heavy ion facilities and heavy ion research at lawrence berkeley laboratory

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HEAVY-ION FACILITIES AND HEAVY-ION RESEARCH AT LAWRENCE BERKELEY LABORATORY

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HEAVY-ION FACILITIES AT LAWRENCE BERKELEY LABORATORY

I. INTRODUCTION

Lawrence Berkeley Laboratory has been heavily involved since 1956 in the construction and adaptation of particle accelerators for the acceleration of heavy ions. At the present time it has the most extensive group of accelerators with heavy-ion capability in the United States: The SuperHILAC, the 88-Inch Cyclotron, and the Bevatron/Bevalac. An extensive heavy-ion program in nuclear and particle physics, in nuclear chemistry, and in the study of biological effects of heavy-ion irradiations has been supported in the past; and the Laboratory has a strong interest in expanding both its capabilities for heavy-ion acceleration and its participation in heavy-ion science.

The first heavy-ion accelerator at LBL was the HILAC, which began operation in 1957. A vigorous program of research with ion beams of masses 4 through 40 began at that time and continued until the machine was shut down for modifications in February 1971. At that time, a grant of $3 M had been received from the AEC for a total reconstruction of the HILAC, to turn it into an upgraded accelerator, the SuperHILAC. This new machine is designed for the acceleration of all ions through uranium to an energy of 8.5 MeV/u. The SuperHILAC is equipped with two injectors. The lower energy injector, a 750-kV Cockcroft-Walton machine, was put into service in late 1972 for acceleration of ions up through ^{40}Ar. By spring of 1973, operation of the SuperHILAC with this injector exceeded the performance of the original HILAC. The second injector, a 2.5-MV Dynamitron, was originally designed for the Omnitron project and built with $1 M of Omnitron R and D funds. Commissioning of this injector began in 1973 and proceeded to the point where nanoampere beams of krypton were available for a series of research studies in May and June. The first publishable new results with beams heavier than ^{40}Ar were obtained at that time. Debugging and injector improvement projects will continue in FY 74 in order to raise performance of the 2.5-MV injector to its design characteristics.

The LBL 88-Inch Cyclotron was constructed in the period 1958-1962. It was one of the first sector-focused cyclotrons and has served as the prototype for the design of cyclotrons built elsewhere. Initial operation was with protons of variable energy up to 60 MeV and with helium ions to 130 MeV. Beginning in 1969, heavy-ion experiments were performed with nitrogen beams, using the original filament ion source. A Penning or PIG-type ion source was installed in 1971, giving greatly increased currents of high-charge-state beams of nitrogen and oxygen. By 1973, beams of lithium, boron, neon, and argon had also been accelerated. Over half the cyclotron time is now devoted to heavy-ion studies. A considerable investment was made in a large double-focusing magnetic spectrometer of high resolution and equipped with a focal-plane, particle-identification system. This spectrometer has greatly increased the possibilities of precise nuclear spectroscopy in nuclear-reaction studies with heavy ions.

The Bevatron has been modified, and tested as a heavy-ion accelerator in highly successful trial experiments inaugurated in 1971. Beams of such ions as ^{12}C, ^{14}N, and ^{16}O were accelerated to energies of 2.5 GeV/u, extracted from the Bevatron ring, and delivered to targets set up in the external beam lines. The trial experiments demonstrated exciting possibilities for physical and biological research with heavy ions of relativistic energies.

The Bevalac project, which uses the SuperHILAC as a heavy-ion injector for the Bevatron, will permit the exploitation of high-energy heavy-ion research by providing a great increase in the intensity and variety of the available ions.

The project consists of the construction of a beam transport line between the two machines and of control modifications to synchronize the operation of the two machines. Funds for these changes were obtained in 1973, and completion of the project is projected for early 1974. During 1974, a vigorous program of research with relativistic heavy-ions will be under way in several fields.

LBL has a continuing program in accelerator theory and development to explore new design concepts. In particular, during the last five years it has mounted the most intensive effort in the United States toward devices using the intense ring-current of electrons. With the electron ring (ER) one may produce highly ionized states for research in atomic spectroscopy-research at present accessible by means of Beam Foil Spectroscopy. An initial experiment to produce and detect X-radiation from Xe has been successful. For the acceleration of heavy-ions, the ER is particularly interesting. Such an accelerator would be both compact and economical; it appears feasible to produce ~ 4 x 10^{12} Ne particles per second with 200 MeV/u. In the same device, the Kr beam would be of slightly less energy and ~10^{12} ions/sec. At 200 MeV/u, the energy spread would be 1%. When released from the ER, the accelerated ions would be in a very short burst. This pulse will broaden naturally so that the energy spread and duty factor can be improved orders of magnitude with debunchers and stretcher rings.

More details on the capabilities of the SuperHILAC, the 88-Inch Cyclotron, the Bevalac, and the ERA are given later in this report. Table I provides an overall summary of heavy-ion capabilities at LBL.

TABLE I.

BERKELEY HEAVY ION FACILITIES							
ION	SUPER HILAC			BEVALAC BEVATRON		88" CYCLOTRON	
	ENERGY (Mev/u)	FLUX (Particles/Second) Time average	FLUX (Particles/Second) Instantaneous (Fully stripped)	ENERGY (Mev/u)	FLUX (Particles per Pulse *)	ENERGY (Mev/u)	FLUX (Particles per Second)
^{4}He				$10^{2}-2.5\times10^{3}$	3×10^{10}	≤ 33	2×10^{14}
^{6}Li	≤ 8.5		5×10^{14}	$10^{2}-2.5\times10^{3}$	3×10^{10}	≤ 13	3×10^{12}
^{10}B	≤ 8.5		5×10^{14}	$10^{2}-2.5\times10^{3}$	3×10^{10}	≤ 10	4×10^{12}
^{12}C	≤ 8.5	5×10^{14}	10^{15}	$10^{2}-2.5\times10^{3}$	6×10^{10}	≤ 9	2×10^{13}
^{14}N	≤ 8.5	3×10^{14}	5×10^{14}	$10^{2}-2.5\times10^{3}$	3×10^{10}	$3-18$	$10^{13}-10^{12}$
^{16}O	≤ 8.5	3×10^{14}	5×10^{14}	$10^{2}-2.5\times10^{3}$	3×10^{10}	$3-13$	$10^{13}-10^{12}$
^{20}Ne	≤ 8.5	3×10^{14}	4×10^{14}	$10^{2}-2.5\times10^{3}$	10^{10}	≤ 7	10^{12}
^{40}Ar	≤ 8.5	10^{14}	10^{14}	$10^{2}-2.5\times10^{3}$	5×10^{8}	≤ 4	10^{10}
^{84}Kr	≤ 8.5	3×10^{12}	1.5×10^{10}	$10^{2}-2.5\times10^{3}$	5×10^{4}		
^{131}Xe	≤ 8.5	10^{11}					
^{200}Hg	≤ 8.5	10^{11}					
^{238}U	≤ 8.5	10^{11}					

* 10–17 Pulses per minute

II. AVAILABILITY OF LBL HEAVY-ION FACILITIES TO OUTSIDE INVESTIGATORS

Selection of proton experiments for the Bevatron has been for some years a function of the Bevatron Program Advisory Committee, a group of distinguished scientists primarily from outside LBL. This committee reviews and schedules experimental proposals on the basis of scientific merit, taking into consideration the ability of the Laboratory or the experimental group to carry out the work. Sixty per cent of all Bevatron experimentalists are from outside LBL. The membership of the Bevatron Program Advisory Committee has recently been extended to include distinguished scientists in the field of heavy-ion interactions. A parallel committee for biomedical research will assume similar responsibilities in the immediate future. The Bevalac beams will have unique characteristics, and all qualified scientists who wish to make use of them may propose experiments through one of these two committees.

A SuperHILAC Users Association, whose membership is open to any research scientist in any field of nuclear science, performs a similar function for the SuperHILAC. The business of the Association is conducted by an Executive Committee, a majority of whose members must be from outside LBL. A minimum of 25 per cent of the beam time of the SuperHILAC is at the disposal of the Users Association. No beam-time charges are levied. When the SuperHILAC becomes fully operational, it will have unique capabilities, particularly for ions heavier than ^{40}Ar. It is the intention of LBL and the management of the Nuclear Chemistry Division, which operates the SuperHILAC, that the SuperHILAC be fully utilized within the limits of the available funds and experimental resources by the scientists with the most worthy experimental proposals.

