-energy phenomena in the fields of cosmic-ray physics and astrophysics, and among those interested in use of heavy ions for biophysics and biomedical research. It must be emphasized, however, that our primary research and development objectives have not changed.

The initial motivation for heavy-ion work was in response to a strong recommendation made by the Program Scheduling Committee to develop a high-energy, monoenergetic neutron beam by stripping deuterons that have been accelerated to high energy and then extracted. A subsequent motivation was a growing interest among experimentalists in the coherent production of pions by deuterons and alpha particles. Thus a development program was planned last year for an initial period of exploratory work in this area of interest. The work was to be carried out during a budgetary shutdown of the normal program scheduled for August 1971.

Later, the scope of the heavy-ion program was expanded to include heavier ions. This was a consequence of some interesting ideas presented at the 1971 Particle Accelerator Conference in Chicago, March 1-3, 1971. The paper by L. Rosen of the Los Alamos Scientific Laboratory on "The Relevance of Particle Accelerators to National Goals" stimulated discussion on the possibility of using the Superhilac, which was nearing completion at Berkeley, as a heavy-ion injector for the Bevatron, thus extending the capability of the Bevatron to acceleration of heavy ions. This possibility, which led to the Bevalac proposal, required preliminary investigations that were deemed within the capability of the Bevatron. Recent technological developments--which included resonant extraction and computer control of the magnetic guide field, acceleration, and extraction system--were the key elements that permitted consideration of this program. A Hilac-type PIG ion-source was adapted to the Bevatron injection system, and a series of preliminary tests were carried out. The immediate success of this effort and the striking results of preliminary investigations in the areas of high-energy physics, nuclear chemistry, biology, and medicine were very encouraging.

During this first series of exploratory runs in August 1971, deuterons, alpha particles, and nitrogen ions were accelerated in the Bevatron and extracted at energies between 280 MeV/nucleon and 2.1 GeV/nucleon. Nitrogen ions were also accelerated to 36 GeV total energy. The intensities were $10^{11}$ particles per pulse for deuterons, $5 \times 10^9$ ppp for alpha particles, and $7 \times 10^5$ ppp for nitrogen ions.

A second heavy-ion run was done in January 1972 during which the characteristics of a neutron beam produced by stripping high-energy deuterons were confirmed and measured in more detail. Preliminary experiments on the coherent production of pions by deuterons and alpha particles were also started. Oxygen beams of about the same intensity and quality as previously achieved with nitrogen were obtained. A number of preliminary experiments were performed using the oxygen beam to study the fragmentation of the nuclei and to make a number of measurements that are of critical interest to investigators considering the use of heavy-ion beams in the fields of biological and medical research. Bragg curves, linear energy transfer, and the oxygen enhancement ratio were studied at 250 MeV/nucleon.

A third heavy-ion run took place during the first half of June with an improved Bevatron vacuum. The cryopanel pumping system was completed except for the 20°K helium refrigeration system. For this run only the liquid-nitrogen-cooled shields were operative. Carbon and oxygen beams with ion intensities of $2 \times 10^6$/pulse were delivered to targets in the experimental area. A modest beam of $^{20}$Ne was also accelerated and extracted at an energy of 2.1 GeV/nucleon.

## MACHINE IMPROVEMENT AND DEVELOPMENT

*Hermann A. Grunder in charge, John Barale, Ted Byrnes, Pierre Germain, James Guggemos, William Holley, Terry Jackson, Henry Lancaster, Robert Richter, Richard Sah, John Staples, Marsh Tekawa, Ferdinand Voelker, and Emery Zajec*

### Resonant Extraction of the EPB

The resonant extraction system was completed last year; this year the system was made fully operable over a wide range of extraction energies. This capability was of specific importance to the success of the heavy-ion program. Beams have been extracted at energies as low

as 250 MeV/nucleon for biomedical studies using heavy-ion beams, and up to full machine energy—6.2 GeV—for protons. The extraction system originally was designed for high-energy proton beam operation and optimized for beams in the energy range 4 to 6 GeV/nucleon. At the present time, extraction efficiency is low for low-energy operation. Development work has begun to improve the extraction system so that extraction efficiency will be high over the full range of energies required by the experimental program. Preliminary studies indicate that a reasonable improvement may be expected for intermediate energies, but that for the lowest energies a new system may be required for high efficiency.

Ion Electron Instability—Clearing Field Electrodes

An unanticipated and heretofore unobserved phenomenon has severely limited the "rf off" extraction efficiency for operation at high beam intensity. A coherent vertical oscillation of the beam occurs during long beam spills on the flat-top if the rf is turned off and if the beam is allowed to coast and debunch. The resultant vertical growth of the beam causes beam to be lost on the first extraction magnet. At 5 GeV the threshold for observable vertical growth is about $10^{11}$ particles/pulse. This behavior is the result of coupled motion between the circulating ions and the neutralizing electrons that come from ionization of remnant gas. A system of clearing field electrodes has been installed along the beam path to sweep out these electrons. This technique has eliminated the phenomenon and high-intensity beams may be extracted with high efficiency.

Cryogenic Pumping of Bevatron Vacuum Tank

Water and organic compounds are poorly pumped by conventional diffusion pumps; and scattering by the residual gas is responsible for a substantial loss of beam particles at injection. To combat this problem, a cryogenic system has been installed which consists of cryopanels in each curved section and each straight section of the Bevatron vacuum tank. The panels consist of liquid-nitrogen-cooled shields which partially enclose a helium-cooled panel. The helium panel is cooled by gas to 20°K. This combination of liquid-nitrogen and low-temperature helium gas-cooled surfaces has more than doubled the present pumping capacity. The liquid-nitrogen-cooled surfaces greatly help to pump down the tank following a shutdown, and during normal operations have a large pumping capacity for water and hydrocarbons. The liquid-helium-cooled surfaces substantially increase the pumping capacity for residual gases other than helium and hydrogen. This system has reduced the vacuum tank pressure from 1 or $2 \times 10^{-6}$ torr to $6 \times 10^{-7}$ torr with the liquid-nitrogen shields cooled, and to $3 \times 10^{-7}$ torr with the helium-cooled panels chilled to 20°K. At the end of this fiscal year the cryopanels had been installed and the liquid-nitrogen system completed. The 20°K helium gas refrigeration system is being installed. Tests of the system with cold helium gas have been accomplished using a temporary dewar system.

New 50-MeV Proton Linac Injector

A major element in the improvement program to increase the Bevatron proton beam intensity from 5 or $6 \times 10^{12}$ protons per pulse to $2 \times 10^{13}$ ppp is the provision of a higher energy, higher intensity injection system. This year the 50-MeV BNL Linac was brought to Berkeley and is being installed in a new injection beam line as a replacement for the present 20-MeV injector. A test ion-source facility is being modified for higher energy and will include a high-gradient column to be used as the preinjector for the 50-MeV Linac. The increase in injection energy from 20 to 50 MeV will overcome present spacecharge limitations in the Bevatron. This improvement, plus the higher brilliance of the modified preinjector, will achieve the desired increase in Bevatron intensity. It is scheduled that the completed 50-MeV injection system will be fully operational on the Bevatron about the end of FY 73.

High intensity is particularly important for detailed studies of rare meson-nucleon interactions and in precision measurements of standard parameters. The long

duty-cycle of the Bevatron and the flexible, variable-energy external beam make systematic studies over a wide range of energies very attractive. The LBL-UCLA Streamer Chamber which is now a Laboratory facility will be actively used in this area of study.

## Computer Control of Acceleration System

Digital control of the low-level rf system of the Bevatron has been developed using a PDP-8 processor. The new system has great flexibility and eliminates a multitide of analog circuits that were required for the complex programming of the acceleration cycle and for accomplishing the multiple beam spills. Many feedback loops have also been eliminated with the new system. Only beam radius, phase, and field information are required.

The new system has greatly increased the quality and flexibility of acceleration system control and to a large degree has eliminatednoise input to the system. As an adjunct to this system a new computerized master oscillator has been developed. Computed values of frequency are generated and stored for the acceleration cycle. The new master oscillator is controlled by a digital processor with provision for on-line monitoring of frequency accuracy.

## High-Intensity Kaon Beams

Special attention is being given to the development of high-quality, high-intensity low-momentum and stopping kaon beams for detailed studies of K-meson decays. These beams are particularly well matched to the Bevatron energy range because production rates are high and shielding requirements are minimal. It is particularly this last feature which will allow the short beam transport and separation systems that are required for usable stopping kaon beams. Particular emphasis is on a stopping kaon beam of high quality and with a substantial increase in flux over existing beams. In addition, a high-intensity kaon beam in the range of 1 to 2 GeV/c is being designed. The designs feature large acceptance, minimum length, and second-order corrections for spherical and chromatic aberrations of magnet elements. Both a stopping K beam and a low-momentum beam are scheduled to be built during FY 1973 in the septum backstop area. A new 40" X 36" will be used in the backstop as a dispersing magnet.

Most of the present mysteries in the weak interaction have appeared in the study of K meson decays. Among these are the $|\Delta T| = 1/2$ rule and its breaking in $K^+ \rightarrow \pi^+ + \pi^0$, the violation of CP-invariance in $K_L^0$ decay, the $\Delta S = \Delta Q$ law, and the apparent absence of neutral current couplings. The Bevatron has been particularly successful in its contributions to low-branching-ratio ($\lesssim 10^{-4}$) measurements. Use of this accelerator in K-decay studies will contribute as much to the understanding of weak interactions as any course of research that can now be anticipated.

## Streamer Chamber Facility

The Bevatron Group has collaborated this year with the UCLA group in the development and commissioning of a streamer chamber experimental facility. This facility will remain at LBL for use in the experimental program.

The technical aspects of making this facility operational have been complicated by an experimental requirement for a long liquid-hydrogen target placed within the electric-field region of the chamber. A further complication is that the vacuum jacket surrounding the chamber must be constructed of scintillator plastic. A satisfactory resolution of all known problems has been achieved, and the chamber is now fully operational. The first experiment, to test C-conservation by mapping the distribution of $\pi^+$ and $\pi^-$ mesons from the decay of the $X^0$ particle, has been completed.

## Heavy-Ion Program

Beams of deuterons, alpha particles, and carbon, nitrogen, oxygen, and neon ions have been accelerated in the Bevatron and extracted at beam energies between 280 MeV/nucleon and 2.1 GeV/nucleon. Nitrogen ions have also been accelerated to 36 GeV total energy.

The duoplasmatron ion-source normally used for proton operation was readily adaptable for the production of deuteron and alpha-particle beams. However,

this source is not efficient or adequate for high charge states of heavier ions. Thus, the PIG source developed for the Berkeley Heavy-Ion Linear Accelerator (HILAC) was adapted for use in the Bevatron preinjector.

Deuteron and alpha ion acceleration (e/m = 1/2) is accomplished through the linac in the $2\beta\lambda$-mode with approximately the same electric field gradient as for protons and with identical quadrupole magnet settings. For acceleration of quintuply charged nitrogen (e/m = 5/14), the linac gradient and the quadrupole magnetic fields had to be increased 40%. These values were attainable with minor modifications. In the $2\beta\lambda$-mode the linac accelerates particles to an energy of 5 MeV/nucleon with an overall transmission of 5%. This compares with a transmission of 50% for protons in the $1\beta\lambda$-mode.

Ions injected into the Bevatron must be fully stripped. The stripping cross section for partially stripped ions is unacceptably high at the Bevatron vacuum of $10^{-6}$ Torr. A stripping foil is used to completely strip the ions before injection.

Acceleration of particles in the Bevatron with charge-to-mass ratio equal to one-half was done on the first harmonic of the rf. The starting frequency of the rf system had to be lowered by a factor of two, but this basic capability was already built into the rf system.

The normal monitoring and feedback systems used for proton acceleration were of no use for beams below $10^8$ particles per pulse. Thus for acceleration of carbon, nitrogen, oxygen, and neon ions the Bevatron was tuned up at high intensity using a tracer particle (alphas) with the same e/m; and then the stability of the accelerator and extraction system were relied upon for higher mass particles. This method proved to work very well. The stability of the Bevatron was impressive.

With the success of the heavy-ion program, new areas of physics research have opened up. The potential applications of heavy-ion research to high-energy, nuclear, and cosmic-ray physics, and to nuclear chemistry and biomedical programs, have already been demonstrated. An early result is the recognized relevance of heavy-ion interactions to contemporary high-energy theoretical work on inclusive interactions and on the concept of limiting fragmentation and the factorization of cross sections. A number of theorists have argued that the study of multiparticle reactions at high energy can lead to fundamental information about the nature of hadrons. Work in this field is also important in the study of nuclear spectroscopy and the study of fragmentation of primary cosmic rays by collision with interstellar hydrogen on helium nuclei.

## PUBLICATIONS AND PAPERS


Robert W. Allison, Jr., Robert M. Richter, and Emery Zajec, Emittance Measurements on an Aberrated Cylindrically Symmetrical Proton Beam, in *Proceedings of the Symposium on Ion Sources and Formation of Ion Beams*, Brookhaven National Laboratory Report BNL-50310 (1971).

E. R. Close, P. Germain, W. R. Holley, Trapping in the Bevatron at Injection, Lawrence Berkeley Laboratory Report LBL-738.

H. A. Grunder, W. D. Hartsough, and E. J. Lofgren, Acceleration of Heavy Ions at the Bevatron, Science **174**, 1128 (1971).

H. A. Grunder, W. D. Hartsough, H. H. Heckman and E. J. Lofgren, Heavy Ion Acceleration at the Bevatron, in *Proceedings of the VIII International Conference on High-Energy Accelerators*, M. Hildred Blewett, Ed. (CERN, Geneva, 1971), p. 574.

H. Grunder, C. Leemann, R. Thomas, P. Bowles, W. Mehlhop, O. Piccioni, and D. Scipione, Momentum Distribution of Neutrons Generated by Stripping 5.8 GeV/c Deuterons, to be published.

H. Grunder, J. Jaros, L. Schroeder, J. Staples, H. Steiner, Negative Pion Production by Protons, Deuterons and Alpha Particles on Beryllium, Copper and Lead, presented at APS Meeting, Washington D.C., April 1972, Lawrence Berkeley Laboratory Report LBL-732.

H. A. Grunder, J. R. Guggemos, F. H. G. Lothrop, and M. M. Tekawa, Performance of the Bevatron with Heavy Ions, IEEE Trans. Nucl. Sci. **NS-19** (2), 212 (1972).

H. A. Grunder, R. M. Richter, M. M. Tekawa, and E. Zajec, Pulsed Heavy Ion Source for the Bevatron, IEEE Trans. Nucl. Sci. **NS-19** (2), 208 (1972).

H. A. Grunder and G. R. Lambertson, Transverse Beam Instabilities at the Bevatron, in *Proceedings of the VIII International Conference on High-Energy Accelerators,* M. Hildred Blewett, Ed. (CERN, Geneva, 1971), p. 308.

Design Study Report. High-Energy Heavy-Ion Facility (Bevalac), Lawrence Berkeley Laboratory Report LBL-780, Jan. 1972.

## 184-INCH SYNCHROCYCLOTRON

James T. Vale in charge

The 184-Inch Synchrocyclotron, basic to the medium energy physics program of the Laboratory, celebrated its 25th anniversary this year. This veteran machine has entered a particularly productive period of life. Unique in its flexibility with regard to particles accelerated, it now provides intense internal and external beams of 740-MeV protons and correspondingly energetic deuterons and alphas. Meson and neutron beams produced by these particles are also available and heavily used. A new type of muon beam has been developed, completely polarized and with a high stopping density, which is being used to produce a copious supply of muonium atoms—more than a million a day. During the past 2 to 3 years, modifications have been made so that the cyclotron can handle up to six experimental setups at once, supplying beam to two or three at a time. This rare versatility, together with being relatively inexpensive to operate, make the machine useful to particle and solid-state physicists, to chemists, biologists, and physicians. During the past year, about 70% of the cyclotron's running time was used by outside groups.

The 184-Inch Cyclotron (for medium energy physics) and the Bevatron (for high energy physics) together comprise an integrated facility which is vigorously employed in the Laboratory's broad program of studying the properties of the elementary particles and nuclei. The work at the two accelerators is closely connected in many ways, including exchange and sharing of auxiliary equipment, developing and testing research apparatus at the Cyclotron for later use at the Bevatron and the conducting of experiments requiring particles in both energy ranges.

Major experiments in physics carried on during FY 1972 include the following:

1. Two LBL experiments continued throughout the year on an intermittent basis. One involved radiative pion capture in nuclei and the other investigated the depolarization of muons in various condensed media.

2. A University of Arizona experiment established that a source of muonium atoms could be made by stopping muons in a hot metal foil from which the muonium evaporated. Moreover, precession of the muonium atoms in a weak magnetic field was observed. It is expected that an experiment using this apparatus to study muonium conversion to negative muons will be attempted in FY 1973.

3. A UCLA group studied the reaction $\pi^+ p \rightarrow \Delta^{++}\gamma$ with the aim of determining the magnetic moment of the $\Delta$.

4. A University of British Columbia group investigated $\pi d$ elastic scattering.

5. An experiment by a University of Toronto group investigated $p + {}^3He$ elastic scattering using polarized and normal gaseous ${}^3He$ targets. The ultimate goal is to determine proton scattering from polarized neutrons.

6. A LBL-UCLA collaboration studied the radiative decay of the positive pion.

7. In addition to the above experiments, a number of brief runs were made to calibrate detecting systems for other experiments here and elsewhere.

The biomedical group spent the first part of the fiscal year completing and installing an automatic system (ISAH) for precision positioning of patients in the particle beam. Patient treatment is now under way; and the biomedical experimental program has been resumed.

# ACCELERATOR STUDIES

Edward J. Lofgren in charge

## ELECTRON RING ACCELERATOR

*Robert T. Avery, Warren W. Chupp, L. Drager, Andris Faltens, Alper A. Garren, D. George, Edward C. Hartwig, W. Hermann, Denis Keefe, Glen R. Lambertson, L. Jackson Laslett, C. Macdonald, D. Möhl, R. Nemetz, Walton A. Perkins, Jack M. Peterson, C. Pike, J. Rechen, V. Romano, A. Salop, William W. Salsig, U. Schumacher, Andrew M. Sessler, Lloyd Smith, and D. Vanecek.*

Further research into the method of accelerating protons and other positive ions by means of electron rings is being actively pursued by the Advanced Development Group. The principle of the electron-ring accelerator (ERA) involves the use of a dense ring of relativistic electrons that forms a stable vehicle for the acceleration of protons or ions imbedded in the ring. Our research program utilizes the 4-MeV electron accelerator for injection into the experimental electron-ring compressor apparatus. This accelerator was placed into operation at the nominal design energy of 4 MeV at the beginning of the fiscal year. Except for a scheduled six-week shutdown for maintenance in September-October 1971 the accelerator has operated continuously and reliably on a 45 hours per week schedule.

### Compressor-4 Experiments

Compressor-4 experiments have occupied most of the year in our efforts to gain a better understanding of electron-ring instability problems and the formation of rings of high holding power.

The studies of instabilities have concentrated upon the collective (high-intensity) phenomena. In a series of experiments, we investigated various sidewall geometries, over a range of electrical conductivities. A stainless-steel "pillbox" geometry with an electrical conductivity of 1/15 ohm per square has given the best results to date. This arrangement has permitted us to raise the intensity above that achieved in our successful Compressor-2 experiment by a factor of 4, to more than 300 amperes.

The stainless pillbox will not permit the external inflector field that we have used in the past to penetrate through; therefore it has been necessary to devise another inflection system. This consists of a "window" cut in the sideplates to admit field penetration into the pillbox from a current pulse applied to the sidewalls themselves. This arrangement of high conducting sidewalls and inflector appears very promising; however, we have not as yet demonstrated that the minor radial dimensions of the electron rings are sufficiently small.

The minor radial width of the electron ring is governed by the distribution of electrons in the two variables of betatron amplitude and closed orbit radius, the latter variable being related to momentum. Knowledge of these distributions is highly desirable; the momentum width is expected to depend on intensity for many reasons and is important in determining Landau damping, whereas the presence or absence of small betatron amplitudes indicates how well radial disturbances have been controlled in forming the ring.

We have developed a measurement method for determining these two distributions. After a beam has been injected and stacked, a "Radial Sweeper" can be switched on to drive the beam radially outward at a constant rate; and as successive portions strike the outer obstacle (in our case, the snout), the x-rays produced give a profile in time of the beam arrival. If the beam is also clipped by a probe at the inner side, a changed x-ray pulse is recorded when that beam is swept outward. The set of x-ray records for various degrees of inner-radius clipping can be analyzed to yield the distribtuion of particles in amplitude and

momentum. This method is to be described by J. M. Peterson in an internal note. An example of the result is shown in Fig. 1.

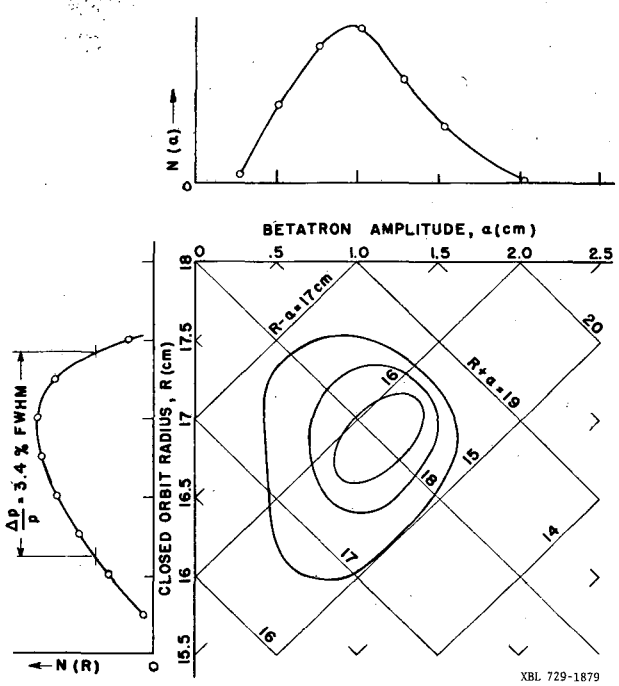



Fig. 1. Distribution of particles in amplitude and momentum determined from X-ray records for various degrees of inner-radius clipping. Diagonal lines lie on the loci of the edges of inner-radius and outer-radius clippers.

Theoretical work and computer simulation studies of an electron beam between highly conducting sidewalls have considerably aided our understanding and interpretation of the high-intensity phenomena.

Compressor-5 Experiments

This class of experiments and the requisite apparatus will be utilized to study the use of electron rings once they are formed. Compressor-5 will study the loading of electron rings with ions of various species (heavy and light), the extraction of loaded rings from the magnetic field of the compressor, and the acceleration of rings by magnetic and electric fields. Emphasis this year has been placed upon:

1. Computer studies of ionization rates of gases utilizing updated cross-section data and the inclusion of Auger effects in excitation calculations. The Auger effects appear to be important predominantly in the ionization of heavy ions.

2. Experiments in outgassing the alumina vacuum chamber with dry hot air at atmospheric pressure. These studies indicate the necessity for cryopumping the apparatus if ions other than hydrogen are to be loaded into the ring.

Injector Facility

The injector has operated efficiently and reliably throughout the year at a nominal energy of 4 MeV and 900 amperes. Operations are normally scheduled for five days per week with a total of 52 hours of operation for experimentation and development and 12 hours of maintenance.

## SUPERCONDUCTIVITY PROGRAM

*Robert C. Acker, William F. Eaton, William S. Gilbert, Edwin F. McLaughlin, Robert B. Meuser, Fred L. Toby, and Ferdinand Voelker.*

Research is conducted in applications of superconductivity to accelerators and particle beam transport.

Bevatron Transport Magnets — Nonpulsed

Two large transport systems, each having 20-cm warm-bore apertures, have been built for Bevatron area use. The dipole has been tested in its horizontal cryostat to a central field of 38kG. The quadrupole doublet has been tested in a vertical floor Dewar to gradients of 5.6 to 5.9kG per inch. With the iron return yoke incorporated in its horizontal cryostat, the doublet should exceed its design gradient of 6kG per inch. Both these systems are undergoing long-term operational tests and magnetic field measurements in our cryogenic laboratory. Actual use in the Bevatron experimental area has been scheduled to begin February to July 1973.

Pulsed Dipoles

Small aperture pulsed dipoles, such as would be used in future accelerators, have been under devel-

opment and test for three years. Such high-field, low-loss magnets are needed for compact rapidly cycled synchrotrons, noncycled storage rings, and slowly cycled boosting storage rings. A central field above 40kG seems desirable for these superconducting accelerators.

Our latest magnets use compacted cable and B-stage epoxy-coated insulation that is cured after the magnet winding is completed. The result is a dense, rigid structure that still allows liquid helium to permeate the windings. Short-sample performance of 39kG central field, with iron return, and low cyclic losses have been achieved. Pulsed magnets with iron return, in the 40 to 50kG central field range, are under construction.

A new system for measuring losses in pulsed superconducting magnets has been put into operation. Previously we used a system based on a Hall multiplier; but certain nonlinearities and drifts limited the precision available. The newly developed system relies on computer developed digital techniques for multiplication of the voltage and current generated signals and the integration of the resultant powers. The greater precision available has allowed us to investigate the small differences in coupling caused by different insulations on the wires in cables.

## Cryopumping

Our cryogenic and vacuum equipment and experience have been utilized in setting up a model test for elements to be used in cryopumping the Bevatron, with some surfaces cooled with liquid nitrogen and other surfaces cooled with liquid or cold gaseous helium. We have built and tested a small cryopanel fed with transfer lines of our design. In our first tests the system pressure was $2.5 \times 10^{-5}$ torr with no cryopumping; it fell to $5 \times 10^{-6}$ torr with liquid nitrogen, and to $4 \times 10^{-7}$ torr when liquid helium was added. The heat load was as we expected so the elements of the tested system seem satisfactory from a performance standpoint. A full-scale system has been installed on the Bevatron.

## Polarized Target Magnet

A superconducting magnet for polarized targets that allows maximum unobstructed solid angle for resultant particles has been designed for, and in conjunction with, the Segre-Chamberlain Physics Group. Construction is scheduled for FY 1973.

## PUBLICATIONS AND PAPERS

R. Acker, W. Gilbert, and F. Voelker, Coupling in Superconducting Braids, Lawrence Berkeley Laboratory Report LBL-571 Abs., Jan. 1972, for Applied Superconductivity Conference, Annapolis, Md., May 1-3, 1972.

R. T. Avery and L. J. Laslett, Eddy Currents, Landau-Damping Coefficients, and their Implications in Electron-Ring Compressor Design, in *Proceedings of the VIII International Conference on High-Energy Accelerators*, M. Hildred Blewett, Ed. (CERN, Geneva, 1971), p. 465.

A. Faltens, E. C. Hartwig, D. Möhl, and A. M. Sessler, Analog Method for Measuring the Longitudinal Coupling Impedance of a Relativistic Particle Beam with its Environment, in *Proceedings of the VIII International Conference on High-Energy Accelerators*, M. Hildred Blewett, Ed. (CERN, Geneva, 1971), p. 338.

W. S. Gilbert, R. B. Meuser, and F. L. Toby, Superconducting Pulsed Dipoles for Future Synchrotrons, Lawrence Berkeley Laboratory Report LBL-924 Abs., May 1972, for 4th International Conference on Magnet Technology, New York, September 19-22, 1972.

W. S. Gilbert, R. B. Meuser, and Ferdinand Voelker, Test Results—Pulsed Superconducting Synchrotron-Type Dipole Magnets, in *Proceedings of the VIII International Conference on High-Energy Accelerators*, M. Hildred Blewett, Ed. (CERN, Geneva, 1971), p. 206.

L. Jackson Laslett and Uwe Schumacher, Enhancement of Landau-Damping Coefficients for Collective Radial Instabilities in an Electron-Ring Accelerator

by an Ancillary $B_\phi$-Field, in *Proceedings of the VIII International Conference on High-Energy Accelerators,* M. Hildren Blewett, Ed (CERN, Geneva, 1971), p. 468.

D. Keefe, Collective-Effect Accelerators, Sci. Amer. 226 (4), 23 (April 1972).

D. Keefe, Status Report on ERA, Berkeley, in *Proceedings of the VIII Conference on High-Energy Accelerators,* M. Hildred Blewett, Ed. (CERN, Geneva, 1971), p. 397.

D. Möhl and A. Sessler, Use of RF-Knockout for Determination of the Characteristics of the Transverse Coherent Instability of an Intense Beam, in *Proceedings of the VIII International Conference on High-Energy Accelerators,* M. Hildred Blewett, Ed. (CERN. Geneva, 1971), p. 334.

J. M. Peterson, Electron Rings for Heavy-Ion Acceleration, IEEE Trans. Nucl. Sci. NS-19 (2), 276 (April 1972).

# Physics Research

## GROUP A EXPERIMENTAL PHYSICS

Arthur H. Rosenfeld in charge

The Group conducts experiments relating to the weak, electro magnetic, and strong interactions of elementary particles. For these studies, use is made of particle accelerators (Bevatron, SLAC, and NAL), liquid hydrogen and deuterium bubble chambers, streamer chambers, and wire chambers. Special liquid-filled and gas-filled multiwire proportional chambers are under development for use in this research.

### BUBBLE CHAMBER EXPERIMENTS

#### K82 Experiment

*Margaret Alston-Garnjost, Angela Barbaro-Galtieri, Stephen Derenzo, Stanley M. Flatté, Jerome H. Friedman, Gerald R. Lynch, Monroe S. Rabin, Frank T. Solmitz, Philip Davis, Maxine Matison, Norman Uyeda, and Victor Waluch*

Scanning and most measuring have been completed on this 35-event/$\mu$b, 12-GeV/c $K^+p$ experiment using film from the SLAC 82-inch hydrogen bubble chamber.

$K^+p \to \pi^+pK^\circ$. Some 1900 events of this type have been fitted to the Bardacki-Ruegg generalization of the Veneziano model.[1] Comparisons are being made with data from the same reaction at 4.6 and 9 GeV/c, and the reaction $\pi^+p \to K^+\bar{K}^\circ p$ at 7 GeV/c.

$K\pi$ scattering. $K\pi$ scattering is being studied in the reaction $K^+p \to K^+\pi^-\Delta^{++}$. The Veneziano model has been tested and found to describe the data. Extrapolations to the pion pole have been made and a phase-shift analysis performed. The results will be published soon.

Low-mass $K\pi\pi$ systems. We have studied the broad $K\pi\pi$ mass enhancements at 1300 MeV in the reactions $K^+p \to pK^+\pi^-\pi^+$ and $pK^\circ\pi^\circ\pi^+$. We observe a two-peak substructure in the $K^\circ\pi^\circ\pi^+$ mass spectrum at 1260 MeV and 1420 MeV. Our estimated contribution of the $K_N(1420)$ accounts for only about half of the 1420 - MeV peak (a discrepancy of about 2.4 standard deviations). The $K^+\pi^-\pi^+$ mass spectrum has a different shape. Further, assuming the $K\pi\pi$ system to be S-wave $1^+K_V(890)\pi$ and $\rho(765)K$, we have fitted separately the $K^+\pi^-\pi^+$ and the $K^\circ\pi^\circ\pi^+$ Dalitz plots. We obtain inconsistent fits. This inconsistency and the differences in the $K\pi\pi$ mass spectra could be explained by an additional contribution of an $I = 0$, S-wave $\pi\pi$ state in $K^+\pi^-\pi^+$. The $K\pi\pi$ angular-decay distributions imply the dominance of the spin-parity state $1^+$ with $M_z = 0$ along the incident beam direction; however, there are other $J^P$ states and states with $M_z \neq 0$. The 1260-MeV $K\pi\pi$ mass region is produced more peripherally than the 1420-MeV region.[2]

$K^+p \to pK^+\phi$ and $pK^+\omega$. We have obtained experimental distributions for the reactions $K^+p \to pK^+\phi$, $\phi \to K^-K^+$ and $K^+p \to pK^+\omega$, $\omega \to \pi^-\pi^+\pi^\circ$ at 12 GeV/c. The cross sections for these reactions are $(11 \pm 1)$ $\mu$b and $(47 \pm 3)$ $\mu$b. We observe $K\phi$, $K\omega$, and $p\omega$ low-mass enchancements with no evidence for narrow structure. The momentum-transfer and angular-decay spectra of these systems have been determined.[3]

---

[1] V. Waluch, S. Flatté, J. H. Friedman, and D. Sivers, Detailed Comparison of the Generalized Veneziano Model with Data on $K^+p \to \pi^+p\,K^\circ$ at 12 GeV/c, Phys. Rev. **D5**, 4 (1972).

[2] P. J. Davis, M. Alston-Garnjost, A. Barbaro-Galtieri, S. M. Flatté, J. H. Friedman, G. R. Lynch, M. S. Rabin, and F. T. Solmitz, Investigation of Low-Mass $K\pi\pi$ Systems in 12 GeV/c $K^+p$ Interactions, Phys. Rev. **D5**, 2688 (1972).

[3] P. J. Davis, M. Alston-Garnjost, A. Barbaro-Galtieri, S. M. Flatté, J. H. Friedman, G. R. Lynch, M. S. Rabin, F. T. Solmitz, and N. M. Uyeda, Experimental Spectra for 12 GeV/c $K^+p \to p\,K^+\phi$ and $pK^+\omega$, Nucl. Phys. **B44**, 344 (1972).

## $\pi$82 Experiment

*Margaret Alston-Garnjost, Angela Barbaro-Galtieri, Stephen Derenzo, Stanley M. Flatté, Jerome H. Friedman, Gerald R. Lynch, Monroe S. Rabin, Frank T. Solmitz, Fred Buhl, Larry Epperson, Ronald Ott, and Serban Protopopescu*

A total of 700 000 pictures (45 events/$\mu$b) using 7-GeV/c $\pi^+$ were taken in 1969 at the SLAC 82-inch hydrogen bubble chamber. All events have been measured at least once, and additional measurements have been made to determine the measuring efficiency.

Anomaly in the $\pi^+\pi^-$ system. An analysis of the final states $\pi^+\pi^-\Delta^{++}$ and $K^+K^-\Delta^{++}$ in terms of pion exchange is in progress. We have observed a definite, narrow anomaly in the $\pi^+\pi^-$ system near 980 MeV, both in the mass distribution and in the angular distributions in the reaction $\pi^+p \to \Delta^{++}\pi^+\pi^-$.[1] The anomaly in the mass distribution exhibits the following characteristics: a shoulder between 910 and 950 MeV, a sharp drop between 950 and 980 MeV, and a flat region above 980 MeV. The sharp drop in the mass distribution, when combined with information on spherical harmonic moments of the $\pi^+\pi^-$ system in this reaction, implies that the *effect we are observing is in the s-wave amplitude.*

The systems we are studying can be analyzed as final states in a $\pi^+\pi^-$ scattering process; the coincidence in mass of the anomaly we are observing and the strong rise in $K\bar{K}$ cross section at threshold then has a natural interpretation. We are seeing the effect of unitarity (conservation of probability) in a two-channel system. Since the $K\bar{K}$ system at threshold is an s-wave, this interpretation requires that the $\pi^+\pi^-$ anomaly at 980 MeV is an s-wave effect, in agreement with our conclusion from the data.[2]

$\pi\pi$ phase-shift analysis. From reactions $\pi^+p \to \pi^+\pi^-\Delta^{++}$ and $\pi^+p \to K^+K^-\Delta^{++}$ we have made an energy-dependent $\pi\pi$ phase-shift analysis for $\pi\pi$ energies between 550 and 1150 MeV. A unique solution was obtained for the $I = 0$ s-wave, which was described by a $2 \times 2$ M-matrix which coupled $\pi\pi$ and $\bar{K}K$ channels. The phase ($\delta_0^0$) obtained for the s-wave rules out the "up" solution (narrow $\epsilon$) and varies rapidly before the $\bar{K}K$ threshold ($\delta_0^0 = 90°$ at 900 MeV, $\delta_0^0 = 180°$ at $\sim$990 MeV). All the fits with reasonable $\chi^2$ gave essentially the same phases and inelasticities within the computed errors. Using the M-matrix parametrization, we looked for poles in the $I = 0$ s-wave amplitude. We always found one pole ($S^*$) on the second Riemann sheet at $980 \pm 6 - i(37 \pm 8)$, which can be interpreted as a $K\bar{K}$ bound state. We believe the evidence for this pole to be conclusive.[3]

Energy dependence of inclusive distributions. By analyzing all event types in a subsample of the SLAC film, we have studied the inclusive reactions $\pi^+p \to \pi^\pm$ + anything and $\pi^-p \to \pi^-$ + anything. These data have been compared with data at 3.7 GeV/c obtained by the Trilling/Goldhaber Group, and with data from $\pi^+p \to \pi^-$ interactions at 8.05 GeV/c and $\pi^-p \to \pi^-$ at 8.05 and 18.5 GeV/c obtained at BNL by a Notre Dame group.

By studying these data in the center-of-mass, laboratory, and projectile systems, we have observed in some detail the approach to scaling in each of three kinematical regions: pionization region, target fragmentation region, and projectile fragmentation region.

One expects that at very high energies the inclusive distributions of the invariant structure function $F(x)$ will be independent of the total c.m. energy for each reaction, and at $x = 2p_{11}/\sqrt{s} = 0$, will be independent of the nature of the incident particles. The data suggest that the distributions from the three reactions may indeed converge to the same value at very large energies, although it seems clear that we are far from scaling in this kinematic region at present accelerator energies.

Recently, a central question has been the rate at which the proton fragmentation will approach the conjectured scaling limit. To investigate this, we looked at all three reactions in the laboratory system and saw a rapid fall in the cross sections for the nonexotic reactions $\pi^+p \to \pi^+$ and $\pi^-p \to \pi^-$ as the energy increases. The exotic reaction $\pi^+p \to \pi^-$ has a very small energy dependence, suggesting that although it has not yet reached the scaling limit, it may not be very far from it.

The data also show that the cross section for $\pi^- p \to \pi^-$ is indeed approaching that for $\pi^+ p \to \pi^-$ at high energy.[4, 5]

Quasi-two-body reactions. Using the 2-prong events, we are making a study of the quasi-two-body reactions $p\rho^+, \Delta^{++}\pi^\circ$, and $N^{*+}\pi^+$.

Properties of the $B^+(1235)$ meson. The mass, width, D/S ratio, production cross section, and branching ratios of the $B^+(1235)$ meson are determined from the reaction $\pi^+ p \to B^+(1235)\, p$ at 7.1 GeV/c. Chung and Berman-Jacob analyses of the $\omega(784)\pi$ decay angular distributions show that the spin-parity of the B(1235) is $J^P = 1^+$ or $2^+, 3^-, \ldots$. The B(1235) production cross section is found to be $42^{+4}_{-7}$ $\mu$b at this momentum; and upper limits for the branching ratios for the decay of the B(1235) into other possible channels relative to $\omega\pi$ were determined to be $\pi\pi/\omega\pi < 0.15$, $\eta\pi/\omega\pi < 0.15$, $K\bar{K}/\omega\pi < 0.08$, and $\phi\pi/\omega\pi < 0.025$ with 90% confidence level.

[1] M. Alston-Garnjost, A. Barbaro-Galtieri, S. M. Flatté, J. H. Friedman, G. R. Lynch, S. D. Protopopescu, M. S. Rabin, and F. T. Solmitz, Observation of an Anomaly in the $\pi\pi$ System at 980 MeV, Phys. Letters **36B**, 152 (1971).

[2] S. M. Flatté, M. Alston-Garnjost, A. Barbaro-Galtieri, J. H. Friedman, G. R. Lynch, S. D. Protopopescu, M. S. Rabin, and F. T. Solmitz, Analysis of the Observed Anomaly in $\pi\pi$ S-Wave Scattering near $K\bar{K}$ Threshold, Phys. Letters **38B**, 232 (1972).

[3] S. D. Protopopescu, M. Alston-Garnjost, A. Barbaro-Galtieri, S. M. Flatté, J. M. Friedman, T. A. Lasinski, G. R. Lynch, M. S. Rabin, and F. T. Solmitz, $\pi\pi$ Phase Shift Analysis from Reactions $\pi^+ p \to \pi^+\pi^-\Delta^{++}$ and $\pi^+ p \to K^+K^-\Delta^{++}$ at 7.1 GeV/c, Lawrence Berkeley Laboratory Report LBL - 787 Rev., Apr. 1972, presented at Intern. Conf. on Meson Spectroscopy, Philadelphia, Pa., Apr. 28-29, 1972.

[4] A. Alston-Garnjost, Energy Dependence of Inclusive Distributions in Pion Induced Reactions, Lawrence Berkeley Laboratory Report LBL - 735, Feb. 1972, presented at the Conference on Inclusive Reactions, U. C. Davis, Feb. 4-5, 1972.

[5] M. Alston-Garnjost *et al.*, Energy Dependence of Inclusive Distributions in Pion Induced Reactions, Lawrence Berkeley Laboratory Report LBL - 733, Feb. 1972, submitted to Physics Letters B.

## High-Energy Photoproduction Experiment

*Berkeley-SLAC-Tufts collaboration: LBL authors from July 1971 to June 1972 were K. C. Moffeit, W. J. Podolsky, M. S. Rabin, and A. H. Rosenfeld*

The collaboration on the high-energy (3, 5, 10 GeV) photoproduction experiment has taken 2 00 000 pictures in the SLAC 82-inch bubble chamber with the Compton back-scattered laser beam. Scanning and preliminary analysis on all the film was completed during FY 72. The exposures were

| | | |
|---|---|---|
| deuterium | 0.8, 3, 5, 6.5 GeV | 50 000 pictures |
| hydrogen | 1.5 GeV | 20 000 pictures |
| | 3 GeV | 300 000 pictures |
| | 5 GeV | 460 000 pictures |
| | 10 GeV | 1 300 000 pictures |

The polarization of the incident photon beam allows us to separate Pomeron exchange (via the vector dominance model) from other particle exchanges. Using this information we have studied $\rho^\circ$, $\omega$, $\Delta^{++}$, and $\rho'$.

During FY 72 three papers were published,[1-3] and three others were submitted to conferences and/or for publication.[4-6] The last paper, on the $\rho'$ meson, covers the most important discovery to come out of the high-energy photon work this year. The $\rho'$ is interesting for several reasons:

(a) It was badly needed to complete the Vector Dominance Model.

(b) It is of great interest to theorists who wonder if the Veneziano Model really implies the existence of hundreds of daughter mesons—apparently it *does*.

(c) The $\rho'$ has unexpected characteristics: we all thought that its dominant, or at least most detectable, decay mode would be into $\pi^+\pi^-$. Instead its partial width to $2\pi$ seems to be less than a few MeV, out of a full width of about 600! Have we discovered the wrong particle? Have we just discovered a threshold effect: (Vector Meson $\to \rho\pi\pi$)? Can the meson be explained by the Deck mechanism? Many interesting questions can be partly answered with our data; but more events will be needed for more complete answers.

An international working session to complete the analysis and publication of the high-energy photon work was held at SLAC, starting in June 72. We worked on the $\rho'$, on the observation of a small s-channel helicity-flip amplitude in vector meson photoproduction, and on summary papers to be entitled "Total and Partial Cross Sections" and "Vector Meson Production."

Work continues on multiparticle final states and on longitudinal phase-space analyses.

All in all, it was a very productive year.

---

[1] K. C. Moffeit *et al.*, The $\rho^{\circ}$–$\omega$ Interference Parameters in Diffractive Photoproduction of Vector Mesons on Hydrogen, Nucl. Phys. **B29**, 349 (1971).

[2] J. Ballam *et al.*, Bubble-Chamber Study of Photoproduction by 2.8- and 4.7-GeV Polarized Photons. I. Cross-Section Determinations and Production of $\rho^{\circ}$ and $\Delta^{++}$ in the Reaction $\gamma p \rightarrow p\pi^{+}\pi^{-}$, Phys. Rev. **D5**, 545 (1972).

[3] K. C. Moffeit *et al.*, A Study of the Inclusive Reaction $\gamma p \rightarrow \pi^{-}$ + (Anything) with Polarized Photons at 2.8, 4.7, and 9.3 GeV, Phys. Rev. **D5**, 1603 (1972).

[4] A. H. Rosenfeld and P. Söding, Photoproduction of Vector Mesons—Experimental, Lawrence Berkeley Laboratory Report LBL-539, submitted to Proceedings of the International School of Subnuclear Physics, Erice, Sicily, July 1971.

[5] J. Ballam *et al.*, Bubble Chamber Study of $\omega$-Meson Photoproduction with Polarized Photons at 9.3 GeV, Lawrence Berkeley Laboratory Report LBL-509, Nov. 1971; and SLAC-PUB-980; presented at the International Symposium on Electron and Photon Interactions at High Energies, Ithaca, New York, Aug. 1971.