III. DETAILED DESCRIPTION OF LBL HEAVY-ION ACCELERATORS

A. SuperHILAC Progress Report

The construction of the SuperHILAC was completed in April 1972[1] and the first beams of carbon were accelerated to full energy in May. Debugging of the system commenced immediately and has continued throughout the past year. During the early phase of the debugging, the net progress at times almost appeared to be negative; new problems were discovered as quickly as old ones were solved. Progress became more rapid when solutions were found for the major problems.

For the SuperHILAC, the shake-down period came at a time when operating expenses were increasing rapidly while operating funds remained static; hence the effort available has been too marginal for an efficient and orderly debugging. An unexpected length of time has been spent in the initial testing of the system, with very little effort expended in the development of permanent solutions for the major problems. Within the past three months, however, with the system operating in a more routine manner, it has been possible to apply manpower to the major areas of concern. In the near future, more rapid progress will be made toward a reliable and versatile accelerator.

In the design of the SuperHILAC, some new cost-saving solutions were applied to the basic design of the linacs. In addition, a major effort was expended in the development of the miniaturized PIG ion source and the high voltage injector system for the production of the very heavy ions.

The status of the major components of the SuperHILAC system is given below.

Linear Accelerators. The SuperHILAC consists of a pre- and a post-stripper linac. To reduce costs, major portions of the existing system were modified and reused. Furthermore, several unique mechanical designs were used in the construction of the linear accelerators. These included: inexpensive drift-tube support systems, a pumping system which depends entirely on hitherto untested cryopumping, an inexpensive rf cavity cooling system, and a new design of drift-tube quadrupole magnet to achieve the extremely high lens strengths necessary for the low charge-to-mass ratio ions.

The rf amplifier system used in the new linacs is a modification of the original HILAC design; but the control and regulation requirement of rf phase and amplitude of the eleven separate amplifiers is an order of magnitude more stringent than for the HILAC.

During the first year of operation, the mechanical portions have proven extremely reliable. The new drift-tube quadrupoles have operated to the designed specifications without incident. The performance of the cryopumping system has been excellent. The pressure in the operating cavities is routinely 10^{-7} Torr. Based on the performance of this system, the Bevatron has installed new cryopumps, and several other accelerators around the world are considering this method of pumping. Some problems have been encountered with the rf system--mainly, noise in the control system of the retained and modified equipment. Over the last year most of these problems have been slowly eliminated. The rf system presently operates reliably and meets the original specifications on the electric gradient, power, and stability.

Performance. For a full-energy beam, and with the synchronous phase angles adjusted to 30^{0} and 20^{0}, respectively, in the pre- and post-stripper linacs, the measured energy spread agrees with calculation and is about 0.5% FWHM with a microscopic time distribution of about 2.5 nsec FWHM.

Measurements of the energy, energy resolution, and the microscopic distribution of the beam have been made. Little is known yet concerning the influence of operating parameters of the linacs on beam characteristics.

The beam energy measurements indicate that, with proper tuning, the full-energy beam can be produced with a quality significantly better than calculated. Beams with dE/E better than 0.025% FWHM and with a time distribution of less than 1 nsec FWHM have been produced without a sacrifice in beam intensity.

The measured transverse phase area of the beam at full energy is close to the calculated area of π cm-mr.

The tuning of the linacs to produce a full-energy beam is simple and rapid, and the transmission of both linacs is as good as expected--essentially 100% for the post-stripper tank. However, the emittance characteristics of the accelerated beam are presently still difficult to reproduce, so that matching of the accelerator to the experimental area transport systems remains a problem. The required stability of all accelerator parameters is considerably more stringent than had been anticipated.

Although only limited experimental evidence exists upon which to base a judgement, the difficulties in tuning are presently attributed to misalignment of the drift-tube quadrupoles. These were originally aligned shortly after the rf cavities were installed and before the system had been pumped. It is known that some irreversible warpage of the cavities occurred under vacuum loading, and in addition, several of the cavity support piers have settled since their installation. It is presently planned that the entire drift-tube system will be realigned in the fall of 1973. A pronounced improvement in the tuning characteristics is anticipated.

A portion of the Bevalac program is the modification and addition to the SuperHILAC system to allow for its operation in a time-sharing mode. Fast (10 millisecond) deflection magnets at the entrance and exit of the linacs will make possible the injection of beams from both injectors on alternate machine pulses (36 per second), and the deflection of the accelerated beam to appropriate transport lines in the experimental area. The system will also contain fast-pulsed quadrupole lenses for the adjustment of the transverse beam characteristics for each of the two beams.

It is expected that this modification will greatly increase the utility of the SuperHILAC itself, by allowing for the tuning of one beam (using a small fraction of the duty factor) to one experimental area, while experiments are being conducted in another area with the major fraction of the duty factor. This will allow for the rapid transfer of a pretuned beam from one experimental station to another.

750-KV Injector. This injector is part of the original HILAC system, modified by the addition of a 100 KHz solid-state Cockroft-Walton generator and a new accelerating tube. The unit was moved to a new enclosure, which allowed for an increase in the terminal-ground spacing of 25%, to five feet.

The terminal and all of the ion-source equipment are unchanged, and operate at beam intensities similar to those of the HILAC.

The beam emittance is approximately 3π cm-mr, and about 70% of the beam can be transported to and accepted by the pre-stripper linac. At present, no buncher is installed so that the linac acceptance phase-angle is about 90^0 maximum. Peak intensities of about 10^{15}/second carbon +2 have been accelerated through the pre-stripper linac.

As a portion of the Bevalac program, a buncher will be installed on this injector, with an anticipated increase in the beam accepted by the linac of a factor of two.

In addition, the stability of some of the transport elements needs to be increased to provide for a highly stable beam.

The reliability of the 750-KV injector is very good.

2.5-MV Injector. This injector must be used for the acceleration of all ions with mass greater than about 40 (argon). The potential at the terminal varies from 1.5 to 2.5 MV, depending on the charge-to-mass ratio of the particles, which ranges from 0.075 to 0.046 for the heaviest elements.

The design of the system was based on the 3.0 MV Dynamitron (Radiation Dynamics Corp.), with the high voltage terminal scaled from 3-ft to 4-ft diameter to accommodate the complex ion-source system necessary for the heavy ions. The HILAC cold-cathode ion source, and its electronics, were completely redesigned and miniaturized to fit within the restricted volume of the pressurized high-voltage terminal. In addition, the high pumping speed necessary for the high gas loads of the heavy-ion sources was provided by installing a cryopump.

The design of the miniaturized, complex heavy-ion source system to operate in this remote and hostile environment has been a major engineering task, but to date cannot be considered completely successful. The debugging of the system has been tedious and time-consuming.

In the past two months, however, a relatively successful operating schedule has been achieved. During the month of May, the system has been operated several times for periods of 48 hours. Krypton beams have been delivered to the experimenters during these periods.

The system is still far from being reliably operational. However, the major difficulty has been identified and the re-design and replacement of the unreliable elements will be undertaken in the near future.