[6] G. Smadja *et al.*, Photoproduction of a New Vector Meson by Linearly Polarized 9.3 GeV Gamma Rays, Lawrence Berkeley Laboratory Report LBL-991, June 1972, presented at 3rd International Conference on Experimental Meson Spectroscopy, Philadelphia, Apr. 28-29, 1972.

## Low-Energy Photoproduction

In contrast to the higher-energy work which was a Berkeley, SLAC, Tufts collaboration, this lower-energy experiment using the backscattered laser beam at SLAC, is entirely LBL Group A: R. Gordon Moorhouse (visiting from Glasgow), Horst Oberlack, Monroe Rabin, Alan Rittenberg, A. H. Rosenfeld, and Gerard Smadja.

The laser beam has been made to work down to 760 MeV, and the following pictures have been taken to study photoproduction with polarized photons in the "2nd" and "3rd" resonance regions.

| Number of pictures | Date taken | BC filling | $E^{\gamma}_{Max}$ (MeV) | Events per $\mu$b |
|---|---|---|---|---|
| 110K | Nov 71 | $D_2$ | 780 | 5 |
| 290K | Jan 72 | $H_2$ | 760 | 16.4 |
| 110K | Jan 72 | $H_2$ | 900 | 5 |
| 90K | Feb 72 | $D_2$ | 780 | 5 |

In addition to taking and analyzing the film, we have written a new partial-wave analysis program, and have checked out on an updated compilation of all the world's low-energy photoproduction data. This new partial-wave analysis is, in fact, the most complete available, and is the current "world standard." During FY 73, we hope to complete the analysis of our own data and to put it into the new partial-wave analysis.

## K70 Experiment

*Robert D. Tripp*

In collaboration with the University of Chicago, we are analyzing 600 000 pictures taken in the 25-inch hydrogen bubble chamber with a $K^{-}$ beam at different momenta from 0.87 to 1.0 GeV/c. The purpose of the experiment is to study in more detail the formation of Y*'s in this energy region, as well as to study the sequential reactions:

$$K^{-}p \rightarrow \Sigma(1765) \rightarrow \Lambda(1520) + \pi$$
$$\rightarrow \Sigma(1385) + \pi.$$

The film has been completely scanned and all 70 000 events have been measured on the Spiral Reader. Analysis of the measurements and some remeasuring are now in progress.

## Antiprotons in Deuterium

*Margaret Alston-Garnjost, Ronald H. Huesman, Ronald R. Ross, and Frank T. Solmitz*

This study of antiproton interactions in deuterium is being done by a collaboration of three Italian laboratories (Padua, Pisa, Turin) with LBL physicists. The CERN 81-cm bubble chamber was exposed to antiprotons with momenta between 1.0 and 1.6

GeV/c, yielding 182 000 events. First and second measurements of these events have been completed on the Spiral Reader, and the data are now being analyzed at LBL and in Italy. A paper is being written on the antiproton-neutron cross section near 1.3 GeV/c.

## $\pi^-$p Inelastic Reactions

*Arthur H. Rosenfeld, Gerard Smadja, David J. Herndon, Larry Miller, Ronald Longacre (LBL); Roger Cashmore, and David Leith (SLAC)*

A fairly recent discussion of this work was presented at the XIV IUPAP Conference at Batavia, Ill., in Sept. 1972, and in the form of LBL-1065; it may be summarized as follows:[1-5]

Elastic phase-shift analysis has provided us with an impressive list of resonances, which is both the essence of our understanding of baryon spectroscopy and also the main testing ground for many of the ideas on the dynamics of hadronic processes. The agreement among the many independent groups is very impressive, and gives confidence in the resulting scattering amplitudes.

Corresponding investigation of the inelastic scattering reactions has not kept pace with the elastic investigations. This derives not only from the lack of data with high statistics and systematic spread in energy but also from the complexity of the phenomenological analysis. However, the study merits the effort. The inelastic cross section represents a very substantial fraction of the total $\pi$N cross section, even at 1.0 GeV/c; and it is therefore intrinsically interesting to understand the scattering process. In addition, the inelastic decays of N* are a very specific signature of the state and its properties, and therefore an important study in their own right. Finally, for resonances with very small coupling to the elastic channel, these studies are the only means of investigating the resonance in a formation experiment.

In the resonance region the principal inelastic reaction is $\pi N \rightarrow \pi\pi N$. We have therefore made a detailed study of this channel in the c.m. energy range 1.3 to 2.0 GeV. In previous analyses of this reaction, two approaches have been taken:

(a) selection of subsamples of the data to isolate specific reactions, e.g., $\pi N \rightarrow \pi\Delta$; and
(b) the use of an isobar model in an effort to fit the whole reaction, taking into account the effects due to strongly overlapping resonances in the final state.

We have developed the second of these approaches by including many more intermediate states and using the maximum likelihood technique in confronting the data with theory. These developments have enabled us to produce a continuous solution from energy-independent fits throughout the energy range we consider.

We have strong evidence for the existence of a resonance in D13 at 1700 MeV. While this has been suggested in previous EPSA and photoproduction experiments, the most recent EPSA finds no evidence for it at current sensitivity; however, such a state has long been required by the quark model. Furthermore, we have strengthened the interpretation of many other resonances while casting serious doubt on the existence of a P33 state at ~ 1700 MeV.

The first reliable determination of $\sigma$N and $\rho$N partial-wave amplitudes has indicated the appearance of many resonances in this channel. These, together with our improved knowledge of the $\pi\Delta$ system, begin to allow a complete picture of the $\pi$N inelastic reactions.

Finally, we are at present using these amplitudes to study resonance parameters and coupling and their relation to other theories of hadron interactions.

---

[1] A. D. Brody, R. J. Cashmore, A. Kernan, D. W. G. S. Leith, B. S. Levi, B. C. Shen, J. P. Berge, D. J. Herndon, R. Longacre, L. R. Price, A. H. Rosenfeld, and P. Söding, Experimental Results on the Reactions $\pi^- p \rightarrow \pi\pi N$ in the c.m. Energy Range 1400-2000 MeV, Phys. Rev. D4, 2693 (1971).

[2] A. D. Brody, R. J. Cashmore, A. Kernan, D. W. G. S. Leith, B. S. Levi, B. C. Shen, D. J. Herndon, L. R. Price, A. H. Rosenfeld, and P. Söding, The Reaction $\pi^- p \rightarrow \pi^+\Delta^-$ at CMS Energies 1640-1760 MeV, Phys. Letters **34B**, 665 (1971).

[3] Ronald Longacre, Ph.D. Thesis, Lawrence Berkeley Laboratory Report LBL-948 (in preparation).

[4] L. R. Miller, Isobar Model Fit to the Reaction $N\pi \rightarrow N\pi\pi$: Fitting Procedures and Fits at 1.7 BeV, Ph.D. Thesis, Lawrence Berkeley Laboratory Report LBL-38, Sept. 1971.

[5] G. Smadja, Resonances That Overlap, Lawrence Berkeley Laboratory Report LBL-382, Oct. 1971.

## $\pi$66 Experiment

*Orin L. Dahl and Paul L. Hoch*

Between February and August 1966, 655 000 pictures were taken of $\pi^+$ mesons incident on deuterium in the 72-inch bubble chamber. The beam momentum ranged from 1.1 to 4.2 GeV/c. A thesis covering various aspects of strange-particle production above 2.7 GeV/c is being completed.

## BP66 Experiment

*Jerome H. Friedman, Clifford Risk, and Dennis B. Smith*

Multiparticle production. We have shown that the negative transverse angle correlation between leading particles in multiparticle production, required by momentum and energy conservation, is substantially reduced if the secondaries are correlated in longitudinal momentum with the leading particles. The multiperipheral model, which produces the pions with ordered longitudinal momenta, and a pionization model that produces each pion randomly in longitudinal phase space, are both compared with experimental results for $pp \rightarrow pp\pi^+\pi^+\pi^-\pi^-$ at 23 GeV/c.[1] The data, which strongly favor random pion production, are from a 72 000-picture proton exposure made in the Brookhaven National Laboratory 80-inch hydrogen bubble chamber in November 1966. Incident beam momenta were 13, 18, 21, 24, and 28.5 GeV/c; and roughly equal amounts of film were exposed at each of the five momenta.

[1] J. H. Friedman, Clifford Risk, and Dennis B. Smith, Long-Range Correlations and the Dynamics of Multiparticle Production, Phys. Rev. Letters 28, 191 (1972).

## P65 Experiment

*Eugene Gellert*

$\pi^-$ production. An exposure of the 72-inch hydrogen bubble chamber to protons at 5.5 and 6.6 GeV/c was made in 1965. Using this film, we are studying the inclusive reactions $pp \rightarrow Z$ + anything, where $Z = \pi^-, \pi^+$, or p (but *not* n). We have found that the reaction $pp \rightarrow \pi^-$ + anything displays "limiting fragmentation" behavior at our energy. That is, when we compared the $\pi^-$ distribution at 6.6 GeV/c with distributions at higher energies, we found that for $p_\perp < 0.6$ GeV/c and Feynman's $x < -0.4$, the laboratory differential cross section $d^2\sigma/dp_\perp dp_{||}$ is independent of energy. The structure function $\rho(x,p_\perp,s) = Ed^3\sigma/dp^3$ is found *not* to be energy independent and is found *not* to be factorizable into functions of transverse and longitudinal momentum.[2]

An additional paper, which reports our results for $Z = \pi^+$ and *proton* as well as $Z = \pi^-$, has been finished.

[1] Eugene Gellert, The Inclusive Reaction $pp \rightarrow \pi^-$ + Anything at 6.6 GeV/c Compared to Higher Energies, in *Proceedings of the International Conference on Inclusive Reactions*, R. L. Lauder, Ed. U. C. Davis, 1972), p. 198.

[2] Eugene Gellert, The Inclusive Reactions $pp \rightarrow \pi^\pm$ + Anything and $pp \rightarrow p$ + Anything at 6.6 GeV/c compared to Higher Energies, Ph.D. Thesis, Lawrence Berkeley Laboratory Report LBL-749, Oct. 1972.

## K65 Experiment

*Roger O. Bangerter, Angela Barbaro-Galtieri, Terry S. Mast, Frank T. Solmitz, and Robert D. Tripp*

During the period from August 1965 to October 1967, the Berkeley 25-inch hydrogen bubble chamber was exposed to a $K^-$ beam of about 400 MeV/c. Roughly 1.4 million pictures were taken, 60 000 of which were in deuterium. The incident momenta range from 280 to 470 MeV/c. Most of the pathlength is close to 390 MeV/c, the momentum required to form the $Y^{*\circ}(1520)$ resonance.

We are also analyzing 115 000 pictures from an exposure of the 25-inch hydrogen bubble chamber to a $K^-$ beam with momenta between 200 and 300 MeV/c. This exposure increases the world's data in this energy range by a factor of 50. These pictures were taken by the Trilling/Goldhaber Group to study the reaction $K^-p \to \Lambda\pi^\circ$.

The analysis of all types of $K^-p$ interactions in the above exposures is nearly completed.

Analysis of $K^-p \to \Lambda\pi^+\pi^-$ in the region of the $\Lambda(1520)$. In a study of the reaction sequence $K^-p \to \Lambda(1520) \to \Sigma(1385)\,\pi \to \Lambda\pi^+\pi^-$, we have measured the decay $\Lambda(1520) \to \Sigma(1385)\,\pi$ to be $1.40 \pm 0.26$ MeV, which is twice as large as the previous measurement of $0.67 \pm 0.17$ MeV. We used a sample of 9200 events of the type $K^-p \to \Lambda\pi^+\pi^-$ obtained in the 25-inch hydrogen bubble chamber. The incident momenta range from 300 to 470 MeV/c. After correction for detection efficiency, an energy-independent partial-wave analysis was performed using an isobar model. The model included a coherent mixture of six partial waves to describe all mass distributions, angular distributions, and the polarization of the lambda. The $\Sigma(1385)\pi$ decay mode was found to dominate the $\Lambda\pi^+\pi^-$ decay of the $\Lambda(1520)$ in disagreement with the results of a production reaction study of the same decay.

Mixing between the $\Lambda(1520)$ and the $\Lambda(1690)$ has been used in the past to describe the $J^P = 3/2^-$ baryons as SU(3) singlet and octet. Combining our rate for $\Lambda(1520)$ with a recently measured rate for $\Lambda(1690) \to \Sigma(1385)\pi$, we calculate the mixing angle $|\theta| = 63°$ to 83°. This is in strong disagreement with the mixing angle derived from the two-body D-wave decays of the singlet and octet of $-25° \pm 6°$. Thus, some modification of the usual SU(3) description of these states needs to be made. A possible explanation of this discrepancy may involve mixing of these states with another octet as predicted by the quark model.[1,2]

Branching ratio of $\Sigma(1385)$. A sample of about 1800 events of the types $K^-p \to \Sigma^+\pi^-\pi^\circ$, $K^-p \to \Sigma^-\pi^+\pi^\circ$, and $K^-p \to \Sigma^\circ\pi^+\pi^-$ has been analyzed. These final states are strongly coupled to the $\Lambda(1520)$, and comparison of these channels with the $\Lambda\pi^+\pi^-$ results has yielded a new measurement of the $\Sigma\pi/\Lambda\pi$ branching ratio of the $\Sigma(1385)$. A paper on these results has been submitted to Physical Review.[3]

$\Sigma$ lifetimes and branching ratios. Currently there is some disagreement among the published values of the $\Sigma^-$ lifetime. We are now measuring the lifetimes for both $\Sigma^+$ and $\Sigma^-$. We are also measuring the branching ratio for $\Sigma^+ \to p\pi^\circ$ and $\Sigma^+ \to n\pi^+$. A detailed study of the detection efficiency for the events used in these measurements is in progress.

$\Sigma N$ interactions. About 75 events each of the reactions $\Sigma^+p \to \Sigma^-p$, $\Sigma^-p \to \Sigma^\circ n$, and $\Sigma^-p \to \Lambda n$ with $\Sigma$ momenta from 150 to 600 MeV/c are being analyzed. Cross sections for 50-MeV/c intervals and angular distributions for 100-MeV/c intervals are being determined. There does not appear to be any significant resonant structure. About 1000 events of $\Sigma^-p \to \Lambda n$ with polarized $\Sigma^-$ at rest are being studied to measure the $\Lambda$ polarization. A paper on these results will be completed in the near future.

---

[1] T. S. Mast, M. Alston-Garnjost, R. O. Bangerter, A. Barbaro-Galtieri, F. T. Solmitz, and R. D. Tripp, A Study of the Decay $\Lambda(1520) \to \Sigma(1385)\pi$, Phys. Rev. Letters 28, 1220 (1972).

[2] T. S. Mast, M. Alston-Garnjost, R. O. Bangerter, A. Barbaro-Galtieri, F. T. Solmitz, and R. D. Tripp, A Study of $K^-p \to \Lambda\pi^+\pi^-$ in the Region of the $\Lambda(1520)$, Lawrence Berkeley Laboratory Report LBL-301, Aug. 1971, submitted to Physical Review.

[3] T. S. Mast, R. B. Bangerter, M. Alston-Garnjost, A. Barbaro-Galtieri, L. K. Gershwin, F. T. Solmitz, and R. D. Tripp, A Study of $K^-p \to \Sigma\pi\pi$ in the Region of the $\Lambda(1520)$, Lawrence Berkeley Laboratory Report LBL-954, June 1972, submitted to Physical Review.

## K63 Experiment

*P. H. Eberhard, R. D. Estes, J. H. Friedman, A. R. Kirschbaum, M. Pripstein, and R. R. Ross*

An exposure of the 72-inch hydrogen bubble chamber to a $K^-$ beam having laboratory momenta of 1.7, 2.1, 2.47, 2.59, 2.64, and 2.73 GeV/c was made,

totaling 30 events/b. The film was taken between mid-1963 and early 1965. More than 300 000 events have been measured.

$K^-p$ four-prong reactions. Approximately 48 000 $K^-p$ interactions producing four charged particles have been measured on the Spiral Reader. Analysis is in progress. Using the one-pion-exchange reaction $K^-p \rightarrow K^-\pi^-\Delta^{++}$, we have measured the cross section for the process $K^-\pi^- \rightarrow K^-\pi^-$ from threshold to 0.84 GeV.[1]

Resonance production. Analysis of resonance production in $K^-p$ interactions, including the study of interference effects between the two $\Sigma(1660)$ resonances, is continuing.

[1] A. R. Kirschbaum, E. Colton, P. M. Dauber, J. H. Friedman, and P. E. Schlein, Measurement of the T = 3/2 $K\pi$ Elastic Scattering Cross Section Using the Durr-Pilkuhn Form Factor, Phys. Rev. D4,3254 (1971).

## SPARK CHAMBER AND COUNTER STUDIES

*Orin I. Dahl and Morris Pripstein*

### Neutral Final States in $\pi^-p$ Interactions

In collaboration with the Kenney Group, a series of spark-chamber experiments at the Bevatron has been undertaken to study various neutral final states in $\pi^-p$ interactions. The program involved three separate experimental set-ups at the accelerator. The data-collection phase was completed in the spring of 1970 with a total of about 1.25 million pictures taken. At present, we are near the end of an intensive analysis of these data which includes a study of eight separate research topics. Since many of the analysis problems are common to the various reactions being studied, the data analysis on each of these topics has proceeded in parallel rather than sequentially. Final results will be forthcoming for publication over the next six months. Some of the major topics under investigation are:

1. A high-statistics measurement of the neutral decay mode branching ratios of the $\eta$ meson in a study of the reaction $\pi^-p \rightarrow n\eta$ just above threshold.
2. A search for the hitherto undetected $n\eta$ decay mode of the two N* resonances with masses both about 1680 MeV and $J^P = 5/2^+$ and $5/2^-$. For this purpose we have measured the differential cross sections for the reaction $\pi^-p \rightarrow n\eta$ at six different $\pi^-$ beam momenta between 880 and 1130 MeV/c. About 500 000 pictures have been taken which contain about 1000 events of the $n\eta$ final state at each momentum. A partial-wave analysis of the differential cross section will determine the $n\eta$ contribution to these spin 5/2 resonances.
3. A study of the reaction $\pi^-p \rightarrow n\pi^0\pi^0$ between 1.5 and 2.5 GeV/c to analyze the properties of the $\pi^0\pi^0$ system in a search for scalar mesons and to measure the $\pi\pi$ phase shifts. In addition, data were taken to measure the charge-exchange differential cross section. We have collected about 500 000 pictures under various operating conditions. Of these, approximately 75 000 four-shower and 45 000 three-shower events were collected for purposes of studying the final state $n\pi^0\pi^0$. In addition, approximately 30 000 two-shower charge-exchange events were collected.

### Polarization Parameter in $\pi^-p \rightarrow n\pi^0$

Using much of the same equipment as in the preceding spark-chamber experiments, but replacing the $LH_2$ target with a polarized target developed at LBL, we have set up an experiment at the Bevatron to measure the polarization parameter in the reaction $\pi^-p \rightarrow n\pi^0$ as a function of angle and beam momentum in the region of 1 to 2 GeV/c. This is an important parameter for purposes of phase-shift analysis in the $\pi p$ system. The data-taking will continue until the end of 1972.

### Counter Experiment at NAL

In collaboration with members of the Kenney group of LBL and scientists from Cal-Tech and NAL, we are preparing an experiment to measure the differential

cross sections of the reactions $\pi^- p \rightarrow n\pi^0$ and $\pi^- p \rightarrow n\eta$ in the beam momentum region of 20 to 200 GeV/c. A measurement of the forward differential cross sections of the $n\pi^0$ and $n\eta$ reactions provides the most direct experimental test of the validity of the simple Regge theory at these high energies. In addition, the $\pi^- p \rightarrow \pi^0 n$ cross section at zero degrees is a sensitive measure of the small difference between the $\pi^- p$ and $\pi^+ p$ cross sections, and thus of the asymptotic behavior of these hadronic total cross sections. Finally, as an important by-product of the experiment, we will be able to measure the reaction $\pi^- p \rightarrow n\pi^0\pi^0$ to search for new I = 0 and I = 2 boson resonances.

The equipment is presently being built, and construction will be completed by the end of 1972.

## STREAMER CHAMBER EXPERIMENTS

Considerable work has been done on the $\Xi^*$ experiment. This collaboration between Group A, U.C. Riverside, and SLAC uses the SLAC streamer chamber to study $\Xi^*$'s and $\Omega$'s produced in hydrogen from a beam of 7 GeV/c $K^-$. During the past year the pencil beam was checked out, and the liquid-hydrogen target was installed and aligned with the beam; the trigger counters and proportional chambers were made, tested, and installed. In a successful run in June, 250 000 pictures were obtained. Another 2 million pictures were taken in July and August, and scanning and measuring of this film will proceed throughout the next year.

## COSMIC RAY EXPERIMENTS

### High Altitude Particle Physics and Cosmic Ray Experimental Facility

*Louis W. Alvarez and Michael A. Wahlig (LBL); Andrew Buffington, Richard A. Muller, George Smoot, and Lawrence H. Smith (Space Sciences Laboratory, University of California, Berkeley)*

In collaboration with the Space Sciences Laboratory, University of California, Berkeley, a second flight of the superconducting magnetic spectrometer was made on May 8, 1970. This flight accumulated 40 000 pictures of cosmic rays with charge 2 or greater. The data of this flight confirmed the results seen in the first flight made in September 1969. The spectral indices of the secondarily produced nuclei of Li, Be, B, and N have a steeper spectrum than that of C and O.[1, 2] This indicates that the higher energy C and O nuclei traverse less intergalactic material on the journey from their originating source. It is not easy to explain why these higher energy particles should be younger unless there is a source of higher energy particles close to us. If this were true, however, there should be anisotrophy which as yet has not been detected.

A new magnet and gondola are well on their way to completion.[3] This gondola will have a stronger magnet, less material in the beam, better charge resolution, and direct viewing of the spark chambers by the magnet. We will use this gondola to measure the isotopic relative abundances and perform an $e^-/e^+$ experiment. The first flight is scheduled for summer 1972.

We have completed a preliminary phase-B study of the HEAO-B satellite experiment. We will measure the electron/positron fluxes and search for antimatter on this experiment.[4-7] The nuclear fluxes will also be measured with high statistics in order to search for any anisotropy.

A contract was given to Airesearch to build a cryostat model with a one-year lifetime. A prime contractor is now being selected to fabricate the detector portions of the experiment. We will be funded this year to perform the phase-B design of the engineering hardware. Flight is anticipated in the first quarter of 1977.

---

[1] G. F. Smoot, A. Buffington, L. A. Smith, L. W. Alvarez, and M. A. Wahlig, Primary Cosmic Ray Nuclei Rigidity Spectra, presented at Joint Meeting of APS and AAS, Puerto Rico, 1-4 Dec. 1971.

[2] A. Buffington, L. H. Smith, G. Smoot, M. A. Wahlig, and L. W. Alvarez, Measurement of the Primary Cosmic Ray Nuclear Rigidity Spectra for Individual Elements of Charge $Z \geqslant 2$, in *12th International Conference on Cosmic Rays*, Vol. 1 (U. Tasmania, Hobart, 1971), p. 147.

[3] L. H. Smith, A. Buffington, M. A. Wahlig, and P. Dauber, Super conducting Magnetic Spectrometer for Cosmic Ray Nuclei, Rev. Sci. Instr. 43, 1 (1972).

[4] A. Buffington, L. H. Smith, G. Smoot, M. A. Wahlig, and L. W. Alvarez, Search for Antimatter in the Primary Cosmic Rays using a Magnetic Spectrometer, in *12th International Conference on Cosmic Rays,* Vol. 1 (U. Tasmania, Hobart, 1971, p. 146.

[5] L. H. Smith, A. Buffington, G. F. Smoot, and L. W. Alvarez, Search for Antimatter in the Cosmic Rays, presented at Joint Meeting of the APS and AAS, Puerto Rico, 1-4 Dec. 1971.

[6] A. Buffington, R. A. Muller, L. H. Smith, and G. F. Smoot, High Energy Particle Astronomy, in *Proceedings of the American Association for the Advancement of Science,* Dec. 1971.

[7] A. Buffington, L. H. Smith, G. F. Smoot, L. W. Alvarez, and M. A. Wahlig, Search for Antimatter in Primary Cosmic Rays, Nature 236, 335 (1972).

## SEARCH FOR MONOPOLES

*Luis W. Alvarez, Philippe Eberhard, Horst Oberlack, and Ronald R. Ross*

Work is progressing on a target and trap for the approved experiment to search for monopoles produced by the NAL beam. An exposure of the target is anticipated early in 1973. This experiment has been delayed about one year because of delay in the schedule of the NAL accelerator.

## DETECTOR DEVELOPMENT

### Detectors Using Liquified Noble Gases

*Luis W. Alvarez, Stephen E. Derenzo, Gerard Smadja, Robert G. Smits and Haim Zaklad (LBL); Richard A. Muller (Space Sciences Laboratory)*

We are investigating the use of liquid xenon-filled ionization and proportional chambers for the accurate localization of charged particles and $\gamma$ rays.[1-3] A minimum ionizing particle passing through 100$\mu$ of liquid xenon produces 2000 ion pairs, making possible thin multiwire chambers with very close wire spacings. In addition, the high Z (54) and high density (3.1 gm/cc) of liquid xenon make it an excellent medium for the conversion of $\gamma$ rays. One fundamental problem, however, has been electronegative impurities which are able even in small concentrations to capture the ionization electrons and form slow, massive ions. Severe electronegative contamination (equivalent to several ppm $O_2$) is observed in cases when the liquid contains only tens of ppb $O_2$ and $N_2$. Recently we have learned to use swarms of field emission electrons to sweep virtually all the remaining electronegative impurities from the active volume of our chambers. The process takes a few minutes and need be repeated only every few hours. Once it is insured that the electrons remain free, they will readily avalanche on fine metal electrodes in electric fields above $10^6$ V/cm. The resulting pulses rise in $10^{-7}$ sec and are proportional to the initial ionization. The best energy resolution we have attained is 10.5% FWHM. The charged-particle detection efficiency is 100%. We have measured the space resolution to be better than 15$\mu$ rms in the ionization mode. Work is in progress to repeat this measurement in the avalanche mode. Borrowing techniques from the phonograph record industry, we have developed a method for inexpensively producing large arrays of fine electrodes. We are developing a readout scheme that requires only one amplifier for every 20 to 50 wires, and are studying the effects of quenching agents to increase the size of the avalanche. When liquid xenon is used in thick layers for $\gamma$-ray detection (either for elementary particle physics or radioisotope imaging),[4] the resolution is poorer but is measured to be better than 1 mm rms for 511-keV annihiliation radiation. For $\gamma$-ray detection above 200 keV, liquid xenon offers a unique combination of density, spatial resolution, and count-rate capability. For large detectors, liquid xenon is less expensive than equivalent crystals of CsI.

Measurement of the 1st Townsend coefficient in liquid xenon. We have measured gain vs. voltage for single-wire cylindrical chambers filled with liquid xenon. From these data the 1st Townsend coefficient (the rate of avalanche per unit distance) can be extracted as a function of electric field strength. This type of research has never before been done on any liquid.

Infrared Detector for Astrophysics.

In collaboration with the Laboratory of Radio Astronomy (U.C. Berkeley) we have built a 1$\mu$ camera using image intensification with a S-1 photocathode. This previously unexploited technique is by far the most sensitive known for taking photographs and spectra at 1$\mu$. The camera has already been used for direct photography at several observatories, and a remote-control version has been built for taking direct photographs and spectra with the 120-inch reflector at Lick Observatory. Our research is primarily concerned with the evolutionary history of young stars that have recently condensed out of the dust and gas of our galaxy.

[1] Richard A. Muller, Stephen E. Derenzo, Gerard Smadja, Dennis B. Smith, Robert G. Smits, Haim Zaklad, and Luis W. Alvarez, A Liquid Filled Proportional Counter, Phys. Rev. Letters 27, 532 (1971).

[2] Stephen E. Derenzo, Gerard Smadja, Robert G. Smits, Haim Zaklad, Luis W. Alvarez and Richard A. Muller. A High Precision Particle Detector Using Noble Liquids, Nature 233, 617 (1971).

[3] S. E. Derenzo, D. H. Anderberg, S. O. Buckingham, J. A. Savignano, R. G. Smits, T. Vuletich, H. Zaklad, and R. A. Muller, A Source of Alpha Particles Collimated to 35 $\mu$m, Lawrence Radiation Laboratory Report UCRL-20857, June 1971.

[4] Haim Zaklad, Stephen E. Derenzo, Richard A. Muller, Gerard Smadja, Robert G. Smits, and Luis W. Alvarez, A Liquid Xenon Radioisotope Camera, in *Proceedings of the 13th Scintillation and Semiconductor Counter Symposium,* IEEE Trans. Nucl. Sci. NS-19 (June 1972).

## DATA REDUCTION OPERATIONS

*Edward H. Hoedemaker*

The manpower level of the Scanning and Measuring Group averaged 30.5 full-time equivalents. Thirty-eight scans on 10 experiments examined 2 178 807 frames.

724 630 measurements were made on 4 machines using film from 11 experiments. The relevant breakdowns are shown in the following tables.

Table I. Scanning distribution

| Experiment name (number) | Frames of production and special scans* | Total scanning effort (h) |
|---|---|---|
| $\pi$82(32) | 104,667 | 1,586 |
| ETA (34) | 369 | 69 |
| N* (35) | 197,077 | 1,895 |
| LASER (37) | 608,512 | 4,070 |
| LASER (38) | 770,091 | 5,058 |
| N$\pi\pi$ (43) | 63,341 | 1,455 |
| $\pi^{o}$N (45) | 397,853 | 3,207 |
| K67 (46) | 1,106 | 95 |
| XI-STAR (47) | 35,791 | 361 |
| Total | 2,178,807 | 17,796 |

*In some instances this number includes relatively large amounts of special scanning; production scanning rates cannot be accurately calculated from information presented in this report. Entries are omitted where the nature of the work performed does not lend itself to quantitative reporting.

Table II. Breakdown of measurements by type of machine used

| Machine type | Events measured | Measuring hours |
|---|---|---|
| Franckenstein (MP2B-NOVA) | 12,947 | 1,186 |
| Spiral Readers (I & II) | 294,683 | 3,859 |
| SASS | 417,000 | 1,207 |
| Total | 724,630 | 6,252 |

Table III. Breakdown of measurements by experiment

| Name (number) | Events measured | Measuring hours |
|---|---|---|
| *Bubble chamber experiments* | | |
| BP66 (26) | 905 | 25 |
| K82 (30) | 130,289 | 1,523 |
| $\pi$82 (32 | 57,939 | 653 |
| LASER (37) | 21,651 | 904 |
| LASER (38) | 49,759 | 885 |
| K70 (44) | 13,781 | 268 |
| K67 (46) | 29,012 | 529 |
| Total | 303,336 | 4,787 |
| *Streamer chamber experiments* | | |
| XI-STAR (47) | 4,294 | 258 |
| *Spark chamber experiments* | | |
| ETA (34) | 3,500 | 11 |
| N* (35) | 37,500 | 106 |
| N$\pi\pi$ (43) | 70,000 | 195 |
| $\pi^{o}$N (45) | 306,000 | 895 |
| Total | 417,000 | 1,207 |
| *Grand total* | 724,630 | 6,252 |

## PROGRAMMING EFFORT

*B. Pardoe (supervisor), U. Arkadir, P. Cook, O. I. Dahl, M. S. Hutchinson, W. O. Koellner, M. Leavitt, E. G. Lieberman, E. A. Romascan, and J. J. Wilson.*

During the year, routine maintenance was performed on the various production and fitting programs used by the group; and these codes were converted, where possible, to the CDC-7600. To carry out the conversion to the CDC-7600, it was necessary to provide a program for staging data on the 7600 and to get the subroutine library on that machine. Development of the programs for the streamer-chamber experiment and the IRATE text-editing system continued.

The following two reports have been accepted for publication in Computer Physics Communications and are due to be published:

P. H. Eberhard and W. O. Koellner, the OPTIME System for Fitting Theoretical Expressions, Lawrence Radiation Laboratory Report UCRL-20159, Oct. 1970.

P. H. Eberhard and W. O. Koellner, Users' Manual for the OPTIME System, Lawrence Radiation Laboratory Report UCRL-20160, Feb. 1971.

Table I. Programming notes

| | | | |
|---|---|---|---|
| P-209 | July 70 | Barrie Pardoe | Rotation of a projection plane about a [3] point array |
| P-210 | Sept 70 | Werner Koellner | Running LYRIC—Some remarks for machine operator |
| P-211 | Oct 70 | N. Gould | NIZRPLT—A program to plot on the Cal-Comp high quality plots suitable for publication (Addendum added 10/71 E. Colton) |
| P-213 | Jan 71 | W. Koellner | Group A—Procedure for testing new BKY-systems |
| P-214 | Jan 71 | L. Miller | RAWMEAT |
| P-215 | Feb 71 | N. Gould | NCRPLT—A subroutine version of NZRPLT (P-211) |
| P-216 | Jan 71 | U. Arkadir<br>R. Decoster<br>S. Flatté<br>S. Protopopescu | CRAD—Editing Program |
| P-217 | Jan 71 | U. Arkadir<br>R. Decoster<br>S. Flatté<br>S. Protopopescu | Kinematic Fitting Program |
| P-219 | July 71 | Max Leavitt | An outline of the DDP-24 SASS Automatic Scanning Program for the High Altitude Particle Physics Experiment |
| P-220 | Dec 71 | B. Pardoe | A first step towards Monte Carlo integration |
| P-221 | Dec 71 | O. Dahl | SIOUX KIOWA for spark chambers |
| P-222 | June 72 | D. Herndon | LETTER—A program for plotting characters entered from data cards in CCSCB format |
| P-223 | July 72 | L. Miller | ZAP—An alternative of the Core Dump |
| P-224 | Sept 72 | Ken Macrae | SCREW—Helicity Matrix Program |
| P-189 Rev. | Jan 71 | Jerry Friedman | SAGE—A general system for Monte Carlo event generation with preferred phase space density distributions |

## PUBLICATIONS AND PAPERS


M. Alston-Garnjost *et al.*, Energy Dependence of Inclusive Distributions in Pion-Induced Reactions, Lawrence Berkeley Laboratory Report LBL-733, Feb. 1972, submitted to Physics Letters B.

M. Alston-Garnjost, Energy Dependence of Inclusive Distributions in Pion-Induced Reactions, Lawrence Berkeley Laboratory Report LBL-735, Feb. 1972, presented at the Intl. Conference on Inclusive Reactions, U. C. Davis, Feb. 4-5, 1972.

L. W. Alvarez, Certification of Three Old Cosmic-Ray Emulsion Events as $\Omega^-$ Decays and Interactions, Lawrence Berkeley Laboratory Report LBL-706, Feb. 1972, submitted to Physical Review.

J. Ballam *et al.*, Bubble-Chamber Study of Photoproduction by 2.8- and 4.7-GeV Polarized Photons. I. Cross-Section Determinations and Production of $\rho^\circ$ and $\Delta^{++}$ in the Reaction $\gamma p \rightarrow p\pi^+\pi^-$, Phys. Rev. **D5**, 545 (1972).

J. Ballam *et al.*, Bubble Chamber Study of $\omega$-Meson Photoproduction with Polarized Photons at 9.3 GeV, Lawrence Berkeley Laboratory Report LBL-509, Nov. 1971; and SLAC-PUB-980; presented at the International Symposium on Electron and Photon Interactions at High Energies, Ithaca, New York, Aug. 1971.

J. Ballam *et al.*, Cross Section Determinations and Production of $\rho^{\circ}$ and $\Delta^{++}$ in the Reactions $\gamma p \rightarrow p\pi^{+}\pi^{-}$, Lawrence Berkeley Laboratory Report LBL-49, Aug. 1971; SLAC-PUB-941; submitted to Physical Review.

A. D. Brody, R. J. Cashmore, A. Kernan, D. W. G. S. Leith, B. S. Levi, B. C. Shen, J. P. Berge, D. J. Herndon, R. Longacre, L. R. Price, A. H. Rosenfeld, and P. Söding, Experimental Results on the Reactions $\pi^{-}p \rightarrow \pi\pi N$ in the c.m. Energy Range 1400-2000 MeV, Phys. Rev. **D4,** 2693 (1971).

A. D. Brody, R. J. Cashmore, A. Kernan, D. W. G. S. Leith, B. S. Levi, B. C. Shen, D. J. Herndon, L. R. Price, A. H. Rosenfield, and P. Söding, The Reaction $\pi^{-}p \rightarrow \pi^{+}\Delta^{-}$ at CMS Energies 1640-1760 MeV, Phys. Letters **34B,** 665 (1971).

A. Buffington, R. A. Muller, L. H. Smith and G. F. Smoot, High Energy Particle Astronomy, in *Proceedings of the American Association for the Advancement of Science,* Dec. 1971.

A. Buffington, L. H. Smith, G. Smoot, M. A. Wahlig, and L. W. Alvarez, Measurement of the Primary Cosmic Ray Nuclear Rigidity Spectra for Individual Elements of Charge $Z \geqslant 2$, in *12th International Conference on Cosmic Rays,* Vol. 1 (U. Tasmania, Hobart, 1971), p. 147.

A. Buffington, L. H. Smith, G. F. Smoot, L. W. Alvarez, and M. A. Wahlig, Search for Antimatter in Primary Cosmic Rays, Nature **236,** 335 (1972).

A. Buffington, L. H. Smith, G. Smoot, M. A. Wahlig, and L. W. Alvarez, Search for Antimatter in the Primary Cosmic Rays using a Magnetic Spectrometer, in *12th International Conference on Cosmic Rays,* Vol. 1 (U. Tasmania, Hobart, 1971), p. 146.

F. S. Crawford, The Clock Paradox and Radioactive Decay, Lawrence Berkeley Laboratory Report LBL-365, Sept. 1971, submitted to Physics Today.

F. S. Crawford, Photon Rest Mass and the Goos-Hänchen Effect, Lawrence Berkeley Laboratory Report LBL-953, June 1972, submitted to Phys. Rev. Letters.

P. J. Davis, M. Alston-Garnjost, A. Barbaro-Galtieri, S. M. Flatté, J. H. Friedman, G. R. Lynch, M. S. Rabin, F. T. Solmitz, and N. M. Uyeda, Experimental Spectra for 12 GeV/c $K^{+}p \rightarrow p K^{+}\Phi$ and $pK^{+}\omega$, Nucl. Phys. **B44,** 344 (1972).

P. J. Davis, M. Alston-Garnjost, A. Barbaro-Galtieri, S. M. Flatté, J. H. Friedman, G. R. Lynch, M. S. Rabin, and F. T. Solmitz, Investigation of Low-Mass $K\pi\pi$ Systems in 12 GeV/c $K^{+}p$ Interactions, Phys. Rev. **D5,** 2688 (1972).

Stephen E. Derenzo, Gerard Smadja, Robert G. Smits, Haim Zaklad, Luis W. Alvarez, and Richard A. Muller, A High Precision Particle Detector Using Noble Liquids, Nature **233,** 617 (1971).

S. E. Derenzo, D. H. Anderberg, S. O. Buckingham, J. A. Savignano, R. G. Smits, T. Vuletich, H. Zaklad, and R. A. Muller, A Source of Alpha Particles Collimated to 35 $\mu$m, Lawrence Radiation Laboratory Report UCRL-20857, June 1971.

P. Eberhard, R. Ross, L. W. Alvarez, and R. Watt, Search for Monopoles in Lunar Material, Phys. Rev. **D4,** 3260 (1971).

S. M. Flatté, M. Alston-Garnjost, A. Barbaro-Galtieri, J. H. Friedman, G. R. Lynch, S. D. Protopopescu, M. S. Rabin, and F. T. Solmitz, Analysis of the Observed Anomaly in $\pi\pi$ S-Wave Scattering near $K\bar{K}$ Threshold, Phys. Letters **38B,** 232 (1972).

J. H. Friedman, Clifford Risk, and Dennis B. Smith, Long-Range Correlations and the Dynamics of Multiparticle Production, Phys. Rev. Letters **28,** 191 (1972).

Eugene Gellert, The Inclusive Reactions $pp \rightarrow \pi^{\pm}$ + Anything and $pp \rightarrow p$ + Anything at 6.6 GeV/c com-

pared to Higher Energies, Ph.D. Thesis, Lawrence Berkeley Laboratory Report LBL-749, Oct. 1972.

Eugene Gellert, The Inclusive Reaction $pp \to \pi^- +$ Anything at 6.6 GeV/c compared to Higher Energies, in *Proceedings of the International Conference on Inclusive Reactions*, R. L. Lauder, Ed. (U.C. Davis, 1972), p. 198.

F. Harris, S. Parker, V. Peterson, D. Yount, M. L. Stevenson, Muon Identification Using Multiwire Proportional Chambers, Lawrence Berkeley Laboratory Report LBL-716 Abs., Feb. 1972, presented at APS Meeting, Washington, D.C., 24-27 Apr. 1972.

A. R. Kirschbaum, E. Colton, P. M. Dauber, J. H. Friedman, and P. E. Schlein, Measurement of the $T = 3/2$ $K\pi$ Elastic Scattering Cross Section Using the Durr-Pilkuhn Form Factor, Phys. Rev. **D4**, 3254 (1971).

T. S. Mast, M. Alston-Garnjost, R. O. Bangerter, A. Barbaro-Galtieri, F. T. Solmitz, and R. D. Tripp, A Study of the Decay $\Lambda(1520) \to \Sigma(1385)\pi$, Phys. Rev. Letters **28**, 1220 (1972).

T. S. Mast, M. Alston-Garnjost, R. O. Bangerter, A. Barbaro-Galtieri, F. T. Solmitz, and R. D. Tripp, A Study of $K^-p \to \Lambda\pi^+\pi^-$ in the Region of the $\Lambda(1520)$, Lawrence Berkeley Laboratory Report LBL-301, Aug. 1971, submitted to Physical Review.

T. S. Mast, R. O. Bangerter, M. Alston-Garnjost, A. Barbaro-Galtieri, L. K. Gershwin, F. T. Solmitz, and R. D. Tripp, A study of $K^-p \to \Sigma\pi\pi$ in the Region of the $\Lambda(1520)$, Lawrence Berkeley Laboratory Report LBL-954, June 1972, submitted to Physical Review.

Larry R. Miller, Isobar Model Fit to the Reaction $N\pi \to N\pi\pi$: Fitting Procedure and Fits at 1.7 BeV, Ph.D. Thesis, Lawrence Berkeley Laboratory Report LBL 38, Sept. 1971.

K. C. Moffeit *et al.*, The $\rho^\circ$-$\omega$ Interference Parameters in Diffractive Photoproduction of Vector Mesons on Hydrogen, Nucl. Phys. **B29**, 349 (1971).

K. C. Moffeit *et al.*, A Study of the Inclusive Reaction $\gamma p \to \pi^- +$ (Anything) with Polarized Photons at 2.8, 4.7, and 9.3 GeV, Phys. Rev. **D5**, 1603 (1972).

Richard A. Muller, Stephen E. Derenzo, Gerard Smadja, Dennis B. Smith, Robert G. Smits, Haim Zaklad, and Luis W. Alvarez, A Liquid Filled Proportional Counter, Phys. Rev. Letters **27**, 532 (1971).

R. A. Muller, Observation of Cascade Hyperon Interactions, Lawrence Berkeley Laboratory Report LBL-566, Dec. 1971, submitted to Phys. Letters B.

S. Parker, R. Jones, J. Kadyk, M. L. Stevenson, T. Katsura, V. Z. Peterson, and D. Yount, Multiwire Proportional Chambers with Uniform Gain, Nucl. Instr. Methods **97**, 181 (1971).

S. Parker, F. Harris, T. Katsura, V. Peterson, B. Brook, J. Mulvey, R. Ellsworth, G. Yodh, and M. L. Stevenson, Transition Radiation in the X-Ray Region, Lawrence Berkeley Laboratory Report LBL-715 Abs., Feb. 1972, submitted to APS Meeting, Washington, D.C., 24-27 Apr. 1972.

S. D. Protopopescu, M. Alston-Garnjost, A. Barbaro-Galtieri, S. M. Flatté, J. H. Friedman, T. A. Lasinski, G. R. Lynch, M. S. Rabin, and F. T. Solmitz, $\pi\pi$ Phase Shift Analysis from Reactions $\pi^+p \to \pi^+\pi^-\Delta^{++}$ and $\pi^+p \to K^+K^-\Delta^{++}$ at 7.1 GeV/c, Lawrence Berkeley Laboratory Report LBL-787 Rev., Apr. 1972, presented at International Conference on Meson Spectroscopy, Philadelphia, Apr. 28-29, 1972.

A. H. Rosenfeld and P. Söding, Photoproduction of Vector Mesons--Experimental, Lawrence Berkeley Laboratory Report LBL-539, submitted to Proceedings of the International School of Subnuclear Physics, Erice, Sicily, July 1971.