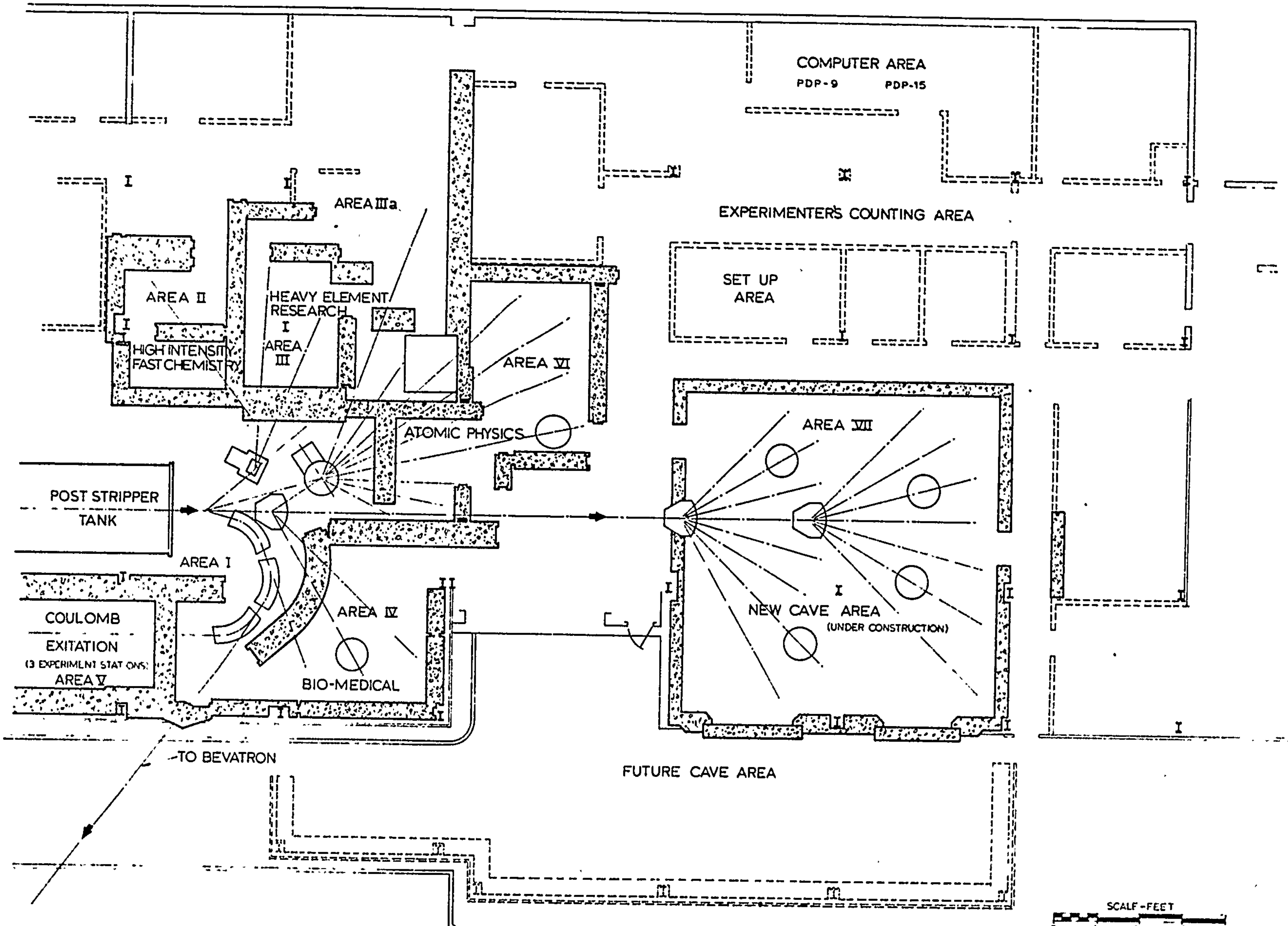
The pressure in the terminal, accelerating column, and the transport lines is quite high, resulting in significant charge-exchange of the ions in transit in all portions of the system.

Furthermore, methods must be developed for the analysis of the complex heavy-ion beams at the exit of the 2.5-MV injector, to speed up the tuning of this device. Some method must also be developed to allow for the separation of the isotopes of the heavy elements.

Experimental Areas. The high dE/dx of the heavy ions, and the consequent heating of target materials, place severe limits on usable beam intensities. Isotope production with these ions, which is followed by fast chemical separation, can be carried out using thick targets, where adequate cooling can be achieved. For most physics experiments, however, thin foils are used as targets; for these targets, maximum beam intensities range from 10^{10} to 10^{11} particles/second. For these modest intensities only modest shielding of the physics experimental area is required. The experimental caves are constructed of 1-1/2 to 2-ft thick concrete wall and roof blocks.

The present experimental area is arranged so that all of the beam distribution system is located in a single room immediately down-stream from the linac (Fig. 1.). Two tandem $\pm 45^0$ magnets distribute the beam directly to four surrounding experimental areas, and to the new cave area. Also in this area is a heavily shielded cave for high-intensity chemistry bombardment. This cave is arranged so that remotely operated manipulators can be installed for the handling of intensely radioactive targets. Immediately adjacent to the cave is a chemistry laboratory equipped with shielded hoods for the preparation and handling of the hot targets. All high-intensity bombardment for isotope production will be restricted to this cave.

Also located in the central beam distribution area is a 180^0 spectrometer system which directs the beam into a 10-ft wide x 50-ft long cave adjacent to the linac. This cave can be used for Coulomb excitation experiments.



SUPERHILAC EXPERIMENTAL FACILITIES

FIGURE I.

XBL 736-833

The magnets of this system can be operated in the nondispersive mode for delivery of maximum beam intensity to the caves, or in the dispersive mode, in which case the beam energy resolution can be increased to about 2×10^4, adequate for all anticipated heavy-ion experiments.[2] Three tandem experimental stations are located in this cave system.

Most of the equipment used in heavy-ion physics is relatively lightweight and small, so that the total area required for an experimental station is modest (50 to 60 sq ft). The beam lines into an experimental station generally require more area than the experimental station itself. The total area presently available at the SuperHILAC (approximately 1500 sq ft) can therefore accommodate only 13 experimental stations. At present, eight of these stations are occupied by continuing experiments.

A new experimental area is presently under construction, with completion expected in late fall, 1973. The area is a 38 ft by 38 ft area, which will be shielded to accommodate beam intensities of approximately 10^{12} particles per second. The interior of the new area will be essentially unobstructed, so that internal wall blocks can be arranged in practically any configuration.

The actual beam distribution system to be installed in this area has not yet been determined; its design will await the establishment of the experimenters' requirements. Funds are available for the fabrication of a portion of the required system.

It is expected that the new cave (essentially doubling the area available at the SuperHILAC) can be arranged so that it will accommodate seven or eight new experimental stations. Additional area is available adjacent to the accelerator building, so that the experimental facilities can be further expanded in the future, if necessary.

References

[1] R. M. Main, Modification of the Berkeley HILAC, Nuclear Instruments and Methods 97 (1971) 51-64.

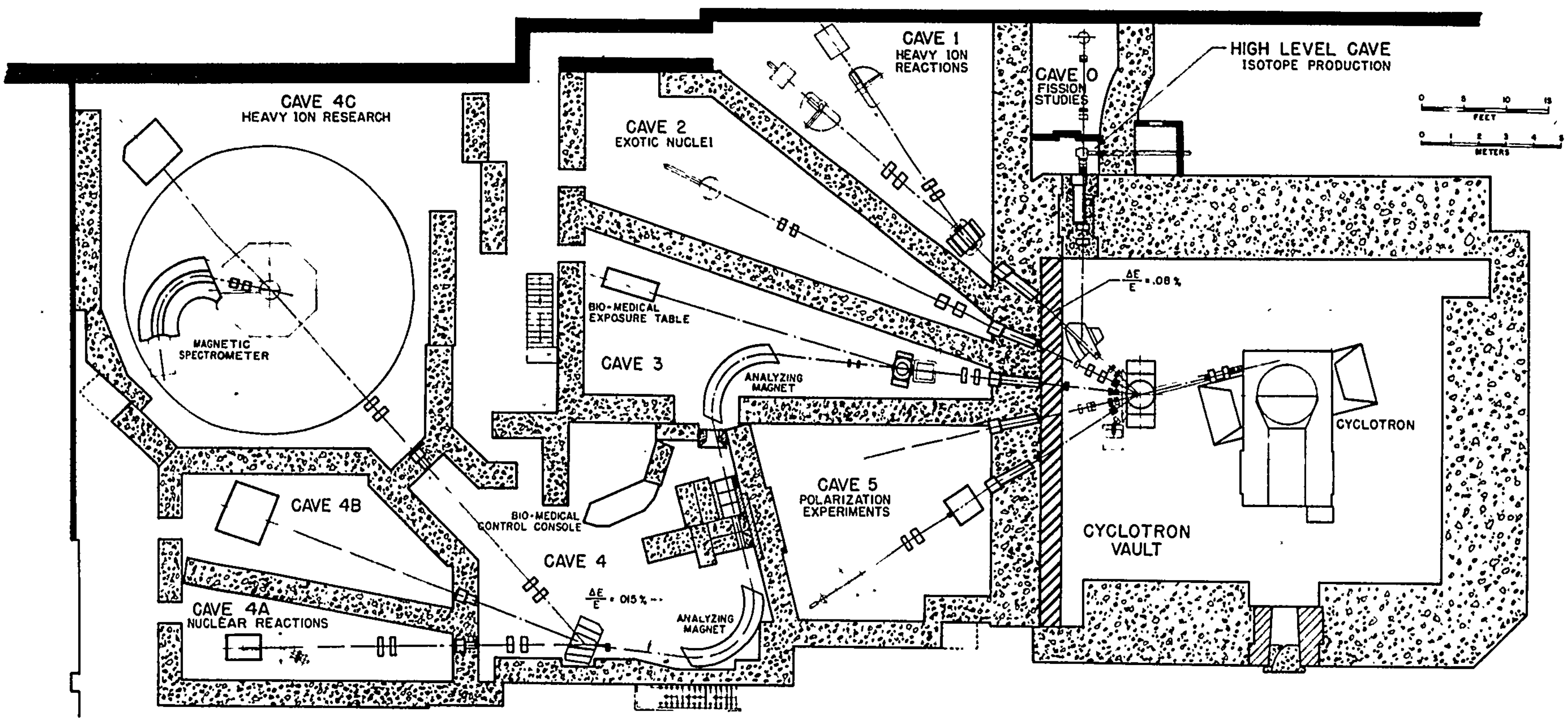
[2] J. R. Alonso and B. G. Harvey, Considerations of Beam Quality Requirements with Very Heavy Ions, LBL-1698.