A. H. Rosenfeld, Resonance and Symmetries, Lawrence Berkeley Laboratory Report LBL-788, Apr. 1972, presented at Conference on Particle Physics, Irvine, CA, 3-4 Dec. 1971.

G. Smadja *et al.*, Photoproduction of a New Vector Meson by Linearly Polarized 9.3 GeV Gamma Rays, Lawrence Berkeley Laboratory Report LBL-991, June 1972, presented at 3rd International Conference on Experimental Meson Spectroscopy, Philadelphia, Apr. 28-29, 1972.

G. Smadja, Resonances that Overlap, Lawrence Berkeley Laboratory Report LBL-382, Oct. 1971.

L. H. Smith, A. Buffington, G. F. Smoot, and L. W. Alvarez, Search for Antimatter in the Cosmic Rays, presented at Joint Meeting of the APS and AAS, Puerto Rico, 1-4 Dec. 1971.

L. H. Smith, A. Buffington, M. A. Wahlig, and P. Dauber, Superconducting Magnetic Spectrometer for Cosmic Ray Nuclei, Rev. Sci. Instr. **43,** 1 (1972).

G. F. Smoot, A. Buffington, L. A. Smith, L. W. Alvarez, and M. A. Wahlig, Primary Cosmic Ray Nuclei Rigidity Spectra, presented at Joint Meeting of APS and AAS Puerto Rico, 1-4 Dec. 1971.

M. L. Stevenson, Predicted Neutrino Fluxes for Ideal Narrow-Band Systems, National Accelerator Laboratory Report TM 318, Sept. 1971.

M. L. Stevenson, High Energy Neutrino Interactions, and The Neutrino Program at NAL, invited papers presented at the Heidelberg International Neutrino Seminar, 25-26 Nov. 1971.

V. Waluch, S. Flatté, J. H. Friedman, and D. Sivers, A Detailed Comparison of the Generalized Veneziano Model with Data on $K^+p \to \pi^+p\,K^\circ$ at 12 GeV/c, Phys. Rev. **D5,** 4 (1972).

Haim Zaklad, Stephen E. Derenzo, Richard A. Muller, Gerard Smadja, Robert G. Smits, and Luis W. Alvarez, A Liquid Xenon Radioisotope Camera, in *Proceedings of the 13th Scintillation and Semiconductor Counter Symposium,* IEEE Trans. Nucl. Sci. **NS-19,** (June 1972).

# LOFGREN EXPERIMENTAL PHYSICS

Edward J. Lofgren in charge

The group is concerned principally with high-energy particle physics research using counter and spark chamber techniques. Most experiments have been performed at the Bevatron; however, some work has been done in the past at the 184-inch cyclotron, and the group expects to make use of the 200-GeV accelerator at NAL in the future.

Most of the recent work has involved the use of a double-arm spectrometer system at the Bevatron to investigate weak interactions by studying various decay modes of the neutral K-meson. The group also has interests in strong interactions, particularly in the areas of nucleon-nucleon cross sections, $\pi$-meson production by deuterons and alpha particles, and diboson production by negative $\pi$-mesons on protons. Each experiment undertaken involves one or more graduate students, and most experiments form the basis for a thesis project.

The group is active in instrumentation development, particularly in the fields of fast electronics, optical and wire spark chambers, high-voltage pulsing systems, multiwire proportional chambers, Cerenkov counters, and on-line computer facilities as needed for the experimental program. Much of the equipment developed has also been used or is being used by other groups at the Bevatron.

Members of the group are involved in the development of the Bevatron and its experimental facilities, and in the investigation of new concepts in accelerator design.

Researchers taking part in this work are:
Alan R. Clark, Tom Elioff, R. Clive Field, William R. Holley, Rolland P. Johnson, Leroy T. Kerth, John F. McReynolds, R. C. Sah, Lee Schroeder, Gilbert Shen, W. A. Wenzel, and Arthur R. Zingher--LBL; Bruce Cork--Argonne National Laboratory; T. N. Rangaswamy--Tata Institute of Fundamental Research, Bombay, India; David Newton--University of Lancaster, England; and Henry J. Frisch--University of Chicago.

## SEARCH FOR $K_S^0 \to \mu^+\mu^-$

We have reported an upper limit on the branching ratio

$$R_L = \Gamma(K_L^0 \to \mu^+\mu^-)/\Gamma(K_L^0 \to \text{all}) < 1.8 \times 10^{-9} \text{ (90\% C.L.)}$$

This result has led to much activity by theorists in an effort to explain this unexpectedly small value. Most of the theories put forward require destructive interference between two intermediate states to achieve a low rate for this process; these theories also predict an anomalously large rate for the decay $K_S^0 \to \mu^+\mu^-$, with *lower* limits for the branching ratio

$$R_S = \Gamma(K_S^0 \to \mu^+\mu^-)/\Gamma(K_S^0 \to \text{all})$$

on the order of $5 \times 10^{-7}$ to $10^{-6}$.

We are setting up an experiment to use the double-arm spectrometer system to search for the process $K_S^0 \to \mu^+\mu^-$. The sensitivity of the apparatus is such that, if *no* events are detected in 1000 hours of data-taking at the Bevatron, we could obtain an upper limit on $R_S$ of $\sim 1 \times 10^{-7}$.

The above numbers are based on extrapolation of test results obtained with the present spectrometer system operated at low incident proton fluxes. In order to do this experiment as proposed, it will be necessary to reduce the background by replacing some of the magnetostrictive wire spark chambers in the present system with multiwire proportional chambers. The group has been actively working on background studies and computer simulation of the experiment to determine the optimum configuration for the new chambers. We are testing a prototype chamber, and we expect to have most of the required chambers by the end of 1972.

## SEARCH FOR A $\pi$-$\mu$ RESONANCE

A search has been made for a reported $\pi^{\pm}\mu^{\mp}$ resonance near 427 MeV/$c^2$. Better resolution and a data sample more than 150 times larger than that of the previous experiment give strong evidence that the resonance does not exist. The K$\ell$3 Dalitz-plot distributions are consistent with the V-A theory. A paper has been published in Nature.

## SEARCH FOR A NEW VECTOR MESON

The two-arm spectrometer system has been used to search for a new vector meson, the $\chi^0$, which has been suggested by Alles and Pati as an explanation of the low experimental limit on the $K_L^0 \to \mu^+\mu^-$ rate. The branching-ratio limit determined by this experiment,

$$\frac{\Gamma(K_L^0 \to \gamma\chi^0 \to \gamma ee;\ 350 < m_{\chi^0} < 425\ \mathrm{MeV}/c^2}{\Gamma(K_L^0 \to \mathrm{all})}$$

$$< 6.6 \times 10^{-5}\ (90\%\ \mathrm{C.L.}),$$

is incompatible with the theoretical prediction.

These results have been presented in LBL-947, and a paper has been submitted to Nuovo Cimento Letters.

## DIBOSON PRODUCTION

We have continued the analysis of data obtained from an optical spark chamber-counter experiment performed at the Bevatron to study details of the $\pi$-$\pi$ interaction exhibited in the reaction $\pi^- + p \to \pi^+ + \pi^- + n$ at incident pion momenta of 3, 4, 4.5, and 5 GeV/c. Our data consist of $1.6 \times 10^5$ events satisfying the above hypothesis with low 4-momentum transfer to the nucleon.

The dominant feature of the dipion mass spectrum is the $\rho$-meson. In addition, we see evidence for the decay $\omega \to \pi^+\pi^-$ for t-values somewhat above the kinematic lower limit. The total cross section also shows a sharp drop by about a factor of 2 at the $K\bar{K}$ threshold.

Our recent efforts have been directed toward an improved calculation of the geometrical acceptance of the apparatus. The data are now being reanalyzed using the new values of the acceptance.

## $(K^+ \to e^+\nu)/(K^+ \to \mu^+\nu)$ BRANCHING RATIO

The Bevatron experimental run was completed in June 1968. About one-quarter million photographs were taken, 90% of these with the analyzing magnet set for $K^+ \to e^+\nu$. Analysis of the data has been completed, yielding $112 \pm 15$ events after a background subtraction. This is to be compared with the previous world's total of $17.0 \pm 7.5$. The present result,

$$\frac{\Gamma(K \to e\nu)}{\Gamma(K \to \mu\nu)} = (2.42 \pm 0.42) \times 10^{-5},$$

is in agreement with the V-A prediction of $2.22 \times 10^{-5}$. This prediction includes radiative corrections.

An upper limit to the branching fraction of $K \to e\nu\gamma$ to all decays has also been measured for $p \geqslant 240$ MeV/c. No events of this type were found giving an upper limit (90% C.L.) of

$$\frac{\Gamma(K \to e\nu\gamma)}{\Gamma(K \to \mathrm{all})} < 10^{-6}.$$

These results have been presented in LBL-506, and a paper has been submitted to Physical Review Letters.

## HEAVY-ION WORK

Some experimental work in high-energy strong interactions has been going on in collaboration with members of the Segré-Chamberlain Group. With the added feature of heavy-ion acceleration at the Bevatron, new areas of research interest have opened up. The production of $\pi^-$ mesons, produced by bombarding Be, Cu, and Pb targets with deuterons and alpha particles, has been studied. By comparing these yields with similar data obtained in proton bombardment of these targets, we hope to unravel the production mechanism of particles by heavy ions. For the most part the interaction appears to be of a "stripping nature," in which only one of the projectile nucleons interacts with a target nucleon to produce the $\pi^-$, while the other nucleons in the projectile are spectators and do not participate. However, preliminary results indicate that a small fraction of the time the incident projectile acts in a coherent fashion; that is, the *whole* projectile interacts with a target nucleon.

## RANGE OF POSITIVE AND NEGATIVE MUONS

Range-momentum data on muons were accumulated in several experiments using the double-arm spectrometer. These data have been used to make a precise measurement of the difference in ranges (in C and Fe) of positive and negative muons of average momenta $\sim$ 1 GeV/c. The negative muon has the longer range by $(0.22 \pm 0.02)$ %, in excellent agreement with the calculated difference, which arises from the two-photon exchange contribution. Experimentally this difference can lead to a non-negligible correction in measurements of $K\mu3$ charge asymmetry. The results have been presented in LBL-926, and a paper has been submitted Physics Letters.

## $K^0\mu3$ POLARIZATION MEASUREMENT

This experiment will examine the variation of the muon polarization direction in $K^0\mu3$ decays as a function of the kinematic configuration of the decay. We intend to measure the variation of the real and imaginary parts of the form factor, on which the polarization is principally dependent, and possibly by this means to illuminate the source of discrepancy in previous measurements of the form factor.

The modifications to the equipment used previously for the $K_L^0 \to \mu^+\mu^-$ experiment were completed in August 1971. The principal effort was the design and construction of a large-volume muon polarimeter consisting of an aluminum-scintillator sandwich in a magnetic field. The polarimeter has a useful volume of 48" X 48" X 56" with a magnetic field of $\sim$ 100 G uniform to $\sim$ 0.1 G.

Data-taking was completed in August 1972. We have accumulated approximately 7.5 million triggers for the imaginary part of the form factor, and approximately 22 million triggers for the real part. Events which pass the cuts and exhibit a decay-positron signal in the polarimeter represent about 3% of the triggers. The background to the positron signal is $\sim$ 20%. Analysis of these data is in progress.

## $K^0\mu3$ AND $K^0e3$ CHARGE ASYMMETRY

In this experiment one measures the ratio of the decay rates $(L_L^0 \to \pi^+e^-\upsilon)/(K_L^0 \to \pi^-e^+\upsilon)$ and $(K_L^0 \to \pi^+\mu^-\upsilon)/(K_L^0 \to \pi^-\mu^+\upsilon)$ to obtain information about the $\Delta S = \Delta Q$ rule in weak interactions. Furthermore a comparison of these two ratios gives a test of $\mu$-e universality. Data-taking began in FY 1971 and was completed in July 1972. The data sample consists of $\sim 8 \times 10^6$ Ke3 events and $\sim 4 \times 10^6$ $K\mu3$ events. Analysis of the data is under way.

## NEUTRAL PARTICLES DECAYING TO $e^+e^-$

A search for long-lived neutral particles of mass $<$450 MeV which decay into $e^+e^-$ pairs was conducted. This work was stimulated by anomalies observed in electron-pair production and by other experiments whose results could possibly be explained by the existence of a light neutral particle decaying to $e^+e^-$. The data were collected during FY 1971, and the analysis was completed this year. No evidence for a particle with lifetime T between $10^{-10}$ and $10^{-6}$ seconds was found. For $T \approx 10^{-8}$ sec, the upper limit on the differential production cross section $d^2\sigma/d\omega\, dp$ was on the order of $10^{-36}$ cm$^2$/(sr MeV/c). These results were reported in the paper LBL-703

## NEUTRINO MASS LIMITS

The zero-mass neutrino is an important assumption of the two-component neutrino theory in weak interactions. At present, data from different experiments throughout the world show that the neutrino mass is consistent with zero. To obtain new upper limits on the neutrino mass, we are analyzing $K_L^0 \to \pi\ell\upsilon$ events collected during the $K_L^0 \to \ell^+\ell^-$ search in FY 1970-1971.

The analysis yields neutrino mass upper limits (90% C.L.) of 0.8 MeV for the muon neutrino and 0.5 MeV for the electron neutrino. The muon neutrino mass limit is smaller than that previously published, and in addition involves neutrinos produced in a strangeness-changing reaction.

A paper is being prepared for publication.

This experiment has been extended to include a measurement of positive-particle production. An experiment to measure heavy-ion total cross sections in collaboration with the Segré-Chamberlain group should start in early 1973.

Studies on the reaction $dd \rightarrow {}^4He + MM$ $(I = 0)$ are still in progress.

PUBLICATIONS AND PAPERS

A. R. Clark, Bruce Cork, T. Elioff, L. T. Kerth, J. F. McReynolds, David Newton, and W. A. Wenzel, Measurement of Branching Ratio For $K^+ \rightarrow e^+\nu$, Lawrence Berkeley Laboratory Report LBL-506, June 1972.

Alan R. Clark, R. C. Field, H. J. Frisch, W. R. Holley, Rolland P. Johnson, Leroy T. Kerth, R. C. Sah, and W. A. Wenzel, Observed Difference in the Ranges of Positive and Negative Muons, Lawrence Berkeley Laboratory Report LBL-926, June 1972.

Alan R. Clark, R. C. Field, W. R. Holley, Rolland P. Johnson, Leroy T. Kerth, R. C. Sah, G. Shen, W. A. Wenzel, and A. R. Zingher, A Search for a New Vector Meson, Lawrence Berkeley Laboratory Report LBL-947, April 1972.

Alan R. Clark, T. Elioff, R. C. Field, H. J. Frisch, Rolland P. Johnson, Leroy T. Kerth, G. Shen, and W. A. Wenzel, Search for Fine Structure in the $K^0_{\ell 3}$ Final States, Nature **237**, 388 (June 16, 1972).

Alan R. Clark, T. Elioff, R. C. Field, H. J. Frisch, Rolland P. Johnson, Leroy T. Kerth, R. C. Sah, G. Shen, and W. A. Wenzel, A Search for Long-Lived Neutral Particles which Decay into Electron Pairs, Lawrence Berkeley Laboratory Report LBL-703, February 1972.

D. E. Coyle, R. C. Field, J. T. Gunn, and J. T. Tanabe, A Large Lightweight Mirror for use in Cherenkov Counters, Nucl. Instr. Methods **95**, 557 (1971).

R. Clive Field, Range-Momentum Correlation in Carbon and Iron for Muons of 500-1500 MeV/c, Lawrence Berkeley Laboratory Report LBL-791, April 1972.

Rolland P. Johnson, Alan R. Clark, T. Elioff, H. J. Frisch, G. Shen, Leroy T. Kerth, and W. A. Wenzel, Neutrino Mass Limits From the $K^0_L \rightarrow \pi^{\pm}\ell^+\nu$ Decay Spectra, Lawrence Berkeley Laboratory Report LBL-4, August 1971, contributed paper to the Rochester Meeting of the American Physical Society, August 30-Sept. 2, 1971.

# GROUP R EXPERIMENTAL PHYSICS

Kenneth M. Crowe in charge

## I. CROWE PHYSICS GROUP

*Kenneth M. Crowe in charge*

### MUON DEPOLARIZATION STUDIES

*Jesse H. Brewer, Kenneth M. Crowe, Fredy N. Gygax, and Bruce D. Patterson (LBL); Alexander Schenck (Univeristy of Heidelberg).*

A polarized $\mu^+$ beam from the 184-inch cyclotron has been stopped in a variety of liquid and solid targets. The spins of the stopped muons precess in a uniform magnetic field applied perpendicular to their polarization. Positrons from the decay $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$ are emitted asymmetrically—that is, they tend to come off along the muon spin direction. Thus as the polarization vector precesses, sweeping past a counter telescope, the probability of detecting a decay positron in that telescope oscillates in time at the muon Larmor frequency. By measuring and histogramming the time interval between the stopping of the muon and the detection of the decay positron, we obtain a quantitative measure of the amplitude of those oscillations, which is proportional to the muon polarization. If relaxation phenomena analogous to those studied by proton NMR cause the polarization to decay with mean lifetime $T_2$, we measure $T_2$ directly.

This technique has been used to study the depolarization of positive muons in condensed media. For instance, in $MnCl_2$ solutions we have extended the data on $T_2$ into the $\mu$sec region;[1] such short relaxation times are difficult to measure accurately by conventional NMR techniques. These "slow depolarization" studies are helpful to an understanding of short-range order in concentrated solutions.

We have also studied the chemistry of atomic muonium ($\mu^+e^-$, a light analog of atomic hydrogen) by this technique. Here we observe the phenomenon of "fast depolarization"—the dependence of the apparent initial polarization upon the chemical properties of the medium, due to the following mechanism: in slowing down, muons capture electrons to form muonium, in which the hyperfine interaction causes rapid depolarization of the muon. The depolarization is complete within a few nsec unless chemical reaction places the muon in a diamagnetic molecule in an even shorter time. This process is complete long before observation begins, and so appears instantaneous. By varying reagent concentrations in solutions we thus change the amount of depolarization; by fitting this dependence to theory, we extract chemical rate constants and "hot chemistry" reaction efficiencies.

Our studies have verified the validity of the theory of the "muonium mechanism."[2,3] We have also discovered situations in which the muon temporarily resides in free radical molecules, in which the hyperfine interaction between the muon and the unpaired electron causes depolarization in much the same way as in muonium. The theory has been expanded to describe such phenomena,[3,4] and measurements have been made of the relevant rates.[3,5] Further studies of this type will give a more complete understanding of fast chemical processes, and many specific measurements of rate constants and the like.

We are now studying the behavior of positive muons in solids, where in many cases long-lived muonium may be observed directly via its fast precession ($\sim$ 103 times that of a free $\mu^+$). In quartz, for instance, muonium precesses essentially as in vacuum. The precession frequency is split into two frequencies due to the mixing of singlet with triplet states by the external field. In germanium, however, muonium precession has been observed with a larger splitting, implying a weaker hyperfine coupling than in quartz or vacuum. This is equivalent to an increase in the size of the muonium atom in the germanium lattice, due to the high local dielectric con-

stant. Details of the effect lead to new insight into the interstitial electron density of the lattice. We have repeated these measurements using silicon instead of germanium, and found an even more pronounced effect.[6] We have also observed the precession of a system involving the muon at a frequency intermediate between that of the free muon and that of muonium. This phenomenon has not yet been adequately explained.

It is becoming increasingly clear that the polarized muon can be used as a nondestructive probe for microscopic interactions and structures in condensed matter. It is not unreasonable to expect that techniques now being pioneered in $\mu^+$ depolarization studies may soon become valuable research tools for a wide variety of fields.

---

[1] A. Schenck, R. W. Williams, J. H. Brewer, K. M. Crowe, and R. F. Johnson, Decay of the Coherent Spin Precession of Polarized Positive Muons in Paramagnetic $MnCl_2$ Solutions, Chem. Phys. Letters 12, 544 (1972).

[2] J. H. Brewer, K. M. Crowe, R. F. Johnson, A. Schenck, and R. W. Williams, "Fast" Depolarization of Positive Muons in Solution--The Chemistry of Atomic Muonium, *Phys. Rev. Letters* 27, 297 (1971).

[3] J. H. Brewer, Muon Depolarization and the Chemistry of Muonium in Liquids, Ph.D. Thesis, Lawrence Berkeley Laboratory Report LBL-950, June 1972.

[4] J. H. Brewer, K. M. Crowe, R. F. Johnson, and A. Schenck, Generalized Mechanism for $\mu^+$ Depolarization in Solutions, Lawrence Berkeley Laboratory Report LBL-593, Jan. 1972, presented at the 4th International Conference on High Energy Physics and Nuclear Structure, Dubna, USSR, Sept. 7–12, 1971, and Muon Physics Conference, Ft. Collins, CO, Sept. 6–10, 1971.

[5] J. H. Brewer, K. M. Crowe, R. F. Johnson, and A. Schenck, Muon Depolarization and the Chemistry of Free Radicals, Lawrence Berkeley Laboratory Report LBL-592, Jan. 1972, presented at the 4th International Conference on High Energy Physics and Nuclear Structure, Dubna, USSR, Sept. 7-12, 1971, and Muon Physics Conference, Ft. Collins, CO, Sept. 6-10, 1971.

[6] K. M. Crowe, R. F. Johnson, J. H. Brewer, F. N. Gygax, D. G. Fleming and A Schenck, Muonium Atoms in Silicon, Lawrence Berkeley Laboratory Report LBL-717 Abs., submitted for the APS Meeting, Washington, DC, April 24-27, 1972.

## RADIATIVE PION CAPTURE

*James A. Bistirlich, Kenneth M. Crowe, Helmut W. Baer, and Nico de Botton (LBL); Jerome A. Helland (Los Alamos Scientific Laboratory); Peter Truöl (Physik-Institute der Universitat Zurich)*

Using a $\pi^-$ beam from the 184-inch cyclotron we have continued the study of light nuclei by radiative pion absorption. Our previous experiments[1] on $^{12}C$ and $^{16}O$ have demonstrated that high-resolution measurements of the photon spectrum in the 80 to 140 MeV region yield new information about both nuclear structure and the relation of radiative $\pi$-capture to $\mu$-capture, $\beta$-decay, electron scattering, and $\gamma$-lifetimes. The latter has been derived in recent years using PCAC and soft pion theorems. Our measurements, the only ones with sufficient resolution, are essential for testing the theory. In the past year we extended the measurements to targets of $^6Li$, $^{14}N$, and $^3He$ and have resolved unambiguously individual bound states in each case. These are being used as test cases for studies in both of the above areas. Some results are briefly summarized below.

### Results for $^6Li$

The $^6Li$ $(\pi^-\gamma)$ spectrum displays three components: a discrete $\gamma$-ray line at 134.0 MeV corresponding to the $^6He$ (g.s.) transition; a continuum component associated with the $^5He+n+\gamma$ channel which peaks at $\sim$ 115 MeV; and a broad resonance peak centered at $\sim$ 24 MeV relative to $^6He$ (g.s.). The branching ratio for the direct transition to the $^6He$ (g.s.) was measured to be $R_\gamma$ = radiative transitions/T-atom formed = $(0.39\pm0.10)\%$. Theoretical calculations based on an elementary particle treatment of nuclei have been performed by Delorme[2] who obtains $R_\gamma$ = 0.75% and by Werntz[3] who obtains 0.41%. Vergados and Baer[4] have performed a shell model analysis of this transition and obtained values in the range 0.40 to 0.42% depending on the choice of coefficients in the effective interaction.

We tentatively identify the broad peak in our spectrum at $E_x \sim 24$ MeV as the $T_z = +1$ analog of the resonance in $^6Be$ observed at approximately the same energy. Measurements of the $^3He$-$^3He$ elastic scattering[5,6] and

the radiative capture reaction,[7] $^3$He($^3$He,$\gamma$)$^6$Be, determined L = 3, S = 1, T = 1 for this resonance; and it has been identified with the $^{33}$F state predicted at ~ 27 MeV by Thompson and Tang[8]. Observation of the $T_z = 0$ member of this isobaric triad in $^6$Li was reported by Ventura *et al.*[9]

Results for $^{14}$N

Radiative $\pi$-capture on $^{14}$N affords a unique possibility for studying the relationship between radiative $\pi$-capture and $\beta$-decay. The $\beta$-transition between the $1^+(^{14}N)$ and $0^+(^{14}C)$ ground states exhibits the well-known anomaly, i.e., log ft = 9 rather than ~3 as expected for an allowed Gamow-Teller transition. In pion capture, the fortunate combination of a high neutron separation energy of $^{14}$C (8.2 MeV) and the high excitation energy of the first excited state in $^{14}$C ($1^-$, 6.1 MeV) permits this transition to be completely resolved experimentally. Our measurement of the spectrum shows the $^{14}$C(g.s.) transition to be extremely weak with an upper limit on its intensity being $8 \times 10^{-5}$ transition/$\pi$-atom formed. The unusually small value of the allowed Gamow-Teller matrix element $\langle {}^{14}C; 0^+ | \vec{\sigma}\, \tau_+ | {}^{14}N; 1^+ \rangle$ thus appears to be reflected in the greatly reduced $\pi$-capture transition rate. We are analyzing this transition as well as the strong transition to the $2^-$ state at 7.3 MeV using realistic shell model wave functions.

Results for $^3$He

The spectrum for $^3$He clearly shows the presence of all four $\gamma$-ray channels predicted in the theoretical study of Messiah[10]: the t + $\gamma$ line at 135.8 MeV, the d + $\gamma$ continuum with the end-point energy of 129.8 MeV, the pnn$\gamma$ continuum with an end-point energy of 127.7 MeV, and the t + $\pi^0$ channel resulting in a uniform distribution of $\gamma$-rays between 53 and 86 MeV. The preliminary analysis of our data shows two surprises. We obtain for the Panofsky ratio of $^3$He:

$$P(^3He) = \frac{\omega(\pi^- + {}^3He \rightarrow \pi^0 + t)}{\omega(\pi^- + {}^3He \rightarrow \gamma + t)} = 3.48 \pm 0.40.$$

This is considerably larger than the 2.28±0.18 measured by Zaimidoroga *et al.*[11] It is also larger than the theoretical estimates of 2.0 by Messiah, and 2.70 by Ericson and Figureau.[12] The theoretical implications of the larger Panofsky ratios should be of interest.

Perhaps the most interesting feature of our data is the existence of a peak at ~ 13 MeV relative to $^3$He(g.s.). There has been much discussion in the literature regarding low-lying, T = 1/2 and 3/2 states in the mass-3 system. Very recently, Chang *et al.*[13] have suggested that a T = 1/2 state exists in the 13 to 15 MeV excitation region of the ppn system. Although it is too early to reach any conclusions, the peak in our spectrum may be evidence for such a low-lying resonance in the mass-3 system.


[1] J. A. Bistirlich, K. M. Crowe, A. S. L. Parsons, P. Sharek and P. Truöl, Phys. Rev. Letters 25, 689 (1970).

[2] J. Delorme, Nucl. Phys. B19, 573 (1970).

[3] C. Werntz, private communication (1972), and to be published.

[4] J. D. Vergados and H. W. Baer, Phys. Letters (to be published).

[5] A. D. Bacher, T. A. Tombrello, E. A. McClatchie, and F. Resmini, in "Nuclear Chemistry Annual Report 1968", Lawrence Radiation Laboratory Report UCRL-18667, Jan. 1969, p. 104.

[6] J. G. Jenkin, W. D. Harrison and R. E. Brown, Phys. Rev. C1, 1622 (1970).

[7] E. Ventura, J. R. Calarco, C. C. Chang, and E. M. Diener, Bull. Am. Phys. Soc. 17, 585 (1972), and private communication with C. C. Chang.

[8] D. R. Thompson and Y. C. Tang, Nucl. Phys. A106, 591 (1968).

[9] E. Ventura, C. C. Chang, and W. E. Meyerhof, Nucl. Phys. A173, 1 (1971).

[10] A. M. L. Messiah, Phys. Rev. 87, 639 (1952).

[11] O. A. Zaimidoroga *et al.*, Soviet Phys. JETP 21, 848 (1965).

[12] M. Ericson and A. Figureau, Nucl. Phys. B3, 609 (1967).

[13] C. C. Chang, E. M. Diener, and E. Ventura, Phys. Rev. Letters 29, 307 (1972).


## $K^0_{\mu 3}$ CHARGE ASYMMETRY

*J. H. Brewer, R. J. Budnitz, A. C. Entis, R. M. Graven, R. L. McCarthy, D. H. Miller, and W. N. Ross*

The experiment to measure the charge asymmetry in the decays $K^0_L \rightarrow \mu^\pm \pi^\mp \nu$ has been finished. An unequal number of positive and negative muons in the decay

would indicate a violation of CP conservation. The $K^0_{\mu 3}$ charge asymmetry is defined to be $\delta = \Gamma_+ - \Gamma_- / \Gamma_+ + \Gamma_-$, where $\Gamma_\pm$ = rate $(K^0_L \rightarrow \pi^\mp \mu^\pm \upsilon)$. We have measured this number to be $\delta_\mu = (6.0 \pm 1.4) \times 10^{-3}$. The error is meant to be interpreted as one standard deviation, and contains both a statistical and a systematic contribution. The systematic contribution is a measure of the accuracy with which a neutron-induced background has been excluded. The measurement should be compared with:

| | |
|---|---|
| previous $K^0_{\mu 3}$ | $\delta_\mu = (5.7 \pm 1.7) \times 10^{-3}$ |
| best value $K^0_{e3}$ | $\delta_e = (3.22 \pm 0.29) \times 10^{-3}$ |
| superweak theory | $\delta = (2.80 \pm 0.08) \times 10^{-3}$ |

$\pi^- p \rightarrow n\gamma$

*P. A. Berardo, R. P. Haddock, B. M. K. Nefkens, L. J. Verhey, M. E. Zeller, A. S. L. Parsons, P. Truöl, A. J. Weiss, D. J. Blasberg, K. M. Crowe, and A. Fainberg*

In collaboration with UCLA we have completed cross section measurements on this reaction. Seventeen differential cross sections of the pion-nucleon charge exchange reaction have been measured at total center-of-mass energies of 1245, 1337, and 1363 MeV. Most measurements are based on the neutron-photon coincidence method, using carefully calibrated neutron counters and an efficient, large-area photon detector. The results are used to test the predictions of charge independence, with which they agree. The results also confirm the Ayed-Bareyre-Sonderegger phase degeneracy hypothesis at $\tilde{\theta}_{\pi^0} = 180°$. Data on $\pi^- p \rightarrow n\pi^0$ were also collected and are being analyzed.

## EXPERIMENTS AT LASL

Equipment is now being prepared for two experiments to be performed at Los Alamos during FY1973.

### Radiative Pion Capture in Light Nuclei

*Kenneth M. Crowe, Peter Truöl, Helmut W. Baer, James A. Bistirlich, and Nico de Botton*

Using established techniques we will study the radiative capture of pions in tritium and other light elements. With information from other weak and electromagnetic processes, tests can be made of CVC, PCAC, etc. Some excitations observed in radiative pion capture belong to collective modes and offer a new way to study these states. The measurements will be expanded to include the angular correlation between the capture $\gamma$-ray and the decay neutrons of the residual nucleus, and a coincidence between the pionic x-ray and the photon emitted as a result of capture. The experiment employs a pair spectrometer as the nucleus of the detection system.

### High-Resolution Study of the Boson Mass Region 0

*Kenneth M. Crowe*

A search will be made of the boson missing-mass spectrum in the reactions $p + d \rightarrow {}^3He + X^0$ and $p + d \rightarrow {}^3H + X^+$. The mass range 0 to 490 MeV is accessible. We will observe the $^3He$ or $^3H$ with a resolution that will yield $\Delta M \leqslant 5$ MeV at M = 300 MeV. Enhancement has been previously observed at lower resolution in the region of 310 MeV, (e.g., the ABC experiment), but the interpretation is unsettled.

## PUBLICATIONS AND PAPERS (Crowe)


H. W. Baer, J. A. Bistirlich, K. M. Crowe, J. A. Helland, and P. Truöl, Study of Mass-6 System in the $^6Li(\pi^-,\gamma)^6He$ Capture Reaction, Lawrence Berkeley Laboratory Report LBL-712 Abs, Feb. 1972, submitted for the APS Meeting, Washington, DC, April 24-27, 1972.

P. S. Berardo, R. P. Haddock, B. M. K. Nefkens, L. J. Verhey, M. E. Zeller, A. S. L. Parsons, and P. Truöl, Measurement of the Differential Cross Section for $\pi^- p \rightarrow n\pi^0$ at 317, 452, and 491 MeV/c, Phys. Rev. **D6**, 756 (1972).

J. A. Bistirlich, K. M. Crowe, A. S. L. Parsons, P. Skarek, and P. Truöl, Photon Spectra from Radiative Absorption of Pions in Nuclei, Phys. Rev. **C5**, 1867 (1972).

D. J. Blasberg, J. C. Comiso, R. P. Haddock, B. M. K. Nefkens, L. J. Verhey, A. J. Weiss, M. E. Zeller, K. M. Crowe, A. Fainberg, A. S. L. Parsons and P. Truöl, Measurement of the Differential Cross Section for $\pi^- p \rightarrow \pi^0 n$ between 502 and 888 MeV/c,

University of California at Los Angeles Report UCLA 10-P25-6Rev., presented at 16th Intl. Conf. of High Energy Physics, Batavia, Ill., Sept. 1972, to be submitted to Phys. Rev.

J. H. Brewer, K. M. Crowe, R. F. Johnson, A. Schenck, and R. W. Williams, "Fast" Depolarization of Positive Muons in Solution--The Chemistry of Atomic Muonium, Phys. Rev. Letters, **27**, 297 (1971).

J. H. Brewer, K. M. Crowe, R. F. Johnson, and A. Schenck, Generalized Mechanism for $\mu^+$ Depolarization in Solutions, Lawrence Berkeley Laboratory Report LBL-593, Jan. 1971, presented at International Conference on High Energy Physics and Nuclear Structure, Dubna, USSR, Sept. 7–12, 1971, and Muon Physics Conference, Ft. Collins, CO, Sept. 6–10, 1971.

J. H. Brewer, K. M. Crowe, R. F. Johnson, and A. Schenck, Muon Depolarization and the Chemistry of Free Radicals, Lawrence Berkeley Laboratory Report LBL-592, Jan. 1972, presented at 4th International Conference on High Energy Physics and Nuclear Structure, Dubna, USSR, September 7–12, 1971, and Muon Physics Conference, Ft. Collins, CO, September 6–10, 1971.

J. H. Brewer, Muon Depolarization and the Chemistry of Muonium in Liquids, Ph.D. Thesis, Lawrence Berkeley Laboratory Report LBL-950, June 1972.

K. M. Crowe, R. F. Johnson, J. H. Brewer, F. N. Gygax, D. G. Fleming, and A. Schenck, Muonium Atoms in Silicon, Lawrence Berkeley Laboratory Report LBL-717 Abs, Feb. 1972, submitted for the APS Meeting, Washington, DC, April 24–27, 1972.

K. M. Crowe, J. F. Hague, J. E. Rothberg, A. Schenck, D. L. Williams, and K. K. Young, Precision Measurement of the Magnetic Moment of the Muon, Phys. Rev. **D5**, 2145 (1972).

R. M. Graven, J. H. Brewer, R. J. Budnitz, R. L. McCarthy, and D. H. Miller, A Charge Asymmetry Measurement System, Nucl Instr. Methods **102**, 45 (1972).

R. L. McCarthy *et al.*, Charge Asymmetry in the Decay $K_L^0 \to \pi\mu\nu$, Lawrence Berkeley Laboratory Report LBL-702, July 1972, submitted to Phys. Rev.

R. L. McCarthy, Measurement of the Charge Asymmetry in the Decay $K_L^0 \to \pi\mu\nu$, Ph.D. Thesis, Lawrence Berkeley Laboratory Report LBL-550, November 1971.

A. Schenck, R. W. Williams, J. H. Brewer, K. M. Crowe, and R. F. Johnson, Decay of the Coherent Spin Precession of Polarized Positive Muons in Paramagnetic $MnCl_2$ Solutions, Chem. Phys. Letters **12**, 544 (1972).

A. J. Weiss, D. J. Blasberg, J. C. Comiso, R. P. Haddock, B. M. K. Nefkens, L. J. Verhey, M. E. Zeller, K. M. Crowe, A. Fainberg, A. S. L. Parsons and P. Truöl, Measurement of Differential Cross Sections for Radiative Pion-Proton Capture in the Second Resonance Region, University of California at Los Angeles Report UCLA 10-P25-7 Rev., presented at 16th Intl. Conf. of High Energy Physics, Batavia, Ill., Sept. 1972, to be submitted to Phys. Rev.

## II. PEREZ-MENDEZ PHYSICS GROUP

*Victor Perez-Mendez in charge*

Our Group research program continues to be diversified, involving experiments at the 184-inch cyclotron and instrumentation development. Most recently a proposal has been accepted for the first round of experiments at the Los Alamos Pion Facility, and a long range Bevatron proposal is in preparation.

Our cyclotron research includes studies in hadron form factors, tests of time-reversal invariance, and investigations into the structure of light nuclei and the few-nucleon problem. At LAMPF, a study of $\pi^- + {}^3He \to \pi^+ + 3n$ will be carried out to investigate the properties of the resonance-like three-neutron enhancement first discovered by our group last year. Finally, a project to use Bevatron energies to study nuclear correlations in light nuclei is being prepared in collaboration with physicists from UCLA.

As in previous years, considerable effort has gone into instrumentation. The particular areas are spark

chambers, multiwire proportional chambers, and readout devices for use with them. The wire proportional chambers have been developed for elementary particle research as well as for biomedical applications. Also, effort has been directed to computer programs for three-dimensional imaging of x-ray data and schemes to improve streamer chamber performance using techniques borrowed from laser technology.

## $\pi^{\circ}$ FORM FACTOR EXPERIMENT

*A. Stetz, B. Smith, V. Perez-Mendez, and D. Fredrickson*

In this experiment we are measuring the slope parameter of the electromagnetic form factor of the $\pi^{\circ}$ by means of a measurement of the momentum transfer distribution of the $e^+e^-$ pairs. We are currently analyzing our data; we expect to get 0.2% momentum resolution from our spectrometer and extract about $10^4$ wide-angle events from our log of $10^6$ triggers.

## $np \rightarrow \gamma d$: TEST OF TIME REVERSAL

*S. Wilson, M. Longo, K. Young (U. Michigan); R. Haddock, J. Helland, B. Schrock (UCLA); D. Cheng, V. Perez-Mendez (LBL)*

The angular distribution of the reaction $np \rightarrow \gamma d$ was measured at incident energies spanning the N* (1238) resonance for the purpose of comparing this distribution with that of the inverse reaction $\gamma d \rightarrow np$. Such a comparison is a direct test of time-reversal invariance, presumably in the electromagnetic interaction.

All the data have now been analyzed and compared with the inverse reaction over a range of incident neutron energies from 350 to 650 MeV. There are no statistically significant discrepancies with the predictions of time-reversal invariance.

## $p+d \rightleftarrows \gamma+{}^3He$: TEST OF TIME REVERSAL

*M. Goitein, A. Stetz, V. Perez-Mendez (LBL); C. Heusch (UCSC); R. Klein (Cal-Tech): J. Carroll, B. McDonald (William and Mary College, Virginia)*

This experiment was designed to test time-reversal in electromagnetic interactions in isospin and angular momentum states which are not accessible in the $np \rightarrow \gamma d$ experiment. The inverse reaction was done at the Cal-Tech synchrotron by Heusch et al. (UC Santa Cruz). The experiment was completed at the 184-inch cyclotron in July 1971, and the data are currently being analyzed. We expect to obtain a complete angular distribution at 450 MeV and several isolated points at 350 and 550 MeV incident proton energy. We will also obtain the differential cross section for the competing process $pd \rightarrow {}^3He\ \pi^0$.

A report on the design and performance of the ${}^3He$ detector, a large total-absorption counter using plastic scintillator, has been presented.

## pd ELASTIC SCATTERING

In collaboration with a UCLA group, complete angular distributions for elastic scattering of deuterons on hydrogen were obtained at 270 and 350 MeV incident deuteron energy using the same experimental apparatus as for the $pd \rightarrow {}^3He+\gamma$ experiment. Our goal was to study the deuteron wave function at small distances, and in particular, to measure the strength of the D-wave component.

The data have now been completely analyzed and two papers submitted for publication. Our results indicate that the D-wave component constitutes about 7% of the total wave function, a somewhat larger admixture than previously expected.

## $\pi^+$ RADIATIVE DECAY

In collaboration with a UCLA group, we are currently setting up an experiment at the 184-inch

cyclotron to measure the branching ratio and decay spectrum of the reaction $\pi^+ \rightarrow e^+ \nu\gamma$. Our goal is to determine the sign and magnitude of the renormalization of the axial vector coupling constant, a parameter which has recently been calculated using some new techniques in current algebra.

Because of the small branching ratio ($\sim 3 \times 10^{-8}$) we have had to obtain a flux of stopping $\pi^+$ an order of magnitude larger ($10^6$/sec) than previously available at the cyclotron. The decay electron will be momentum analyzed in a magnet-spark chamber spectrometer and the photon detected in a large-solid-angle, lead-glass Cerenkov counter. We expect to obtain about 300 radiative decay events as well as some data on other rare decays, such as $\mu^+ \rightarrow e^+ \nu\nu\gamma$ and $\mu^+ \rightarrow e^+ \gamma$.

## INSTRUMENTATION

We have continued to work on the development of proportional wire chambers and the electromagnetic delay-line readout. Various forms of delay lines have been developed which have increased the coupling efficiency to the chamber and have made the two-pulse resolution better than 2 cm. Alternative forms of phase-dispersion compensations were used, and we have obtained improved rise times per unit delay.

We have tried various gas mixtures for obtaining greater amplification while maintaining the proportionality of the amplitude signals, and are now using an argon-xenon-carbon dioxide mixture for particle physics applications and a xenon-carbon dioxide mixture for imaging applications of x-rays and $\gamma$-rays.

In particle and nuclear physics, the electromagnetic delay-line readout scheme has been applied to chambers for magnetic focusing spectrometers, to gamma-shower detection chamber arrays, and to transition-radiation detection chambers. We have also used these chambers for imaging x-rays, low-energy $\gamma$-rays, and thermal neutrons for industrial and medical radiological applications and for nuclear medicine situations.

### Neutron Radiographic Imaging

*K. Valentine, S. Kaplan, L. Kaufman and V. Perez-Mendez*

As an extension of the work of two of the present authors on multiwire proportional chambers for low-dose x-radiography, a proportional chamber employing delay-line readout has been adapted for thermal-neutron imaging. Preliminary measurements and analysis have been made with a small prototype chamber.

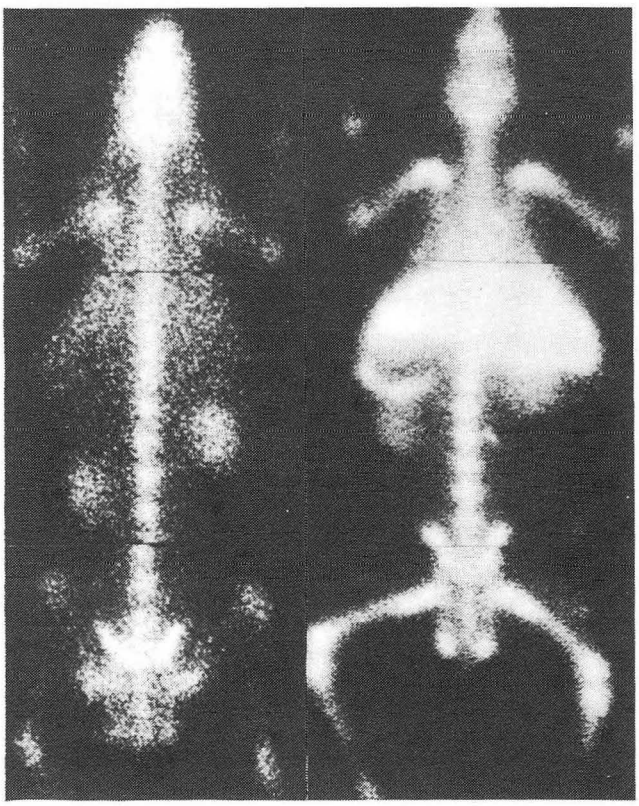
This chamber, using natural B for a converter, has achieved 0.5% thermal-neutron-detection efficiency and better than 2 mm resolution (10% to 90% knife-edge). A converter-plate-model calculation gives good agreement with the measurements and shows how efficiency and resolution vary with chamber thickness, energy discrimination, and B and Al overcoating thicknesses. Substitution of $^{10}B$ for the natural B would give a five-fold increase in efficiency; and the calculations indicate that a further improvement in both efficiency and resolution of up to 50% is achievable in a single-plate system.