B. The 88-Inch Cyclotron Heavy-Ion Facility

1. General Description of Facility. The LBL 88-Inch Cyclotron[1] is a variable energy, multiparticle, sector-focused cyclotron[2] which accelerates protons to energies up to 60 MeV, α-particles to 130 MeV, and heavier ions to 140 Q^2/A MeV, where Q and A are particle charge and mass in proton units. It has an external polarized ion source for beams of polarized protons and deuterons. There are seven separate shielded experimental areas with ten target stations, as shown in Fig. 2. An important part of the facility for heavy-ion experiments is the high-resolution, beam-analyzing magnet system, which provides beam for the spectrometer magnet used for reaction product analysis. Operation is scheduled 24 hours/day, 7 days/week, with one 8-hour maintenance shift each week. The number of heavy-ion experiments has increased greatly in the last several years.[3] At present, over half the operating time is used for ions heavier than α-particles.

2. Cyclotron Performance with Heavy Ions. The first heavy-ion experiments in 1969 used the standard filament ion source. In 1971 a PIG (Penning Ion Gauge) type of source was installed[4] to increase the high-charge-state intensities. For beams from solid materials such as lithium, a compound was placed in the cathode or anode region, and vaporized by sputtering with the arc. The charge-exchange losses during acceleration have been greatly reduced by a vacuum improvement program. Insert electrodes are used in the center region for better acceleration on the third harmonic mode (heavy-ion energies below 6 MeV/u). The present heavy-ion performance of the cyclotron is shown in Table I, and in more detail in Reference 5. The analyzing magnet system[6] provides heavy-ion beams with an energy resolution as good as $\Delta E/E = .015\%$, about the same as a Van de Graaff.[2] This is more than adequate for any proposed heavy-ion experiments.

3. Improvement Plans for the Cyclotron. The present ion source operates with cathodes heated by the arc, after striking. Development work is being done on a modified version with filament heating of the lower cathode, which will give more control over arc conditions for better optimizing of high-charge-state output. Pulsing of the arc is also planned, to increase the charge states during a high current pulse but leave the average power about the same as at present.



88-INCH CYCLOTRON EXPERIMENTAL AREA

XBL 722 3318

FIGURE 2

A cryopumping system is being designed to reduce charge exchange and increase the intensities of the heavier ions by a factor of 2 to 5.

Some effort is being devoted to improving an external heavy-ion source. If ions such as Kr and Xe could be produced with Q/A = .22, the 88-Inch Cyclotron could accelerate them to 7 MeV/u. Such a source would be valuable to other cyclotrons which also have external injection systems, such as ORNL, Texas A. & M., and Indiana.

Some studies are being done on the use of more than one cycle of acceleration, for economical production of heavier ions; other studies are under way on a booster cyclotron which would be injected by the 88-Inch Cyclotron. These studies are described in Reference 7.

4. The Magnetic Spectrometer.[8] The Berkeley 88-Inch Cyclotron magnetic spectrometer is designed to give high performance in the detection of charged particles over a wide range of experimental conditions. It has double focusing, a broad energy range of 30%, a resolving power of 3000, and a large solid angle of 2×10^{-3} sr. The dispersion of 4 meters is large enough to facilitate use of active focal plane detectors. Further, to simplify use of active detectors, the design was made so that particles enter the focal plane at right angles. The rays are sufficiently parallel to give very little time-spread over the entire solid angle. In order to achieve the large solid angle but still maintain good experimental angular resolution, the entrance aperture is very large in the direction perpendicular to the scattering plane. This feature, along with the moderate dispersion and the separately controlled entrance quadrupole and sextupole magnets, allows the elimination of kinematic broadening effects over a wide experimental range. The spectrometer and beam analysis magnets[6] are operated in the dispersion matched "energy loss" mode, so that a large fraction (20%) of the cyclotron beam can be used with no loss of resolution.

These properties of the spectrometer, along with a suitably designed detector,[9] make it especially useful for heavy-ion experiments. The present system consists of a thin (40-60 $\mu g/cm^2$) scintillator near the entrance aperture, a 6-wire Borkowski proportional counter 45 cm long at the focal surface, followed by a 6-wire regular proportional counter and a thick scintillator.

The spatial resolution of the Borkowski counter is less than 1 mm, matching the resolving power of the spectrometer. The second proportional counter is used for particle identification, providing a dE/dx resolution of 5% and allowing a separation of reaction product species differing in charge by 1 part in 40. The entrance and exit scintillators measure the flight-time of reaction products to 2 nsec out of a flight path of seven meters, allowing mass identification of 1 part in 50. The combination of position, dE/dx, and time of flight allows a clean identification of all isotopes produced in nuclear reactions up to mass 50, with energy resolutions of better than 0.08%. Energy resolution is limited mainly by target thickness.

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*1. B. G. Harvey and D. J. Clark, Cyclotrons - 1972, A.I.P. Conf. Proc. No. 9, 774 (1972).

2. D. J. Clark, Rep. Prog. Phys. 35, 1007 (1972).

*3. 88-Inch Cyclotron Particle Distribution History.

*4. D. J. Clark et al., Cyclotrons - 1972, A.I.P. Conf. Proc. No. 9, 265 (1972).

*5 Table of Typical 88-Inch Cyclotron Heavy-Ion Beams, June 1973.

*6. R. E. Hintz et al., Nucl. Instr. Methods 72, 61 (1969).

*7. Studies on Double Cycle Acceleration and a 2nd Stage Cyclotron.

*8. F. Selph, LRL Eng. Note UCID-3388 (1969), unpublished.

*9. B. G. Harvey et al., Nucl. Instr. Methods 104, 21 (1972).

*Copy attached.

C. The Bevatron/Bevalac Heavy-Ion Facility

Stimulated by the multidisciplinary aspects of the Lawrence Berkeley Laboratory, the Bevatron has undergone a change in utilization. In the near future it is anticipated that running time will be divided equally between research with high-intensity protons ($\sim 10^{13}$ protons per pulse) and heavy ions with intensities as shown in Table I. The heavy-ion program will include physics, cosmic ray, biomedical, and chemistry research.[1]

The large increase of beam intensities that can be expected from the Bevalac is due mainly to the SuperHILAC which will serve as an injector for the Bevatron with 8.5 MeV/u injection energy.[2] The projected construction schedule for the Bevatron/Bevalac project is depicted in Table II.

The present experimental area of the Bevatron facility is appropriate for heavy-ion research (Fig. 3). In addition, the Bevalac project incorporates two experimental caves for biomedical research with heavy-ion beams. It is anticipated that heavy-ion beams will provide new methods of cancer therapy and diagnosis. Through radiobiology, important new knowledge regarding cellular dynamics will be explored.

It is evident that there are logistics problems for such a diversified program. However, after some experience with the Bevalac project (by early 1975), operational mode changes (energy and particle) of less than an hour are planned. Shorter changeover periods may be realized in the future with full time-sharing. This can only be accomplished if most of the parameters are computer-controlled. For the Bevatron operation, which is to a large extent already computer-controlled, this would be a logical extension of its control capabilities. The limitation is often the detailed knowledge of conditions required by an experimental group.

To date, heavy-ion beams between 250 MeV/u and 2.5 GeV/u have been extracted. The capability of extracting a 100 MeV/u beam also exists. Constant beam current with good duty cycle has been a usual requirement of the experimental group. However, the present hardware allows for pulses and modulations of the beam spill, which could become an important requirement. It may be useful to point out a few characteristics of the beams from the Bevatron. A pulse rate of 10 pulses per minute for the high energies and up to 17 pulses per minute for the low energies is typical. An rf-off spill can be provided with a pulse duration of up to 1.5 seconds. Hence a DC spill with a 25-30% duty cycle is

HIGH ENERGY HEAVY ION FACILITY (BEVALAC)

CONSTRUCTION SCHEDULE

FEB. 1973

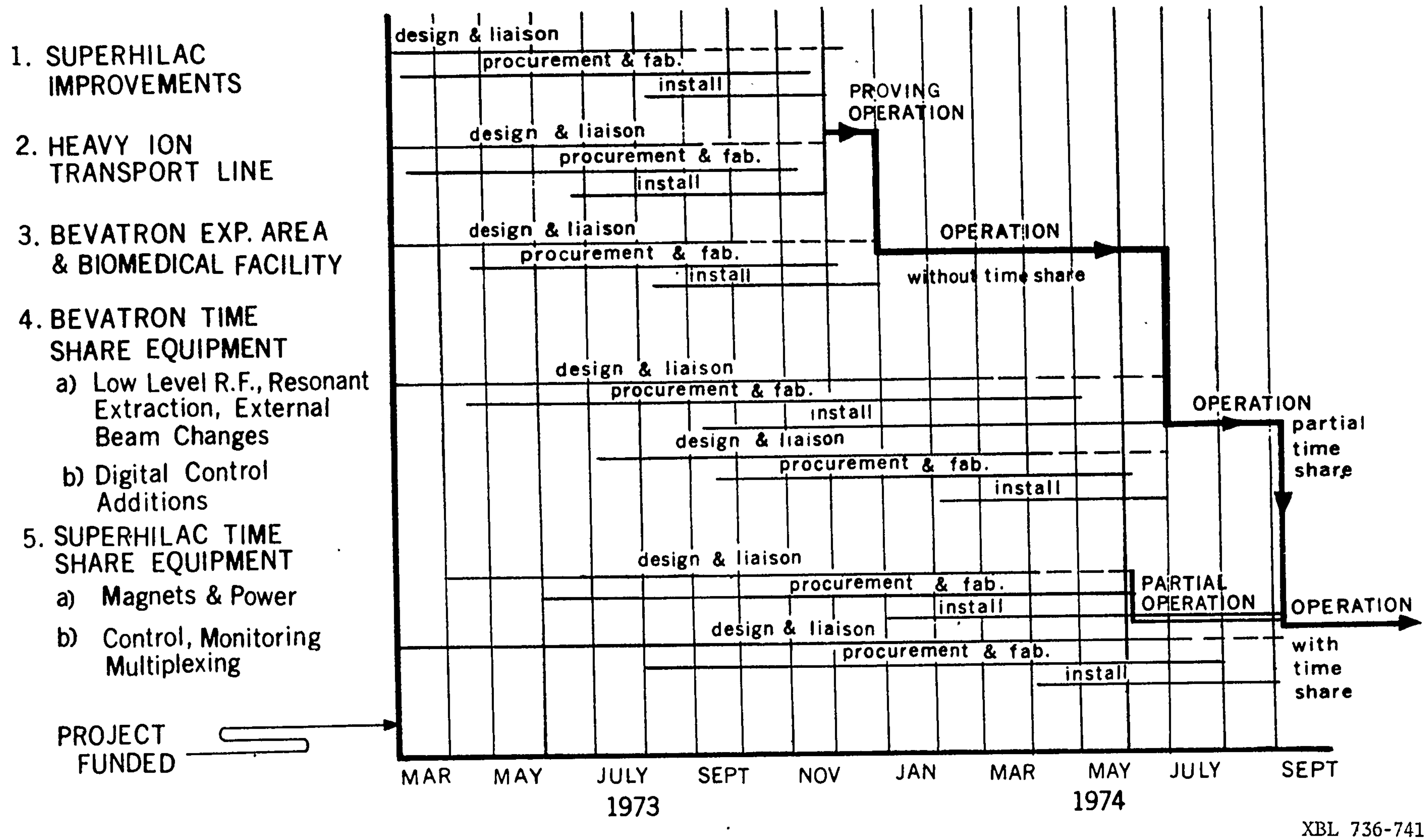

TABLE 2.