Neutron radiography has become an extremely valuable tool for nondestructive testing; and present imaging techniques can produce very high resolution images, particularly with reactor neutron sources. Where high resolution is not required but where high efficiency or contrast sensitivity are desirable, the optimum imaging characteristics would be provided by an efficient system with reasonable resolution that is sensitive to a single interaction and capable of digitizing its coordinates. Such a system could broaden the application of low-intensity, non-reactor neutron sources, such as $^{252}Cf$, and also make possible more extensive exploration of medical diagnostic applications of neutron radiography.

## Multiwire Proportional Chamber for Nuclear Medicine

*L. Kaufman, V. Perez-Mendez, D. Shames, and G. Stoker (UC San Francisco and LBL)*

We have developed a xenon-filled multiwire proportional chamber (MWPC) with delay-line readout of coordinates that can be used in nuclear medicine as a reliable, low-cost imaging system for low-energy gamma rays. This system, with an active area of 30.5 X 30.5 $cm^2$, is identical in construction and operation to a smaller chamber described earlier. Filled with a 90% xenon, 10% carbon dioxide gas mixture at atmospheric pressure, the chamber has an effective mass of 2.21 X $10^{-2}$ $cm^2$. Energy resolution is of the order of 15%.



$^{159}$Dy-HEDTA 24 hours post 10 min

$^{159}$Dy-Polyphosphate 120 hours post 10 min

*Fig. 1. Photographs of radioisotope distribution were taken at UC Medical Center in San Francisco by Drs. L. Kaufman, D. C. Price, M. R. Powell, and V. Perez-Mendez, using a multiwire proportional chamber made by the Perez-Mendez Group at LBL.*

The system is being used to image internally administered radioisotope distributions in animals for research purposes (see Fig. 1). In its present form, the MWPC can compete favorably with or surpass conventional imaging cameras in a variety of studies. The development of radiochemicals suited to the chamber is certain to enhance the attractiveness of the device; operation at pressures of a few atmospheres will increase its useful energy range by increasing efficiency and improving resolution.

## PUBLICATIONS AND PAPERS (Perez-Mendez)

D. Fredrickson, J. Carroll, M. Goitein, R. Kline, B. MacDonald, V. Perez-Mendez, and A. Stetz, Measurement of Total Particle Energy in a Large Solid Angle High Resolution Detector, Bull. Am. Phys. Soc. **17**, 120 (Jan. 1972).

R. Z. Fuzesy, L. Kaufman, J. Mariner, S. Parker, V. Perez-Mendez, S. Redner, and H. M. Steiner, A Gas Mixture for Multi-Wire Chambers with High Proportional Gain, Nucl. Instr. Methods **100**, 267 (1972).

M. B. Goitein, Three-Dimensional Density Reconstruction from a Series of Two-Dimensional Projections, Lawrence Berkeley Laboratory Report LBL-547, Dec. 1971.

R. Grove, L. Kaufman, V. Perez-Mendez, J. Sperinde, and G. Stoker, Medical Applications of Digitized Proportional Wire Chambers, Bull. Am. Phys. Soc. **17**, 120 (Jan. 1972).

R. Grove, L. Kaufman, B. Leskovar, V. Perez-Mendez, J. Sperinde, and G. Stoker, Wire Chamber Readouts Using Electromagnetic Delay Lines, in *Proceedings of Hawaii Topical Conference in Particle Physics (4th)*, D. E. Yount and P. N. Dobson, Eds, (U. Hawaii Press, Honolulu, 1972), p. 100.

G. Igo, J. Fong, S. Verbeck, M. Goitein, J. Carroll, D. Hendrie, B. MacDonald, V. Perez-Mendex, A. Stetz, and M. Makino, Large Angle Scattering of Deuterons from Hydrogen and the D State

Probability $P_D$, presented at European Conference on Nuclear Physics, Aux-en-Provence, France, June 30, 1972, to be published in Phys. Rev. Letters.

G. Igo, J. Fong, S. Verbeck, A. Stetz, and M. Makino, Large Angle Elastic Scattering of Deuterons from Hydrogen, $P_K$ = 432 MeV, 370 MeV, and 280 MeV, to be published in Nucl. Phys.

S. N. Kaplan, L. Kaufman, V. Perez-Mendez, J. Sperinde, and K. Valentine, Biomedical Applications of Proportional Wire Chambers with Delay-Line Readouts, Lawrence Berkeley Laboratory Report LBL-721 Abs., Feb. 1972, for APS Meeting, Washington, D.C., April 24-27, 1972.

S. N. Kaplan, L. Kaufman, V. Perez-Mendez, and K. Valentine, Multiwire Proportional Chambers for Biomedical Application, Lawrence Berkeley Laboratory Report LBL-778, June 1972, to be published in Nucl. Instr. Methods.

S. Kaplan, K. Valentine, L. Kaufman, and V. Perez-Mendez, Neutron Radiography with a Multiwire Proportional Chamber – Performance and Projections, ANS Transactions **15,** (1), 140 (June 1972).

L. Kaufman, V. Perez-Mendez, M. Powell, and G. Stocker, Laminographic Excitation Camera for Thyroid Imaging, IEEE Trans. Nucl. Sci. **NS-19** (1), 46 (Feb. 1972).

L. Kaufman, V. Perez-Mendez, D. Shames, and G. Stoker, A Multi-Wire Proportional Chamber for Nuclear Medicine Applications, Lawrence Berkeley Laboratory Report LBL-713, Feb. 1972, to be published in IEEE Trans. Nucl. Sci.

L. Kaufman, V. Perez-Mendez, J. Sperinde, and G. Stoker, Multi-Wire Proportional Chambers for Low-Dose X-Radiography, Am. J. Roentgenol. Radium Ther. Nucl. Med. **113,** 378 (Oct. 1971).

L. Kaufman, V. Perez-Mendez, A. Rindi, J. Sperinde, and H. Wollenberg, Wire Chambers for Clinical Imaging of Gamma Rays, Phys. Med. Biol. **16,** 417 (July 1971).

V. Perez-Mendez and J. Sperinde, Double Charge Exchange on Helium-4 and Helium-3 Leading to Multi-Neutron Final States, in *Proceedings of the International Seminar on π-Meson-Nucleus Interactions* (Centre de Recherches Nucléaires de Strasbourg, Strasbourg, France, 1972), p. III-19.

B. L. Schrock, R. P. Haddock, H. A. Helland, M. L. Longo, S. S. Wilson, K. K. Young, D. Cheng, and V. Perez-Mendez, An Experimental Test of Time Reversal Invariance in the Reaction $n + p \rightarrow \gamma + d$, Phys. Rev. Letters **26,** 1659 (1971).

J. Sperinde, Double Charge Exchange and Inelastic Scattering in $\pi^- + {}^3He$, Ph. D. Thesis, Lawrence Berkeley Laboratory Report LBL-1347, Aug. 1971.

J. Sperinde, E. Temple, V. Perez-Mendez, J. M. Miller, and A. Rindi, Techniques for Mapping the Spatial Distribution of Stopping $\pi^-$Mesons in Tissue, Nucl. Instr. Methods **97,** 331 (1971).

K. Valentine, S. Kaplan, L. Kaufman, and V. Perez-Mendez, The Adaptation of Multi-Wire Proportional Chambers with Delay-Line Readouts for Neutron Radiographic Imaging, IEEE Trans. Nucl. Sci. **NS-19** (1), 374 (Feb. 1972).

## III. KAPLAN PHYSICS GROUP

*Selig N. Kaplan in charge*

In medium-energy physics, there is increasing evidence for significant, identifiable, structural characteristics in excited nuclear energy-levels: for example, the superposition of shell and core excitation in the so-called "doorway" states; residual-hole excitations identified in pickup experiments and new muon capture; and the isobaric analogue levels profusely excited by $\mu^-$ and radiative $\pi^-$ capture. There has been a recent indication of such significant new structural features following $\mu^-$ excitation of nuclei as heavy as Pb. Our measurements to date on O, Al, Si, Ca, and Co indicate muon capture should provide a rich new source of nuclear structure

data. This work uses the stopping $\mu^-$ beam in the meson cave and the high-resolution Ge(Li) detectors that have been developed to a high performance level at LBL.

Multiwire proportional chambers with delay-line readout developed originally as track-imaging devices for high-energy physics also show promise for high-efficiency, moderate resolution, radiographic imaging, and may have important medical radiology applications. Development work, particularly for neutron imaging, in addition to broadening the applications of these chambers, is intended also to improve detection efficiency and resolution for general neutral-particle-detection application.

## NUCLEAR STRUCTURE STUDIES

*S. N. Kaplan, R. V. Pyle, and L. E. Temple*

Analysis and interpretation of the de-excitation gamma-ray spectra from residual nuclei following $\mu^-$ capture in natural Al, Si, Ca, and Co targets are nearly completed and have been reported in part. The identified gamma transitions account for 81, 60, 45, and 71% of the nuclear muon captures, respectively. Charged-particle emission is observed 15% of the time in Ca, 10% of the time in Si, and not at all in Al and Co. Levels corresponding to an excitation energy of 27 MeV above the ground state in $^{59}$Co and more than 20 MeV above the ground state in the other targets were observed. Levels populated in the $^{40}$Ca($\mu^-$,$\upsilon$n)$^{39}$K and $^{27}$Al($\mu^-$,$\upsilon$n)$^{26}$Mg reactions correlate closely with those observed in the $^{40}$Ca($\gamma$,p$\gamma'$)$^{39}$K and $^{27}$Al($\gamma$,p$\gamma'$)$^{26}$Mg photoexcitation reactions. A comparison of the Si target results with the photoexcitation and electro-excitation reactions on $^{28}$Si suggests the presence of a giant magnetic resonance in muon capture. The strong correlation of the probabilities for populating levels in residual nuclei following muon capture in Ca and Si with the probabilities for exciting these same levels in single-particle pickup reactions clearly indicates a preference for the formation of single-particle single-hole states in muon capture.

## PULSE-HEIGHT ANALYZER

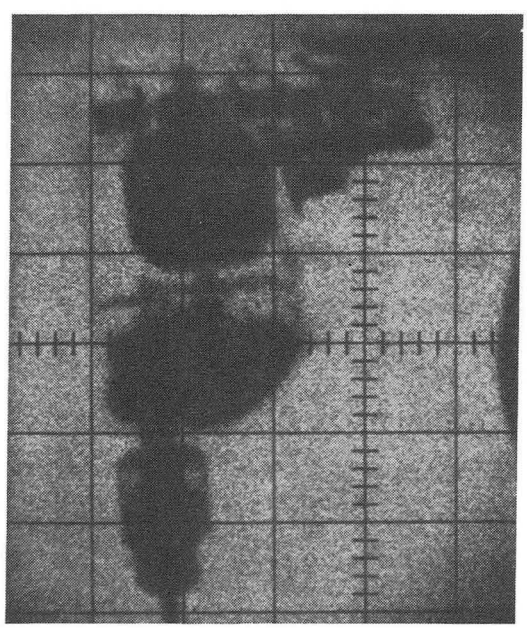
*W. Yuen and S. Kaplan*

A PDP-5 computer is being adapted for use as a two-dimensional pulse-height analyzer. This will provide capability both for $\gamma$ spectroscopy measurements and for simultaneous $\gamma$-spectrum and neutron time-of-flight measurements. Although the efficiency is low for the latter type of measurement, such a measurement will yield a detailed picture of any nuclear isobaric resonance together with its decay mechanism. All hardware and most software work should be completed this fiscal year.

## MULTIWIRE PROPORTIONAL CHAMBERS

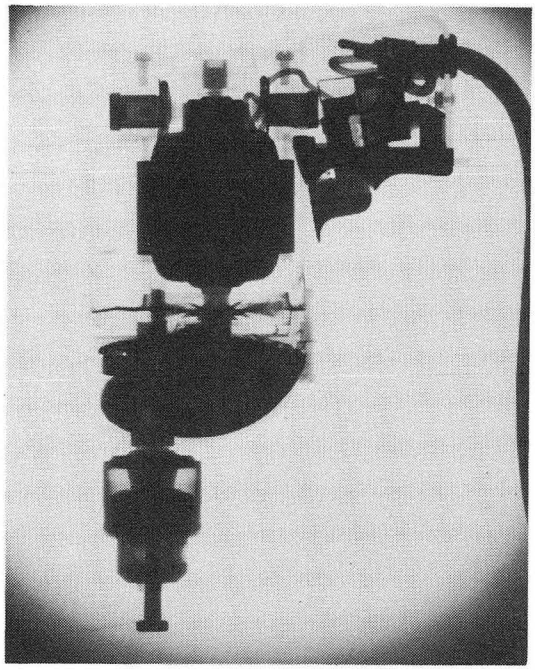
D. Chu, S. Kaplan, K. Valentine, in collaboration with the Perez-Mendez Group.

A small multiwire proportional chamber (3 cm×4cm) has been adapted for thermal neutron imaging by coating the inside surface of one window with boron. This prototype chamber has a spatial resolution of 2mm (10 to 90%), a detection efficiency of 0.5% with a natural boron converter, and good n/$\gamma$ discrimination. Calculated performance characteristics and confirming experimental results have been reported. A larger chamber (22 cm × 22 cm) with provisions for interchanging converters and pressurizing has been constructed and some preliminary measurements have been made (Fig. 2).



a)

b)



c)

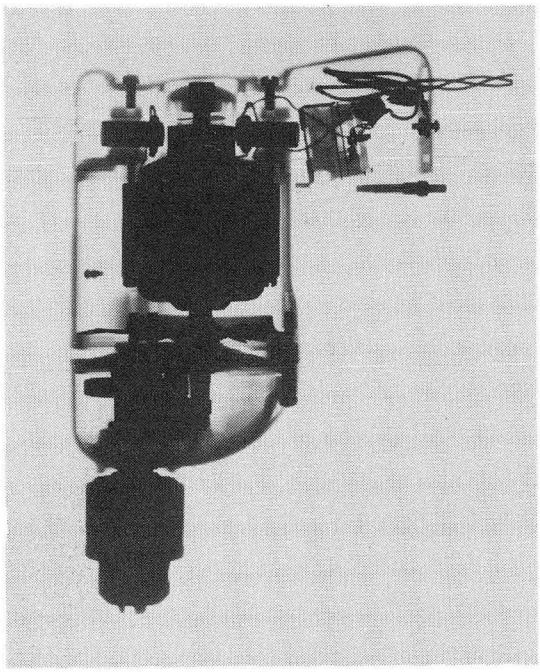


*Fig. 2. Wire-chamber neutron radiograph of electric drill. a) Low-dose thermal-neutron radiograph of an electric drill taken with the 22 cm X 22 cm neutron-sensitive proportional chamber; b) high-resolution neutron radiograph of the drill made photographically using a Gd conversion screen; c) x-radiograph of the same drill. Both neutron radiographs show the grease in the gear box and the nylon screw in the jaws of the chuck, features unobservable in the x-radiograph. The photographic neutron image (b) required $10^4$ to $10^5$ times as many neutrons as the wire-chamber image (a). Work is in progress to improve both the resolution and the sensitivity of the wire-chamber system.*

Detection of neutral particles (neutrons and photons) requires neutral-to-charged-particle conversion either in the chamber gas or in the chamber wall. For conversion in the chamber walls detection efficiency is limited primarily by the escape probability of the charged secondaries. Techniques for increasing converter efficiency are being studied. The present effort is primarily in studying various ways of increasing the effective surface area of the converter.

## PUBLICATIONS AND PAPERS (Kaplan)


S. N. Kaplan, L. Kaufman, V. Perez-Mendez, J. Sperinde, and K. Valentine, Biomedical Applications of Proportional Wire Chambers with Delay-Line Readouts, Lawrence Berkeley Laboratory Report LBL-721 Abs., Feb. 1972, for APS Meeting, Washington, D.C., April 24-27, 1972.

S. N. Kaplan, The Measurement of Nuclear Excitation Following $\mu^-$ Capture in Complex Nuclei, Lawrence Berkeley Laboratory Report LBL-748, March 1972, invited talk at Muon Physics Conference, Colorado State University, Fort Collins, CO, Sept. 6–10, 1971.

S. N. Kaplan, L. Kaufman, V. Perez-Mendez, and K. Valentine, Multiwire Proportional Chambers for Biomedical Application, Lawrence Berkeley Laboratory Report LBL-778, June 1972, to be published in Nucl. Instr. Methods.

S. N. Kaplan, K. Valentine, L. Kaufman, and V. Perez-Mendez, Neutron Radiography with a Multiwire Proportional Chamber--Performance and Projections, ANS Transactions **15** (1), 140 (June 1972).

L. E. Temple, S. N. Kaplan, R. V. Pyle, G. F. Valby, Nuclear Excitation of Al, Si, Ca, and Co Produced by $\mu^-$ Capture, Lawrence Berkeley Laboratory Report LBL-24, December 1971, presented at Muon Physics

Conference, Colorado State University, Fort Collins, Co, Sept. 6–10, 1971.

L. E. Temple, S. N. Kaplan, R. V. Pyle, and G. F. Valby, Nuclear Excitation of Aluminum, Silicon, Calcium, and Cobalt Produced by $\mu^-$ Capture, Lawrence Berkeley Laboratory Report LBL-533 Abs., presented at APS Meeting, San Francisco, CA, Jan. 31–Feb. 3, 1972.

L. E. Temple, Study of Nuclear Structure from the Analysis of Gamma-Rays Following $\mu^-$ Capture in Aluminum, Silicon, Calcium, and Cobalt, Ph.D. Thesis, Lawrence Berkeley Laboratory Report LBL-781, May 1972.

K. Valentine, S. Kaplan, L. Kaufman, and V. Perez-Mendez, The Adaptation of Multiwire Proportional Chambers with Delay-Line Readouts for Neutron Radiographic Imaging, IEEE Trans. Nucl Sci. **NS-19** (1), 374 (Feb. 1972).

# GROUP S EXPERIMENTAL PHYSICS

## I. TRILLING/GOLDHABER PHYSICS GROUP

*George H. Trilling and Gerson Goldhaber in charge*

The Group is carrying on programs involving both bubble-chamber data analysis and counter-spark chamber experiments. The principal acitvities have been the following:

(1) The study of $K\pi$ scattering and of diffractive processes, using film taken in an exposure of the SLAC 82-inch bubble chamber filled with deuterium to a 12-GeV/c separated $K^+$ beam.

(2) The study of production mechanisms in quasi-two-body final states produced by the interactions of 3.8-GeV/c positive pions with protons. This work uses a large sample of film, part of which has already been taken, from the SLAC 82-inch bubble chamber. It is an extension, with a very large statistics increase, of earlier studies of $\pi^+p$ interactions near 3.7 GeV/c.

(3) The study of the interactions of $\Lambda$ hyperons in the momentum range 0.5 to 8 GeV/c with protons. This is done with a special platinum target mounted inside the SLAC 82-inch bubble chamber and exposed to a 12-GeV/c separated $K^-$ beam. The interactions of the kaons in the platinum provide a relatively copious source of $\Lambda$ particles.

(4) The construction and testing of special counters for the identification of electrons and photons which are to be part of a large detector being constructed in collaboration with several groups at SLAC and with W. Chinowsky in the Chamberlain Group. This detector is to be used in the initial experiments run with the electron-positron storage ring facility, SPEAR, at SLAC.

### $K^+d$ INTERACTIONS AT 12 GeV/c

*Alexander Firestone, J. Ginestet, Gerson Goldhaber, David Lissauer, and George Trilling*

We have completed the analysis of various interesting classes of events obtained in the 500000-picture exposure of the SLAC 82-inch bubble chamber filled with deuterium to a 12-GeV/c rf-separated $K^+$ beam. These classes include events with a $K^0$ decay, three-pronged events, and four-pronged events with one stopping track. Recent results include the following.

#### Coherent Production of $Q^+$

We have made a detailed study of the production of the $Q^+$ enhancement in the coherent reaction

$$K^+d \rightarrow Q^+d \rightarrow K^+\pi^+\pi^-d.$$

From an analysis of 5606 $K^+\pi^+\pi^-d$ events, the major result is that, except for some easily understood kinematic effects, the $Q^+$ production in deuterium looks just the same as that in hydrogen; and, in particular, the $K\pi\pi$ mass spectrum is the same. The consequence of this result is that the production mechanism for the entire enhancement is non-flip isoscalar exchange, presumably Pomeranchukon exchange.[7] The interest of this result arises from the fact that the quark model predicts two $J^P = 1^+$ strange bosons, only one of which, in the absence of mixing effects, should be produced diffractively. One might, therefore, have expected *a priori* a narrower mass spectrum in coherent deuterium interactions, where diffraction is favored, than in hydrogen. Our result establishes that this is not true, and hence that there is strong mixing of the two $1^+$ bosons.

Observed decay angular distributions for the Q are very similar to those found in hydrogen interactions.[7]

#### $K\pi$ System

The $K^+\pi^-$ system produced in the reaction

$$K^+n \rightarrow K^+\pi^-p$$

has been studied with a sample of 6400 events. We have found evidence of structure for $M(K^+\pi^-)$ near 1800 MeV.

The most natural interpretation is in terms of a strange counterpart of the g meson.[8]

We have also studied $K^+\pi^-$ scattering phase shifts by making a Chew-Low extrapolation for the above reaction. Using a simple model for the resonant P and D wave amplitudes, we have investigated the energy dependence of the I = 1/2, S-wave phase shift for $M(K\pi) \leqslant 1.6$ GeV. There are ambiguities near both the K*(890) and the K*(1420) which permit both "down" and "up" solutions. In addition to whatever happens in these regions, the S-wave phase shift moves slowly through 90° near $M(K\pi)$ = 1100 to 1200 MeV.[6]

Diffractive Production of Baryons

We have investigated diffractive production of baryon states via the reaction

$$K^+n \rightarrow K^+N^{*0} \rightarrow K^+p\pi^-.$$

The $M(p\pi^-)$ spectrum at low momentum transfer has a peak near 1250 to 1300 MeV whose quantum numbers are most likely $P_{1/2}$. This structure thus falls about 200 MeV lower than the Roper resonance of phase-shift analysis. These results suggest that great caution must be used in the interpretation of masses and widths of diffractive enhancements such as the $A_1$ and Q systems in terms of the properties of resonant states.[16]

## $\pi^+p$ INTERACTIONS AT 3.7 GeV/c

*G. S. Abrams, K. W. J. Barnham, W. R. Butler, D. G. Coyne, G. Goldhaber, J. MacNaughton, and G. H. Trilling*

Although the film handling on our 3.7-GeV/c $\pi^+p$ experiment was completed some time ago, some further analysis of the data has been carried on.

Vector Meson Production

Density matrix elements for joint vector meson $\Delta(1236)$ production in the reactions

$$\pi^+p \rightarrow \rho^0\Delta^{++}$$

$$\pi^+p \rightarrow \omega\Delta^{++}$$

have been determined, and some new correlation effects found. The data are in good agreement with class A and class B predictions of the quark model, but fail the class C predictions for all possible coordinate systems. Publication of these results is in preparation.

Other Topics

Studies of two-prong events have given some results on both $\pi^+p$ elastic scattering and single-pion production. The elastic scattering analysis has provided a complete angular distribution and a measured cross section of 7.07±0.20 mb.[18]

The study of the reactions

$$\pi^+p \rightarrow \pi^+\pi^0p$$

$$\pi^+p \rightarrow \pi^+\pi^+n$$

has indicated that in addition to the usual $\rho$ and $\Delta(1236)$ production, diffractive dissociation of the incident nucleon plays an important role. It has been further suggested that $\pi^+\pi^0$ mass distributions in the neighborhood of the $\rho$ exhibit interference between $\rho$ production and diffractive dissociation.[19]

Another topic still under analysis is the production of strange particles, including cross sections for practically all observable strange-particle final states, plus more detailed studies of those states where sufficiently large event samples exist to permit analysis of production mechanisms. This work is being prepared for publication.

## $\pi^+p$ INTERACTIONS AT 3.8 GeV/c

*G. S. Abrams, B. Y. Daugeras, G. Goldhaber, A. D. Johnson, and G. H. Trilling*

We have obtained approximately 750 000 pictures of $\pi^+p$ interactions at 3.8 GeV/c in the SLAC 82-inch bubble chamber. It is anticipated that in the next year this data sample will be roughly doubled. The film is pre-scanned; and for most event topologies, information consisting only of the event type, the vertex, and a fiducial in one view is recorded on tape. The frames so chosen are measured on the Berkeley Flying-Spot Digitizer operating in the DAPR (Digital Automatic Pattern Recognition) mode. Considerable effort has gone into optimizing the efficiency of this process. Production is

presently well under way, although there are no new results as yet to report.

## $\Lambda p$ INTERACTIONS IN THE RANGE 0.5 to 8.0 GeV/c

*J. A. Kadyk, G. H. Trilling, and J. M. Hauptman*

The analysis of an experiment to study $\Lambda$-proton interactions at medium energies is in the final stages, the scanning having been completed for the 0.5-million pictures from the SLAC 82-inch bubble chamber. A brief report on an intermediate analysis was presented at the Batavia Conference, at which time about 2/3 of the data had been analyzed. The following reactions were examined:

$\Lambda p \to \Lambda p$ (517 events) $\Lambda p \to \Sigma^+ p\pi^-$ (53 events)

$\Lambda p \to \Sigma^0 p$ (51 events) $\Lambda p \to \Lambda p\pi^+\pi^-$ (143 events)

$\Lambda p \to \Sigma^- p\pi^+$ (101 events)

Cross sections, angular distributions, and mass distributions for these reactions exhibit some striking similarities with corresponding nucleon-nucleon processes. The slope of the diffraction peak in elastic scattering as a function of incident momentum agrees well with that for proton-proton elastic scattering. The cross section for the $\Sigma^0 p$ channel rises very rapidly just above threshold, an effect also observed in a previous experiment at lower energy, and then diminishes rapidly to a very small value above about 1 GeV/c. The inelastic channels are dominated by $\Delta(1236)$, $\Sigma(1385)$ resonances. There is evidence for $K^*$ exchange in the $\Sigma^+ p\pi^-$ channel, with an indication of some $\Lambda(1405)$ production. The cross section for the $\Sigma^- p\pi^+$ channel is in reasonable agreement with the SU(3) prediction based upon the pp cross section and known $N\Lambda K$ and $N\Sigma K$ coupling constants.

## SPEAR EXPERIMENT

*G. S. Abrams, C. E. Friedberg, G. Goldhaber, J. A. Kadyk, G. H. Trilling, and J. S. Whitaker*

Together with W. Chinowsky (Chamberlain Group), we are collaborating with SLAC groups on the first experiment on the new electron-positron colliding beam ring, SPEAR, which began initial operation this year. The design of the large electron shower detector modules to be used as part of the SPEAR magnetic detector was completed, and about two-thirds of the modules were built and tested. Each module consists of alternate ¼-inch layers of lead and plastic scintillator ten feet long by 1-½ feet wide viewed at each end by photomultiplier tubes, and weighs about ¾ ton. Twenty-four of these large units surround the circumference of the SPEAR detector to identify electrons and gamma-rays resulting from the $e^+e^-$ collisions. Extensive tests at the Bevatron using electron and pion beams, and cosmic rays, have verified their ability to perform the required electron-pion separation over their large area. Although the schedule for SPEAR has been delayed somewhat, it is now expected that the experiment will begin in Spring 1973.

## PUBLICATIONS AND PAPERS *(Trilling/Goldhaber)*


1. G. S. Abrams, K. W. J. Barnham, W. R. Butler, D. G. Coyne, G. Goldhaber, B. H. Hall, and J. MacNaughton, Evidence for a Charge Asymmetry on the $\omega$ Dalitz Plot, Phys. Rev. **D4**, 653 (1971).
2. G. S. Abrams, G. Goldhaber, and B. H. Hall, Proposed Method for a Search for C Violation via $\rho^0$ Interference in $\omega$ Decay, Phys. Rev. **D4**, 647 (1971).
3. M. Alston-Garnjost, K. Barnham, M. S. Rabin, A. Barbaro-Galtieri, S. M. Flatte, J. H. Friedman, G. R. Lynch, J. N. MacNaughton, F. T. Solmitz, C. Risk, W. D. Shepard, J. T. Powers, N. N. Biswas, M. M. Cason, V. P. Kenney, and D. W. Thomas, Energy Dependence of Inclusive Distributions in Pion-Induced Reactions, Phys. Letters **39B**, 402 (1972).
4. Jonathan H.-S. Chan, Measurement of the $K^0_L \to \pi e \nu$ Absolute Decay Rate, Ph.D. thesis, Lawrence Berkeley Laboratory Report LBL-350, Oct. 1971.
5. D. G. Coyne, W. R. Butler, G. Fang-Landau, and J. N. MacNaughton, General Remarks on Experiments Measuring Particle Widths and the Width of the $\omega$, Nucl. Phys. **B32**, 333 (1971).
6. A. Firestone, G. Goldhaber, D. Lissauer, and G. H. Trilling, Analysis of $K\pi$ Scattering from the Reaction $K^+n \to K^+\pi^-p$, Phys. Rev. **D5**, 2188 (1972).

7. A. Firestone et al., Coherent $K^+d$ Interactions at 12 GeV/c, Phys. Rev. **D5**, 505 (1972).
8. A. Firestone, G. Goldhaber, D. Lissauer, and G. H. Trilling, Evidence for Structure in the $K\pi$ Mass System near 1.85 MeV, Phys. Letters **36B**, 513 (1971).
9. C. Fu, Double Peripheral Model Analysis of the Reaction $K^+p \rightarrow K^+\pi^-\Delta^{++}(1236)$ at 9 GeV/c, Phys. Rev. **D3**, 92 (1971).
10. C. Fu, J. MacNaughton, and G. H. Trilling, Single Pion Production in $K^+p$ Interactions at 4.6 GeV/c, Nucl. Phys. **B28**, 528 (1971).
11. G. Goldhaber, Selected Topics on Boson Resonances, Lawrence Berkeley Laboratory Report LBL-534, July 1971, lecture series presented at "Ettore Majorana" Center for Scientific Culture, International School for Subnuclear Physics, Erice, Trapani, Sicily, July 8-26, 1971.
12. A. A. Hirata, G. Goldhaber, B. H. Hall, V. H. Seeger, G. H. Trilling, and C. G. Wohl, $K^+n$ Charge Exchange near 1 GeV/c, Nucl. Phys. **B30**, 157 (1971).
13. A. A. Hirata, G. Goldhaber, V. H. Seeger, G. H. Trilling, and C. G. Wohl, A Study of $K^+d$ Interactions from 865 to 1585 MeV/c, Nucl. Phys. **B33**, 525 (1971).
14. J. A. Kadyk, J. M. Hauptman, and G. H. Trilling, A Study of $\Lambda p$ Interactions at 0.5 to 8.0 GeV/c in the 82-Inch Bubble Chamber, Lawrence Radiation Laboratory Report UCRL-20649, submitted to the Amsterdam conference.
15. David Ariel Lissauer, $K^+d$ Interactions at 12 GeV/c, Ph.D. thesis, Lawrence Radiation Laboratory Report UCRL-20644, Aug. 1971.
16. D. Lissauer, A. Firestone, J. Ginestet, G. Goldhaber, and G. H. Trilling, A Study of the Reaction $K^+n \rightarrow K^+N^{*0}$ at 12 GeV/c, Phys. Rev. **D6**, 1852 (1972).
17. J. MacNaughton, W. Butler, D. Coyne, C. Fu, and G. H. Trilling, Interference Effects in the Process $\pi^+p \rightarrow \rho^+p$, Lawrence Radiation Laboratory Report UCRL-20833, June 1971.
18. J. MacNaughton, W. R. Butler, D. G. Coyne, G. M. Hicks, and G. H. Trilling, $\pi^+p$ Elastic Scattering at 3.6 GeV/c, Nucl. Phys. **B33**, 101 (1971).
19. Jimmy N. MacNaughton, Studies of Two-Prong Interactions in $K^+p$ at 4.6 GeV/c and $\pi^+p$ at 3.6 GeV/c, Ph.D. thesis, Lawrence Radiation Laboratory Report UCRL-20178, May 1971.
20. G. H. Trilling, Some Topics in Boson Spectroscopy, in *Particles and Fields*, A. C. Melissinos and P. F. Slattery, Eds. (Amer. Inst. of Phys., New York, 1971), p.1.
21. G. H. Trilling, Tests of SU(3) in Particle Reactions, Nucl. Phys. **B40**, 13 (1972).


## II. BIRGE PHYSICS GROUP

*Robert W. Birge in charge*

The Birge Group is performing research in high-energy physics based on film taken of interactions in bubble chambers, and is planning a streamer chamber experiment. To carry out this research, we maintain scanning and measuring machines and a mix of computer guidance and/or personnel to use these machines to abstract data from the film. Finally, we maintain and develop computer programs for data reduction and analysis. We are currently working on several projects in different stages of development.

We are finishing the analysis of $\pi^+p$ and $K^-p$ interactions at various energies using film taken with the 25-inch hydrogen bubble chamber at the Bevatron. Film taken with a triggered bubble chamber at SLAC is currently being analyzed to study peripheral $\pi^-p$ interactions at 14 GeV/c. We have recently collaborated on an experiment at the Rutherford Laboratory in England using a track-sensitive hydrogen target in a $H_2$-neon mixture. In this experiment we plan to study reactions involving neutral pi-mesons by means of decay $\gamma$-rays which produce electron pairs in the neon.

In addition, we have scheduled an experiment using film to be taken in the LBL streamer chamber to study backward inelastic scattering. This experiment will involve triggering only for events of interest.

## $\pi^+p$ INTERACTIONS

These studies of resonance formation and Regge exchange processes are nearing completion.

### Non-Strange-Particle Final States (1.1 to 2.0 GeV/c)

*William Michael, George Gidal, and Donald Grether*

A partial-wave analysis of the reaction $\pi^+p \to \Delta^{++}\pi^0$ has been completed in collaboration with a group at the University of California at Riverside and submitted for publication.

It was found that this reaction is dominated by formation of the $F_{37}$ (1950) resonance with a mass of 1930±20 MeV, a width of $227^{+12}_{-30}$ MeV, and a product of branching fractions of $0.24^{+0.01}_{-0.03}$.

An analysis of the reaction $\pi^+p \to \rho^+p$ is in progress in collaboration with the Riverside group. Work thus far shows this reaction to be dominated by exchange processes rather than resonance formation. The details of these processes are being studied, and results will soon be submitted for publication.

The elastic-scattering angular distributions and Legendre shape coefficients have been determined for three additional momenta in this range: 1.15, 1.20, and 1.62 GeV/c. These results will be made available for elastic phase-shift analyses.

Analysis of the reaction $\pi^+p \to \eta\Delta^{++}$ has been completed in conjunction with an analysis of higher momentum data and has been submitted for publication. The reaction was found to be relatively well described by an extrapolation of an $A_2$ Regge-pole exchange model fit to the higher momentum data. No evidence was found for any substantial contribution from s-channel resonance formation.

### Non-Strange-Particle Final States (2.0 to 4.1 GeV/c)

*William Michael, George Gidal, and Donald Grether*

A detailed study of the reaction $\pi^-p \to \rho^+p$ at 2.67 GeV/c incident momentum has been completed and the results submitted for publication. The differential cross section and spin-density matrix elements were found to have features characteristic of $\pi$, $\omega$, and $A_2$ exchange. Additional information was obtained by combining these $\rho^+$ results with those from a similar experiment carried out at Saclay in which $\rho^-$ and $\rho^0$ were produced. The contribution of the $\omega$-trajectory was isolated and its parameters determined. Strong evidence was found for the presence of an $I = 0$, $J^{PG} = 1^{+-}$ exchange that would correspond to the previously unestablished H-meson.

The reaction $\pi^+p \to \eta\Delta^{++}$ has been analyzed in terms of $A_2$ Regge-pole exchange and the results submitted for publication. The minimum in the differential cross section expected when the $A_2$ trajectory passes through -1 has been observed. The effective $A_2$ trajectory has been calculated and shown to be in fair agreement with that expected from $\rho$–$A_2$ exchange degeneracy.

Analysis of the reaction $\pi^+p \to \omega^0\Delta^{++}$ has been completed and submitted for publication. The $\rho$ and B exchange contributions were isolated and effective trajectories calculated for the two exchanges. The $\rho$ effective trajectory was consistent with the normal value obtained in other reactions. The B trajectory was not consistent with $\pi$-B exchange degeneracy as has been suggested by other experiments.

### Strange-Particle Final States

*Philip Hanson, George Kalmus, and James Louie*

Angular distributions and polarization measurements for the reaction $\pi^+p \to \Sigma^+K^+$ have been completed at 9 incident momenta between 1.28 and 1.84 GeV/c and have been published together with a partial-wave analysis. We have also published cross sections and Dalitz plots at these momenta for the three-body strange-particle final states $\Sigma^+K^+\pi^0$, $\Sigma^+K^0\pi^+$, $\Sigma^0K^+\pi^+$, $\Lambda K^+\pi^+$, $pK^+\bar{K}^0$, and angular distributions for the quasi-two-body final state $Y^{*+}K^+$.

Scanning and measuring of two more momenta in this range (1.15 and 1.20 GeV/c) have been completed. In addition, scanning and measuring of strange-particle final states for $\pi^+p$ interactions at 5 momenta between 2 and 3 GeV/c have been finished; and analysis is in progress.

## $\pi\pi$ Scattering by Pole Extrapolation Methods

*Frederick Lott*

The 300 000 pictures of $\pi^+p$ interactions at 2.67 GeV/c are being used to do Chew-Low extrapolations using the reactions $\pi^+p \rightarrow \pi^+p\pi^0$ and $\pi^+p \rightarrow \pi^+\pi^+n$. Preliminary extrapolations show results comparable to those found by other investigators. Other extrapolation methods such as the Durr-Pilkuhn method and that of Benecke-Durr are also being used. In addition, the possible interference of the H(990) meson with the exchanged $\pi^0$ is being investigated.

## $K^-p$ INTERACTIONS (0.85 TO 1.70 GeV/c)

*Andrew Van Horn, Robert Ely, and Daniel Kane*

Final event reconstruction, scanning efficiencies, and throughput efficiencies were completed for the following topologies: events with vees, events with kinks, and three-prong ($\tau$) decays. Seventeen reaction channels have been constrained and fit. Scanning and measuring were done on the COBWEB system; kinematic fitting on the FOG, CLOUDY, FAIR system.

Final cross sections, angular distributions, and polarizations (for $\Lambda$ and $\Sigma^+$) have been calculated for $\Lambda\pi^0$, $\bar{K}^0n$, $\Sigma^\pm\pi^\mp$. Dalitz plots and invariant-mass plots are completed for $\Sigma^\pm\pi^\mp\pi^0$. The data from the 0-prong vee topology have been submitted for publication. The data and the partial-wave analysis of the $\Sigma^\pm\pi^\mp$ channel have been accepted for publication in Physical Review.

## PHOTOPRODUCTION IN DEUTERIUM

*George Gidal and Robert Birge*

In collaboration with the University of California at Riverside, we have been studying photoproduction in deuterium. We have taken 500 000 pictures in the 82-inch bubble chamber at the Stanford Linear Accelerator Center, using a polarized photon beam produced by backscattering a laser beam off the high-energy electron beam. Scanning and measuring of the film are proceeding. We are modifying a version of SIOUX, the geometrical reconstruction and kinematic fitting program, to suit our needs for the data reduction.

## PERIPHERAL $\pi^-p$ INTERACTIONS

*Robert Ely, Donald Grether, Piermaria Oddone*

In collaboration with the California Institute of Technology, we are studying diffractively produced isobars, using a spark-chamber spectrometer in back of the 40-inch hydrogen bubble chamber at the Stanford Linear Accelerator Center to examine 14-GeV/c $\pi^-p$ interactions. The spark chambers were used to trigger the bubble chamber camera when the interaction resulted in a very fast outgoing $\pi^-$. In addition we attempted to discriminate against elastic scattering.

The results were quite successful, providing an interesting event every 4 pictures whereas in an untriggered exposure the same events would have occurred only in one of every 40 pictures. The spark chambers also provide a more precise measurement of the fast outgoing momentum than can be obtained with the bubble chamber only--a crucial point in this experiment.

We took 400 000 pictures which are being scanned and measured. The scanning is about one-half finished. Measuring is being done on both the COBWEB system and on the FSD using automatic pattern recognition, DAPR. Approximately 100 000 pictures have been measured to date.

A second exposure to measure the complementary reaction, $\pi^+p$, at 14 GeV/c has been proposed.

## CLOUD-CHAMBER QUARK SEARCH

*Wilson M. Powell*

Negative results of this study were published. We are continuing a small effort on this collaboration with the Lawrence Livermore Laboratory.

## PUBLICATIONS AND PAPERS (Birge)

A. F. Clark, R. D. Ernst, H. F. Finn, G. G. Griffin, N. E. Hansen, D. E. Smith, and W. M. Powell, Cloud Chamber Quark Quest, Negative Results, Phys. Rev. Letters **27**, 51 (1971).

A. Dzierba, W. T. Ford, R. Gomez, P. Oddone, C. W. Peck, J. Power, C. Rosenfeld, A. V. Tollestrup, R. Ely,

D. Grether, and W. Michael, Study of Nucleon Diffraction Dissociation in $\pi^-p$ Interactions at 14 GeV: A Hybrid Spark Chamber Bubble Chamber Experiment, in *Proceedings of 4th Hawaii Topical Conference in Particle Physics,* D. E. Yount and P. N. Dobson, Eds. (U. Hawaii Press, Honolulu, 1972).

G. Gidal, Exchange Mechanisms in Some Resonance Production Reactions, in *Proceedings of the Seventh Recontre de Moriond, Vol. 1, Two-Body Collisions,* J. Tran Thanh Van, Ed. (CNRS, Paris, 1972), p. 401.

George Gidal, Experimental Status of the Leading Non-Strange Meson Trajectories, Lawrence Berkeley Laboratory Report LBL-352, Sept. 1971, presented at the 1971 Annual Meeting of the Division of Particles and Fields, U. Rochester, New York, Aug. 30 - Sept. 2, 1971.

D. Grether, G. Borreani, and G. Gidal, Measurement and Analysis of the Reaction $\pi^+p \to \eta^0\Delta^{++}$, Lawrence Berkeley Laboratory Report LBL-722, Mar. 1972, to be submitted for publication.

D. F. Grether and G. Gidal, The Reaction $\pi^+p \to \eta^0\Delta^{++}$: A Test of $A_2$ Regge Pole Exchange, Phys. Rev. Letters **26**, 792 (1971).

P. Hanson, G. E. Kalmus, and J. Louie, Strange Particle Production From $\pi^+p$ Interactions in the c.m. Energy Range 1820 to 2090 MeV, Phys. Rev. **D4**, 1296 (1971).

G. E. Kalmus, G. Borreani, and J. Louie, Additional Data in the Reaction $\pi^+p \to \Sigma^+K^+$ at 1.28 and 1.41 GeV/c and a Test of Charge Independence in the c.m. Energy Range 1.820 to 2.090 GeV, Phys. Rev. **D4**, 916 (1971).

G. E. Kalmus, W. Michael, R. W. Birge, S. Y. Fung, and A. Kernan, $\pi^+p$ Elastic Scattering Data between 1820 and 2090 MeV c.m. Energy, Phys. Rev. **D4**, 676 (1971).

Daniel F. Kane, Jr., Partial Wave Analysis of $K^-p \to \pi^\pm\Sigma^\mp$ Between 1.73 and 2.11 GeV, Phys. Rev. **D5**, 1583 (1972).

Daniel F. Kane Jr., A Study of the Reactions $K^-p \to \Sigma^\pm\pi^\mp(\pi^0)$ Between 0.85 and 1.15 GeV/c, Lawrence Radiation Laboratory Report UCRL-20676, Apr. 1971.

Daniel F. Kane, Jr., A Study of the Reactions $K^-p \to \Sigma^\pm\pi^\mp(\pi^0)$ Between 1.1 and 1.7 GeV/c, Ph.D. thesis, Lawrence Radiation Laboratory Report UCRL-20682, Apr. 1971.

W. Michael and G. Gidal, The Reaction $\pi^+p \to \rho^+p$ at 2.67 GeV/c; A Study of Isoscalar Exchanges, Phys. Rev. Letters **28**, 1475 (1972).

W. Michael, G. Gidal, and D. Grether, The Reaction $\pi^+p \to \rho^+p$ at 2.67 GeV/c, Lawrence Berkeley Laboratory Report LBL-32, presented at the 1971 Annual Meeting of the Division of Particles and Fields, U. Rochester, New York, Aug. 30 - Sept. 2, 1971.

A. J. Van Horn, R. P. Ely, and J. Louie, The Reactions $K^-p \to \Lambda\pi^0$ and $K^-p \to \bar{K}^0n$ in the Center-of-Mass Energy Range from 1700 to 2100 MeV, Phys. Rev. **D6**, 1275 (1972).