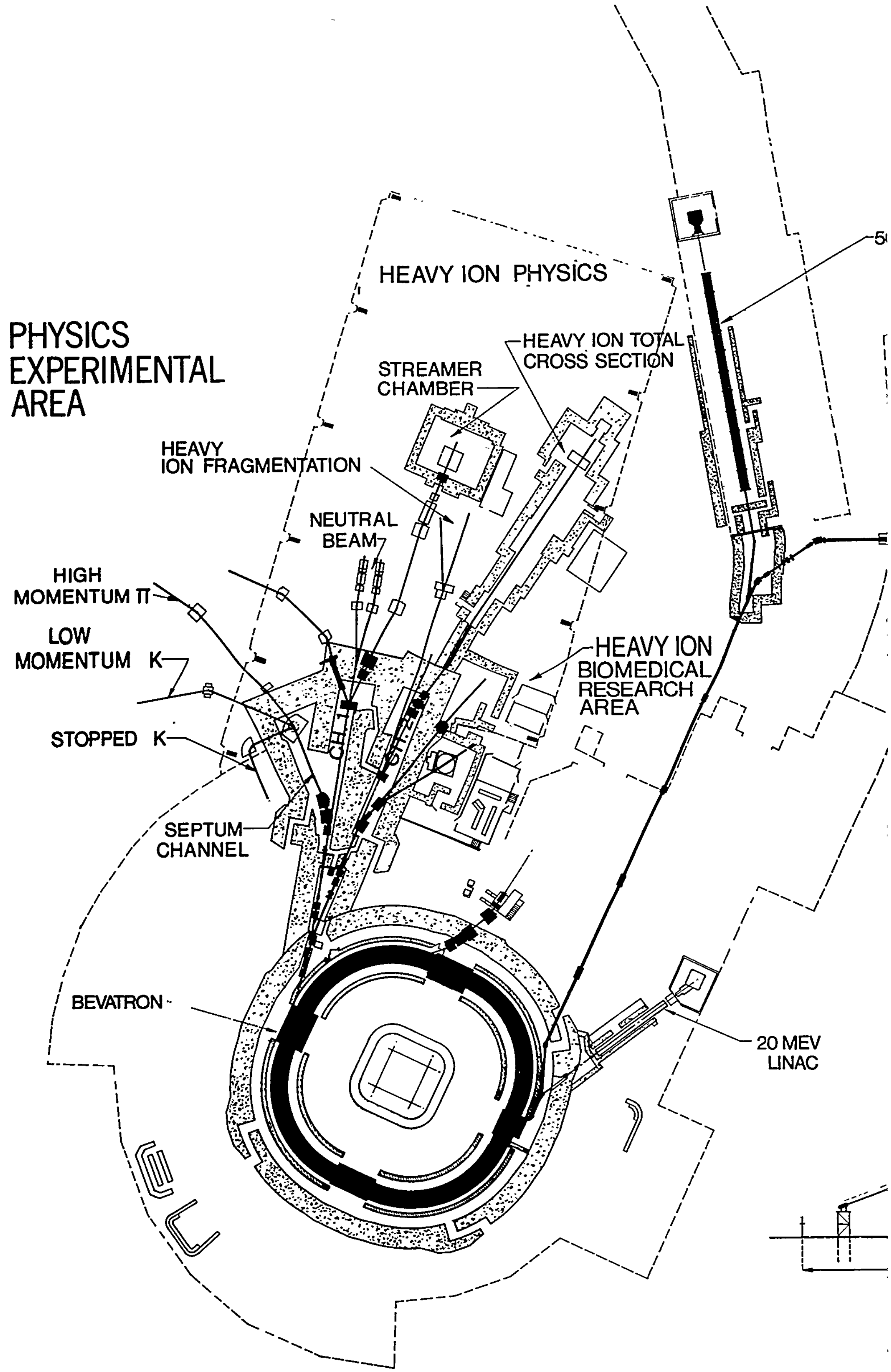
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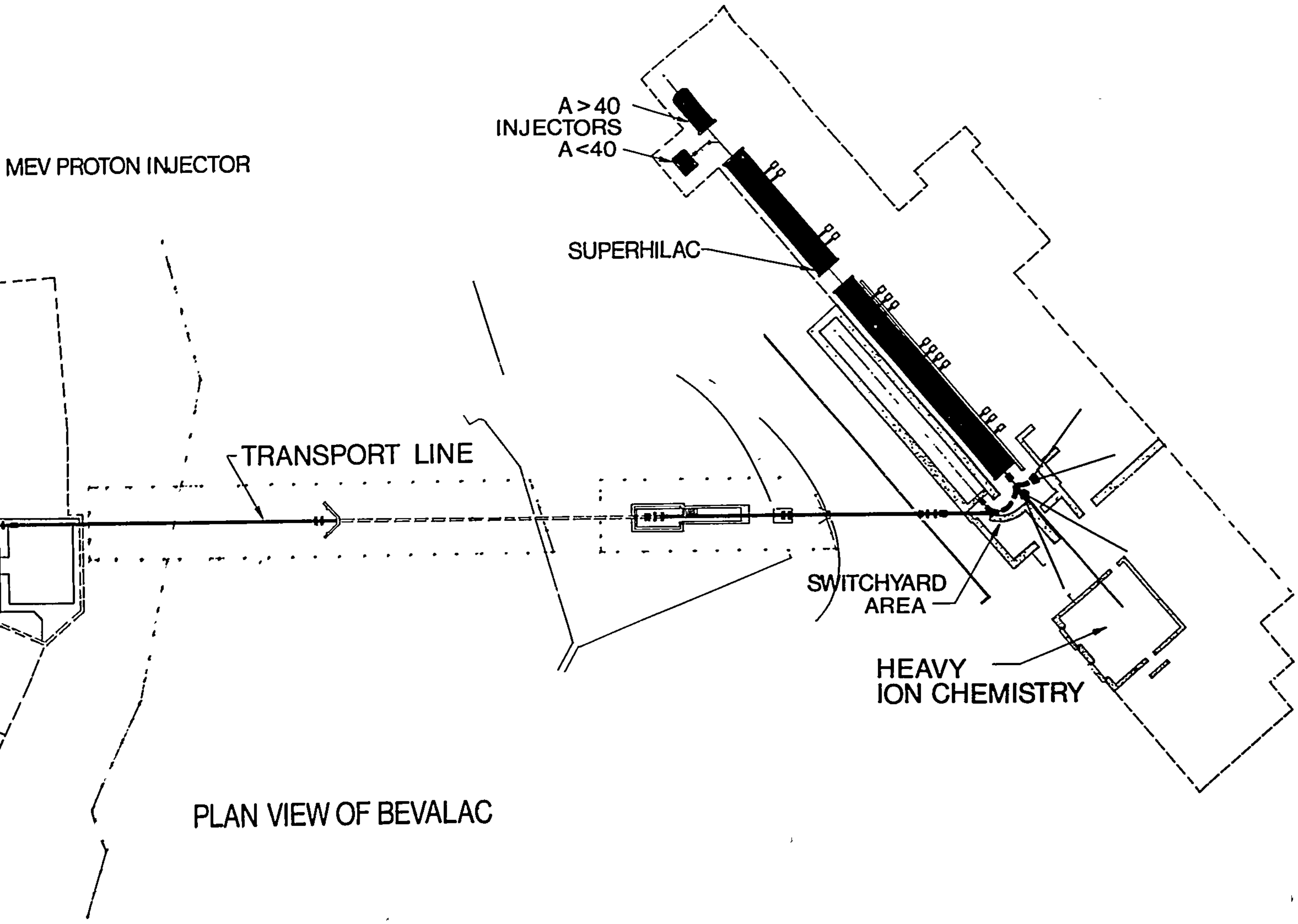
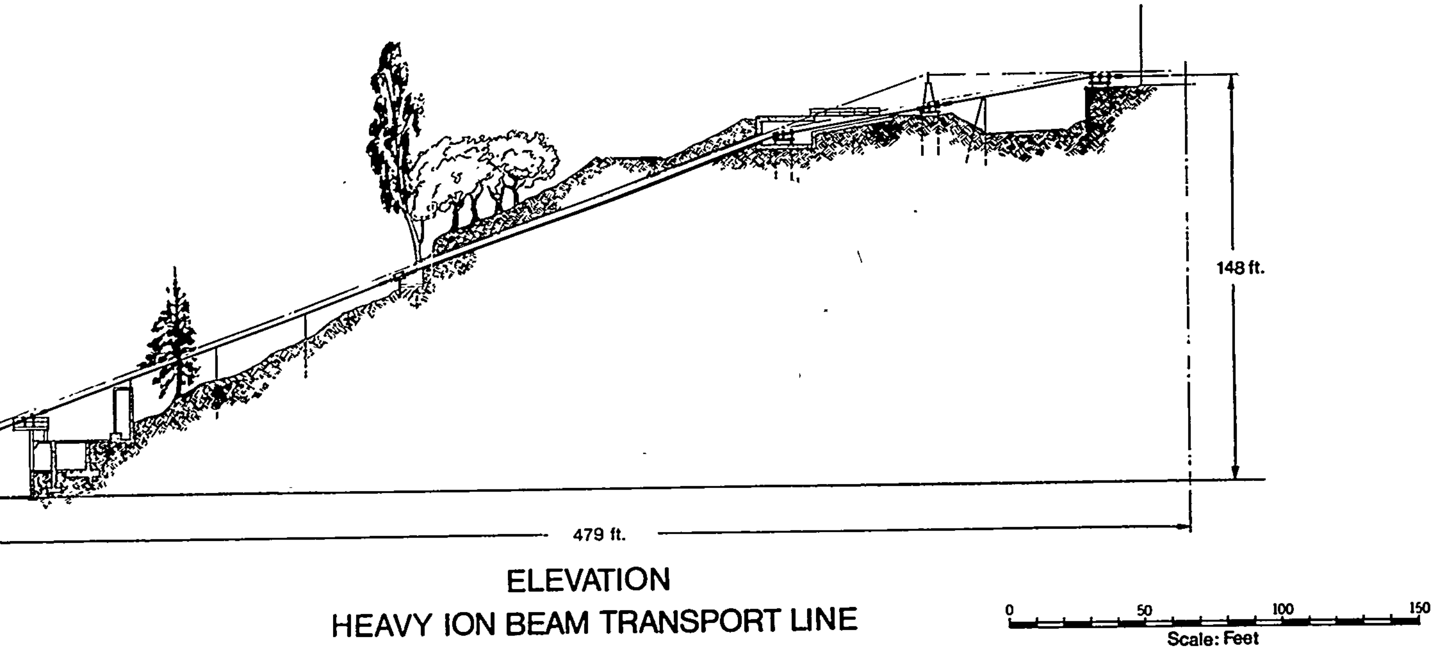
FIGURE 3



PLAN VIEW OF BEVALAC



ELEVATION

HEAVY ION BEAM TRANSPORT LINE

XBL 736-740

available. The emittance in the radial plane is given by the control of the extraction parameters driving the 2/3-integral betatron resonance, and is typically 2 cm-mrad. The vertical emittance is somewhat larger. The inherent energy spread determined by the acceptance of the Bevatron varies from $\Delta E/E = 10^{-3}$ for low energies down to $\Delta E/E = 10^{-4}$ for high energies.

The eventual success of the Bevalac project will depend, in no small way, on the development of a balanced program of experiments which will fully exploit the interdisciplinary feature of this unique facility. Towards this end, the Bevatron Program Advisory Committee (Scheduling Committee) has recently been expanded to include scientists competent in the field of heavy-ion interactions. Similarly, a committee to evaluate and schedule experiments for the biomedical research program will be recruited from the biomedical community. Interdisciplinary collaboration, which has provided mutual benefits in the initial phases of the project, will be enhanced by the involvement of the Bevatron staff in both committees.