## III. DATA-HANDLING GROUP

*Howard S. White in charge*

The Data-Handling Group is involved in designing specialized systems for scanning, measuring, and analyzing experimental data from bubble chambers used in high-energy particle-physics applications; in improving the effectiveness of computer programming in areas related to high-volume precision analysis systems; and in operating data systems in support of experimental physics research.

### DAPR: AUTOMATIC SCANNING AND MEASURING OF BUBBLE CHAMBER EVENTS

*Barbara Britton, Joan Franz, Wen-Sue Gee, Dennis Hall, Howard White*

This year the Digital Automatic Pattern Recognition (DAPR) system was first used to measure a substantial volume of data from the SLAC 40-inch and 82-inch hydrogen bubble chambers. This system uses the same IBM 7094 II computer and Flying Spot

Digitizer (FSD) as the HAZE system which it will replace. DAPR, unlike HAZE, is able without manual assistance to perform the entire scanning, measuring, and analysis of bubble chamber events. It is also possible to operate DAPR in a prescan control mode, in which analysis is performed only on those frames which have been selected by a manual scanner. This allows a more economical analysis operation when the event density is sufficiently low. This prescan mode was used for most measurements made this year. About 750 000 frames have now been analysed by DAPR, including 350 000 this year.

A second FSD unit is being fabricated to form a Tandem FSD system which will nearly double the present measurement capacity, now that DAPR has removed the "bottleneck" of manual road guidance.

The HAZE measurement system continued to be used for special groups of events difficult to measure with DAPR. First used for physics measurements in FY 1964, HAZE utilizes a large digital computer, operating the FSD and related computer programs, to automatically measure film in which manual scanning has previously identified tracks and events of interest. More than 2 300 000 events have been analyzed by the HAZE system, including about 25 000 this year.

Events measured by the microscope and Franckenstein hardware continued to be analyzed. Primarily these are remeasurements and initial measurements of events having very sparse distribution through the film.

Processing of all film from the LBL 25-inch chamber was successfully completed by mid-November 1971. Abstraction of film from the SLAC 40-inch chamber started in September, and film from the SLAC 82-inch chamber was being processed by November.

Several changes to the track-following program (511) were required in order to process film from the SLAC 40-inch chamber. Because of the placement of the fiducials it was necessary to allow the program to initiate both beam and non-beam track following simultaneously. Because the chamber does not produce a data box which could be read with existing hardware, it was necessary to read the frame numbers with the Flying Spot. A sprocket counting algorithm was implemented in conjunction with the new frame readout to achieve proper positioning of the film. Both of these features were completed by September. It was discovered that the number of sprocket holes required to advance from one frame to the next varied from roll to roll. This problem was traced to a design weakness in the camera of the 40-inch chamber. A procedure for monitoring the inter-frame sprocket count was implemented which allowed successful film positioning to occur over a wide range of camera operating conditions.

A revised assembly of the track-linking program (512) was completed in February, and work began on improvements to the linking algorithm and to the program running speed.

The new procedure for resolving conflicting hypotheses in the vertex-finding program (513) continued to be developed. This procedure was originally designed for film from the SLAC 82-inch chamber, and first implemented on data from an optimally spaced beam in a clean chamber background on 46mm film. Changing over to the current experiment proved more difficult than had been anticipated. The program was forced to deal with a significantly smaller image, closer beam-track spacing, and a denser background of unwanted digitizings. Procedures for dealing with these problems are still under development.

A procedure to allow output onto the HAZE library of all tracks associated with a manually scanned vertex was started in February. This was designed as a feedback mechanism for correlating spark chamber information with events which failed to be properly assigned by DAPR in the SLAC 40-inch chamber.

## FCF: GEOMETRY, KINEMATICS, DISPLAY

*Shirley Buckman, Vivian Morgan, Loren Shalz*

Improvements to the FOG, CLOUDY, and FAIR systems were limited to determination of optical constants in the SLAC 40-inch and 82-inch chambers, and the usual special calculations for data display.

Major effort was expended on assimilating the SIOUX system and implementing modifications to allow reduction of FSD data. Changeover to this system running under the 7600-BKY system was well under way

Design of a new data display system (FAIR 76) which operates on the 7600 but incorporates the unique data selection features of FAIR was started. The 7600 data display program ERGON, written by the Birge Group, was being incorporated into FAIR 76. This will allow data produced by FAIR on the 7094 to be displayed via the 7600 CRT, and will allow the 7094 CRT display hardware to be phased out.

A program which allows momentum and angle measurements from a spark chamber to be added to bubble chamber measurements on a CLOUDY library was designed and implemented.

## TRIST: SYSTEMS MONITOR

*Priscilla Davis, Carol Osborne*

A new system update program was designed and implemented. This program incorporates many improved features: A more efficient disc allocation algorithm was written which provided more usable room in the protected area of the disc. A simplified deck setup and running procedure was established. More thorough error checking routines and error diagnostics were provided. The error recovery and backup procedures were generalized to allow easy transfer from disc to tape and vice versa.

The use of microfiche for bulk printing was started. The weekly printout of the entire system library is now routinely listed on microfiche. Core dumps from system breakdowns are also printed on microfiche. Further use of microfiche is intended for the future, but will require minor TRIST modification for implementation.

The reassembly of the monitor program which provides more core storage space in the system area by storing relatively inactive subroutines on the disc was temporarily set aside in favor of the new update program and the microfiche features. Work was resumed on this project in February and was completed by June.

## FSD MONITOR

*Loren Shalz*

Monitoring of the performance of FSD Unit I continued to produce excellent results. The integrator diagnostic subroutine was reassembled and the calibration program was modified to punch new coefficients automatically. This reduces the time delay between detection of a drift and implementation of the correction. A memory test routine and display routine were written for FSD Unit II. Final debugging will occur when fabrication of Unit II is complete, probably October to December, 1972.

## QUARKS

*Shirley Buckman*

The QUARK experiment continued routine operation with 7630 tracks being processed during the year. No further development effort is expected for this project.

EVENT MEASUREMENTS PROCESSED

The following table summarizes the processing of events measured on the COBWEB, HAZE, and DAPR systems. An event is the entire collection of related vertices measured in a bubble chamber picture. New measurements of the same event are counted separately, but the effect of any computer reprocessing has been eliminated from the totals.

Table I: Event measurements processed, 1 July 1971 through 30 June 1972

| Experiment | Chamber | Beam | Group | Number of Events |
|---|---|---|---|---|
| | | COBWEB SYSTEM | | |
| 55 | 25" HBC-LBL | 1.3 GeV/c $K^-$ | Birge | 8604 |
| 67 | 40" HBC-SLAC | 14.0 GeV/c $\pi^-$ | Birge | 38523 |
| 68 | 40" HBC-SLAC | 14.0 GeV/c $\pi^-$ | Birge | 3087 |
| 96 | 82" HBC-SLAC | 3.5 GeV/c $\pi^+$ | Trilling-Goldhaber | 1734 |
| | | Total COBWEB Measurements Processed | | 51948 |
| | | HAZE SYSTEM | | |
| Experiment | Chamber | Beam | Group | Number of Events |
| 58 | 25" HBC-LBL | 2.9 GeV/c $\pi^+$ | Birge | 13854 |
| 72 | 80" DBC-BNL | 8.0 GeV/cp | Segre-Chamberlain | 2787 |
| 96 | 82" HBC-SLAC | 3.5 GeV/c $\pi^+$ | Trilling-Goldhaber | 5581 |
| 97 | 82" HBC-SLAC | 3.5 GeV/c $\pi^+$ | Trilling-Goldhaber | 2328 |
| | | Total HAZE Measurements | | 24550 |
| | | DAPR SYSTEM | | |
| Experiment | Chamber | Beam | Group | Number of Events |
| 60 | 25" HBC-LBL | 2.9 GeV/c $\pi^+$ | Birge | 46417 |
| 67 | 40" HBC-SLAC | 14.0 GeV/c $\pi^-$ | Birge | 105931 |
| 68 | 40" HBC-SLAC | 14.0 GeV/c $\pi^-$ | Birge | 25361 |
| 96 | 82" HBC-SLAC | 3.5 GeV/c $\pi^+$ | Trilling-Goldhaber | 139742 |
| 97 | 82" HBC-SLAC | 3.5 GeV/c $\pi^+$ | Trilling-Goldhaber | 35279 |
| | | Total DAPR Measurements | | 352730 |
| | | Total Events Processed | | 429228 |

## IV. SPECIAL PROJECTS GROUP

*Jack V. Franck in charge*

The Special Projects Group is charged with:

Design and construction of specialized systems for photographing, scanning, measuring, and analyzing experimental data from bubble, spark, and streamer chambers used in high-energy particle physics.

Improving the reliability and performance of existing hardware and systems

Extension and application of the knowledge and techniques developed in the fields of bubble, spark, and streamer chamber data processing to other scientific fields and efforts.

Maintenance of data systems and special equipment in support of several experimental physics research groups.

Furnishing engineering support and consultation as required on a reimbursable basis for NASA, AEC, HEW, NSF, and Livermore development programs.

During the past year we have been involved in the following projects:

*For Birge Group*

Provided maintenance, repair, improvement, and support service for their scanning, measuring, and photographic equipment.

*For Data Handling Group*

Completed the "construction fund" phase of the FSD-2 and Tandem systems; completed the design phase of FSD-2 as well as most of the assembly and debugging; and provided maintenance, repair, improvement, and support service for the scanning, measuring, and photographic equipment.

*Trilling-Goldhaber Group*

Provided engineering design and fabrication support for the SPEAR Project; and provided maintenance, repair, improvement, and support service for the scanning, measuring, and photographic equipment.

*For Lofgren Group*

Continued support of the UCLA experiment on the streamer chamber; and provided maintenance, repair, improvement, and support service for the scanning, measuring, and photographic equipment.

*For Kenney Group*

Provided maintenance, repair, improvement, and support service for the scanning, measuring, and photographic equipment.

*For Segre-Chamberlain Group*

Provided maintenance, repair, improvement, and support service for the scanning, measuring and photographic equipment.

*For Heckman Group*

Designed mechanical and electronic equipment and instrumentation (on-line PDP-11, remote control servos, digital readouts) for the Bevatron Heavy-Ion Experiment #162; and provided maintenance, repair, improvement, and support service for the scanning, measuring, and photographic equipment.

*For Math and Computing*

Completed engineering and design effort to implement the installation of the Remote Computer Access System (RCAS); installed two improved 32-channel multiplexers (to RECC) providing a total of 96 teletype channels: completed the initial design and development of Computer Output Microfilm (COM) interface; made initial design studies for connection to ARPA Net (nationwide computer network); continued development on RCAS and RECC; and provided maintenance, repair, improvement, and support service for the scanning, measuring, and photographic equipment.

*For Crowe Group*

Provided maintenance, repair, improvement, and support service for the scanning, measuring, and photographic equipment.

*For Inorganic Materials Research Division*

Provided maintenance, repair, improvement, and support service for the scanning, measuring, and photographic equipment.

*For Biology and Medicine Division*

Provided maintenance, repair, development and support service for the body-positioning equipment.

*For NASA Manned Space Flight Center, Houston*

Continued feasibility study on a "Plastic" Scanner.

*For Livermore Laboratory*

Provided engineering, consulting, mathematics and computer programming for the 5102-85 program as required: again expanded the 3-parameter digital recording system for "S" Division--designed on-line computer system; and continued design and hardware fabrication

of X-Ray Micrometer.

*For Electronics Department*

Completed programming for computer controlled bin wiring; and aided in the development of SRI design automation program.

*For Special Projects Group*

Continued multi-shift maintenance support services for various groups within the Laboratory; continued improving the reliability and performance of all the machines manufactured or maintained by this group; continued the development of circuit boards, servo amplifiers, micro-logic, and other electronic components used in scanning and measuring equipment; continued participation in the environmental proposal related to Lake Tahoe.

# SEGRÈ/CHAMBERLAIN EXPERIMENTAL PHYSICS

Emilio G. Segrè and Owen Chamberlain in charge

The project is divided into several topics:

(1) We have continued the measurements of the energies and intensities of x-rays emitted by the system of negative kaon and atomic nucleus. This study continues to yield information about the K-nucleon interaction, and the properties of the nuclear surface and of mesonic and hyperonic atomic systems.

(2) The decays of positive kaons have been studied as a probe of basic interactions; in particular, detailed angular and polarization measurements have been made, and very rare decay modes have been sought, as a means of finding the nature of the weak interactions.

(3) A polarized target is being used to study the spin-dependence of elastic scattering of hadrons on protons, and the charge-exchange scattering of negative pions on protons.

(4) Bubble chamber studies of reactions arising from $\bar{p}p$, pp, and pd collisions are being completed.

(5) Pion production spectra arising from high-energy collisions of heavy ions with complex nuclei are being studied at the Bevatron, using its new Heavy-Ion Facility.

(6) Preparations for running with the magnetic detector at SPEAR, the colliding-beams (electrons and positrons) machine at SLAC, have continued.

(7) We have continued to develop and improve techniques and equipment for use in our experimental program. A new $^3$He-cooled polarized target was designed, and further effort went into research on multiwire proportional chamber detecting systems.

## KAONIC ATOMS

*C. Wiegand, J. Gallup, and G. Godfrey*

Analyses of the results of the experiments on kaonic atoms done in 1971 at the Bevatron have continued. Earlier we published results on some of the features of the investigations: measurements on kaonic helium,[1] observation of kaon-induced nuclear gamma rays,[2] and a possible coupling between a kaonic atom and a nuclear energy state.[3] In tabulating the intensities of the principal kaonic lines of the elements, we note unexpected variations. The anomalies may stem from atomic structure that in turn affects the mechanism of kaon capture at large values of n, the principal quantum number. A more comprehensive account of the experiments is in preparation.

---

[1] Clyde E. Wiegand and Richard H. Pehl, Measurement of Kaonic X Rays from $^4$He, Phys. Rev. Letters 27, 1410 (1971).

[2] Clyde E. Wiegand, Jeffrey M. Gallup, and Gary L. Godfrey, Observation of Nuclear $\gamma$ Rays from Kaon Capture, Phys. Rev. Letters 28, 621 (1972).

[3] Gary L. Godfrey and Clyde E. Wiegand, Kaonic Atom Transition Coupled to Nuclear Level, Lawrence Berkeley Laboratory Report LBL-776, June 1972.

## SEARCH FOR $K^+ \to \mu^+ \nu\bar{\nu}\nu$ AND $K^+ \to \pi^+ \nu\bar{\nu}$

*Roger Hildebrand, Gary Cable, Harlan Evans, and Chan Pang (University of Chicago); Rae Stiening (LBL).*

The experiment seraching for the rare decay modes $K^+ \to \mu^+ \nu\bar{\nu}\nu$ and $K^+ \to \pi^+ \nu\bar{\nu}$ has been concluded with no evidence found for the existence of either decay mode. Upper limits on the branching ratios, $6.1 \times 10^{-6}$ for $K^+ \to \mu^+ \nu\bar{\nu}\nu$ and $6.1 \times 10^{-7}$ for $K^+ \to \pi^+ \nu\bar{\nu}$ (assuming vector coupling interaction), were established.

From the $\mu^+$ decay mode we could set a limit on the strength of the possible non-weak neutrino-neutrino interaction, $F_{\nu\nu} < 1.7 \times 10^5$ G, while the $\pi^+$ decay mode showed the neutral weak currents are suppressed by a factor of at least $2.9 \times 10^3$ relative to the charged weak currents. These results also enabled us to set constraints on various theoretical models of weak interaction.

The major component of the experimental apparatus was an anticoincidence assembly of high-density lead-glass blocks forming a cube 54 cm on a side.

## TWO-PRONG $\bar{p}p$ ANNIHILATIONS

*W. Chinowsky and Carlos Lima*

An exposure of the Brookhaven National Laboratory 30-inch hydrogen bubble chamber to an antiproton beam at six momenta settings centered at 0.68, 0.77, 0.86, 0.95, 1.04, and 1.1 GeV/c was made. From the runs at the three lowest momenta, a sample of 50 000 pictures was scanned at LBL for two-pronged events. Within the restricted fiducial volume imposed, about 20 000 events were found, which were measured with the digitizing system COBWEB, reconstructed and kinematically analyzed with the TVGP-SQUAW programs. Cross sections obtained for the various identified annihilation channels are given in the table. Maximum likelihood fits have been made to the mass spectra of dipion systems in the $\pi^+\pi^-\pi^0$ events to yield estimated of $\rho_0$ and $f_0$ resonance production cross sections in the table below. These results are consistent with a smooth variation of cross sections with energy, smoothly interpolated between previously measured values, and so yield no evidence for heavy meson s-channel production in the $\bar{p}p$ annihilation process.

Scanning and measuring of the three highest momenta exposures is in progress at U.C. Irvine. When available, these data will be included in the analysis.

Table I. Cross Sections

| Channel | $p_{lab}$=0.68 GeV/c | $p_{lab}$= 0.77 GeV/c | $p_{lab}$=0.86 GeV/c |
|---|---|---|---|
| 2 prongs annihilation | 30.8 ± 2.4 mb | 25.4 ± 1.8 mb | 24.3 ± 3.0 mb |
| $\pi^+\pi^-$ | 313 ± 79 μb | 283 ± 87 μb | 286 ± 72 μb |
| $\pi^+\pi^-\pi^0$ | 5.5 ± 0.5 mb | 4.6 ± 0.5 mb | 4.4 ± 0.5 mb |
| $\rho\pi$ | 1.3 ± 0.2 mb | 1.1 ± 0.2 mb | 0.9 ± 0.2 mb |
| $f^0\pi^0$ | 230 ± 35 μb | 125 ± 38 μb | 110 ± 40 μb |

## PION PRODUCTION IN HEAVY-ION REACTIONS

*H. Steiner and J. Jaros*

As part of the Heavy-Ion Program at the Bevatron, we have collaborated with the Lofgren Physics Group to measure pion yields from collisions between high-energy protons, deuterons, and alphas and targets of beryllium, copper, and lead. Naively, one might expect the pion production to result from collisions between a single nucleon in the projectile with one in the target. Then, for example, the deuteron-induced yield would be rougly twice the proton-induced yield, independent of the energy of the produced pion. Instead, we have observed pions produced at energies greater than is kinematically possible in such individual nucleon-nucleon collisions and have found that the ratio of the deuteron-induced pion yield to the proton-induced yield depends on the pion's energy. This suggests that coherent production may be occuring; that is, both nucleons of the deuteron sometimes act jointly to produce pions. These pieces of information are consistent with the picture of nucleons within nuclei being in motion. We intend to make further tests to determine whether internal Fermi motion is sufficient explain the results or whether coherent mechanisms must be invoked.

## ASYMMETRY IN $\pi^- p \to \pi^0 n$

*S. Shannon, L. Anderson, A. Bridgewater, O. Chamberlain R. Fuzesy, W. Gorn, J. Jaros, G. O'Keefe, J. Papp, P. Robrish, G. Shapiro, and H. Steiner*

In collaboration with the Kenney Group and Group A, we are measuring at the Bevatron the polarization asymmetry in the process $\pi^- p \to \pi^0 n$, using a polarized target. This is an experiment long needed in the study of detailed scattering amplitudes for the pion-nucleon system.

Data have already been completed at incident beam momenta of 1030, 1250, and 1590 MeV/c. We will extend the measurements to momenta of 1440 and 1790 MeV/c during the coming months. Analysis of the data remains to be done. Preliminary analysis shows that the data at the lower momenta are in qualitative agreement with phase-shift analysis predictions, while there seems to be quantitative disagreement at the higher momenta.

## SPEAR

*W. Chinowsky, R. Hollebeek, and J. Zipse*

Preparations for running with the magnetic detector at SPEAR have continued. At present it is expected that testing of the apparatus at SPEAR will begin in March 1973. Half of the 24 shower-counter modules have been completed and tested with cosmic rays, and a number have been tested at the Bevatron and SLAC in electron and pion beams. It has been established that all the modules are able to adequately separate pions from electrons. Programming has concentrated on preparation for on-line reconstruction, display, and analysis of events, usjng the Sigma-5 computer. The pattern recognition program has been modified and tested with generated events. A program to produce space points from measurements of the angular position of the magnetostrictive readout signal has been written and operated successfully. It is now possible to construct points into tracks in about 10 msec for two-body events, in about 100 msec for multi-track events. Programs to display readout signal coordinates, spark coordinates, and tracks have been written for the Sigma-5 and successfully tested, using generated "events" and random background sparks. Various parameters to correct for misalignments of the spark chambers will be determined from measurements of cosmic-ray tracks and SPEAR events without magnetic field. Programs to reduce those data and determine the "optical parameters" are being written.

This work is being done on a collaborative basis with the Trilling-Goldhaber Group.

## PROPORTIONAL WIRE CHAMBERS

*R. Fuzesy, J. Jaros, G. O'Keefe, and H. Steiner*

Our efforts in proportional wire chamber development have been along several lines. Chamber construction techniques have been improved, and testing procedures developed. Chamber winding machines have been improved, a new uniform-wire-tension device included, and tests performed on wire tensile strengths. New testing procedures have been developed which allow careful evaluation of each chamber.

Several new chambers have been built. Some 5 cm X 5 cm chambers have successfully served as beam tuning hodoscopes, their small size allowing them to be placed in nearly inaccessible spots. Larger 0.5 m X 0.7 m chambers along with their accompanying electronics have been readied for use in a Bevatron experiment to calibrate the polarization of the target used in the $\pi^- p\ (\pi) \rightarrow \pi^0 n$ asymmetry experiment. A new set of chambers to be ready early in 1973, including some with 1 mm resolution, have been designed for use in a forthcoming Bevatron experiment.

We have worked with the Nuclear Instrumentation Group in the development of the electronics necessary for wire chamber readout and in the design of some matrix logic systems. A new electronics system to be used in conjunction with the new chambers has been planned and is now being developed and tested.

## POLARIZED-PROTON TARGET DEVELOPMENT

*Owen Chamberlain, Gilbert Shapiro, Herbert Steiner, Raymond Z. Fuzesy, and Don Hunt*

We continue to work on development of the following two improvements for polarized target work:

a) A cryostat, operating at 0.5°K and cooled by liquid helium-3, to obtain higher target polarization.

b) A superconducting magnet which will provide a field of 25 kG of sufficient uniformity for polarization purposes over the volume of the target. Access will be provided for particles to enter and leave the target in directions near the direction of the magnetic field (hence, of the target polarization) as well as perpendicular to it.

## PROTON-DEUTERIUM INTERACTIONS

*Eugene Colton*

Our study of pd collisions at 5.9 and 7.825 GeV/c is nearly completed. A study (UCRL-20106-Rev) of the reaction $pd \rightarrow p_{sp}pp\pi^-$ has been published in Nucl. Phys. **B46**, 21 (1972). Another paper (LBL-1022) from the three- and four-prong events treats double-isobar production in $pn \rightarrow \Delta^{++}(1238)\ \Delta^-(1238)$ at 5.9 GeV/c; this work

has been submitted to Physical Review D. Some inclusive studies of the reactions $pn \rightarrow \pi^- +$ anything are still planned at both 5.9 and 7.825 GeV/c incident momenta.

## PROTON-PROTON INTERACTIONS

*Eugene Colton*

Work on all aspects of pp interactions at 6.6 GeV/c has been completed; the last report (LBL-997) has been completed and submitted to Physical Review D. This paper presents studies of the reactions $pp \rightarrow pp$, $pp \rightarrow pp\pi^0$, and $pp \rightarrow p\pi^+n$.

## WORLD $pp \rightarrow pp\pi^+\pi^-$ COLLABORATION

*Eugene Colton*

The collaboration tape is being utilized for detailed s- and t-dependent studies of the reaction $pp \rightarrow pp\pi^+\pi^-$. The first paper resulting from this analysis is Weizmann Institute preprint WIS-72/30 PH by L. Lyons and E. Colton.

## PUBLICATIONS AND PAPERS


Eugene Colton, Z. Ming Ma, Gerald A. Smith, and Peter E. Schlein, Analysis of Two-Prong Events in Proton-Proton Interactions at 6.6 GeV/c, Lawrence Berkeley Laboratory Report LBL-997, July 1972.

Eugene Colton and Z. Ming Ma, Separation of Isotopic-Spin ½ and 3/2 $\pi N$ Systems in $pp \rightarrow N\pi N$ Reactions at 6.6. GeV/c, Lawrence Berkeley Laboratory Report LBL-390, October 1971.

Eugene Colton and Alan R. Kirschbaum, Study of $|T_z| = 3/2$ $\Delta(1238)$ Production in pp Interactions at 6.6 GeV/c, Phys. Rev. **D6**, 95 (1972).

A. Firestone and Eugene Colton, Determination of the Effective Trajectory in $\Delta(1238)$ - Producing Reactions, Cal-Tech report CALT-68-353, May 1972.

R. Fuzesy, J. Jaros, L. Kaufman, J. Marriner, S. Parker, V. Perez-Mendez, and S. Redner, A Gas Mixture for Multi-Wire Chambers with High Proportional Gain, Nucl. Instr. Methods **100**, 267 (1972).

W. Gage, E. Colton, and W. Chinowsky, Reaction $pn \rightarrow pp\pi^-$ and N* (1450) Production at 5.9 GeV/c, Nucl. Phys. **B46**, 21 (1972).

Eugene Gellert, The Inclusive Reaction $p + p \rightarrow \pi^- +$ Anything at 6.6 GeV/c Compared to Higher Energies, Lawrence Berkeley Laboratory Report LBL-784, February 1972.

Gary L. Godfrey and Clyde E. Wiegand, Kaonic Atom Transition Coupled to Nuclear Level, Lawrence Berkeley Laboratory Report LBL-776, June 1972.

A. Kirschbaum, E. Colton, J. Friedman, and P. Schlein, Measurement of the T = 3/2 $K\pi$ Elastic Scattering Cross Section, Phys. Rev. **D4**, 3254 (1971).

A. R. Kirschbaum and E. Colton, The Reaction $pn \rightarrow \Delta^{++}(1238)\,\Delta^-(1238)$ at 5.9 GeV/c, Lawrence Berkeley Laboratory Report LBL-1022, Aug. 1972.

J. H. Klems, R. H. Hildebrand and Rae Stiening, Limits on the $K^+ \rightarrow \pi^+ + \upsilon + \bar{\upsilon}$ and $K^+ \rightarrow \pi^+ + n\gamma$ Decay Rates, Phys. Rev. **D4**, 66 (1971).

G. Shapiro (Ed.), Proceedings of the IInd International Conference on Polarized Targets, Lawrence Berkeley Laboratory Report LBL-500, December 1971.

H. Steiner, High Energy Physics and Nuclear Structure Research at Berkeley, in *Proceedings of the 4th International Conference on High Energy Physics and Nuclear Structure*, JINR-D1-6349 (Dubna, 1972).

H. Steiner, Multiwire Proportional Chambers; An Introduction, in *Proceedings of the LAMPF Summer Study Session*, Los Alamos, N.M., Aug. 1971 (LA-4824).

H. Steiner, Negative Pion Production by Protons, Deuterons, and Alpha Particles on Beryllium, Copper, and Lead, paper presented at the Washington Meeting of the American Physical Society, April 1972.

H. Steiner, Tuning-Up Procedures of Pion Beam Channels, in *Proceedings of the LAMPF Summer Study Session*, Los Alamos, N.M., Aug. 1971 (LA-4824).

Clyde E. Wiegand and Richard H. Pehl, Measurement of Kaonic X Rays from $^4$He, Phys. Rev. Letters **27**, 1410 (1971).

Clyde E. Wiegand, Jeffrey M. Gallup, and Gary L. Godfrey, Observation of Nuclear $\gamma$ Rays from Kaon Capture, Phys. Rev. Letters **28**, 621 (1972).

# THEORETICAL PHYSICS

Geoffrey F. Chew in charge

The efforts of the Theoretical Physics Group are directed toward problems arising from the overall program of the Laboratory. Seven categories of activity may be identified: particle theory, design of accelerators and accessory equipment, nuclear physics, atomic physics, plasma physics, training of Ph.D. students, and other work.

We have eight theorists from the UCB faculty and eight LBL senior staff members as well as a number of temporary postdoctoral researchers. Only four of the latter are supported by laboratory funds; the rest come here to participate in our program under the sponsorship of research fellowships, on sabbatical funds from their own universities, or in some cases on their own funds. These men contribute to the vitality of our research work and make significant contributions. There are now ten post-doctoral physicists in the Theoretical Group in addition to the four which we actually support.

## PARTICLE THEORY

The Theoretical Group places heavy emphasis on particle theory since particle physics is the primary concern of the LBL physics division. Six faculty members, three LBL senior staff members, and most of our temporary postdoctoral men are active in this area.

The broad framework upon which most of our work is based is the concept of the scattering matrix. It represents the collection of all possible particle reaction amplitudes. These amplitudes are not independent of one another but are related through the requirement of unitarity. In our work, as in that carried out elsewhere, we are continuing to explore the validity of more specific requirements which must be added to that of unitarity in order to allow a determination of the S matrix.

During the past year our work has been concerned with the development of this program along the following lines:

### Theoretical Analysis of General S-Matrix Concept

H. P. Stapp has initiated a series of reports in which S-matrix theory is to be systematically developed from first principles.[1] The first three reports have been completed. The first one deals with the connection between theory and experiment. It describes the basic logical structure of the theory, and emphasizes that all of the observable time dependencies obtained from ordinary canonical quantum theory are contained also in S-matrix theory. That is, S-matrix theory does not give only asymptotic time dependencies; it gives all the observable time dependencies that canonical quantum theory gives. The second report describes the macrocausality condition, which is a formulation in terms of S-matrix quantities of the idea that momentum-energy is carried over macroscopic distances only by stable systems--all effects not attributable to stable systems are required to drop off exponentially under space-time dilation. This macrocausality property is mathematically equivalent to a set of physical-region analyticity properties called the normal analytic structure. This structure, which is described in the third report, provides the analytic basis of the theory.

To properly formulate the foundations of S-matrix theory a clear statement is needed of the logical structure of quantum theory itself. Bohr's writings on the subject are generally regarded as obscure. Heisenberg's views depart significantly from those of Bohr. Wigner's views, which are an elaboration of those of von Neumann, and which are claimed by Wigner to be the orthodox view, differ from those of both Bohr and Heisenberg. To bring order to this situation Stapp has written an article expounding a viewpoint that is both clear and logical, and which represents, it is claimed, the essential common ground in the thinking of Bohr and Heisenberg.[2] This view is differentiated from Wigner's view, and from Heisenberg's further individual speculations. The article

is entitled "The Copenhagen Interpretation" and has been endorsed by Heisenberg and Rosenfeld. The viewpoint expounded in the article forms the natural logical framework for S-matrix theory.

The Mueller formula relating the inclusive cross section to a discontinuity of the $3 \rightarrow 3$ scattering function, which had been previously derived from field theory,[3] has now been derived by Stapp within the S-matrix framework. The S-matrix derivation gives also a large number of similar formulas which, however, are not as closely connected to physical observables as the Mueller formula.

[1] Henry P. Stapp, Foundations of S-Matrix Theory. I. Theory and Measurement, LBL-759, March 1972; Foundations of S-Matrix Theory. II. Macrocausality, LBL-956, April 1972: Foundations of S-Matrix Theory. III. The Normal Analytic Structure, LBL-959, June 1972.

[2] Henry P. Stapp, Am. J. Phys. 40, 1098 (1972).

[3] H. P. Stapp, Phys. Rev. D6, 1007 (1972).

## Bootstrap Hypothesis

Investigation of the hadron bootstrap hypothesis is continuing mainly by further exploration of the multiperipheral model.

C. F. Chan and B. R. Webber have investigated the solution of the ABFST multiperipheral integral equation with a narrow-resonance kernel.[4] An approximation scheme leading to a tractable analytic approximate solution was presented for both the forward and nonforward equations and compared, together with previously proposed approximations, to the exact numerical solutions. The new approximate solution was found to be good to within about 10% in the region of interest and should be useful both in the general study of the output of the multiperipheral model and in Pomeranchukon perturbation theory.

Previous work on generalizations of the ABFST multiperipheral model has been extended by D. R. Avalos* and C. Sorensen to allow for vector meson exchange.[5] The intercept of the Pomeranchon pole, the magnitude of asymptotic total cross sections, and off-shell corrections to them have been calculated.

Inclusive cross sections in the triple-Regge region have been calculated by C. Sorensen using a version of the ABFST multiperipheral model that amounts to an extension of the Deck model.[6] Even though almost no parameters are available for adjustment, presently available moderate-energy data are described in a qualitatively satisfactory manner. Predictions are made for future experiments at higher energies, and the various triple-Regge couplings are extracted from the model. It is found that vertices corresponding to high-lying trajectories are suppressed. In particular the dimensionless parameter $\eta_{ppp}$ that characterizes the triple-Pomeranchon vertex turns out to be $\lesssim 10^{-3}$.

The high-energy forward scattering of a pseudoscalar meson and a baryon has been discussed by Chun-Fai Chan on the basis of the ABFST multiperipheral model. He obtained an expression for the high-energy limit of the meson-baryon total cross section by assuming that the low-energy amplitude is dominated by the baryon pole plus the first elastic resonance, and using the approximate solution to the meson-meson integral equation proposed by Abarbanel, Chew, Goldberger, and Saunders. A numerical estimate based on SU(3) symmetry was in satisfactory accord with experiment.

Recent measurements of p-p elastic near-forward scattering at intersecting storage-ring energies suggested a change of slope of the Pomeron trajectory around $|t| \approx 0.08\ (\mathrm{GeV}/c)^2 \cong 4\ m_\pi^2$. Gribov's calculations, which attributed this effect entirely to the vicinity of the $\pi$-$\pi$ threshold, gave too small a curvature. G. I. Ghandour† and H. H. Nickel‡ have undertaken to calculate the combined effect of the $\pi$-$\pi$ threshold and the Pomeron-Reggeon cut.

Recent work by Abarbanel and White has produced a similar formula for the discontinuity across the two-Reggeon cut, but with opposite sign (with respect to the pole) for Pomerons. J. Koplik has studied a crucial assumption of Abarbanel's concerning the asymptotic behavior of irreducible absorptive parts, and found support for it in the case of unit Pomeron intercept.

The mechanism of cancellation of unphysical singularities and the relation to an effective range expansion were also examined.

The mysterious status of the Pomeron continues to receive vigorous attention. Using the Abarbanel formalism, Chew has been able to generalize the order-of-magnitude relation between the Pomeron intercept and the triple Pomeron coupling. If Sorensen's estimate of the latter is correct, the difficulties of principle arising from a factorizable Pomeron of finite slope and unit intercept will in practice be of no consequence.

*Fellow of the National Research Council of Argentina.

†CNRS-Lebanon Graduate Fellow and participating guest, Lawrence Berkeley Laboratory.

‡University of Southern Illinois, Carbondale, Illinois.

[4]C. F. Chan and B. R. Webber, Phys. Rev. **D5**, 933 (1972).

[5]Daniel R. Avalos and Cristian Sorensen, Multiperipheral Model with Pseudoscalar and Vector Meson Exchange, LBL-1308, submitted to Comments and Addenda, Phys. Rev. D.

[6]Christian Sorensen, Deck Model for Triple-Regge Couplings, LBL-908, Apr. 1972, to be published in Phys. Rev. D.

## Studies of the Consequences of Regge Behavior

W. Rarita and W. A. Greiman have been extending to the new ISR data their study of Regge fits to pp and $p\bar{p}$ elastic scattering.[7,8]

M. Dubovoy has looked for evidence of fixed poles in $K^+p$ elastic scattering.[9] Assuming that exchange degeneracy is exact, he calculated the residue of the Pomeron in $K^+p$ elastic scattering from finite energy sum rules and low-energy phase shifts. It was shown that in order to be consistent with s-channel helicity conservation for Pomeron-dominated processes, at least one fixed pole must be included in the B amplitude; in particular, a fixed pole at $J = 0$ would suffice.

The assumption that the $I = 2$ $\pi\pi$ amplitude satisfies an unsubtracted dispersion relation, together with crossing symmetry, implies that a sum rule due to Wanders is valid. M. R. Pennington has shown that if an $\ell = 4$ recurrence of the $f_0$ resonance exists with width given by the Lovelace-Veneziano model, then this sum rule is satisfied. He also has shown that the $I = 2$ s-wave amplitude not only reasonably satisfies a Froissart-Gribov representation, as required by the no subtractions assumption, but also has parameters consistent with those predicted by Weinberg's current-algebra model.[10]

M. B. Einhorn, M. B. Green,* and M. A. Virasoro† have presented a scheme for the generalization[11,12] of the two-component theory of Harari and Freund to multiparticle amplitudes and, in particular, to inclusive reactions. Their scheme is based on duality and borrows the terminology of dual perturbation theory but is not restricted to any specific model. A criterion was obtained for the absence of secondary (nonscaling) Regge contributions in inclusive reactions; and it was shown how inclusive reactions may approach their limiting values from below, in contrast to total cross sections which always have positive secondary contributions. The scheme suggests a novel interpretation of diffraction dissociation, in which direct-channel resonances in the Pomeron-particle amplitude build the Pomeron in the crossed channel.[13] A result of the enforcement of the Harari-Freund conjecture for particle-particle amplitudes is that the Pomeron-Pomeron-Reggeon coupling is small. A variety of phenomenological tests of the model have been formulated.

*Institute for Advanced Study, Princeton, New Jersey 08540.

†University of Buenos Aires, Buenos Aires, Argentina.

[7]Donald M. Austin, William H. Greiman, and William Rarita, Phys. Rev. **D2**, 2613 (1970).

[8]Donald M. Austin and William Rarita, Phys. Rev. **D4**, 3507 (1971).

[9]M. Dubovoy, Phys. Rev. **D5**, 193 (1972).

[10]M. R. Pennington, Do Dispersion Relations for the I=2 $\pi\pi$ Amplitude Require Subtraction?, LBL-918, April 1972, submitted to Nucl. Phys.

[11]M. B. Einhorn, M. B. Green, and M. A. Virasoro, Phys. Letters **37B**, 292 (1971).

[12]M. B. Einhorn, M. B. Green, and M. A. Virasoro, Duality Constraints on Inclusive Reactions II: The Role of the Harari-Freund Conjecture, LBL-767, May 1972, to be published in Phys. Rev.

[13]M. B. Einhorn, M. B. Green, and M. A. Virasoro, Duality and Diffractive Dissociation, LBL-768, July 1972, to be published in Phys. Rev.

## Classical S-Matrix Phenomenology

G. I. Ghandour* and R. G. Moorhouse† have evaluated the real parts of the pion-nucleon charge-exchange amplitudes[14] using fixed-t dispersion relations with the imaginary parts of the amplitudes deduced at low energy from partial-wave analysis and at high energy from a simple s-channel absorptive model. They found that the calculated polarization, though quantitatively somewhat small, has all the correct qualitative features.

A method to remove possibly causality-violating singularities from an experimental partial-wave phase shift has been proposed by Chih Kwan Chen.[15] This method is designed to save effort in numerical analysis compared with previous smoothing techniques.

Although low-energy $\pi\pi$ interactions have been the subject of intense study for the past ten years, the experimental situation, particularly with regard to the $I = 0$ s-wave phase shift, has until now been confused by ambiguities. However, recent high-statistics experiments performed at Berkeley indicate that the "down" solution is the correct one for this partial wave beyond the $\rho$-resonance region. Using these clarified experimental data from 500 MeV to 1 GeV and the rigorously provable equations of Roy, M. R. Pennington and S. D. Protopopescu have been able to show that the experimental phase shifts are consistent with crossing and analyticity requirements.[16] They also have computed the s- and p-wave phase shifts in the experimentally unknown region from threshold to 500 MeV. The scattering lengths turn out to be $a_0^0 = 0.15 \pm 0.07$ and $a_0^2 = -0.053 \pm 0.028$, supporting the current-algebra predictions of Weinberg. It is concluded that the minimum of dynamics necessary to understand low-energy $\pi\pi$ scattering, in addition to crossing, elastic unitarity, and analyticity, is the on-mass-shell appearance of the Adler zero.

P. Langacker has attempted to use unitarity as an explanation of s-channel helicity conservation in elastic processes.[17] Defining helicity-total-flip elastic amplitudes as those in which both helicities change sign, he observed that the unitarity equation suggests that the imaginary part of the helicity-total-flip partial-wave amplitude is much smaller than that of the nonflip amplitude at high energies. Appealing to a plausibility argument, he estimated the ratio of helicity-total-flip to helicity-nonflip partial-wave amplitudes to be $(1/s)^{1/2}$ or smaller.

*CNRS-Lebanon Graduate Fellow and Participating guest, Lawrence Berkeley Laboratory.

†Glasgow University, Glasgow, Scotland.

[14] G. I. Ghandour and R. G. Moorhouse, Phys. Rev. D6, 856 (1972).

[15] Chih Kwan Chen, A Method to Remove Experimentally Determined Phase Shifts, LBL-1032, Aug. 1972.

[16] M. R. Pennington and S. D. Protopopescu, The $\pi\pi$ Scattering Amplitude in the Low-Energy Region, LBL-963, submitted to Phys. Rev.

[17] P. Langacker, Phys. Rev. D5, 2864 (1972).

## Theory of Inclusive Reactions

M. Bishari has discussed the relevance of pion exchange in inclusive distributions in high-energy pp inelastic collisions.[18] It was shown that $\pi$-exchange is important in $p + p \to p + X$ and therefore will influence the determination, e.g., of Pomeron-particle amplitudes. More importantly it was shown that the $\pi$-pole is crucial in $p + p \to n + X$, and an approximate spectrum was predicted. The prominent features (in $p + p \to n + X$) of the model are: (i) a strong dip at $x \approx 1$ (where x is the Feynman variable); (ii) a maximum at $x \approx 0.81$ for $q_T = 0.1$ GeV/c (the transverse momentum of the emitted neutron). Both predictions are in striking agreement with recent CERN data. Using inclusive sum rules, he also made a rough estimate of the contribution of $\pi$-exchange to the inelastic pp total cross section. The ABFST model is mostly applicable to $p\,p \to n + X$, a difficult process to measure. However, from inclusive sum rules (those derived from energy-momentum conservation), the total pp cross section, and the measured processes $p + p \to p + X$, $p + p \to \pi + X$ ($\pi = x^{\pm}, \pi^0$), a strong, constraint on the $p + p \to n + X$ distribution has been obatined by Bishari, who then derived the *scale* for off-shell extrapolation[19] in the ABFST model.

Bishari and Yesian* have shown that in inclusive distributions the diffractive resonance excitation of the

projectile (target) generates part of the background in the target (projectile) excitation spectrum.[20] This explains the origin of the background in diffractive models. Using accelerator data, they have shown that diffractive models highly *underestimate* the normalization but correctly predict the shape of the observed spectra.

The excess of protons over neutrons in the atmosphere is determined by a quantity $z_{pn} = \int_0^1 x^{\gamma-1} f_{pn}(x)\,dx$, which essentially measures the amount of proton fragmentation into neutrons. The parameter $\gamma$ determines the energy behavior of the primary radiation and $f_{pn}(x)$ is the inclusive spectrum of $p + p \to n + X$ with the neutron having a fractional longitudinal momentum $x$ (Feynman variable). A simple model[21,22] has been applied by Bishari and Yesian to evaluate $z_{pn}$ and the result agrees with cosmic-ray measurements.

*Department of Physics, University of California, Berkeley.

[18] Mordechai Bishari, Phys. Letters 38B, 510 (1972)

[19] M. Bishari, Nucl. Phys. B47, (1972).

[20] Mordechai Bishari and Harry J. Yesian, Phys. Rev. D6, 921 (1972).

[21] M. Bishari, Phys. Letters 38B, 510 (1972).

[22] Mordechai Bishari and Harry J. Yesian, Phys. Rev. D6, 919 (1972).

## Field Theoretic Investigations

By saturating the intermediate parton states in electroproduction with quark states, Michio Kaku and N. Pak have been able to derive the Gell-Mann-Fritsche current light-cone commutators. The light-cone singularity emerges naturally from on-mass-shell conditions on the intermediate quark line in the scaling region. The close correspondence between the parton model and light cones is easily displayed in this approach.

The assumption that the $\epsilon$-meson is the Goldstone boson of broken scale-invariance leads to a number of low-energy theorems derived by Kleinert and Weisz. In a recent paper, Renner and Staunton have sought to test those theorems that involve the trace of the energy-momentum tensor between one-pion states by using phenomenological $I = 0$ s-wave $\pi\pi$ phase shifts of both the up-down and the down-up type. Despite the fact that this avoided the highly unrealistic narrow-width approximation for the $\epsilon$-pole used in previous treatments, Renner and Staunton found it impossible to satisfy these theorems with just $\epsilon$-resonance contributions.

M. R. Pennington has considered the effect on these theorems of including both $\epsilon$ and $S^*$ resonance contributions,[23] motivated by the results of a recent $\pi^+\pi^- \to \pi^+\pi^-$ scattering experiment which shows that the $I = 0$ s-wave amplitude has an $S^*$-resonance at 980 MeV, coupled strongly to the $K\bar{K}$ channel. It was found that the low-energy theorems can, in fact, be satisfied.

From the equal-time commutation relations, which are powerful in exploring two-body hadron scattering, S.-S. Shei and M. Suzuki have derived various sum rules for inclusive hadron reactions.[24] By using the partially-conserved axial vector current hypothesis, they found a sum rule which may be experimentally tested using the inclusive pion reactions.

The 12 radiative decays of mesons that involve the vector-vector-pseudoscalar meson couplings in the vector meson dominance model have been analyzed[25] by W. Lee,* M. Suzuki, and J. Thaler*. Using new experimental data of the Columbia group, they found a good fit to the data in a naive model incorporating SU(3) symmetry with $\omega$ - $\phi$ and $\eta$ -$\eta'$ mixing.

P. Langacker and M. Suzuki have established a model-independent relation[26] between $\lim_{\omega\to\infty} F_2(\omega)$ of the electroproduction amplitude and $\lim_{\upsilon\to\infty} \sigma_{tot}^{\pi N}(\upsilon)$ that is based on a phenomenological generalized scaling. The deep-inelastic scaling function has thereby been related to the $\pi N$ scattering amplitude through two parameters which have values consistent with those suggested by other observations. The same results have also been deduced from the Deser-Gilbert-Sudarshan representation.[27] Also found was a relation between the threshold behavior of $F_2(\omega)$ and the asymptotic behavior of the form factor, which is less restrictive but more rigorous than that of Bloom and Gilman.

P. Langacker has derived a class of inequalities that relate weighted integrals of the electron-positron annihi-

lation cross section to slopes of certain weak and electromagnetic form factors.[28] These inequalities are very sensitive to deviations from vector meson dominance. Typical applications involve the hadronic contribution to the muon magnetic moment, the pion charge radius, and the $K_{\ell 3}$ decay parameters.

From PCAC and the equality between $\nu W_2$ for vector and axial vector currents in the Bjorken scaling limit, $\pi N$ cross sections have been calculated by P. Langacker and M. Suzuki.[29] These are found to be in good agreement with measurement, through an extrapolation of $\nu W_2$ for electroproduction. These cross sections are further related to photoproduction cross sections.

Starting from the recent U(3) ⊗ U(3) gauge model of strong interactions, I. Bars,† M. B. Halpern, and M. Yoshimura‡ have discussed the very natural synthesis[30] with Weinberg's model of leptons. Because of the interplay of the two models, neutral $\Delta S = 1$ currents are eliminated without enlarging the number of quarks, and a natural $(3,\bar{3}) \otimes (\bar{3},3)$ symmetry-breaking emerges for the hadrons.

I. Bars‡ and M. Yoshimura‡ have calculated the weak-interaction contribution [31] to the muon anomalous magnetic moment of the order $G_W m_\mu^2$ in the Weinberg model for leptons. Using a $\xi$-limiting procedure they obtained a finite correction to ½(g - 2) which has the value $(1.8 - 2.2) \times 10^{-9}$

*Physics Department, Columbia University, New York, N.Y. 10027.

†Physics Department, University of California, Berkeley.

‡Physics Department, Univeristy of California, Berkeley.

[23] M. R. Pennington, Phys. Rev. D6, 1458 (1972).

[24] S.-S. Shei and M. Suzuki, Lett. Nuovo Cim. 2, 1127 (1971).

[25] W. Lee, M. Suzuki, and J. Thaler, preprint under preparation at Columbia University.

[26] P. Langacker and M. Suzuki, Phys. Letters 40B, 561 (1972).

[27] P. Langacker and M. Suzuki, preprint under preparation at LBL.

[28] P. Langacker, part of Ph.D. thesis, LBL-766, Mar. 1972.

[29] P. Langacker and M. Suzuki, Phys. Letters 40B, 561 (1972).

[30] I. Bars, M. B. Halpern, and M. Yoshimura, LBL-990, July 1972.

[31] I. Bars and M. Yoshimura, Phys. Rev. D6, 374 (1972).

### Proton-Electron-Positron Colliding Beams (PEP)

During this year physicists at SLAC and at Berkeley have been engaged in the discussion of a proposed new high-energy physics facility involving the construction of a proton-electron-positron colliding beam storage ring (PEP). Members of the Theoretical Group and their counterparts at Stanford have been active in attempting to foresee important theoretical and experimental developments which may be expected to result from PEP. There has been vigorous discussion of presently foreseeable options among theorists at both laboratories (see the section on Accelerator Theory).

### Other Work

When a charged particle travels through a material medium, Cerenkov radiation is emitted if the velocity of the particle is greater than that of light in the medium. An accompanying effect is radiation emitted when the particle enters or leaves the medium; this is called transition radiation. J. V. Lepore and R. J. Riddell, Jr., have analyzed the theory of transition radiation in considerable detail. The work constitutes a review of earlier studies, but some new results are presented. In particular, the case in which the particle enters the medium obliquely is treated and equations are developed for the situation where the boundaries of the medium are not sharp. These equations are then used to show that the sharp boundary approximation is always valid for relativistic particles since the distance over which the radiation develops is always large compared with the thickness of the boundary. This effect is of importance in the development of detectors for very high energy particles since it depends on particle energy rather than speed.

## PARTICLE ACCELERATORS

### Proton-Electron-Positron Colliding Beam Facility

In the summer of 1971, interest began to grow at LBL and SLAC over the possibility of constructing a storage ring facility which would provide high-luminosity colliding beams of protons, electrons, and positrons in various combinations (thus the acronym PEP). A paper

was presented at the International Accelerator Conference held in Geneva in September 1971 which described a possible configuration involving an $e^{\pm}$ ring intersecting a proton storage ring, and which discussed the types of experiments that could be carried out. The lepton energy was taken to be 15 GeV, the proton energy 70 GeV, and the luminosity $10^{32}/cm^2$ sec. In October, several informal committees involving high-energy experimentalists and theorists at LBL and SLAC began to explore the potentialities of such a tool. It was soon verified that many fundamental questions in high-energy physics that are beyond the reach of present or projected devices could be attacked in this way, and enthusiasm grew steadily at both laboratories. Accordingly, in January 1972, a joint LBL-SLAC committee of accelerator specialists was formed to make a preliminary search for an appropriate machine design which would safely fulfill the requirements in as economical a way as possible. The accelerator committee is exploring the broad range of problems involved, with particular emphasis on the proton accelerator-storage ring and on the interaction of proton and lepton beams; these subjects are quite novel to the field of accelerator design and central to the success of the project. The goal is to complete a conceptual design by about the end of this calendar year, and then to proceed to detailed engineering considerations and design optimization. To this end several ring lattices have been designed by A. A. Garren. One, called PEP Model 1, is described in a PEP note.[32] In this example, a luminosity $\mathcal{L} = 0.6 \times 10^{32}\ cm^{-2}\ sec^{-1}$ is produced at each of two interaction points where 15-GeV electrons/positrons collide with 70-GeV protons or with each other.

The most recent design, improved in various ways from Model 1, has four interaction points with $\mathcal{L} = 0.5 \times 10^{32}\ cm^{-2}\ sec^{-1}$, with an average ring radius R = 350 m.

[32] A. A. Garren, PEP Note 23, June 16, 1972.

Electron Ring Accelerator

Theoretical and computational support of the Electron Ring Accelerator project has continued, with the greater part of the work recorded in the form of ERAN reports. A large portion of this work has been in connection with the present experimental program directed toward the understanding of high-intensity injection into an electron-ring compressor and toward the specification of means for controlling instabilities that can limit the intensity with which high-quality rings can be produced.

Electric charges and currents induced in nearby conducting walls can have a pronounced influence on an injected beam, especially if, as a result of surface resistance, the induced currents quickly redistribute or decay; an uncompensated electric field then remains to affect the transverse motion of the injected electrons. The problem of decay of induced currents, in simplified geometrical configurations, has been analyzed by L. J. Laslett and the results compared with earlier computational work. The results indicate that only by the use of walls with quite low surface resistivity can the times that characterize the decay of induced currents be made sufficiently long to preclude unacceptable disturbance of the ring beam. The dynamical implications of the time-dependent forces arising from induced charges and currents were illustrated, in an approximate but informative way, by a simple "simulation program." This program omitted some mechanisms that would provide Landau damping but illuminated the experimental observations made at the time of injection of multiturn beams into chambers of various wall resistances.

A. Faltens and L. J. Laslett have studied a longitudinal instability that can develop in an intense electron-ring beam if the surroundings are not such as to reduce the longitudinal coupling impedance to a sufficiently low value. They find that a geometrical arrangement which might be suitable at the end of compression, just prior to the release of a ring beam from the magnetic well, is one in which the ring is situated close to a coaxial conducting tube. Extending earlier work of A. Garren concerning a ring beam inside a surrounding metal tube, they have performed computations to evaluate the

longitudinal coupling impedance for a ring beam circulating between a *pair* of conducting tubes. Proximity of the beam to one or the other of the tube walls is favorable for reducing the coupling impedance for low-order dynamical modes. Proximity to an *inner* wall appears to be preferable, however, unless one is prepared to suppress the excitation of higher-order resonant modes by a deliberate adjustment of the quality factors for such high-frequency natural electromagnetic modes.

L. J. Laslett, D. Möhl,* and A. M. Sessler have studied the collective oscillations of ions *vs* electrons. These can impose a severe limitation on the attainable quality of electron rings, and indeed on the intensity of conventional accelerators (such as the Bevatron, where clearing electrodes have been introduced to remove electrons whose presence was previously found to be troublesome for this reason). Analytic work to determine the possible utility of Landau damping and of image focussing to suppress a potential electron-ion instability has been checked by digital computations that provide the roots of the secular equations arising from dispersion analyses of this phenomenon.

The performance characteristics--or attainable quality--of electron rings have been re-examined in the light of these new analytic and computational results. Examination specifically was applied to rings at the end of compression, just prior to release from a magnetic well. It appeared clear from this work that, according to our present understanding, the longitudinal instability and the electron-ion resonance constitute the most important constraints to be considered in evaluating the ring-quality attainable at the end of compression in an electron-ring device.

The use of an electron-ring device as an accelerator of heavy ions motivates an interest in the rate at which successive ionic charge states are built up by the ionization of neutral atoms. Computer programming by Drager concerning this problem has been refined by L. J. Laslett, and interest is now being directed to the possibility of including the important Auger processes in these computations.

Further analytical calculations were made by A. Entis, A. Garren, and D. Möhl of the longitudinal instability of electron rings in various conditions,[33,34] A very general computer program AZTEC for calculating coupling impedances has been designed and written in collaboration with S. Sackett of the Mathematics and Computing Group. This program solves the appropriate boundary-value problem for rings in arbitrary axially symmetric geometries containing conductors and dielectrics.

---

*Visitor from CERN, Geneva, Switzerland.

[33] A. A. Garren and D. Möhl, ERAN-176, 1971.

[34] A. C. Entis, A. A. Garren, and D. Mohl, ERAN-174, 1971.

## NUCLEAR PHYSICS

In the last year a number of more or less related nuclear problems have been considered by W. Myers, S. G. Nilsson, W. Swiatecki, and C. F. Tsang. In the study of nuclear masses an anomaly in the location of the valley of $\beta$-stability has been isolated. Attempts to explain it have led to estimates of the effect on the nuclear Coulomb energy of nucleon form factors, and to speculations regarding a decrease of the neutron-proton mass difference for nucleons bound inside nuclei.

Several studies have been stimulated by the developing field of heavy-ion physics. The creation of superheavy elements, soon to be attempted at the Superhilac, has necessitated estimates of production cross sections. Values around $10^{-30}$ cm$^2$ are anticipated *unless* nuclear viscosity cuts down or inhibits entirely the fusion of a heavy ion and the target nucleus. Various attempts to estimate nuclear viscosity, including analogy to liquid $^3$He, are being made. A related problem, that of the viscous drag between a nucleus and a grazing heavy ion, is being formulated. The effect of angular momentum on heavy-ion collisions is under continued study, and recent experiments on $^{27}$Al + $^{20}$Ne seem to confirm the predicted decrease in compound nucleus formation cross sections due to centrifugal forces.

Recent interest in the relativistic quantum electrodynamic description of an electron orbiting a superheavy nucleus (or a pair of heavy nuclei in close proximity) has led to a study of this problem.

In connection with studies of nuclear stability by means of the Strutinsky method, the calculations of Nilsson, Tsang, and others are being extended to include a new degree of freedom which describes variations of the diffuseness of the nuclear surface.

Using the liquid-drop model of the nucleus and Glauber's scattering theory, G. Nixon has computed the excitation of the 4.4-MeV ($2^+$) and 9.6-MeV ($3^-$) levels in $^{12}C$ by protons at high energy. The nuclear transition densities are taken from inelastic electron scattering measurements and the elementary proton-nucleon amplitudes from high-energy experiments. There are no free parameters in the calculation. The computed cross sections agree very well with the existent proton-$^{12}C$ data. They correctly describe the minimum in the $2^+$ cross section and predict one in the $3^-$ cross section at a momentum transfer just outside the range of the experimental data.

The most important nuclear levels to be excited in pion photoproduction at small momentum transfers are thought to be analogues of the giant resonances seen in inelastic electron scattering and photoabsorption. G. Nixon has extended the Glauber high-energy scattering formalism to include inelastic incoherent processes which occur in pion and rho meson photoproduction. Using the particle-hole description of collective excitation in the Tamm-Dancoff approximation and taking the elementary production to be given by the Born amplitude (not a bad assumption at high energies and in the forward direction), he has computed the $^{12}C$ production cross section for 8 and 16 GeV photons. Comparison with the low-t experimental data is favorable.

The phase difference between strong and electromagnetic contributions to the scattering amplitude has been derived from diffraction theory by V. Franco.[35] The results are consistent with relativistic calculations. New expressions for the amplitude have been obtained to all orders in $Z_1 Z_2 e^2 / \hbar v$ for the point charge and extended charge cases.

[35] V. Franco, Coulomb-Nuclear Interference, LBL-1057, Aug. 1972.

## ATOMIC PHYSICS

Work on the program of studying slow collisions between atoms and ions or molecules is continuing. More recently, because of the ERA program, there has been considerable interest in the multiple ionization of atoms by high-energy electron impact.

J. Chen,* Y. Hahn,† and K. Watson have applied the eikonal theory of electronic transitions in slow collisions of atoms and molecules[36] to the study of electron pick-up in the collision of protons with $H^-$.

A general procedure has been formulated by Y. Hahn and K. M. Watson by which the hierarchy of many-particle scattering equations of the Faddeev type can be reduced systematically to matrix equations of lower dimensions.[37] As illustrations, they derive such reduced sets explicitly for the three-particle system by rearranging different components of the total Green's function. The resulting equations iterate with connected kernels *only* in the explicit channels. Using the reduction method, the connection between the various versions of scattering equations derived earlier have been exhibited. The effect of implicit channels may be taken into account non-iteratively using the channel projection operators. They also show that an arbitrary set of distortion potentials may be introduced for the purpose of minimizing the coupling between the rearrangement channels, thus improving the convergence of the multiple scattering series.

Projection operators onto various subsets of states of a quantum mechanical system have been constructed by Y. Hahn and K. M. Watson[38] in a semiclassical approximation based on the Wigner transformation of statistical mechanics. Explicit operator expressions are derived for the cases of central Coulomb potential, one-dimensional harmonic oscillator, and the radial Coulom-

bic states of specified angular momenta. The accuracy of these operators has been examined in some detail in terms of the overlap integrals and dipole transition probabilities. The semiclassical approximation is found to be effective in the energy regions away from the classical turning points.

The single-particle model for atoms and ions has been used to calculate rates of transitions to bound and continuum electronic states induced by high-energy electron impact. The projection operators described above are applied to treat the large numbers of final states involved. Ionization cross sections of atoms and ions by high-energy electron impact have been estimated.[39]

The absorption coefficient for the rotation and vibration-rotation bands of water vapor at high pressures has been computed from a classical calculation of the molecular dipole autocorrelation function by J. Coakley. The results compare favorably with the results for the coefficient calculated from quantum mechanics. They also indicate that minor modifications can be made to the classical calculations to improve agreement with the quantum calculations.

Work by P. J. Mohr and E. H. Wichmann‡ on the calculation of the Lamb shift in high-Z ions continues. The one-photon contribution to the energy shift is being evaluated numerically to all orders in $Z\alpha$. Results of this calculation are of interest in determining the Z dependence of radiative corrections to the inner levels in heavy atoms. They are also of interest in view of recent advances in Lamb-shift experiments, as evidenced by measurements made in the $^{16}O^{7+}$ ion.[40,41]

*Physics Department, University of California, San Diego

†On leave from the Physics Department, University of Connecticut, Storrs, Connecticut 06268.

‡Physics Department, University of California, Berkeley

[36]J. C. Y. Chen, V. Ponce, and K. M. Watson, submitted to Phys. Rev.

[37]Yukap Hahn and K. M. Watson, Phys. Rev. A5, 1718 (1972).

[38]Yukap Hahn and Kenneth M. Watson, Phys. Rev. A6, 548 (1972).

[39]Yukap Hahn and Kenneth M. Watson, Transition Probabilities and Multiple Ionizations of Ions by High Energy Electron Impact, LBL-992, July 1972, submitted to Phys. Rev.

[40]M. Leventhal, D. E. Murnick, and H. W. Kugel, Phys. Rev. Letters 28, 1609 (1972).

[41]George P. Lawrence, C. Y. Fan, and S. Bashkin, Phys. Rev. Letters 28, 1612 (1972).

## PLASMA PHYSICS

For several years there has been great interest in applying the potentialities of a laser beam for the heating of a plasma in order to generate fusion reactions. The earliest suggestions involve direct laser heating of an inserted D-T pellet to start further reactions in the plasma itself. More recently the suggestion has been made by Rosenbluth and Kroll that a plasma might be heated directly by using the beat frequency between two laser beams to excite plasma modes. B. I. Cohen, A. N. Kaufman, and K. M. Watson have shown that nonlinear interactions resonantly excite longitudinal plasma oscillations. These then induce transitions to transverse modes. Nonlinear damping of the longitudinal mode heats the plasma. The process is optimized by having parallel beams, equal laser intensities, and damping equal to the frequency mismatch.[42]

J. Wedell has developed a general expression for multiphoton ionization rates in terms of Coulomb Green's functions. The effects of circular and linear polarization in multiphoton ionization processes have been found and interpreted physically. Approximate evaluation of transition rates has been carried out; more precise evaluation on a computer has just begun.

4

[42]Bruce I. Cohen, Allan N. Kaufman, and Kenneth M. Watson, Phys. Rev. Letters 29, 581 (1972).

## GRADUATE STUDENTS

The junior members of the Theoretical Group--the doctoral candidates--are of central importance in our activity. They work vigorously on research suggested by the established members of the Theoretical Group and sometimes contribute beyond this to generate new ideas. At present we have 14 doctoral candidates.

This number, a reduction from that in the late nineteen sixties, represents a planned effort on our part to be highly selective in the selection of Ph.D. candidates. During this year, 5 students have completed the requirements for the Ph.D. degree.

OTHER WORK

During the past year there has been some interest in dealing with environmental problems. Accordingly, members of our group, in conjunction with others, have prepared two research proposals in this area.

The first is concerned with a study of limnology as applied to Lake Tahoe, Nevada, to be carried out together with members of the Institute for Ecology at the University of California at Davis. It has been submitted to the National Science Foundation for approval and support. Our particular concern is a study of heating and mixing processes in the lake. These depend on hydrodynamic phenomena such as wind driven turbulence.

The second proposal has been prepared in conjunction with Professor Bruce Bolt, head of the Department of Geology and Geophysics at Berkeley and Director of the U.C. seismological stations. We have proposed a program of seismic studies concerned with the calculation of the ground motions generated by given sources. Such calculations represent an almost new area of activity within the field of seismology and are only now possible because of the existence of high-speed computers. This proposal has been submitted to the AEC Reactor Division and the Division of Research.

PUBLICATIONS AND PAPERS

H. D. I. Abarbanel, G. F. Chew, M. L. Goldberger, and L. M. Saunders, Self-Consistent Pomeranchon Coupling Ratios in the Multiperipheral Model, Phys. Rev. **D4**, 2988 (1972) and Ann. Phys. (N.Y.) **73**, 156 (1972).

M. Allen, S. M. Berman, S. J. Brodsky, M. Davier, S. D. Drell, S. Flatte, F. J. Gilman, M. Lee, P. Morton, A. Odian, J. Rees, B. Richter, M. Schwartz, S. Wojcicki, G. Abrams, G. Chew, C. Friedberg, A. Garren, G. Gidal, G. Goldhaber, J. Kadyk, S. Parker, A. Sessler, L. Smith, M. L. Stevenson, and M. Suzuki, Particle Physics With Positron-Electron-Proton Colliding Beams, Lawrence Berkeley Laboratory Report LBL-750 and Stanford Linear Accelerator Center Report SLAC-146 (April 1972).

Donald M. Austin and William Rarita, Slope of the Forward Peak in pp Scattering and the Regge-Pole Model, Phys. Rev. **D4**, 3507 (1971).

D. R. Avalos and B. R. Webber, Effects of Off-Mass-Shell Continuation in the Multiperipheral Model, Phys. Rev. **D4**, 3313 (1971).

R. T. Avery and L. J. Laslett, Draft Notes Concerning Eddy Currents, Regard to Their Influence on Landau-Damping Coefficients, in "Design of Compressor V.," ERAN-156, July 7, 1971.

R. T. Avery and L. J. Laslett, Eddy Currents, Landau-Damping Coefficients, and Their Implications in Electron-Ring Compressor Design, in *Proceedings of the VIII International Conference on High Energy Accelerators,* M. Hildred Blewett, Ed. (CERN, Geneva, 1971).

I. Bars, M. B. Halpern, and M. Yoshimura, Gauge Theory of Strong, Weak, and Electromagnetic Interactions, Lawrence Berkeley Laboratory Report LBL-990, July 1972.

Mordechai Bishari and Harry J. Yesian, The Background in Missing Mass Experiments, Phys. Letters **38B**, 312 (1972).

Mordechai Bishari, Pion Exchange and Inclusive Spectra, Phys. Letters **38B**, 510 (1972).

Mordechai Bishari and Harry J. Yesian, Interrelation between the Background and Resonances in Inclusive Distributions, Phys. Rev. **D6**, 921 (1972).

Mordechai Bishari, Form Factors, Dimensionalities of Operators, Fixed Singularities, and Bjorken Limit in Exclusive Processes, Phys. Rev. **D6**, 294 (1972).

Mordechai Bishari and Harry J. Yesian, Pion Exchange and the Cosmic Ray Nucleon Cascade, Phys. Rev. **D6**, 919 (1972).

Mordechai Bishari, Off-Shell Behavior in Peripheral Dynamics and Inclusive Sum Rules, Lawrence Berkeley Laboratory Report, LBL-987, July 1972, to appear in Nucl. Phys.

K. Cahill and H. P. Stapp, A Basic Discontinuity Equation, Phys. Rev. **D6**, 1007 (1972).

R. N. Cahn and M. B. Einhorn, Consequences of Internal Symmetries for Inclusive Processes, Phys. Rev. **D4**, 3337 (1971).

Robert N. Cahn, On Inclusive Photon Distribution Contributions from $\pi^0$'s and Bremsstrahlung, Lawrence Berkeley Laboratory Report LBL-943, May 1972, submitted to Phys. Rev.

C. F. Chan, Estimation of the Asymptotic Pseudoscalar-Meson-Baryon Total Cross Section from the ABFST Multiperipheral Model, Phys. Rev. **D4**, 3466 (1971).

C. F. Chan and B. R. Webber, Solution of the ABFST Equation with a Resonance Kernel, Phys. Rev. **D5**, 933 (1972).

C. K. Chen, Is it Possible to Generate a Physical $\rho$ Meson With No CDD Poles? Lawrence Berkeley Laboratory Report LBL-5, July 1971, submitted to Phys. Rev.

Chih Kwan Chen, The Generalized Partial Wave Dispersion Relation and the N/D Method, Phys. Rev. **D5**, 1464 (1972).

Chih Kwan Chen, A Method to Remove Experimentally Determined Phase Shifts, Lawrence Berkeley Laboratory Report LBL-1032, Aug. 1972.

J. C. Y. Chen, C. J. Joachain, and K. M. Watson, Electronic Transitions in Slow Collisions of Atoms and Molecules. IV. Multistate Eikonal Approximation for Quasi-Adiabatic Transitions, Lawrence Berkeley Laboratory Report LBL-26, July 1971.

J. C. Y. Chen, V. Ponce, and K. M. Watson, Electronic Transitions in Slow Collisions of Atoms and Molecules. V., submitted to Phys. Rev.

Bruce I. Cohen, Allan N. Kaufman, and Kenneth M. Watson, Beat-Heating of Plasma, Phys. Rev. Letters **29**, 581 (1972).

J. Druzbick, J. A. White, and A. M. Sessler, Relativistic Contribution to the Hyperfine Interval of the Metastable Triplet State of $He^3$, Phys. Rev. **A5**, 2683 (1972).

M. Dubovoy, FESR and Fixed Poles for $K^+p$ Elastic Scattering, Phys. Rev. **D5**, 193 (1972).

M. B. Einhorn, M. B. Green, and V. A. Virasoro, Duality Constraints in Inclusive Reactions, Phys. Letters **37B**, 292 (1971).

Martin B. Einhorn, John Ellis, and J. Finkelstein, Finite Mass Sum Rules for Inclusive Reactions, Lawrence Berkeley Laboratory Report LBL-575 and Stanford Linear Accelerator Center Report SLAC-PUB-1006, January 1972, submitted to Phys. Rev.

M. B. Einhorn, M. B. Green, and M. A. Virasoro, Duality Constraints on Inclusive Reactions II: The Role of the Harari-Freund Conjecture, Lawrence Berkeley Laboratory Report LBL-767, May 1972, submitted to Phys. Rev.

M. B. Einhorn, M. B. Green, and M. A. Virasoro, Duality and Diffraction Dissociation, Lawrence Berkeley Laboratory Report LBL-768, submitted to Phys. Rev.

A. C. Entis, A. A. Garren, and D. Möhl, Shielding of Coherent Radiation to Suppress Longitudinal Instabilities in Electron-Ring Compressors: Laminated Sidewalls, ERAN-174.

A. Faltens, E. Hartwig, D. Möhl, and A. M. Sessler, An Analog Method for Measuring the Longitudinal Coupling Impedance of a Relativistic Beam with its Environment, in *Proceedings of the VIIIth International Conference on High Energy Accelerators*, M. Hildred Blewett, Ed. (CERN, Geneva, 1971), p. 338.

Richard D. Field, Jr., Duality, Exchange Degeneracy, and Regge Cut Models in Two-Body Collisions, Ph.D. Thesis, Lawrence Berkeley Laboratory Report LBL-33, August 1971.

Jerome H. Friedman, Clifford Risk, and Dennis B. Smith, Long Range Correlations and the Dynamics of Multiparticle Production, Phys. Rev. Letters **28**, 191 (1972).

A. A. Garren and D. Möhl, Longitudinal Coupling Impedance of an Electron Ring in a Long Metal Tube, ERAN-176, Dec. 7, 1971.

Al Garren, PEP Model One--A Machine Design Example, PEP Note 23, June 16, 1972.

G. I. Ghandour and R. G. Moorhouse, Fixed-t Dispersion Relations and Polarization in Pion Nucleon Charge Exchange Scattering, Phys. Rev. **D6**, 856 (1972).

Yukap Hahn and K. M. Watson, The Reduction Method and Distortion Potentials for Many-Particle Scattering Equations, Phys. Rev. **A5**, 1718 (1972).

Yukap Hahn and Kenneth M. Watson, A Note on the Construction of Projection Operators in the Semi-Classical Approximation, Phys. Rev. **A6**, 548 (1972).

Yukap Hahn and Kenneth M. Watson, Transition Probabilities and Multiple Ionizations of Ions by High Energy Electron Impact, Lawrence Berkeley Laboratory Report LBL-992, July 1972, submitted to Phys. Rev.

C. Harper, Temperature Dependence of the Damping of Nonlinear Lattice Resonance in Ionic Crystals, Phys. Rev. **B5**, 1613 (1972).

C. Harper, Temperature Dependence of Damping of Lattice Resonance in Alkali Halides, Phys. Letters **36A**, 387 (1971).

J. D. Jackson and R. L. McCarthy, On the $z^3$Corrections to Energy Loss and Range, Lawrence Berkeley Laboratory Report LBL-742, May 1972, submitted to Phys. Rev. A.

Michio Kaku and Namik Pak, A Simple Parton Derivation of the Fritsch-Gell-Mann Light-Cone Commutators, Lawrence Berkeley Laboratory Report LBL-590, February 1972.

Allan N. Kaufman, Quasilinear Diffusion of Axisymmetric Toroidal Plasma, Phys. Fluids **15**, 1063 (1972).

E. Keil, C. Pellegrini, and A. M. Sessler, Long-Range Beam-Beam Interaction of Crossing Beams, Brookhaven National Laboratory Report CRISP 72-34, BNL 17017, June 1972.

E. Keil and A. M. Sessler, RF Stacking in ISABELLE, Brookhaven National Laboratory Report CRISP 72-74, BNL-17274, June 1972.

Yu-yun Kuo, Backscattering of Electromagnetic Wave from Underdense Turbulent Plasma, Ph.D. Thesis, Lawrence Berkeley Laboratory Report LBL-41, September 1971.

G. R. Lambertson and L. J. Laslett, Quadrature Forces that Drive Coherent Radial Motion of a Beam in the Neighborhood of Thin, Imperfectly-Conducting Side Plates, ERAN-157, July 8, 1971.

Paul Langacker, The Isovector Spectral Function and $K_{\ell 3}$ Decays, Phys. Rev. **D5**, 710 (1972).

P. Langacker, S-Channel Helicity Conservation in Elastic Processes, Phys. Rev. **D5**, 2864 (1972).

P. Langacker, Part I: Applications of the Schwarz Inequality to Weak and Electromagnetic Processes; Part II: S-Channel Helicity Conservation in Elastic Processes, Ph.D. Thesis, Lawrence Berkeley Laboratory Report LBL-766, March 1972.

P. Langacker and M. Suzuki, The $\pi$N Cross Section through an Extrapolation of Deep Inelastic Electroproduction and Photoproduction Data, Phys. Letters **40B**, 561 (1972).

L. J. Laslett, A Further Comment Concerning the Focussing Action of a Supplemental $H_\phi$-Field When the Electron Ring is in Motion, a Sequel to ERAN-148, ERAN-153, June 28, 1971.

L. J. Laslett, Interactive Teletype Programs for Computing the Self and Mutual Inductances of Axially-Symmetric Coils--Programs LANDM and BANDF, ERAN-154, June 30, 1971.

L. J. Laslett, An Analytic Formula for the Field Derivative $\partial^2 B_z/\partial r^2$ Arising from a Circular Current-Carrying Loop, ERAN-155, July 7, 1971.

L. J. Laslett, Note: Concerning the Program BANDF (ERAN-154) for Computing Self and Mutual Inductances of Co-axial Axially-Symmetric Coils, ERAN-158, July 21, 1971.

L. J. Laslett, Concerning the Adiabatic Damping of Betatron Oscillations in an Electron-Ring Compressor Employing an Ancillary $H_\phi$-Field, ERAN-159, August 11, 1971.

L. J. Laslett, Utility of the Maxwell Stress Tensor for Computing Magnetic Forces, ERAN-160, August 24, 1971.

L. Jackson Laslett, Examples of Electron-Ring Compressors with High Landau Damping Coefficients for Longitudinal and Transverse Collective Instabilities, ERAN-163, Oct. 8, 1971.

L. J. Laslett, Provisional Interactive (TTY) Programs for Studying the Successive Ionization of Gas Molecules by an Electron Ring Beam, ERAN-164, Oct. 12, 1971.

L. J. Laslett, A Preliminary Investigation Concerning the Inclusion of a Third Compression Coil in the Redesign of Compressor 4, ERAN-165, October 13, 1971.

L. J. Laslett and U. Schumacher, The Enhancement of Landau-Damping Coefficients for Collective Radial Instabilities in an Electron-Ring Accelerator by an Ancillary $B_\phi$-Field, ERAN-167 and Lawrence Radiation Laboratory Report UCRL-20855, Sept. 1971.

L. Jackson Laslett, Some Estimated Ionization Cross Sections, ERAN-168, Oct. 15, 1971.

L. Jackson Laslett, On the Formulation and Use of Approximate Interactive Computer Programs to Estimate the Cumulative Development of Ions in an Electron-Ring Compressor, ERAN-169, Oct. 25, 1971.

J. Jackson Laslett, Estimation of Eddy-Current Characteristics, Parameters of Simulation Circuits, and Computational Trials, ERAN-170, Oct. 28, 1971.

L. J. Laslett, Numerical Evaluation of Roots of a Dispersion Equation Considered Relevant to the CERN ISR, ERAN-173, Nov. 8, 1971.

L. Jackson Laslett, Numerical Evaluation of Roots of a Dispersion Equation Considered Relevant to the CERN ISR, ERAN-175, Dec. 2, 1971.

L. J. Laslett, A Numerical Illustration of the Effect of Dispersion on the Electron-Ion Instability, ERAN-177, Dec. 14, 1971.

L. J. Laslett, Numerical Work Relating to Stability of Electron-Ion Collective Motion, ERAN-181, Jan. 4, 1972.

L. Jackson Laslett, The Computational Check of Compressed and Loaded Electron Rings, and Examination of Their Subsequent Acceleration in a Static Magnetic Field Without Flux-Bars, ERAN-182, Jan. 8, 1972.

L. J. Laslett, The Computed Performance Characteristics of Some Existing Electron Rings, ERAN-184, Jan. 20, 1972.

L. J. Laslett, Computation of Approximate Resonant Radii for a Modulated Beam Circulating Between a Co-Axial Pair of Circular Conducting Tubes, ERAN-185, March 15, 1972.

L. J. Laslett and Andris Faltens, The Longitudinal Electric Field of a Modulated Straight Relativistic Beam Moving Parallel to a Perfectly-Conducting Infinite Plane, ERAN-188, Feb. 18, 1972.

D. Möhl and A. M. Sessler, A Model for a High Energy Proton-Electron-Positron Colliding Beam System: SPEAR Plus a Proton Ring, PEP-Note 2, Sept. 1971.

D. Möhl and A. M. Sessler, Speculations on the Mechanisms Leading to a Limit on Stacked Current in the ISR, ERAN-180, Oct. 1971.

D. Möhl and A. M. Sessler, On the Use of ISABELLE in a PEP System and Other Related Topics, PEP-Note 9, Nov. 1971.

D. Möhl and A. M. Sessler, Optimum Ring Analysis, ERAN-172, Nov. 1971.

D. Möhl and A. M. Sessler, Proton-Electron Coupling Instability of Debunched Beams in the CERN PS and the Bevatron, ERAN-186, March 1972.

D. Möhl and A. M. Sessler, PEP Parameters PEP-Note 18, April 1972.

D. Möhl and A. M. Sessler, The Use of RF-Knockout for Determination of the Characteristics of the Transverse Coherent Instability of an Intense Beam, in *Proceedings of the VIIIth International Conference on High Energy Accelerators*, M. Hildred Blewett, Ed. (CERN, Geneva, 1971), p. 334.

Namik K. Pak, Final State Hadron Distributions and Generalized Scaling Laws in Deep-Inelastic Electroproduction Processes, Ph.D. Thesis, Lawrence Berkeley Laboratory Report LBL-773, March 1972.

B. K. Pal, Neutron-Proton Charge Exchange Polarization, Nuovo Cimento **6A**, 29 (1971).

Blake Patterson, The Connective Evolution of Large Amplitude Alfven Waves in the Solar Wind, Ph.D. Thesis, Lawrence Berkeley Laboratory Report LBL-45, August 1971.

C. Pellegrini, J. Rees, B. Richter, M. Schwartz, D. Möhl, and A. M. Sessler, A High-Energy Proton-Electron-Positron Colliding Beam System, in *Proceedings of the VIIIth International Conference on High Energy Accelerators,* M. Hildred Blewett, Ed. (CERN, Geneva, 1971), p. 153.

M. R. Pennington and S. D. Protopopescu, Phys. Letters **40B**, 105 (1972).

M. R. Pennington, The I = 0 $\pi\pi$ s-Wave and Broken Scale Invariance, Phys. Rev. **D6**, 1458 (1972).

M. R. Pennington, Do Dispersion Relations for the I = 2 $\pi\pi$ Amplitude Require Subtraction? Lawrence Berkeley Laboratory Report LBL-918, April 1972, submitted to Nucl. Phys.

M. R. Pennington and S. D. Protopopescu, The $\pi\pi$ Scattering Amplitude in the Low-Energy Region, Lawrence Berkeley Laboratory Report LBL-963, submitted to Phys. Rev.

E. A. Rauscher, Closed Cosmological Solutions to Einstein's Field Equations, Lett. Nuovo Cim. **3**, 661 (1972).

E. A. Rauscher, A Set of Generalized Heisenberg Relations and a Possible New Form of Quantization, Lett. Nuovo Cim. **4**, 575 (1972).

Clifford Risk, William P. Swanson, and Jerome H. Friedman, A Multi-Regge Model Applied to High-Energy Inclusive Photoproduction, Lawrence Berkeley Laboratory Report LBL-556, Dec. 1971, submitted to Nucl. Phys.

A. M. Sessler, Book Review of *Linear Accelerators* by P. Lapostolle and A. Septier, Nucl. Instr. Methods **95**, 395 (1971).

A. M. Sessler, The Possibilities and Problems of Present and Future Accelerators, in *Proceedings of the VIIth International School on Particle Physics, Yerevan,* Nov. 1971, to be published.

A. M. Sessler, Instabilities of Relativistic Particle Beams, in *Proceedings of the VIIth International School on Particle Physics, Yerevan,* Nov. 1971, to be published.

A. M. Sessler, The Self-Destructive Behavior of Stored Electron Beams: The Disease Patterns, Symptoms, and Cures, PEP-Note 22, May 1972, also ERAN-192.

S. S. Shei and M. Suzuki, Current Algebra in Inclusive Hadron Scattering, Lett. Nuovo Cim. **2**, 1127 (1971).

S. S. Shei, The S-Channel Unitarity Constraint of the Multiperipheral Bootstrap Models, Phys. Rev. **D4**, 3704 (1971).

Cristian Sorensen, Deck Model for Triple-Regge Couplings, Lawrence Berkeley Laboratory Report LBL-908, Apr. 1972, to be published in Phys. Rev. D.

Cristian Sorensen, Deck Model for Triple-Regge Couplings, Ph.D. Thesis, Lawrence Berkeley Laboratory Report LBL-981, June 1972.

Richard Spitzer, Neutral K in an rf Field, Lawrence Berkeley Laboratory Report LBL-740, Feb. 1972, submitted to Phys. Letters.

Henry P. Stapp, Foundations of S-Matrix Theory. I. Theory and Measurement, Lawrence Berkeley Laboratory Report LBL-759, March 1972; Foundations of S-Matrix Theory. II. Macrocausality, LBL-956, April 1972; Foundations of S-Matrix Theory. III. The Normal Analytic Structure, LBL-959, June 1972.

H. P. Stapp, Inclusive Cross Sections are Discontinuities, Phys. Rev. **D6**, 3177 (1972).

Henry P. Stapp, The Copenhagen Interpretation, Am. J. Phys. **40**, 1098 (1972).

W. J. Swiatecki, Fission and Fusion Dynamics. I. Lawrence Berkeley Laboratory Report LBL-549, Dec. 1971.

W. J. Swiatecki, Common Features and Differences Between Fission and Heavy Ion Physics, Lawrence Berkeley Laboratory Report LBL-972, June 1972, presented at European Conference on Nuclear Physics, Aix-en-Provence, France, June 26-July 1, 1972.

B. R. Webber, The Dependence of Multiplicity on Recoil Momentum in High-Energy Collisions, Lawrence Berkeley Laboratory Report LBL-309, Aug. 1971, submitted to Lett. Nuovo Cim.

# ATOMIC BEAM GROUP

Howard A. Shugart in charge

The Atomic Beam Group specializes in studying and measuring the electric, magnetic, and mechanical properties of atoms, molecules, and nuclei as well as in testing various fundamental concepts of physics. Most of this work is performed on simple atomic systems, so the interpretation of the results is unambiguous and the comparison with theoretical predictions is especially favorable. The methods employed are primarily those of atomic and molecular beams, ion beams, optical and electron pumping, radiation and particle detection. In most cases these techniques are noted for their sensitivity and reliability.

## LOCAL HIDDEN-VARIABLE THEORIES

*John Clauser and Stuart Freedman*

We have measured the linear polarization correlation of the photons emitted in the atomic cascade $4p^2\ {}^1S_0 \rightarrow 4s4p\ {}^1P_1 \rightarrow 4s^2\ {}^1S_0$ of ${}^{40}Ca$ as a test for the existence of local hidden variables in quantum mechanics. The photons are directed through polarizers and counted in delayed coincidence. A generalization of Bell's inequality, applicable to this experiment, imposes a restriction on the correlation which is violated by the predictions of quantum mechanics. The restriction can be shown to take the form

$$\delta = [R(22.5^\circ) - R(67.5^\circ)]/R_0 - 1/4 \leqslant 0,$$

where $R(\phi)$ is the coincidence rate with angle $\phi$ between the polarizers, and $R_0$ is the rate with polarizers removed. We find $\delta = +0.050 \pm 0.008$, in violation of this inequality. We find no evidence for a deviation of $R(\phi)$ from the predictions of quantum mechanics. This result is strong evidence against local hidden-variable theories, and a verification of the quantum mechanical results.

## LIGHT TRAPPING IN AN ATOMIC BEAM

*Melvin K. Simmons*

This project was set up to test the effect of light-trapping on the lifetime of a radiating state. The equipment consists primarily of that used in the photon-polarization correlation experiment which has just been completed. Several runs were made which agreed with recent theoretical predictions of trapping in an atomic beam. The experiment has been terminated and the equipment disassembled.

## METASTABLE STATE OF CARBON MONOXIDE

*Charles E. Johnson and Robert S. VanDyck, Jr.*

Discovery of carbon monoxide and strong uv emission from its $a\,{}^3\Pi - X\,{}^1\Sigma$ Cameron band in the Martian upper atmosphere by the Mariner missions appears to have stimulated considerable interest in this forbidden transition. We have investigated the rotational dependence of the lifetime of the $a\,{}^3\Pi$ metastable state of CO using the time-of-flight technique with which we previously successfully measured the lifetime of the $2\,{}^1S_0$ metastable state of helium. The velocity distribution of metastable molecules is sampled and detected at two positions, 1.9 m and 6.7 m from the pulsed electron gun used to excite the ground-state molecules effusing from a cooled source slit. The initial population distribution among rotational levels is changed by varying the temperature of the source. A comparison of the number of metastables within given velocity intervals at the two detectors determines the number which decay in flight and yields an experimental plot of the number which decay versus time of flight. A theoretical decay plot is also obtained using the $a\,{}^3\Pi$ metastable state lifetimes calculated by James, who predicts rotational

level lifetimes ranging from three msec to several hundred msec. For two different source temperatures, the experimental and theoretical decay plots are in good agreement.

## EFFECT OF ELECTRIC FIELD QUENCHING

*Charles E. Johnson*

We have begun a study to investigate the effect of electric field quenching on the lifetimes of metastable electronic states. The first step has been to use the time-of-flight technique to measure the quenching of the $2\,^1S_0$ metastable state of helium by a static electric field. Our experimental result for the quenching constant with E in kV/cm is $k = 0.930 \pm 0.005$; this value is in good agreement with, but four times more accurate than, an earlier experiment. The theoretical value for $\Sigma\, M_n(0)$ used by Jacobs in his calculation of the two-photon decay rate of the $2\,^1S_0$ state is $\Sigma\, M_n(0) = -25.70$; thus $k = 0.931$. An independent calculation by Drake gives $k = 0.932$. The excellent agreement between experiment and theory for the quenching constant k therefore serves as a test of the two-photon decay matrix element ten times more precise than the previous measurement of the $2\,^1S_0$ metastable state lifetime. The result can be interpreted not only as a test of the calculated two-photon decay rate $\gamma_0$ of the $2\,^1S_0$ state, but also as an independent confirmation of the quenching theory used in the $Li^{2+}$, $C^{5+}$, and $O^{7+}$ Lamb shift measurements.

## PRECISION SPECTROSCOPY

*Tetsuo Hadeishi and Joseph Yellin*

Studies of precision spectroscopy using quantum beats continue, with the Nuclear Chemistry Isotope Separator as the source of 50 to 100 keV ions for beam-foil optical studies. The technique is now being applied to the study of the fine structure of helium.