References

1. K. C. Crebbin et al., First Phase of Heavy-Ion Acceleration at the Bevatron.

2. A. Ghiorso et al., The Bevalac--An Economical Facility for Very Energetic Heavy Particle Research.

D. Research Utilizing Relativistic Electron Rings

Introduction: The most advanced experiments toward utilizing the collective field of a ring current of relativistic electrons are being carried out at JINR (Dubna, USSR), Max Planck Institut (Garching, W. Germany), LBL (Berkeley), and the University of Maryland.

The strong Coulomb field of the ring of electrons forms a potential well for positively-charged particles. The well may be loaded with ions from a puff of vaporized material. Stripping by the relativistic electrons progressively ionizes the captured atoms. For rapid increase in the state of ionization one desires a dense current of electrons. To achieve this, the electrons are injected into a magnet at comparatively large radius, then the field is pulsed to add energy and compress all dimensions. Loading with ions may be done at any time in this sequence.

In the simplest concept of an electron ring accelerator, the loaded ring is accelerated axially in its entirety by a small radial component of magnetic field added to a uniform axial guide field. A schematic diagram of this is shown in Fig. 4. Such a device has the feature that both the production of ions and their acceleration are carried out by the ring; moreover, the acceleration rate is very high, typically ten (or more) MeV/u per meter of axial solenoid. The acceleration of He^{++} ions to an energy of 8 MeV/u in an ER-accelerator was announced by the Dubna group early in 1971. Since then they have been engaged in a large program of building a new injector, compressor, and accelerating column that can operate at 100 Hz for heavy-ion work, at Professor Flerov's laboratory.

LBL Program: As noted above, the intensity and compactness of the ring is of critical importance to electron ring (ER) devices. The accelerator development group at the Laboratory has been developing apparatus for forming the most dense rings. In this apparatus an experiment has been performed to see if X-rays from Xe ions trapped in the ring could be detected (R. Schmieder: The Relativistic Electron-ring as a New X-ray Spectroscopic Source (1973), to be published.); the L and K_α and K_β lines were clearly identifiable with low background level.

Encouraged by the results with Xenon, the accelerator group is considering construction of an ER facility for studies of highly ionized atoms. A ring containing around 10^{13} electrons would be compressed to a radius of 2 cm and a few millimeters thickness. It would be held in this state to permit development and observation of the ionized states. An example of the progressive ionization of Argon in this ring is shown in Fig. 6. As an initial goal, it would be of interest to be able to observe the hydrogen-like state of krypton and higher masses if possible.

This field of physics is studied at present by the techniques of Beam-foil Spectroscopy in which ions travel at high speed through a stationary stripping foil. By contrast the relativistic ring of electrons acts like a moving stripper and leaves the stripped ions virtually at rest.

A compressor with an expansion solenoid for the acceleration of ion-loaded rings is now set up and under test. The success of this will depend in part on the suppression of instabilities that may destroy or dilute the dense ring during compression, ion loading, and acceleration. The techniques for achieving this stability during injection and early compression were developed in experiments with the previous apparatus referred to above.

The characteristics of an electron ring accelerator for heavy ions have been derived consistent with known requirements. The ring injection and ring-forming cycle of less than a millisecond would be followed by a holding stage of about 4 milliseconds for the stripping of the desired load of heavy atoms. Longer stripping time would yield a higher ionization state but would reduce repetition rate and cause more contamination from background gases. In this example, the repetition rate could be 200 Hz and, at 2×10^{10} ions per cycle, the flux would be 4×10^{12} ions (for example Ne) per second. The sets of possible ring parameters which Laslett has derived by extensive

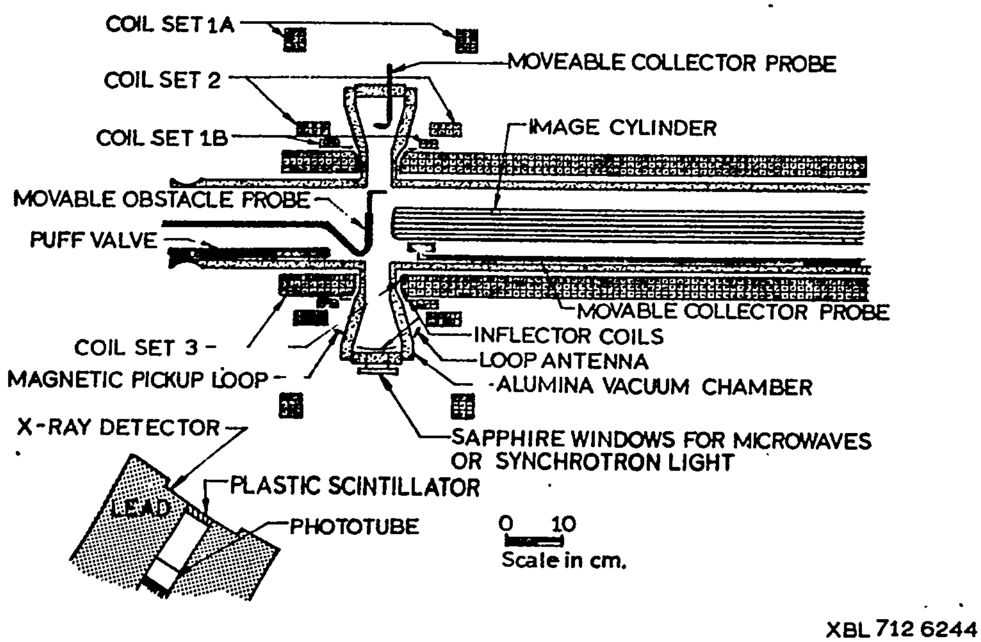


Figure 4a. Cross section of an experimental electron ring compressor. The three sets of coils are pulsed sequentially. The innermost set of coils is developed on the right side into a l meter long solenoid for magnetic acceleration of the rings.

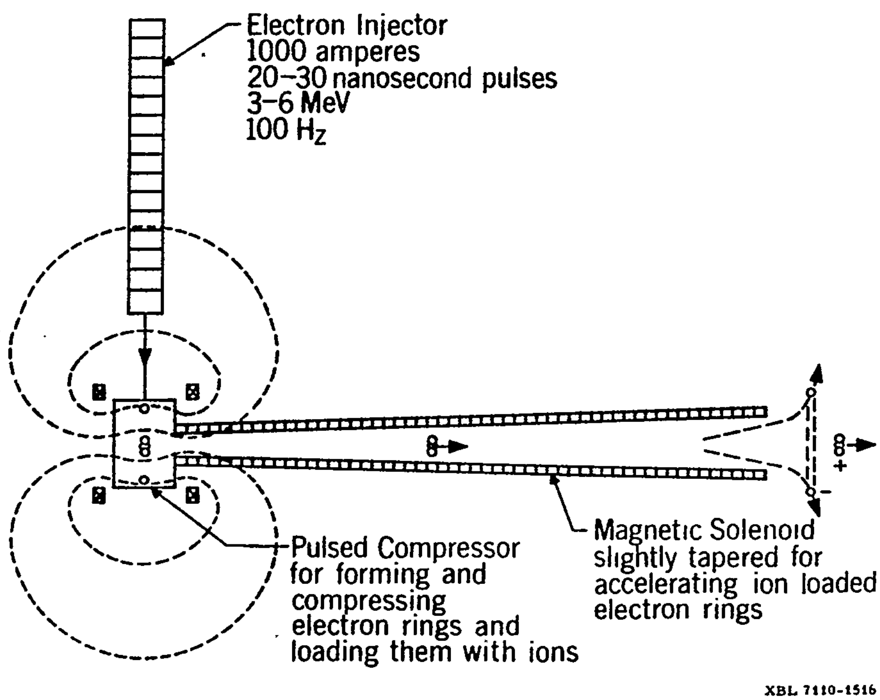


Figure 4b. Schematic layout of a heavy-ion ERA

computational work had the following features:

i) The number of ions was adequate to ensure positive axial focusing of the electrons.

ii) The momentum spread and the number of electrons in the ring were suitably chosen to remain below the threshold for the negative-mass instability.

iii) The numbers of ions and electrons were such as to ensure stability for ion-electron oscillations of the type studied by Koshkharev and Zenkevich. Specifically, the numbers were chosen to avoid the lowest quadrupole resonance; whether this is limiting is not known yet.