## MERCURY DETECTOR

*Tetsuo Hadeishi*

The hyperfine Zeeman-effect atomic absorption spectrometer developed last year to detect mercury in fish at sea has reached a high degree of perfection and is now being constructed commercially. Under a new grant from the National Science Foundation we will further increase the sensitivity of the instrument and will extend its use to two additional elements of environmental concern--lead and cadmium.

## HYDROGENLIKE AND HELIUMLIKE ATOMS

*Robert Schmieder, Richard Marrus, and Harvey Gould*

Lifetimes and spectra of hydrogenlike and heliumlike ions of high Z have been determined by accelerating atoms down the Berkeley HILAC and into a beryllium-foil target. Emerging excited ions give off characteristic x rays that can be detected by lithium-doped silicon detectors. Most of our effort this year has been devoted to planning new experiments and constructing equipment to use when the SuperHILAC begins operation. Several experiments are ready to begin as soon as possible.

## PRECISION MEASUREMENT OF $g_J\,(N^{14}, {}^4S_{3/2})$

*Bernard D. Zak and H. A. Shugart*

The atomic beam magnetic resonance technique has been used to measure the g-factor ratio of the ground state of nitrogen to the ground state of potassium. The result is $g_J(N^{14}, {}^4S_{3/2})/g_J(K^{39}, {}^2S_{1/2}) = 0.9999196(20)$, where the quoted error represents the 90% confidence level. Combining this result with that of other researchers, we find the absolute $g_J$ factor for nitrogen to be $g_J(N^{14}, {}^4S_{3/2}) = -2.002134(5)$. This value is in much better agreement with the result of a recent calculation carried out according to the theory of Kambe and Van Vleck than is the earlier measurement of Heald and Beringer. The discrepancy between calculated and measured values is reduced from $13.5 \pm 2$ ppm to $4 \pm 2.5$ ppm. The atomic nitrogen was generated in an electrodless discharge and detected with a recently completed mass spectrometer-universal detector.

The observed discrepancy between calculation and measurement for $g_J(N^{14}, {}^4S_{3/2})$ is approximately 5% of the relativistic-diamagnetic correction; this discrepancy is similar in relative magnitude to, but opposite in sign

from, that obtained for $g_J(F, {}^2P_{1/2})$. These discrepancies are to be contrasted with the agreement to within 1 ppm for the ${}^3P_1$ and ${}^3P_2$ states of oxygen, and the ${}^2P_{3/2}$ state of fluorine.

Traditionally, responsibility for any such discrepancy is placed on the inaccuracy of the wavefunctions used in the calculations. Now, however, Leduc, Laloe and Brossel have questioned whether effects of higher order in $\alpha$ than those accounted for in the theory might not be responsible for a 2-ppm discrepancy between their measured value of $g_J(He^4, 2\,{}^3S_1)/g_J(H, {}^2S_{1/2})$ and a calculated value. Their result also differs from an earlier measured value of this ratio which is in agreement with theory.

Atomic beam measurements of $g_J(He^4, 2\,{}^3S_1)/g_J(H, {}^2S_{1/2})$ are in progress. As yet, insufficient data have been accumulated to quote a value for this ratio.

## PUBLICATIONS AND PAPERS


J. F. Clauser, Experimental Limitations to the Validity of Semiclassical Radiation Theories, Phys. Rev. **A6**, 49 (1972).

J. F. Clauser, Experimental Limitations to the Validity of Semiclassical Radiation Theories, Bull. Am. Phys. Soc. **16**, 1346 (1971).

J. F. Clauser, Experimental Limitations to the Validity of Semiclassical Radiation Theories, Lawrence Berkeley Laboratory Report LBL-941 Abs., presented at Third Rochester conference on Coherence and Quantum Optics, Rochester, NY, June 21–23, 1972.

J. F. Clauser, Von Neumann's Hidden-Variable Argument, Am. J. Phys. **39**, 1095 (1971).

J. F. Clauser, Reply to Dr. Wigner's Objections, Am. J. Phys. **39**, 1098 (1971).

E. D. Commins, The Intermediate Vector Boson, New Scientist **50**, 382 (1971).

J. V. Franck, W. Low, and R. W. Schmieder, Feasibility Tests for a Large Diameter Rotating Chamber, Lawrence Berkeley Laboratory Report LBL-769, Mar. 1972.

S. J. Freedman and J. F. Clauser, Experimental Test of Local Hidden Variable Theories, Bull. Am. Phys. Soc. **17**, 150 (1972).

Stuart Jay Freedman, Experimental Test of Local Hidden-Variable Theories, Ph.D. thesis, Lawrence Berkeley Laboratory Report LBL-391, May 1972.

S. J. Freedman and J. F. Clauser, Experimental Test of Local Hidden-Variable Theories, Phys. Rev. Lett. **28**, 938 (1972).

Donald Claude Girvin, Test of Time Reversal Invariance in ${}^{19}$Ne Beta Decay, Ph.D. thesis, Lawrence Berkeley Laboratory Report LBL-731, March 1972.

T. Hadeishi, R. D. McLaughlin, and M. C. Michel, Alignment of ${}^7$Li Atom Formed by Charge-Capture Collisions with Crossed Atomic Beam and Carbon Foil, J. Opt. Soc. Am. **61**, 653 (1971).

T. Hadeishi, Coherence Phenomena in Fast-Ion-Beam Foil and Gas Collisions, Bull. Am. Phys. Soc. **16**, 1356 (1971).

T. Hadeishi and R. D. McLaughlin, Hyperfine-Zeeman-Effect Atomic Absorption Spectrometer for Mercury, Science **174**, 404 (1971).

T. Hadeishi, Isotope-Shift Zeeman Effect for Trace-Element Detection: An Application of Atomic Physics to Environmental Problems, Lawrence Berkeley Laboratory Report LBL-751, Mar. 1972, submitted to Phys. Rev. Letters.

C. E. Johnson, R. Petrasso, and A. T. Ramsey, A Comment on the Lamb-Shift Measurements Using Electric Field Quenching, Lawrence Berkeley Laboratory Report LBL-710, Feb. 1972.

C. E. Johnson, Lifetime of the Metastable ${}^3\Pi_u$ State of $H_2$ and $D_2$, Bull. Am. Phys. Soc. **16**, 633 (1971).

C. E. Johnson and R. S. Van Dyck, Jr., Lifetime of the $a\,{}^3\Pi$ Metastable State of Carbon Monoxide, J. Chem. Phys. **56**, 1506 (1972).

C. E. Johnson, Lifetime of the Metastable ${}^3\Pi_u$ State of HD, Bull. Am. Phys. Soc. **16**, 1344 (1971).

C. E. Johnson, Lifetime of the $c\,{}^3\Pi_u$ Metastable State of $H_2$, $D_2$, and HD, Phys. Rev. **A5**, 1026 (1972).

C. E. Johnson, Lifetime of the Metastable $2p^3 3s\,{}^5S$ State of Oxygen, Bull. Am. Phys. Soc. **17**, 476 (1972).

C. E. Johnson, Lifetime of CO($a\,^3\Pi$) Following Electron Impact Dissociation of $CO_2$ Lawrence Berkeley Laboratory Report LBL-739, submitted to J. Chem. Phys.

C. E. Johnson, Quenching of the $2\,^1S_0$ Metastable State of Helium by an Electric Field, Lawrence Berkeley Laboratory Report LBL-949 Abs., presented at Third International Conference on Atomic Physics, Boulder, CO, Aug. 7–11, 1972.

C. H. Liu, S. Bashkin, W. S. Bickel, and T. Hadeishi, Measurements of Atomic g Values of Neutral and Charged States by the Beam-Foil Technique, J. Opt. Soc. Am. **61**, 653 (1971).

R. Marrus, Forbidden Decay Modes of One- and Two-Electron Atoms, Bull. Am. Phys. Soc. **16**, 1343 (1971).

R. Marrus and R. W. Schmieder, Forbidden Decays of Hydrogenlike and Heliumlike Argon, Phys. Rev. **A5**, 1160 (1972).

M. H. Prior and C. E. Johnson, $g_J$ of the $5d\,[7/2]_{4,3}$ and $5d\,[3/2]_2$ States in Xe and Hyperfine Structure of the $5d[7/2]_4$ State in $^{129}Xe$, Phys. Rev. **A5**, 550 (1972).

M. H. Prior and H. A. Shugart, Lifetime of the Metastable $2^1S_0$ State of $Li^+$, Bull. Am. Phys. Soc. **16**, 1344 (1971).

M. H. Prior, Lifetime of the 2s State of $He^+$, Lawrence Berkeley Laboratory Report LBL-937 Abs., presented at Third International Conference on Atomic Physics, Boulder, CO, Aug. 7–11, 1972.

M. H. Prior, Lifetime of the 2S State of $He^+$, Phys. Rev. Letters **29**, 611 (1972).

M. H. Prior and H. A. Shugart, Radiative Lifetime of Metastable Li II $2^1S_0$, Phys. Rev. Letters **27**, 902 (1971).

A. A. Ross-Bonney, Calculation of Several Nuclear Magnetic Moments, Bull. Am. Phys. Soc. **16**, 1167 (1971).

A. A. Ross-Bonney, A Reply to Sachs' Resolution of the Clock Paradox, Lawrence Berkeley Laboratory Report LBL-380, Sept. 1971, letter to the editor of Physics Today (29 Sept. 1971).

R. W. Schmieder, Interference Effects in Laser Modulated Electron Beams, Appl. Phys. Letters **20**, 516 (1972).

R. W. Schmieder and R. Marrus, Lifetime of the $2^2S_{1/2}$ State of Hydrogenlike Sulphur, Bull. Am. Phys. Soc. **16**, 848 (1971).

R. W. Schmieder, Proposed Electron/Laser Interferometers: Theory, Bull. Am. Phys. Soc. **16**, 833 (1971).

R. S. Van Dyck, Jr., C. E. Johnson, and H. A. Shugart, Lifetime Lower Limits for the Metastable $^3P$ States of the Noble Gases, Bull. Am. Phys. Soc. **16**, 533 (1971).

R. S. Van Dyck, Jr., C. E. Johnson, and H. A. Shugart, Radiative Lifetime of the $2^1S_0$ Metastable State of Helium, Phys. Rev. **A4**, 1327 (1971).

R. S. Van Dyck, Jr., C. E. Johnson, and H. A. Shugart, Lifetime Lower Limits for the $^3P_0$ and $^3P_2$ Metastable States of Neon, Argon, and Krypton, Phys. Rev. **A5**, 991 (1972).

B. D. Zak and H. A. Shugart, The $N^{14}$, $^4S_{3/2}$ $g_J$ Factor Measured by an Atomic Beam-Universal Detector Technique Lawrence Berkeley Laboratory Report LBL-737, May 1972, submitted to Phys. Rev.

Bernard Daniel Zak, A Precision Measurement of the $g_J$ Factor of the $^4S_{3/2}$ Ground State of Nitrogen: The Design, Construction, and Initial Use of the Sensitive, Universal, Molecular-Beam Detector, Ph.D. thesis, Lawrence Berkeley Laboratory Report LBL-8, Aug. 1971.

B. D. Zak and H. A. Shugart, A Precision Measurement of the $g_J$ Factor of the $^4S_{3/2}$ Ground State of Atomic Nitrogen, Bull. Am. Phys. Soc. **16**, 1351 (1971).

B. D. Zak, Precision Measurement of $g_J(N^{14}, {}^4S_{3/2})$ by an Atomic Beam Technique, Lawrence Berkeley Laboratory Report LBL-952 Abs., presented at Third International Conference on Atomic Physics, Boulder, CO, Aug. 7-11, 1972.

# CONTROLLED THERMONUCLEAR RESEARCH AND PLASMA PHYSICS

Wulf B. Kunkel in charge

## RESEARCH PROGRAMS

The research activity of this group in plasma physics and related atomic physics is part of the controlled fusion program centered at Lawrence Livermore Laboratory. Additional information about this work is included in the Controlled Thermonuclear Research Annual Report.[1]

One of the more promising methods for the production, maintenance, and heating of plasmas for a number of controlled fusion experiments is the injection of very large currents of energetic neutral deuterium beams. The need for much higher particle fluxes than are currently available has led to the development of large extended ion sources, which, when coupled with compatible accelerating structures, will be capable of producing such beams. The development of the required technology has required most of the resources of the Berkeley CTR Group during FY 72.

Our initial effort was directed primarily toward the extraction of a usable deuterium ion beam current of 20 A, with an energy of 20 keV, for subsequent neutral injection into the LLL 2X II mirror-confinement experiment. The ion beam is converted to energetic neutrals by electron capture in passing through ~ 100 mtorr-cm of gas. In this way about 10 A equivalent of fast neutrals enter the 2X II machine. The diameter of the experimental plasma plus the restricted size of existing entrance ports require the beam to be of high quality (maximum divergence = $\pm 1.8^0$ in x, $\pm 0.9^0$ in y).

For the production of these intense beams a large ion extraction area is required, and the plasma source[2] must generate the required density uniformly over this large region. A high premium also is placed on extractors capable of making high-current, low-divergence ion beams. The performance of such an extractor, designed with the aid of a digital computer program which determines the trajectories of particles from an emitting surface through a set of electrodes, taking into account the space charge of the beam, is described in a recent report.[3] The success of this development effort makes it possible to do new types of experiments on high-temperature, high-density plasmas.

Development and construction of apparatus for the laser-plasma experiment described in the previous annual report[4] was completed with successful production and collimation of frozen deuterium target pellets. The pellets are chopped with a vibrating wire from a 50-$\mu$ diameter solid $D_2$ thread.

The experimental study of a beam-plasma interaction has continued. A 4-kV, 40-mA electron beam of 1-mm diameter is shot along a magnetic field of 6000 to 75000 G into a chamber containing helium at a pressure of 0.2 torr. The electron beam initially produces a plasma by direct collisional ionization of the neutral gas, and then interacts with this plasma by means of the beam-plasma instability. Measurements of combined Zeeman and high-frequency Stark effects[5] have been used to determine the frequency, polarization, and amplitude of the electric fields produced by the beam-plasma instability. From the position and intensity of a satellite line the frequency and amplitude of the electric fields were determined to be approximately 50 GHz and 2500 V/cm. The measured frequency is near the plasma frequency ($N_e \approx 7 \times 10^{13}$) or upper hybrid frequency. Work has started on simulation of the linear and nonlinear development of the beam-plasma instability using a one-dimensional computer code for comparison with the experimental results.

We have continued our study of the correlation-in-phase of the light from a self-luminous plasma. This investigation, which was first described in the previous annual report, is based upon an analysis which shows that measurements of the mutual coherence of the

light emitted in different directions from a plasma should provide information about the distribution of light sources within the region observed. The purpose of the study is to explore the practicality of using this type of measurement for plasma diagnostics. The main advance made during the last year was the design and partial construction of an efficient multi-beam equivalent of the simple two-beam spectroscopic apparatus which was first considered.

Experimental and theoretical studies of transport caused by coherent, low-frequency plasma waves in a hollow-cathode-discharge plasma have been completed. A single-fluid model of waves in a rotating plasma yields results in good agreement with observations. The shape of the radial density profile is explained semi-quantitatively by including wave-enhanced convection in a simple diffusion theory. Dc and ac feedback potentials applied to segmented end plates suppressed the oscillations and the enhanced particle transport. In a subsidiary experiment we verified experimentally that a directional Langmuir probe correctly measures the plasma streaming velocity.

We have completed the measurements on the formation and destruction of the $(1s\sigma^2)X^1\Sigma_g^+$ ground state and the $(1s\sigma 2p\pi)c^3\Pi_u$ long-lived electronically excited state of molecular hydrogen. The molecules were formed by electron capture by 1- to 43-keV/nucleon $H_2^+$ or $D_2^+$ ions in Mg vapor.

The injection of pure beams of $D_2(^3\Pi_u)$ could, for low beam energies and plasma electron temperatures, lead to trapping in a magnetically confined plasma that is many times more efficient than that calculated for beams of ground-state atoms or molecules. However, the production of $^3\Pi_u$ molecules is accompanied by a mixture of ground-state and highly excited atoms and molecules which tend to mask the $^3\Pi_u$ contribution. To study the differences between atomic and molecular beams, we have calculated plasma trapping for beams prepared by neutralizing either 20-keV $D^+$ or 40-keV $D_2^+$ in Mg vapor.[6] In this calculation we show the fraction (per ion incident on the neutralizer) of beams trapped vs plasma line density.

Quasilinear theory has been applied to the toroidal confinement problem. In a toroidal plasma with axial symmetry, the three adiabatically invariant actions of a particle are the magnetic moment, the canonical angular momentum, and the toroidal flux enclosed by the drift surface. Resonant interactions between particles and the normal modes of collective oscillation produce mode growth or decay and random changes in the actions. This random walk is represented by a diffusion equation in action space. Both the diffusion tensor and the growth rate depend upon a coupling coefficient which represents the work done by a normal-mode field eigenfunction on the current density of an unperturbed particle orbit. The diffusion of the plasma causes adiabatic changes in the electric and magnetic self-consistent fields. Accordingly, energy is not conserved but is exchanged with external currents.

We have initiated a theoretical study of plasma heating by nonlinear interactions of intense laser radiation. If two laser beams have a difference frequency nearly equal to the plasma frequency, nonlinear interaction resonantly excites longitudinal plasma oscillations. These then induce transitions to other transverse modes. Nonlinear damping of the longitudinal mode heats the plasma. The process is optimized by having parallel beams, equal laser intensities, and damping equal to the frequency mismatch.

The results of this study are sufficiently encouraging that an associated experimental program is planned.

---

[1] Controlled Thermonuclear Research Annual Report, Lawrence Livermore Laboratory Report UCRL-50002-71.

[2] K. W. Ehlers and W. B. Kunkel, Lawrence Berkeley Laboratory Report LBL-915.

[3] William S. Cooper, Klaus H. Berkner, and Robert V. Pyle, Lawrence Berkeley Laboratory Report LBL-916.

[4] Physics Annual Report, Lawrence Berkeley Laboratory Report LBL-40.

[5] W. W. Hicks, R. A. Hess, and W. S. Cooper, Phys. Rev. A 5, 490 (1972).

[6] K. H. Berkner, T. J. Morgan, R. V. Pyle, and J. W. Stearns, Lawrence Berkeley Laboratory Report LBL-1026, August 1972, to be published in Nuclear Fusion.

PUBLICATIONS AND PAPERS

W. R. Baker, K. W. Ehlers, W. B. Kunkel, and A. F. Lietzke, Large-Area High-Current Ion Source, in *Proceedings of the Symposium on Ion Sources and Formation of Ion Beams, Oct. 19-21, 1971, Brookhaven National Laboratory,* BNL-50310, p. 145.

K. H. Berkner, W. S. Cooper, and R. V. Pyle, Multiple-Aperture Extractor Designs for Producing Constant Current, Variable Energy Ion Beams for Neutral Injection, APS Division of Plasma Physics Meeting, Madison, Wisc., Nov. 15-18, 1971, Bull. Am. Phys. Soc. 16, 1266, (1971).

K. H. Berkner, W. S. Cooper, and R. V. Pyle, Multiple-Aperture Extractor Design for Producing Intense Ion and Neutral Beams, in *Proceedings of the Symposium on Ion Sources and Formation of Ion Beams, Oct. 19-21, 1971, Brookhaven National Laboratory,* BNL-50310, p. 165.

K. H. Berkner, W. S. Cooper, C. C. Damm, K. W. Ehlers, A. H. Futch, G. W. Hamilton, J. E. Osher, and R. V. Pyle, Plasma Production by Neutral Beam Injection in Mirror Systems, in *Plasma Physics and Controlled Nuclear Fusion Research,* Vol. 2 (International Atomic Energy Agency, Vienna, 1971), p. 707.

Ian G. Brown, Alan B. Compher, and Wulf B. Kunkel, Response of a Langmuir Probe in a Strong Magnetic Field, Phys. Fluids 14, 1377 (1971).

W. S. Cooper, K. H. Berkner, and R. V. Pyle, Multiple-Aperture Extractor Design for Producing Intense Ion and Neutral Beams, Nucl. Fusion 12, 263 (1972).

William W. Hicks, Roger A. Hess, and William S. Cooper, Combined Zeeman and High-Frequency Stark Effects, with Applications to Neutral-Helium Lines Useful in Plasma Diagnostics, Phys. Rev. A 5, 490 (1972).

Allan N. Kaufman, Quasilinear Diffusion of an Axisymmetric Toroidal Plasma, Phys. Fluids 15, 1063 (1972).

Allan N. Kaufman, Resonance Broadening in Mode Coupling, Phys. Rev. Letters 27, 375 (1971).

Wulf B. Kunkel, The Many Uses of Plasma Physics, Annual Meeting of the Deutsche Physikalisch Gesellschaft e. V., Essen, Germany, Sept. 27-Oct. 2, 1971, in *Physik 1971 Plenarvorträge,* p. 37; Lawrence Berkeley Laboratory Report LBL-344, Sept. 1971.

Wulf. B. Kunkel, Momentum Balance for Mirror-Confined Plasma with Neutral Injection, APS Division of Plasma Physics Meeting, Madison, Wisc., Nov. 15-18, 1971, Bull. Am. Phys. Soc. 16, 1254 (1971).

T. J. Morgan, K. H. Berkner, R. V. Pyle, and J. W. Stearns, Cross Sections for the Destruction of 1- to 42-keV/Nucleon $1s\sigma^1\Sigma_g^+$ and $2p^3\Pi_u$ $H_2$ Molecules in $H_2$ Gas, APS Division of Electron and Atomic Physics Meeting, Atlanta, Ga., Dec. 1-3, 1971, Bull. Am. Phys. Soc. 16, 1343 (1971).

Thomas J. Morgan, Collisional Production and Loss of 1- to 42-keV/ Nucleon $X^1\Sigma_g^+$ and $c^3\Pi_u$ Hydrogen Molecules, and Application to Controlled Nuclear Fusion, Ph.D Thesis, Lawrence Berkeley Laboratory Report LBL-394, Sept. 1971.

T. J. Morgan, K. H. Berkner, and R. V. Pyle, Experimental Yields of Metastable $H_2^0$ Molecules for Neutral Injection at Intermediate Plasma Densities, APS Division of Plasma Physics Meeting, Madison, Wisc., Nov. 15-18, 1971, Bull. Am. Phys. Soc. 16, 1266 (1971).

Thomas J. Morgan, Klaus H. Berkner, and Robert V. Pyle, Production (in Mg Vapor) and Loss (in $H_2$ Gas) of 1- to 42-keV/Nucleon $X^1\Sigma_g^+$ and $c^3\Pi_u$ Hydrogen Molecules, Phys. Rev. A 5, 1591 (1972).

J. Warren Stearns, Klaus H. Berkner, Robert V. Pyle, Bruce P. Briegleb, and M. Laird Warren, Dissociation Cross Sections for 0.5- to 1-MeV $HeH^+$ Ions in $H_2$, He, $N_2$, and Ne Gases, Phys. Rev. A 4, 1960 (1971).

George M. Wheeler, Low-Frequency Waves, Stabilization, and Enhanced Transport in the Plasma

Surrounding a Hollow Cathode Discharge, Ph.D. Thesis, Lawrence Berkeley Laboratory Report LBL-577, Jan. 1972.

George M. Wheeler and Robert V. Pyle, Particle Transport and Wave Stabilization in a HCD Plasma, APS 1972 June Meeting in the Southwest, Albuquerque, N.M., June 5-7, 1972, Bull. Am. Phys. Soc. 17, 684 (1972).

# HEALTH PHYSICS

H. Wade Patterson in charge

## ENVIRONMENTAL RADIATION MONITORING

*L. D. Stephens and H. R. Dakin*

Centralized monitoring and recording of accelerator-produced radiation fields at points on the Lawrence Berkeley Laboratory site boundary began in 1964.

The basic system uses standard radiation detectors at remote locations connected to a central recorder system by standard voice-grade telephone lines. The most important part of the system is a pulse converter-transmitter providing signals of sufficient pulse amplitude and width to be transmitted over long distances and to be correctly received. By use of a prescaler, radiation varying over several orders of magnitude can still be monitored by the highly reliable electromechanical recorders by transmitting signals from two consecutive decades from the detector.

The received information is processed using a CDC-7600 program PLOTDOG to provide both a table and a semilogarithmic plot of the daily or hourly dose-rate distribution.

Since the recorders operate on fairly high level signals, usual background noise on the telephone lines is not a problem. By using ground isolation and common mode rejection circuitry, small fast signals have been successfully transmitted on telephone lines over long distances.

This system could be used to transmit and receive with high reliability any information that can be sent by pulse techniques. Since the lines are provided and maintained by the Telephone Company for a nominal charge and the associated equipment is relatively inexpensive, this system is more economical than any of several other remote monitoring options available today.

## SPARK CHAMBER NEUTRON SPECTROMETER

*C. B. Lim and A. J. Miller*

Development of a neutron spectrometer utilizing an array of 12 spark chambers, each of them sandwiched between a triggering scintillator and a polyethylene n-p converter, has continued throughout 1971-1972.

Development progress this year has centered around successfully testing and calibrating the spark chamber array and associated electronics in the proton beam at the 184-inch cyclotron. As a result of these tests and the experience gained in operating the spectrometer, the two computer programs which have been written to reduce and analyze the spark chamber data have been extended and refined.

Presently the spectrometer is taking data on the stray neutron fields at the 184-inch cyclotron. Preliminary results show that we are able to record and identify the neutron sources that cause the n-p reactions in the polyethylene converters.

## SHORT PULSE RADIATION DETECTOR

*C. D. Pike[1] and H. W. Patterson*

The injector for the Electron Ring Accelerator is an induction linear accelerator which produces short (10 to 30 ns) pulses of 4 MeV electrons at peak currents of ~ 1000 amperes and at a repetition rate of 1 pulse/3 sec. A radiation detector, pulse stretcher-integrator,[2] and remote readout-interlock suitable for the short intense bremsstrahlung pulses produced by the injector have been assembled, tested, and calibrated.

The detector consists of four reverse biased 1N1190 silicon diodes in parallel and has a suitable sensitivity and frequency response. The pulse stretcher-integrator response is in units of volt-nanoseconds/pulse but has been calibrated with photographic film and LiF dosimeters in units of

mr/pulse. The dynamic range of the system is about 200 and at present is from 1 to 200 mr/pulse.

The remote readout-interlock unit displays the magnitude of the last radiation pulse and compares this with a pre-set value. If the pre-set value is exceeded, the injector is disabled. Thus, the assembly serves as part of the accelerator interlock system. (Also incorporated is a push-button test of the complete system with the exception of the diodes.) In addition, the display of pulse-to-pulse intensity by the remote readout section can be used to tune the accelerator.

[1] Accelerator Study Group.
[2] Designed by D. E. Campbell, LLL Electronics Engineering.

## THERAPY WITH HEAVY IONS

*Roger Wallace*

The range-energy, specific ionization-energy and range-specific ionization relations for all ions incident on all targets have been extended and put in a form that will be more usable by the radiobiologists who are working with heavy ions. A code has been secured and is being investigated which models an entire human body including bones and organs by means of mathematical surfaces. It is hoped that this computer body can be combined with the range-specific ionization-energy code to produce a three-dimensional dose and cell-response code.

## GROUND WATER CONTAMINATION STUDIES

*Ralph H. Thomas (LBL) and G. B. Stapleton (Rutherford Laboratory)*

Ground water studies at the Rutherford Laboratory have continued.[1] The radioactive nuclides produced in rock surrounding a high-energy accelerator may migrate if subjected to hydraulic gradients and possibly contaminate neighboring water supplies with long-lived radionuclides. Chemical sorption on rock surfaces may substantially reduce leach rates. A specific study of the migration of $^{7}$Be through chalk soils showed chemical sorption to play a dominant role in minimizing leach rates. The leach rates of other radionuclides may be similarly influenced.[2]

Studies of possible contamination of ground water systems by high-energy accelerators have continued. In experimental studies at the Stanford 1 GeV Linear Accelerator the total quality and spatial distribution of $\gamma$-emitting radionuclides induced in an earth beam dump was determined. These measurements indicate that ground water contamination from earth beam dumps will be insignificant at the operating power of current high-energy electron accelerators.[3]

[1] G. B. Stapleton and R. H. Thomas, Estimation of the Induced Radioactivity of the Ground Water System in the Neighborhood of a Proposed 300 GeV High Energy Accelerator Situated on a Chalk Site, Health Physics Journal (in press).
[2] G. B. Stapleton and R. H. Thomas, The Effect of Sorption on the Migration of $^{7}$Be from a High Energy Accelerator Constructed on a Chalk Site, submitted to Water Research.
[3] R. H. Thomas, Radioactivity in Earth Induced by High Energy Electrons, Nucl. Instr. Methods 102, 149 (1972).

## SHIELDING STUDIES AT 28 GeV

*R. H. Thomas (LBL); G. W. Bennett, H. Foelsche, D. Lazarus, G. Levine, W. H. Moore, T. Toohig (BNL); and J. Kostoulas (U. Rochester)*

The gross distribution of the nuclear cascade produced in steel by 28-GeV protons as measured using $^{11}$C activation detectors has been found to be in good agreement with Monte Carlo calculations by Ranft.[1] An attenuation length for the laterally integrated cascade of 197 ± 3 g cm$^{-2}$ was obtained (cf. calculated values of 192 ± 10 g cm$^{-2}$). A buildup factor of 60 ± 4 was measured, intermediate between the calculated value for tracks of 46 ±10 and the value for stars of 105 ± 10.[2] We intend to compare these data in detail with Monte Carlo calculations.

[1] J. Ranft, Nucl. Inst. Methods 48, 133 and 261 (1967).
[2] G. W. Bennet et al., Particle Distribution in a Steel Beam Stop for 28 GeV Protons, submitted to Particle Accelerators.

## NEUTRON PERSONAL DOSIMETRY ABOVE 20 MeV

*H. Wade Patterson and Ralph H. Thomas*

Ilford L4 nuclear emulsions are being calibrated for use as personal neutron monitors. Emulsions were exposed to D-T neutrons (14 MeV), and to neutrons produced from stripped deuteron beams from the 88-inch and 184-inch Berkeley cyclotrons (these latter exposures corresponding to neutron energies of ~ 25 MeV and ~ 220 MeV, respectively.) In addition, NTA films were exposed to confirm their expected insensitivity to high-energy neutrons. Track scanning is in progress.

During these emulsion exposures the opportunity was taken to investigate the buildup corrections in activation detectors (due to interactions within the detector), to compare measurements of $^{11}C$ production by different techniques, and to expose several fission foil detectors.

## RADIOELEMENTS AND HEAVY MINERALS

*Harold Wollenberg*

In a U. S. Geological Survey-LBL cooperative study, measurements of the natural radioelement and trace-element contents of the Ione Formation (of the foothills of the Sierra Nevada in central California) were summarized to see if there was a correlation between radioactivity and gold and heavy-mineral abundances. Radioactivity and content of uranium plus thorium correlate with titanium, zirconium, and lanthanum, suggesting a general correspondence between the radioelements and heavy minerals. However, there was no apparent correlation between gold and U+Th, mainly because of the very low abundance of gold in the formation. Regional variations were noted in the potassium content of the formation and of comparable Eocene sandstones and clays of the Coast Ranges, while sandstones from all of the areas sampled are similar in U and Th. These factors, coupled with a comparison of the Ione's radioelement contents with the U, Th, and K of possible source rocks, indicate that processes associated with transportation and deposition, rather than composition of source rocks alone, may have significantly affected the distribution of radioelements in the formation. The work is described in a report "Radio and Trace-Element Content of the Ione Formation, California" by Harold Wollenberg and Franklin C. W. Dodge, to be published by the U. S. Geological Survey.

## NATURAL ENVIRONMENTAL RADIATION

*Harold Wollenberg and Alan R. Smith*

In preparation for the Second International Symposium on the Natural Radiation Environment, radioelement data for geologic terranes in California and western Nevada were summarized and converted to natural gamma-ray dose rates. Gamma-ray spectrometric analyses of samples from several hundred field locations, covering a broad range of lithology, were treated; these correlated closely with dose rates measured on-site. Data were adequate to characterize rock types and some of their derived soils by radioelement contents and associated radioactivities. The distribution of uranium, thorium, and potassium in rocks of the Coast Ranges and the Sierra Nevada batholith may be controlled to some extent by features of plate tectonism. The radioelement contents (and thus the natural gamma-ray dose rates) of Quaternary soils of the San Francisco Bay region reflect their bedrock parentage, pointing out the close relationship between geologic factors and the terrestrial environmental radiation. LBL-914, "Geologic Factors Controlling Terrestrial Gamma-Ray Dose Rates" by Harold A. Wollenberg and Alan R. Smith, describes this study.

## ELECTRON AND PROTON IRRADIATION OF GLASS—NASA SKYLAB PROJECT

*A. J. Miller and L. D. Stephens*

The Skylab Space Station will pass through the South Atlantic Anomaly of the Van Allen Radiation Belt as a part of its regular orbital pattern. Since this region is one of high radiation intensities of both electrons and protons, it is necessary to know the

extent of the radiation damage the viewing ports will suffer during this time.

The Lawrence Berkeley Laboratory Electron Linear Accelerator was used to simulate the electron radiation to which the glass will be subjected. The 88-inch cyclotron was used for the proton irradiation.

During each irradiation, the test specimen of Bk-7 glass was subjected to a stress pattern similar to the one to be experienced by the actual viewing port. This was achieved by applying a differential pressure on the test specimens during irradiation. Thirty test specimens were exposed to 30 MeV and 4.2 MeV protons and to 0.54 MeV electrons. During the irridiation process there were no failures of any test samples.

In order to accomplish this work, use was made of the 88-inch cyclotron beam raster system and beam energy calibrator system. Dr. Graham Welch provided help in operating the systems as well as in the actual energy calibrations. Energy determinations for the electron irradiation were made by range-energy measurements.

Future work in this field may possibly be in the area of damage studies to solar panels from accelerator-produced equivalents of cosmic-ray radiation.

## RADIATION LEVELS IN COMMERCIAL AIRCRAFT

*Roger Wallace*

Experimental measurements have been extended to the southern hemisphere. The experimental values agree fairly well with the theoretical calculations. A code which takes into consideration latitude, longitude, altitude, and solar cycle has been revised and used to compare and extend the experimental results. This work will be completed soon.

## COAL VS NUCLEAR POWER GENERATION

*Roger Wallace*

A comparison has been made between coal and nuclear power, taking into consideration the overall risk including that of fuel reprocessing, mining, and other auxiliary activities in the generation of electric power. While this risk–benefit analysis is not as inclusive as it will be in the future, and many pieces of data must be estimated at the present state of our knowledge, it seems to be clear that the risk from coal generation far exceeds that from nuclear power generation, using even the most extreme interpretation of the nuclear risk.

## ACCELERATOR HEALTH PHYSICS TRAINING PROGRAM

*H. Wade Patterson and Ralph H. Thomas*

As part of the Accelerator Health Physics Training Program, sponsored by the Division of Nuclear Education and Training, a training manual has been completed. The volume consists of eight chapters dealing with particle interactions, radiation fields, particle accelerators, human response to radiation, radiation detectors, shielding, induced activity, and the administration of an accelerator health physics program. A laboratory manual is included.

## ICRP PUBLICATION #21

*Ralph H. Thomas*

The International Commission on Radiological Protection (ICRP) has prepared a report containing supplementary material to ICRP #15 (Protection Against Ionizing Radiation from External Sources). The Health Physics group has participated in the preparation of this report, which will contain material of interest to those engaged in high-energy radiation problems. For example, particle quality factors and fluence-to-dose conversion factors are tabulated as a function of energy; and some shielding information is provided. The report will be issued shortly.

## THE ACTIVITIES AT RISØ, 1969-1971

*Harold Wollenberg*

From September 1969 through July 1971, Harold Wollenberg was on leave of absence from LBL at the Danish Atomic Energy Commission's research establishment, Risø, about 20 miles west of

Copenhagen. He worked with a group devoted to applying nuclear techniques to evaluate the mineral resources of Greenland. Applications included airborne, ground, underground, and laboratory gamma-ray spectrometric methods for uranium and thorium. The Risø group is also vigorously applying non-dispersive X-ray fluorescence techniques, both in the field and laboratory, to evaluate base metal, zirconium, niobium, and rare-earth element deposits. Parts of two summers were spent in the field in South Greenland. At Risø, he introduced the fission-track radiographic method to determine the location, abundance, and mineralogical affinity of U and Th in petrographic thin sections. Close ties were established with geologists at the University of Copenhagen and the Geologic Survey of Greenland.

Publications describing aspects of these studies are: "Determination of rare-earth elements in rocks by isotope-excited X-ray fluorescence spectrometry," H. Kunzendorf and H. A. Wollenberg, Nucl. Inst. Meth. **87** (1970); "Field determination of uranium and thorium by gamma-ray spectrometry, exemplified by measurements in the Ilímaussaq alkaline instrusive, South Greenland," Leif Løvborg, Harold Wollenberg, Poul Sørensen, and John Hansen, Economic Geology **66** (May 1971); "Isotope-excited X-ray fluorescence analyses for Nb, Zr, and La+Ce on outcrops in the Ilímaussaq instrusion, South Greenland," Harold Wollenberg, Helmar Kunzendorf, and John Rose-Hansen, Economic Geology **66** (Nov. 1971); "Drill core scanning for radioelements by gamma-ray spectrometry," Leif Løvborg, Harold Wollenberg, John Rose-Hansen, and Bjarne Leth-Nielsen, Geophysics **37** (Aug. 1972).

Reports covering work done predominantly at Risø and scheduled for publication in the near future are: "Heat flow and surface radioactivity at two sites in South Greenland," J. H. Sass, B. L. Nielsen, H. A. Wollenberg, and R. J. Munroe, to appear in Journal of Geophysical Research; and "Fission-track radiography of uranium and thorium in radioactive minerals," Harold Wollenberg, in Proceedings of Fourth International Geochemical Symposium, London, 1972.

## PUBLICATIONS AND PAPERS


T. F. Budinger, J. R. Farwell, A. R. Smith, and H. Bichsel, Human Tissue Trace-Element Detection by Neutron Activation without Chemical Separation, Int. J. Appl. Radiat. Isotop. **23**, 49 (1972).

Rudolph H. Henninger, Development of Neutron Leakage Spectrometers with Emphasis on the keV Range, Ph.D. thesis, Lawrence Radiation Laboratory Report UCRL-20148, Mar. 1971.

H. Kunzendorf, L. Løvborg, and H. Wollenberg, Assay of Powdered Metallic Ores by Means of a Portable X-Ray Fluorescense Analyzer, Risø Report #251, Nov. 1971.

T. H. Lim, Some Quantitative Risk and Benefit Comparisons from Generating Electricity of Coal Fired and Nuclear Fueled Power Plants Using Decision Analysis, M.S. thesis, Lawrence Berkeley Laboratory Report LBL-933, June 1972.

Leif Løvborg, Harold Wollenberg, Paul Sorensen, and John Hansen, Field Determination of Uranium and Thorium by Gamma Ray Spectrometry, Exemplified by Measurements in the Ilimaussaq Alkaline Intrusion, South Greenland, Economic Geology **66** 3, (1971).

Masao Oshino, Response of NTA Personnel Neutron Monitoring Film Worn on Human Phantom, Lawrence Berkeley Laboratory Report LBL-342, Sept. 1971.

H. W. Patterson and R. H. Thomas, Radiation and Risk—The Source Data, in *Pollution and Health*, Sixth Berkeley Symposium on Mathematical Statistics and Probability, Vol. 6 (University of California Press, Berkeley, 1972).

A. Rindi and R. H. Thomas, Absorbed Dose—An Unfortunate "Red Herring" in Radiation Protection, in *Radiation Protection Standards: Quo Vadis*, Proceedings of the 6th Annual Health Physics Society

Mid-year Topical Symposium (Health Physics Society, Columbia Chapter, Richland, Washington, 1972).

A. Rindi, Applications of Methods Developed in High-Energy Research Centers to Problems of Medicine and Dosimetry, Minerva Med. **15,** 159 (1971).

A. Rindi and R. H. Thomas, Povera E Nuda Vai, Dosimetria, Health Phys. **23,** 715 (1972).

J. M. Sperinde, L. E. Temple, V. Perez-Mendez, A. J. Miller, and A. Rindi, Techniques for Mapping Spatial Distribution of Stopping $\pi$ Mesons in Tissue, Nucl. Instr. Methods **97,** 331 (1971).

G. B. Stapleton and Ralph H. Thomas, The Production of $^{7}$Be by 7 GeV Proton Interactions With Oxygen, Nucl. Phys. **A175,** 124 (1971).

L. D. Stephens and H. S. Dakin, A High Reliability Environmental Radiation Monitoring and Evaluating System, presented at the Sixth International Congress of the Societe Francaise de Radioprotection, Bordeaux, France, March 27-31, 1972, Lawrence Berkeley Laboratory Report LBL-585, Jan. 1972.

R. H. Thomas, High Energy Heavy Ions, Phys. Bull. (Lond.) **23,** 143 (1972).

Ralph H. Thomas, Radioactivity in Earth Induced by High Energy Electrons, Nucl. Instr. Methods **102,** 149 (1972).

Ralph H. Thomas, Radiation Protection Standards, Phys. Bull. (Lond.) **23,** 109 (1972).

C. A. Tobias, A. Chatterjee, and A. R. Smith, Radioactive Fragmentation of $N^{7+}$ Ion Beam Observed in a Beryllium Target, Phys. Letters **37A,** 119 (1971).

C. A. Tobias, J. T. Lyman, A. Chatterjee, J. Howard, H. D. Maccabee, M. R. Raju, A. R. Smith, J. M. Sperinde, and G. P. Welch, Radiological Physics Characteristics of the Extracted Heavy Ion Beams of the Bevatron, Science **174,** 1131 (1971).

Harold Wollenberg, Fission Track Radiography of Uranium and Thorium in Radioactive Minerals, Risø Report #228, July 1971.

H. A. Wollenberg and A. R. Smith, Geologic Factors Controlling Terrestrial Gamma-Ray Dose Ratees, presented at Meeting for Natural Radiation Environment II, Houston, August 7-11, 1972, Lawrence Berkeley Laboratory Report LBL-914, July 1972.

H. Wollenberg, H. Kunsendorf, and J. Rose-Hansen, Isotope-Excited X-Ray Fluorescence Analyses for Nb, Zr, and La + Ce on Outcrops in the Ilimaussaw Intrusion, South Greenland, Economic Geology **66** 1048 (1971).

# NUCLEAR EMULSION GROUP

Harry H. Heckman in charge

The Nuclear Emulsion Group engages in interrelated programs of research in the fields of high-energy heavy-ion physics, cosmic rays and geomagnetically trapped radiation. A major part of this research program is being done in cooperation with the University of California Space Sciences Laboratory. The LBL-UCSSL collaborative effort utilizes a recently developed computer-controlled solid-state (Si) particle identifier system to carry out heavy-ion fragmentation experiments at the Bevatron. A flight model version of the particle identifier will be part of the experimental payload for the OSO-J satellite, to be launched in 1975-6. Cosmic-ray heavy-ion physics is being pursued with nuclear emulsion detectors that are part of a balloon-borne, superconducting magnetic spectrometer. This work is a cooperative effort with the Cosmic-Ray Division, MSC-NASA, Houston. The purpose of this work is to determine the momentum and charge spectra of heavy cosmic-ray primaries for rigidities (=p/z) up to 300 GV/c.

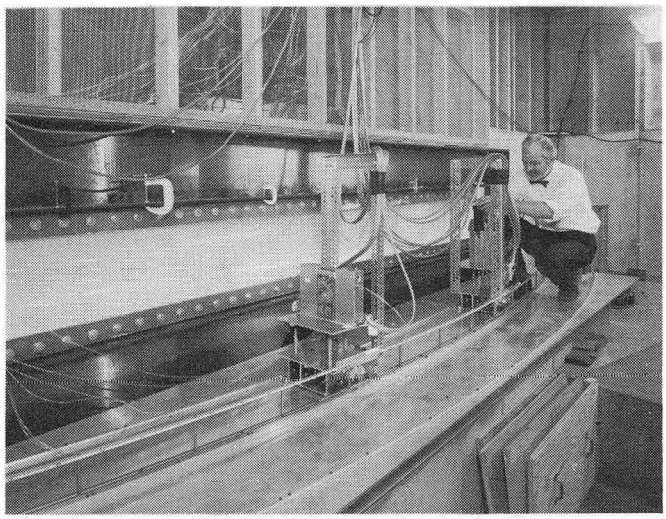


*Fig. 1. Fragments from the breakup of heavy ions emerged from the vacuum chamber downstream from the Bevatron target. The detector system moved along a track in front of the vacuum chamber, scanning the magnetically separated groups of fragments.*

## BEVATRON HEAVY-ION RESEARCH

*Harry H. Heckman (LBL); Douglas E. Greiner, Peter J. Lindstrom, and Frederick S. Bieser (UC Space Sciences Laboratory).*

Concurrently with the successful acceleration and extraction of 2.1-GeV/nucleon $^{14}N$ ions from the Bevatron, an exploratory experiment was undertaken to study the fragmentation of energetic heavy ions in matter. In these experiments the external proton beam channel was used as a rudimentary magnetic spectrometer to analyze the rigidity (=p/z) of the nuclear fragments of $^{14}N$ nuclei, produced at $0^0$ in carbon and polyethylene targets (Fig. 1). Additional measurements of energy loss (dE/dx) and velocity enabled us to identify the fragments isotopically. The first observations strikingly demonstrated that virtually all of the $0^0$ fragments heavier than He (Z=2) have velocities that differ little from the incident $^{14}N$ beam. This is of practical importance because it makes possible the production of isotopically pure secondary beams.

Preliminary estimates of the differential cross section (at $0^0$) for fragment production in carbon and hydrogen ($CH_2$) targets were also made. For a sample of nine nuclides, $^7Li$ through $^{13}N$, we found that the ratios of the differential cross sections for the production of the $i^{th}$ isotope in hydrogen and carbon, $\sigma_H^i(0^0)/\sigma_C^i(0^0)$, are constant to within the 20% measurement error, the mean ratio being 0.62 ±0.07. This is evidence that the modes of fragmentation of the $^{14}N$ nucleus are the same for hydrogen and carbon targets. Such behavior is characteristic of high-energy multiparticle interactions and of the concept of the

factorization of cross sections when the fragmentation is limiting, i.e., cross section is constant. To extend these observations, further measurements on the fragmentation of $^{12}C$ and $^{16}O$ ions at 2.1 GeV/nucleon in several targets H through Pb were performed to determine the total partial inelastic cross sections for the production of N, C, and B nuclei. The experimental results given in Fig. 2 show that the fragmentation

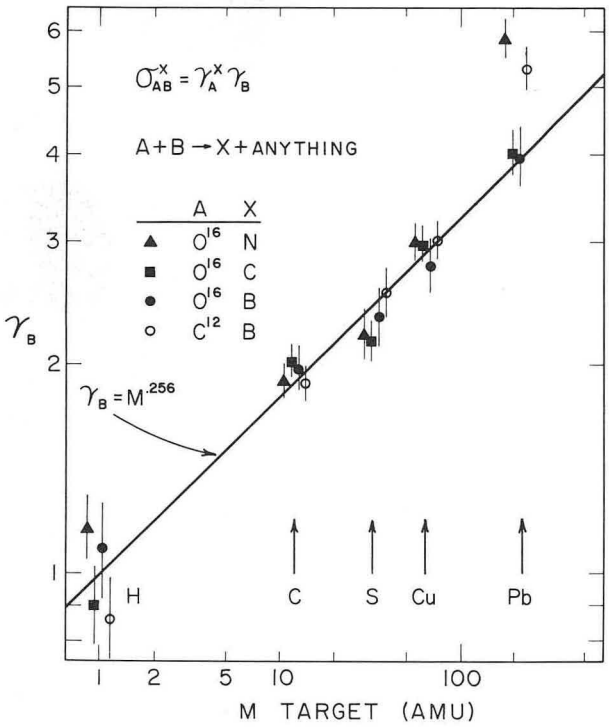



*Fig. 2. Fragmentation cross sections of heavy-ion beams can be expressed as $\sigma^X_{AB} = \gamma^X_A \gamma_B$, where $\gamma^X_A$ is the probability of beam ion A fragmenting into particle X. Since this probability is independent of target nucleus B, the cross sections are factorable into $\gamma^X_A$ and a target factor $\gamma_B = M^{0.256}$*

modes of heavy nuclei are, to good approximation, independent of the nature of the target nuclei.

This result implies that heavy-ion interactions may, in part at least, be interpreted in terms of contemporary high-energy theories on inclusive interactions and the concepts of limiting fragmentation and factorization. With the availability of relativistic heavy ions, it will now be possible to extend studies of hadron-hadron interactions to systems involving large baryon numbers.

## COSMIC RAY HEAVY IONS

*Robert L. Golden (Manned Spacecraft Center, NASA, Houston); and Harry H. Heckman (LBL).*

In collaboration with Manned Spacecraft Center, NASA, Houston, we are analyzing nuclear emulsions exposed to momentum-analysed cosmic-ray heavy ions. The balloon experiments were carried out in August 1969 at Palestine, Texas (ridigity cutoff Rc=4.5 GV/c), and at Paraná, Argentina (Rc=11 GV/c), in November 1970. The rigidities of the heavy ions are measured by using doubly coated emulsion plates in a 10-kG field supplied by a superconducting magnet. Scanning of the August 1969 flight emulsions has been completed, and the rigidity and charge measurements are in their final stages of reduction. Scanning of the "target" stack of emulsions from the 1970 flight has begun. To date, data gathered on $Z \geqq 3$ nuclei indicate a differential rigidity spectrum of the form $R^{-2.5 \pm 0.1}$ for rigidities of 8 to 300 GV/c. The spectra for the L, M, and H charge groups are mutually consistent. No candidates for antinuclei have been observed.

## MAGNETIC BREMSSTRAHLUNG

*M. Mashkour (Illinois Institute of Technology); and Harry H. Heckman (LBL).*

This nuclear emulsion experiment is on the bremsstrahlung radiation emitted by 19-GeV electrons in megagauss magnetic fields; it is a joint IIT, SLAC, and LBL effort. The MG fields were generated in volumes $\approx 1$ cm$^3$ by capacitor discharge in single-turn coils. Useful lifetimes of the fields were $\approx 10^{-6}$ sec. Objectives of the experiment are: to examine the spectral distribution of the synchrotron radiation in the photon energy range 15 to 150 MeV emitted from 19-GeV electrons in 1.2 and 1.6 MG fields; to measure the polarization of the synchrotron radiation; and to study the radiation as a function of magnetic field intensity. Byproducts of this work are measurements on the electron-pair production in nuclear emulsion, the distribution of recoil momenta of the nuclei, and

the partition energy distribution between the pair members. The scanning and measuring of the emulsions are nearing completion, the data analysis programs are completed, and interpretation of the data in terms of the above objective is proceeding well.

## MOMENTUM MEASUREMENTS IN EMULSIONS

*H. H. Heckman (LBL); F. Herlach (Universiteit Leuven, Belgium).*

Although the generation of a megagauss magnetic field inevitably destroys the field-producing coil, the explosion is radial, permitting nuclear emulsions to be exposed in the field without physical damage. We report on the measurements of particle momenta by track curvature in nuclear emulsions exposed to a pulse of electrons from the Stanford Linear Accelerator while in a 0.92 megagauss field. The errors in the curvature measurements are accounted for by the effects of multiple Coulomb scattering alone. The rms error is given by the expression $\sigma(\rho)/\rho = 2.5\ell^{-1/2}$, where $\ell$ (microns) is the track length upon which $\rho$, the radius of curvature, is based.

## GEOMAGNETICALLY TRAPPED RADIATION

*Harry H. Heckman (LBL); Douglas E. Greiner (UC Space Sciences Laboratory).*

In September 1970, two rocket-borne experiments were successfully flown from Natal, Brazil, to altitudes about 1000 km at the geomagnetic equator. The instruments were space-flight models of the type of solid-state particle identifier used for beam analysis and experimentation during the recent heavy-ion development program at the Bevatron. The analysis of the rocket data has been curtailed because of the Bevatron experiments. However, major advances have been made in the theory of the particle identifier and the computer analysis of the particle data obtained with it. The analysis of the rocket data will be greatly facilitated by the improved programming, and will be completed shortly. (Project supported in part by NASA.)

On the basis of this work, a proposal was submitted to and accepted by NASA to perform an OSO-J satellite experiment on the inner-belt protons. One of the objectives is to measure the isotopic abundances of light nuclei in the inner radiation zone as a means to search for non-neutron decay sources of the inner belt. Launch date is in 1975-6.

## RESPONSE OF TRAPPED PARTICLES TO A COLLAPSING DIPOLE MOMENT

*Harry H. Heckman (LBL); Peter J. Lindstrom (UC Space Sciences Laboratory).*

Particle motion in the secularly varying geomagnetic field has been investigated in terms of a dipolar magnetic field with decreasing magnetic moment M. For M equal to the rate of decay of the earth's dipole component, we find there is drift in B-L space, resulting in an inward drift of particles accompanied by increased energy and unidirectional intensity. Secular variation of the geomagnetic field appears to be a dominant mechanism for radial drift in the inner radiation belt.

## PUBLICATIONS AND PAPERS

R. L. Golden, J. H. Adams, W. R. Boykin, C. L. Deney, T. M. K. Marar, H. H. Heckman, and P. L. Lindstrom, The Rigidity Spectrum of $Z \geqq 3$ Nuclei from 5 GV to over 300 GV, in *Proceedings of the 12th International Conference on Cosmic Rays,* Vol. 1 (U. Tasmania, Hobart, 1971), p. 203.

D. E. Greiner, F. S. Bieser, P. J. Lindstrom, and H. H. Heckman, Particle Identification at Medium and High Energies, Bull. Amer. Phys. Soc. 17, 488 (1972).

H. A. Grunder, W. D. Hartsough, H. H. Heckman, and E. J. Lofgren, Heavy Ion Acceleration at the Bevatron, Lawrence Berkeley Laboratory Report LBL-376, Sept. 1971, presented at 8th International Conference on High Energy Accelerators, CERN, Sept. 20-24, 1971.

H. H. Heckman, D. E. Greiner, P. J. Lindstrom, and F. S. Bieser, Fragmentation of Nitrogen-14 Nuclei at 2.1 GeV per Nucleon, Science 174, 1130 (1971).

H. H. Heckman, D. E. Greiner, P. J. Lindstrom, and F. S. Bieser, Fragmentation of $^{14}N$ Nuclei at 29 GeV: Inclusive Isotope Spectra at $0^0$, Phys. Rev. Letters 28, 926 (1972).

H. H. Heckman, High-Energy Heavy Ion Fragmentation at the Bevatron (Invited paper, San Francisco APS Meeting), Bull. Amer. Phys. Soc. 17, 15 (1972).

H. H. Heckman and F. Herlach, Momentum Measurements in Nuclear Emulsions Exposed in a Megagauss Field, Lawrence Berkeley Laboratory Report LBL-1023, Aug. 1972.

H. H. Heckman, Physics Experiments with High-Energy Heavy Ions (Invited paper, Cambridge APS Meeting), Bull. Amer. Phys. Soc. 16, 1431 (1971).

H. H. Heckman and P. J. Lindstrom, Response of Trapped Particles to a Collapsing Dipole Moment, Geophys. Res. 77, 740 (1972).

P. J. Lindstrom, D. E. Greiner, and H. H. Heckman, Assorted Cross Sections for Beams of $^4He$, $^{12}C$, and $^{16}O$ at 2.1 GeV/nucleon, Bull. Amer. Phys. Soc. 17, 488 (1972).

## PARTICLE DATA CENTER

Arthur H. Rosenfeld in charge

Three major activities are undertaken by the Particle Data Center:

1. Compilation of particle properties, and the annual issuance of *Reviews of Particle Properties,* with its associated data booklet.

2. Compilation of cross-section and angular-distribution data on particle interactions. During FY 72 two reports appeared: LBL-55 on $K^{\circ}N$ interactions and LBL-58 on $\bar{p}N$. LBL-52 on $\pi^{+}N$ will appear in FY 73.

3. Compilation of all experimental references in particle physics, grouped by beam and momentum. This index, called LBL-90, will include proposals, preprints, and publications. It will appear first in FY 73.

In the future, the group will issue a series of Stable-Two-Body (S2) magnetic tapes, with covering reports, compiling all available data on two-body reactions. These tapes will combine our own data with data contributed by many groups now involved in partial-wave analyses—e.g., Lovelace of CERN, Wagner of Munich, and Spillantani of Rome. These data will be merged and checked.

A similar series will be issued of Quasi-Two-Body (Q2) tapes and reports, covering reactions such as $K^{+}p \rightarrow K^{\circ}\Delta^{++}$, or $K^{*}\Delta^{++}$. This work is being done in collaboration with Professor Geoffrey Fox of Cal Tech.

In collaboration with Panvini, Law, Ludlum, and Yang, there will be a compilation of inclusive reactions.

PUBLICATIONS

1. Particle Data Group, Review of Particle Properties, Phys. Letters **39B,** 1 (1972).
2. F. Uchiyama and James S. Loos, $K^{\circ}_{L}N$ Interactions—a Compilation, Lawrence Berkeley Laboratory Report LBL-55, March 1972.
3. James E. Enstrom *et al.*, $\bar{N}N$ and $\bar{N}D$ Interactions—a Compilation, Lawrence Berkeley Laboratory Report LBL-58, May 1972.

# Mathematics and Computing

# MATHEMATICS AND COMPUTING

James A. Baker in charge

The Mathematics and Computing Group provides advanced computing services to the Laboratory's research and support groups. These services include installing and operating the Central Computing Facility, which consists of a CDC-7600/6215 computer complex, two multiprogrammed CDC-6600's, several smaller IBM computers, and associated peripheral equipment and instrumentation. Large data files are maintained in machine-readable form.

The Systems Programming staff develops, maintains, and modifies the software for these computers, while the Applications Programming staff provides programming support to the many Laboratory physicists and other researchers who use computers for data collection and analysis.

The Group offers consultation services in mathematics, statistics, and programming, and also carries on a program of research in mathematics and computer science. Increasingly, these services are being provided to scientific groups outside the Laboratory.

## MATHEMATICS AND COMPUTING RESEARCH

*Donald Austin, James A. Baker, Paul Concus, Harvard Holmes, Mark Horovitz, David Jenson, Loren Meissner, Grove Nooney, Leo Vardas, and Jonathan Young*

Our research in Applied Mathematics is directed toward the development of numerical techniques for the solution of partial and ordinary differential equations and toward the automation of certain areas of numerical analysis. Research in Computer Science is in the areas of symbol manipulation, computer graphics, programming languages, scheduling algorithms for multiprogrammed computer systems, and the development of optimal man-machine interfaces. Advances in mathematical and computing techniques are applied to the analysis and simulation of physical, biological, and environmental systems.

### Applied and Numerical Mathematics

Studies continued on the *quasilinear elliptical partial differential equation* describing a capillary surface. Analytic characterizations of the solution were obtained for both positive and negative gravitational accelerations. Numerical techniques were developed for solving this and related nonlinear equations for special geometries.

An iterative technique was developed that permits the *fast direct methods* for numerically solving the Poisson equation in a rectangle to be applied effectively to more general linear elliptic equations. This technique achieves its efficiency through the use of an appropriate scaling and splitting of the discretized operator; and for equations with smooth coefficients it converges at a rate that is essentially independent of mesh size.

Algorithms were developed and computer programs written to construct an *optimal bicubic spline* over a rectangle and to determine ordinary second-order differential eigenvalues using the matrix method with cubic spline formulation.

A computer program using Gaussian elimination was written to solve systems of linear algebraic equations whose coefficient matrix had diagonal band form.

### Mathematical Models in Biology

A system of nonlinear parabolic partial differential equations describes the *progressive mineralization of bone.* The system accounts for deposition, diffusion, and resorption, with chemical activities depending on degree of crystallization. Questions of skeletal configuration are avoided with consequent loss of anatomical specificity. The equations allow the theoretical investigation of incorporation into bone of elements such as calcium, strontium, and fluorine.

A study of *passive transport by membranes* led to the conclusions that transport by diffusion against the concentration gradient is possible when the higher concentration is in bound or ordered form, as expected in living cells, and that otherwise any active component of transport need act only at the surface of higher concentration of the membrane.

*Singular diffusion processes,* in which diffusion occurs across surfaces with zero diffusion coefficient, are under study and provide the explanation for previously anomalous diffusion phenomena (for example, the rate of evaporation through a membrane may be greater into a humid atmosphere than into a dry one).

*The Principle of Pessimal Performance* (Nooney's Law) is primary to Parkinson's Law. A semantic extension of Nooney's Law has been discovered.

## Graphic Output of Digitized Pictorial Data

Questions of picture representation were studied, using only pure black and white areas (no intermediate shades of gray).

*Random halftones.* Black dots are printed with a probability depending upon the local intensity of the picture to be represented. At each point, the intensity is scaled between 0 and 1; then a random number (uniform between 0 and 1) is generated, and an output point is produced if the intensity exceeds the random number. Nonlinear scaling can be used to lighten or darken the picture, increase contrast, etc. Excellent results were obtained, comparable to standard photographic halftones with equivalent resolution.

*Over-discretization.* Researchers at Bell Telephone Laboratories (Harmon, 1971, private communication) reported that a group of 14 fellow employees were able to recognize, with a 50% probability of success, 400-bit "averaged" pictures of each other. These pictures consisted of 100 squares, each printed at one of 24 gray levels. Similar experiments were conducted here, but smaller squares of pure black and white were used. The conclusion was drawn that a given number of bits is about equally effective, whether some of the bits are used to represent intensity levels or whether these bits are instead used for higher space resolution.

*Edge-finding.* Further compression of information should be possible by converting photographs into line drawings, since the latter have many large blank areas that can be represented compactly by well-known techniques. (Such techniques are widely used for bandwidth reduction in connection with commercial facsimile transmission.) A simple "local gradient" calculation is made, and the gradients are plotted instead of the original picture. It has been found that a nonlinear transformation to increase the contrast is necessary in order to produce acceptable line drawings. The best results are obtained by plotting a point whenever the gradient exceeds a given threshold value. However, at present no general technique is known for automatically determining the proper threshold value.

## Computerized Mapmaking

Research into mapmaking proceeded on two fronts: boundary detection and shading. *Boundary detection* requires sophisticated algorithms for rapid determination of whether a point is inside or outside a given figure. A package of routines is now available for arbitrary views of 3-D objects, including manipulation of such objects via light pen. Objects may be shaded with hidden lines removed. Color pictures will eventually be available.

Effective *shading* requires experimentation to determine the capabilities of the hardware and to determine, with due regard to the cost of the various alternatives, schemes which are aesthetically satisfying.

## APPLICATIONS PROGRAMMING

A major effort was made to convert existing applications programs and library routines to run on the 7600 computer. In addition, Applications Programming personnel provided programming support for most of the research groups at the Laboratory.

## Physics

*Herbert C. Albrecht, Donald Austin, Emmett Burns, Victor Elischer, Fredric Gey, Art Habegger, and Edna Williams*

### Medium-Energy Physics

Two experiments are currently interfaced to the PDP-15 at the cyclotron. The *muon experiment* has been running continuously for a year. Interface programs were written for existing 6600 programs.

The *pion spark-chamber experiment* will be expanded to included proportional chambers. The data-acquisition monitor was revised to handle almost twice as many data as before. Additional monitor background funtions were added, including a procedure to communicate with the 6600 data files during an experiment. An RCAS channel is used to transmit selected events and initiate jobs on the 6600; the results can be displayed on the PDP-15 teletype or display scope.

An interactive graphics program (SPECTRA) for investigating the *Fourier structure of muonium data* from the cyclotron was completed. This program allows for rapid processing of several disc files of separate runs in a short amount of real-time. In addition, noise filtering may be accomplished on-line, and hooks have been provided for interfacing a VARMIT fitting program operating on the filtered data for parameter determination. An interactive program (CHIRP) using the results of the above processor is now in operation. Both programs create publication-quality microfilm.

### Helmholz Group

The SPARKY data-acquisition program for wire-chamber particle physics experiments was completed and documented. The program has been exchanged with the NP division at CERN.

SPARKY is being utilized for data acquisition on the new *radiative pi-decay* experiment. Further applications programming for this experiment include orbit calculations and investigation of approximations to initial conditions for 3-dimensional orbits of particles.

Similar orbit calculations were generated for the *pi-zero form factor experiment* utilizing the extended-core-storage feature on the CDC-7600 for rapid codes for 3-dimensional magnetic field interpolation. An efficient file structure for polynomial approximation coefficients was developed.

### Birge Group Bubble-Chamber Programming

Modifications have been made to COBWEB to improve its performance and give greater user access. Measurers may correct an erroneous event type, data analysts may determine the backlog of events yet to be measured, and an experimenter may generate new adjustable constants on-line. Two modes of automatic film drive have been incorporated in COBWEB. Except for program modification and debugging, COBWEB is now a totally on-line system.

The data-editing program, COBEDIT, generates all output formats for both physics groups measuring events in the COBWEB system. That is, an experimenter may now obtain data formatted for processing in the FOG system, SIOUX system, or in the form of FSD "roads" from COBWEB measurements.

All production codes have been converted to the CDC-7600.

## Accelerator and Magnet Design Group

*Victor Brady, Bruce Burkhart, Elon Close, John Colonias, Robert Healey, Ardith Kenney, Arthur C. Paul, and Steven Sackett*

Progress in the *Electron-Ring Accelerator Program* has continued with the implementation of new programs to investigate various aspects of the design. For example, programs were developed to estimate the abundance of various types of ions generated by the ionization of gas atoms by an electron ring; to analyze the longitudinal coupling impedance of azimuthally modulated high-intensity electron-ring beams, as influenced by resistive and/or dielectric walls; and to investigate the behavior of the potentially unstable collective motion of ions vs. electrons in an electron-ring device. This phenonemon

has been found to be of interest in other accelerators such as the CERN ISR, the Bevatron, etc.

Mathematical models of the components of the Electron-Ring Accelerator, described in previous reports, have been modified considerably to reflect new ideas and findings from previous research.

The development, testing, and utilization of computer programs associated with the *Bevatron beam injection studies* have continued during this period. The object of these studies has been to understand the present 19.3-MeV injection process and to use this understanding to predict design parameter values for the 50-MeV injector. This requires studying the Bevatron beam behavior for about the first 500 turns. Programs INJECT, PHASE, and HINJ have been developed, tested, and used in this study.[1] Associated data-storage programs[2] have also been utilized. Results of these studies at 19.3 MeV and 50 MeV have been documented.[3]

Program BUNCH is presently operational. It was developed to calculate fields due to an azimuthaly bunched beam in a cylindrically symmetric structure of arbitrary geometry. The computed fields are then used to calculate the self-impedance of the Beam, a quantity very useful in investigating negative-mass instabilities which develop immediately after injection.

Program SAP is presently operational. It was developed to study the linear elastic, static, and dynamic analysis of complex structural systems. This code is currently being used in the design of large superconducting magnets and nuclear reactor pressure vessels, and in the earthquake analysis of buildings. Future improvements to the code will include extension to nonlinear effects.

We have spent considerable time in assisting the Livermore Storage-Ring Group in investigating equilibrium orbit properties and nonlinear phase space motion of this machine. Some effort was directed towards the determination of the properties of two simultaneously generated beams at the 184-inch cyclotron. These measurements were compared with the calculated values of a computer model based on elliptical phase-space contours.[4] Reasonable agreement was found for the profiles of both beams. The phase-space contours were compared with those calculated from an extraction study based on the cyclotron's magnetic field and Bevatron oscillation amplitudes[5] in connection with the acceleration of heavy ions in the Bevatron. A heavy-ion spectrometer for 9 GeV was designed,[6] consisting of two quadrupole doublets and two bending magnets. It gives a momentum resolution of 0.4 to 2.0%, with a minimum angular acceptance of 4.3 mrad.

Further development studies on the Bevatron have resulted in the preparation of program ABSURD[7] to evaluate the performance of *large aperture secondary beams.*[8]

Program TRANSPORT[9] has been converted for teletype interactive use. It retains all the desirable features of the off-line version; in addition, it has new optimization routines which significantly improve the ability of TRANSPORT to solve more complicated beam transport problems.

---

[1] E. Close, P. Germain, and W. Holley, Bevatron Beam Injection Program, Lawrence Berkeley Laboratory Report LBL-727, Vols. I and II, Feb. 1972.

[2] E. Close, VFDS, A Collection of Programs and Subroutines for Variable Format Data Storage, Lawrence Berkeley Laboratory Report LBL-728, Feb. 1972.

[3] E. Close, P. Germain, and W. Holley, Trapping in the Bevatron Injection, BEV-2057, Jan. 1972.

[4] A. C. Paul, The External Beam of the Berkeley 184-Inch Synchrocyclotron, Lawrence Berkeley Laboratory Report LBL-370, Nov. 1971.

[5] A. C. Paul, Study of the Regenerative Extractor of the Berkeley 184-Inch Synchrocyclotron, Lawrence Radiation Laboratory Report UCRL-18211 Apr. 1968.

[6] A. C. Paul, 9 GeV Heavy Ion Spectrometer, UCID-3539, Feb. 1972.

[7] A. C. Paul, ABSURD—A Computer Program for a Beam Separator Using Range Differentiation, 1972, unpublished.

[8] W. A. Wenzel, Large Aperture Secondary Beams for the Bevatron, BEV-2026, 1971.

[9] A. C. Paul, User Guide for LBL Teletype and Vista Transport 1972, Lawrence Berkeley Laboratory Report LBL-951, May 1972.

## Nuclear Chemistry

*Billie Bearden, Noel Brown, Tom Clements, M. L. Clinnic, Victor Elischer, Penny Fink, Ruth Hinkins, and Gerald Litton*

A PDP-15 based *data-acquisition and analysis system* for use at the SuperHILAC was constructed and put into operation. This PHA-15 system can accept input from two simultaneous experiments and carry out single-parameter pulse-height analysis; it permits storage, display, and manipulation of the collected data.

### Nuclear Calculations

Two programs were developed to compute parameters of the nuclear surface expressed as moments. For spherical nuclei, the central radius, the charge radius, and the quadratic radius were calculated for given density distributions. An existing program which computes *droplet model fission barriers* was modified, and a new method of estimating the saddle-point shape was developed.

Programs were written to extract the beta stability properties of nuclei by fitting parabolas to isobaric mass chains. The results were compared with the predictions of various theoretical formulae.

Several one-parameter nuclear models were fitted to observed level densities. The calculations were then refined by using multiparameter nuclear models.

Statistical calculations were begun for the analysis of excited nuclei on the basis of the *Nilsson shell model* and of the pairing Hamiltonian with explicit introduction of angular momentum.

A set of programs which compute *electron energy levels* and g-factors for rare earth and actinide elements was converted to run on the CDC-7600. This program package undergoes continual correction, improvement, and expansion.

### Analytic Chemistry

Routines were developed to compute peak areas of *x-ray fluorescence spectra* and provide concentration calibrations. The programs are used to compute trace concentrations of miscellaneous elements from x-ray fluorescence of blood samples, pottery, and rock specimens.

A set of on-line interactive routines was written for the rapid analysis of *anodic stripping measurements.* CRT displays of the fit of theoretical curves to the data are provided, and the user has on-line control of the sequence of calculations. A library of anodic stripping data is now kept in the LBL mass-storage system. Routines were written to make it easy to retrieve sections of the data.

Maintenance work continues on a set of programs for processing *optical spectroscopic data.* The results give information on the energy levels of various nuclei.

### Field Free X-Ray Photospectrometers

A second x-ray photospectrometer was acquired from Hewlett-Packard. It was interfaced to the same 8K PDP-8I that is used to control the LBL photospectrometer.

A real-time data-acquisition system was written to run both spectrometers concurrently. Two teletypes are provided for operator control. The output data are mixed on the same magtape. The data output file structure was defined and a data-management program written to interface it to existing 6600 programs. A Calcomp plotter and a CRT display will also be utilized as output devices.

The real-time monitor is still in the design phase. A disc save/restore routine and magtape loader have been written. The PDP-8 is almost always in use controlling experiments, so all program development must be done on the 6600.

## Environmental Simulation

*Donald Austin, D. Bradwell (Consultant), John Colonias, Robert Healey, Brad Heckman, Ruth Hinkins, Harvard Holmes, Mark Horovitz, E. Lofting (Consultant), Carl Quong, Esther Schroeder, and Silvia Sorrell*

During this period our group began intensive work on the economic analysis of environmental problems. This area of activity is expected to grow in the future.

A linear input-output analysis of the economic activities related to *water resource use* in the state of Nevada was completed.

A study relating *water-borne pullution* to economic activities in the San Francisco Bay region was completed.

A demonstration *housing information management system* was constructed for the Housing and Urban Development Agency.

Work started on a cluster of problems relating to efficient methods of *computerized map making* and display of visual scenes. Programs for generating street maps from census data-tapes and editing them on-line were implemented. Economical methods of map-shading were devised. Boundary detection algorithms were studied. Programs for visual display of 3-dimensional scenes were tested.

Using the 1970 census 4th count and 2nd count population data-tapes, a data base is being formed for all of the United States on varying politico-geographic levels, the smallest area being a census tract, the largest a state. The data are used to print tables of *population, income, employment, poverty levels*, etc., on selected areas for the U.S. Department of Labor, Manpower Administration. These tables are distributed throughout the country for use in employment and welfare programs. The data are now going on Chipstore and are being indexed for random access of any geo-area in the Nation. This will lead to possible on-line use of the data.

Program OZONE has been modified to perform steady-state calculations of the effect of *supersonic transports* on ozone concentration. Future modifications will include time dependence and possibly an attempt to model the global stratosphere.

## Biology and Medicine

*Robert Belshe, Victor Elischer, Robert L. Fink, Fredric Gey, William Hogan, Harvard Holmes, Mark Horovitz, Claudette Lederer, Marjory Simmons, and Kenneth Wiley*

### Small Computer Systems

Development work continued on programs for ISAH, a computer-controlled patient chair for use in radiation therapy. A small magnetic-tape library operating system was created and formalized.

The PDP-8L data-acquisition system used by A. Bearden for EPR spectroscopy was rewritten to provide more flexibility in display and to multiplex the data input from several sources. New data analysis functions were also added.

P. L. Richards' (IMRD) PDP-11 system for acquisition of *infrared spectra* was completed and the hardware was debugged. This system includes data-collection, display, and Fourier transform capabilities.

Some work was done in cooperation with Donner Laboratory staff to plan and specify a *radioisotope imaging* data-acquisition system. An HP2100 A-based system was selected and went into operation.

Software for the PDP-8 based NMR data-collection system at the Laboratory of Chemical Biodynamics is under continual development.

### General Biomedical Applications

The PICASSO graphics modelling program was used to construct a model of the human *cardiovascular system.*[10] The MIMIC and PICASSO programs were used to construct a compartmental model of plutonium deposition in the rat.[11,12]

A *biomedical program library* was established and documented to assemble the computer programs commonly used in biomedical research and information processing at LBL. The writeup should serve as a guide to the computer resources available at LBL for biomedical applications efforts.

Program METAGSP extended the GASP compartmental analysis collection of programs[13] for research on the physiology of assimilation of carbon-14 into the breath of human and animal subjects. Program HWBCB determined the parameters for the model of instantaneous assimilation of bicarbonate into the breath, a necessary prerequisite to the METAGSP physiology model.

Program SEXPO attempted to extract the periodic behavior (both long- and short-term) of various blood cell concentration data, viewed as a discrete time series with measurements taken at irregular intervals.

A package of 6600-FORTRAN programs to perform file maintenance and simple retrieval operations using Medical Services' *LBL employee medical records* was reactivated. This entailed writing several new routines to permit data input, to monitor the growing data file (10 000 70-word records involving 3000 individuals), and to expand the user's retrieval capability. 7600-counterparts for each of the programs were made. Work was begun on making this information accessible via RFMS, the Remote File Management System.

GOLUX gamma-ray spectrum analysis program. Development of this program package continued during fiscal 72 with the addition of retrieval subroutines.

HARPO wire-chamber data-analysis program. This 6600 program generates histograms, contour maps, and profiles of activity detected by a wire chamber connected to a PDP-5 data-collection system. This analysis system was used with the recently produced heavy-ion beams at the Bevatron.

### Laboratory of Chemical Biodynamics

During fiscal year 1972 the ACQUIRE Project has been active in the following areas:

1. The PDP-8 system is now operational for teletypes and displays.
2. ACQUIRE users are now able to run graphic output through a generalized graphics package. This package can be used for interaction at the display scope, or for Calcomp plots.
3. The *data-collection system* is now operational in a multi-user environment, allowing up to 16 real-time processes to run simultaneously. The first experimental device is now on-line. It is a magnetic circular dichroism spectrometer. At completion of a run, the data are left in a permanent "polished" form allowing easy access by various applications programs.
4. A true time-sharing system for ACQUIRE was designed and is being implemented.
5. Programming for the *magnetic circular dichroism spectrometer* proceeded through an initial analysis phase consisting of curve fitting and display functions.
6. The first edition of an ACQUIRE User's Manual was issued.[14]
7. Program GAMET, written for the CDC-6600, was debugged and used in the analysis of absorbtive and dichromatic *light spectra.*
8. Two programs were written to facilitate the use of program BRAINCHM. Program CHMCDS was written to reformat old input data for use in the new *brain chemistry analysis* program. A program PCHWT was written to read and edit a paper-tape output by a digital balance with teletype. The edited information is punched on cards for use by program BRAINCHM.
9. A program BCDUMP was written for dumping BCD or binary magtape on the CDC-6600 (as on the IBM-1410). The user specifies which files or records are to be dumped and has the option of attaching a user output routine for reformating to a different file.

---

[10] Mark W. Horovitz, Donald Austin, and Harvard Holmes, Symbolic Computer Graphics and Biological Models, ACM/SIG Graph Symposium, Pittsburgh, March 1972.

[11] Control data MIMIC Reference Manual, Publication no. 44610400, Control Data Corp., Apr. 1968.

[12] Patricia W. Durbin, Mark W. Horovitz, and Elon R. Close, Plutonium Deposition Kinetics in the Rat, Health Phys. (in press).

[13] H. S. Winchell and K. Wiley, Considerations in Analysis of Breath $^{14}CO_2$ Data, J. Nucl. Med. **11**, 12, (1970).

[14] M. S. Itzkowitz and K. G. Wiley, ACQUIRE User's Manual, UCID-3475, July 1971.

### General Applications

*Donald Austin, Victor Elischer, Fredric Gey, Harvard Holmes, Mark Horovitz, David Jensen, Marjory Simmons, John Telford, and Leo Vardas*

A top-down, fast-back, list structure-driven PARSER was written to help implement a family of interpreters and experimental translators.

A *sorting system* written exclusively for the CDC-7600 was completed. The system makes use of LCM as an intermediate holding area. As a consequence, many programs which required time-consuming external sorting have become simple internal-sort applications.

PICASSO is a graphics editor and processor currently in use by the EE Department for production of printed

circuits. PICASSO is continually undergoing major and minor modifications. The macro processor has been substantially improved. A user's manual has been prepared.[15] A SNOBOL processor has been written which interfaces PICASSO output with a wire-wrap program AUTOWRAP.

The MIMIC differential equations simulation system[11] has been modified to provide more flexible on-line plot specifications and a new plotting routine which reduces the I/O and time required for plotting. This modification has also reduced the field length required.

Several *cross-assemblers,* which run on the CDC-6600/7600 to produce object code for mini-computers, were brought into operation. These programs were adapted from codes running at other installations. The MACRO-8 assembler produces code for the PDP-8, NOVASSM is a new version of a Nova/Supernova assembler, and ASSM 11 produces code for the PDP-11.

Since most small computers are in use at the Laboratory for the control of experiments in progress, software development and assembly must be done on the CDC-6600. A need has thus arisen for a general library of software support programs. This is presently in the development stage. For the PDP-8 series, the MACRO-8 assembler was chosen because it is most compatible with DEC assemblers. Through it we hope to draw on the DECUS source library. Some work is still required to make MACRO-8 entirely compatible with the DEC source language. An object code converter was written to produce *DEC-binary-loader* compatible paper tape. On the input side, a translator was written to convert ASCII DEC sources to a nearly compatible input source for the 6600 MACRO-8 assembler. Some of the PS-8 systems sources are now available in the 6600 UPDATE library format. All source programs will be available in the near future. Users will be able to modify and assemble them using either the 6600 or the 7600.

Program CONCUS used the SAC-1 symbolic algebra system[16] to generate a rational function solution to a nonlinear ordinary differential equation arising in liquid free-surface problems. In connection with this a $SNOBOL_4$ program was written to translate from the cumbersome SAC-1 output format to a card format suitable for numerical evaluation of polynomials and rational functions within FORTRAN IV programs.

---

[15] Donald M. Austin and Harvard H. Holmes, PICASSO—A General Interactive Graphics Modelling Program, Lawrence Berkeley Laboratory Report LBL-580, Jan. 1972.

[16] F. C. Gey, A User's Introduction to SAC-1, UCID-3447, June 1970.

## Data Management Project

*Marilyn Mantei, Samuel Penny, John Telford, Leo Vardas, and Edna Williams*

Much of the Project effort has been devoted to supplying programming and consulting services to the LBL Physics Division Office and the Naval Electronics System Command, Mare Island. Work for the Physics Division has centered around planning for a *Personnel File System* and implementation of a *Budgetary Analysis System (SIMBA).* Work for Navalex has been centered on helping them plan the construction and evaluation of a very large data base and supplying them with some of the preliminary tools needed to manage and access it. Spinoffs from these services have been the systems developments described below.

STOFI. This is a multifile, controlled access, index-sequential file system. It allows the user to construct a family of files in which records, files, and directories can be accessed by key (name) or sequentially. This subroutine package is now operating on the 6600's.

FIFI. This is a general purpose *Data Management System* built around STOFI. It includes facilities for data entry structure definition, various modes of updating, report generation, and certain kinds of file inversion and indexing. A user-oriented language will be used to control the system. Access may be either batch or interactive. A preliminary version of this system will be in operation in June 1972. But the more sophisticated procedures will be installed next year.

COMPTRIX. This is a system that is used to compare and operate on the logical implications between sets and members of sets of data entries in a large data

base. Its primary utilization is in the evaluation of data bases for Navalex.

DIMBA. This is a program that does a simple *Econometric Simulation* as defined by a user-supplied model and produces reports from the results. SIMBA operates on a set of time-series vectors. It runs in either batch or interactive mode.

## SYSTEMS PROGRAMMING

### CDC-7000/6000 Computer Complex

The CDC-7600 and CDC-6215 computers were accepted in the first quarter of FY 1972 and connected to each other and to the 6600-B machine. The systems effort was concentrated on support for this network. In particular, the WALNUT subsystem was added to the BKY-6000 system to interface with the extended SCOPE 1.1 system on the CDC-7600; a dynamic buffering algorithm driven by a CPU monitor was added to BKY; and the initial version of the shared file system (utilizing the 841 Multiple Disc Drive between the 6215 and 6600-B) was installed. Access to the data cell and chip store systems (PSS and MSS, respectively) from the CDC-7600 was provided via staging through WALNUT; remote batch access to both 6600-B and the 7600 was provided via COPE.

During the third quarter of FY 1972, LBL again evaluated CDC's SCOPE 2.0 operating system for the 7600 and judged it unsuitable for use in the near future, both because of the high cost of conversion and because of limitations in the system itself.

CDC's successive extensions to the SCOPE 1.1 system on the 7600 were installed as they were released by CDC throughout the year. The BKY generalized COPY utility was installed on the 7600 in place of the standard version.

Most of the work of transferring the functions of the 6411 to the 6215 was completed. A number of new/improved products were installed on the BKY-6000 system, including PERT (time), RFMS (a file management system developed at the University of Texas), and Version 3 of FTN (CDC's ANSI-compatible Fortran). Nine-track tape support was provided.

A second data cell was added to the PSS system in the fourth quarter of FY 1972.

### Remote Batch and Interactive Systems

The UCC COPE controller, with seven lines, was accepted in the first quarter of FY 1972, and was almost immediately in heavy use. By early in the third quarter, more than 200 jobs per day (approximately 15% of the total) were being entered through COPE, and the system was frequently saturated. Five additional lines were added during the fourth quarter; and by the end of the year, 400 to 500 jobs per day were being submitted through COPE. The original system supported only UNIVAC 1004 and CDC 200 UT line disciplines; support for the COPE discipline (including tape output) was provided during the second and third quarters of FY 1972; and work was begun on installation of UCC's EXECM system which would also support the IBM multi-leaving discipline.

RCAS and IRATE became operational during the last half of FY 1972. The facility to call for program execution on the 7600 was added to the interactive PTSS system.

### COM

The Strombert-Datagraphix 4460 COM device was accepted for off-line use during the second quarter of FY 1972, and was connected on-line to the 6215 in the fourth quarter. By the end of the fiscal year, more than 100 jobs per day were requesting fiche output of 50 000 pages per day (the equivalent of two printers running at full speed).

## COMPUTER OPERATIONS

The CDC-6215 system was installed during the first quarter of FY 1972. Basic software allowing use of a nine-track tape on this system became available during the second quarter.

Conversion of the CDC-6603 disks from air to water cooling was completed in the fourth quarter of 1972, effectively increasing the available building cooling capacity.

The COPE Remote Batch Communications Controller was installed and became operational during the first quarter of FY 1972. At the completion of FY 1972, the Controller provided medium-speed data communications to more than 25 non-LBL research installations utilizing six telephone dial-up ports, two Inter-campus Data Switching System ports, and four dedicated ports. Installation of additional memory and a code converter box to facilitate the improved EXECM software was accomplished during the third quarter.

The Stromberg-Datagraphix 4460 Microfilm Recorder was installed and became operational during the first quarter of FY 1972. An interface allowing on-line transmission of data from the computer to the Micro film Recorder was installed during the fourth quarter. The Kodak Versamat High-Speed Partial Reversal Film Processor also became operational during the first quarter. In addition to processing 105mm microfiche, the processor enables Computer Operations to provide rapid processing of film from existing 35mm graphical recorders.

The expansion of RECC to 96 ports during the first half of FY 1972 allowed conversion of all hardwared user teletypes to full duplex operation. The RECC dial-up facility was expanded to 16 ports. These dial-up ports can accommodate ASCII devices with speeds to 300 bauds. Acquisition of 100 teletypes from GSA surplus during the third quarter allowed greatly expanded user communications with RECC.

An "expeditor" service, providing personalized input/output materials handling for selected remote sites, was inaugurated during the third quarter.

## PUBLICATIONS AND PAPERS


Donald M. Austin and Harvard H. Holmes, PICASSO—A General Interactive Graphics Modelling Program, Lawrence Berkeley Laboratory Report LBL-580, Jan. 1972.

E. Close, P. Germain, and W. Holley, Bevatron Beam Injection Program, Lawrence Berkeley Laboratory Report LBL-727, Vols. I and II, Feb. 1972.

E. Close, VFDS, A Collection of Programs and Subroutines for Variable Format Data Storage, Lawrence Berkeley Laboratory Report LBL-728, Feb. 1972.

P. Concus and G. H. Golub, Use of Fast Direct Methods for the Efficient Numerical Solution of Nonseparable Elliptic Equations, Lawrence Berkeley Laboratory Report LBL-932, June 1972.

Patricia W. Durbin, Mark W. Horovitz, and Elon R. Close, Plutonium Deposition Kinetics in the Rat, Health Phys. (in press).

Mark W. Horovitz, Donald Austin, and Harvard Holmes, Symbolic Computer Graphics and Biological Models, ACM/SIG Graph Symposium, Pittsburgh, Mar. 1972.

M. S. Itzkowitz and K. G. Wiley, ACQUIRE User's Manual, UCID-3475, July 1971.

G. C. Nooney, Fejer Means in Fourier Synthesis, Lawrence Berkeley Laboratory Report LBL-7, July 1971.

G. C. Nooney, Flocking and the Principle of Pessimal Performance, Lawrence Berkeley Laboratory Report LBL-11, July 1971.

G. C. Nooney, Diffusion Coefficients in Heterogeneous Media, Lawrence Berkeley Laboratory Report LBL-909, Apr. 1972.

A. C. Paul, The External Beam of the Berkeley 184-Inch Synchrocyclotron, Lawrence Berkeley Laboratory Report LBL-370, Nov. 1971.

A. C. Paul, 9-GeV Heavy Ion Spectrometer, UCID-3539, Feb. 1972.

A. C. Paul, User Guide for LBL Teletype and Vista Transport 1972, Lawrence Berkeley Laboratory Report LBL-951, May 1972.

H. F. Vogel and J. Colonias, Use of Large Computer Programs in Time-Sharing and Interactive Mode,

A. E. C. Computer Information Meeting, Los Alamos, June 1-2, 1972.

J. D. Young, Numerical Solution of Nonlinear Second Order Ordinary Differential Equations by Use of Cubic Splines, Logistics Review **7**, 5 (1971).

J. D. Young, Smoothing Data with Tolerances by Use of Linear Programming, J. Inst. Math. Appl. **8**, 69 (1972).

J. D. Young, An Optimal Bicubic Spline on a Rectilinear Mesh over a Rectangle, Logistics and Transportation Review **8**, 33 (1972).

J. D. Young, Cubic Spline Formulation for a Matrix Method for Second Order Ordinary Differential Eigenvalues, Lawrence Berkeley Laboratory Report LBL-764, Mar. 1972.

LEGAL NOTICE

*This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Atomic Energy Commission, nor any of their employees, nor any of their contractors, sub-contractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.*