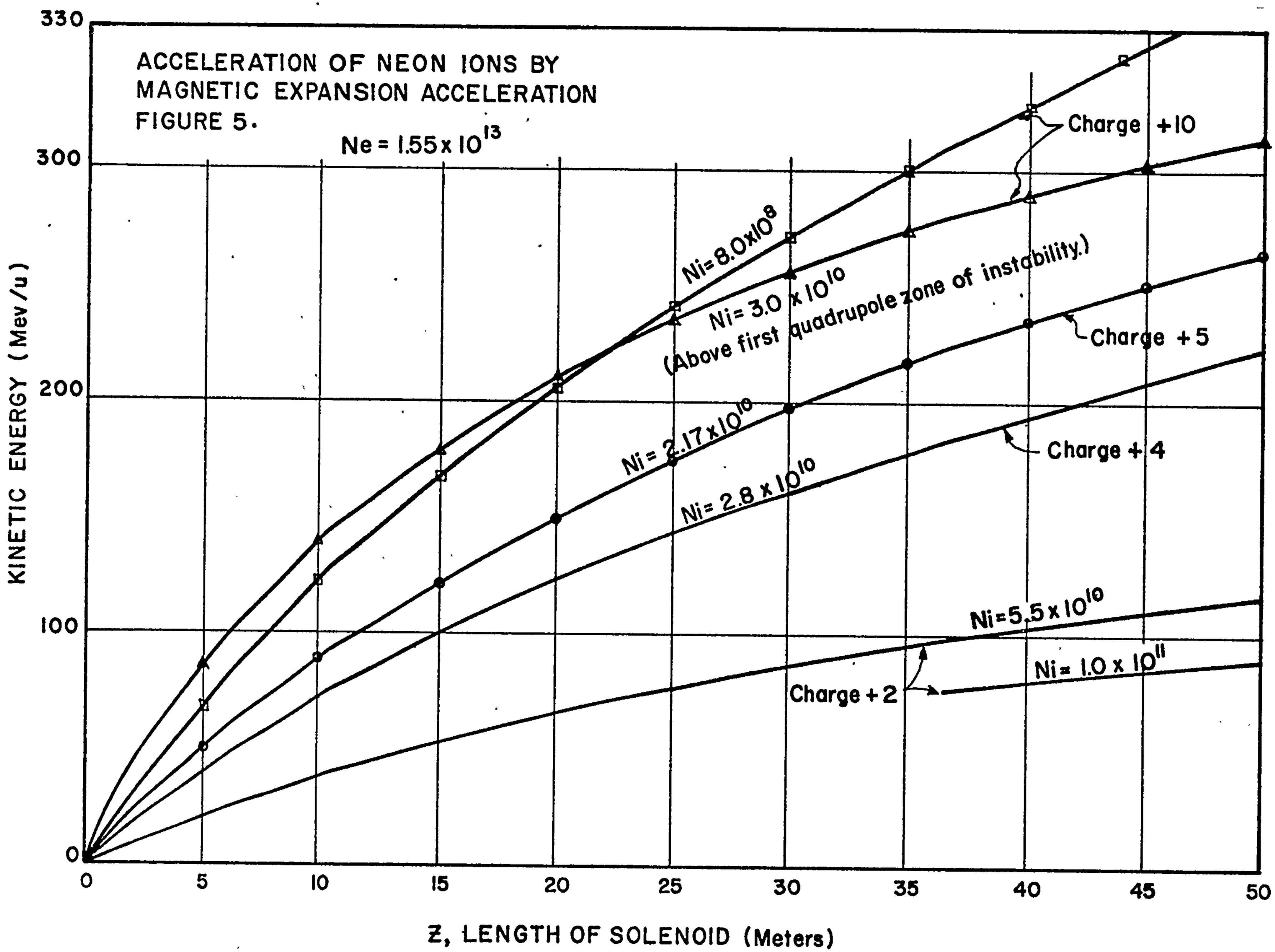
Briefly, Laslett's results are as follows:

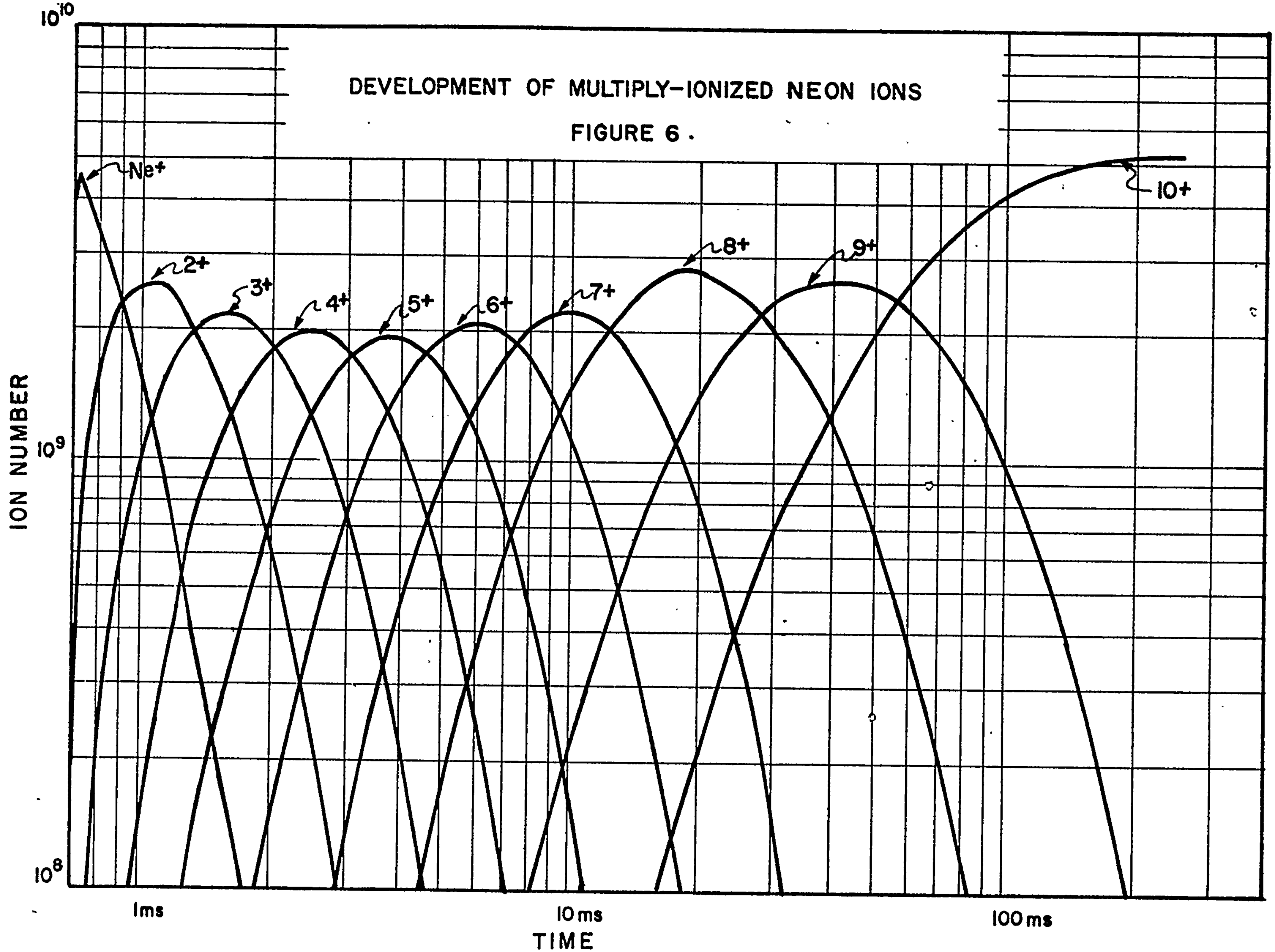
- The electron number, N_e, was typically (1-1.5) x 10^{13}.
- The ion number, N_i, was typically $10^{11}/C$, where C is the charge state of the ion.
- The length of the solenoid required to accelerate ions to a certain energy depends on the selected charge state, C. (See Fig. 5).
- Alternatively, the final ion energy achievable with a solenoid of given length depends on the selected charge state, C. For example, a 35 meter solenoid would produce neon ions with 300 MeV/u for C = 5 and 100 MeV/u for C = 2.
- To produce neon ions mainly with C = 5 or more would require holding the ring for 3 to 4 milliseconds before release into the accelerating column. To produce ions mainly with C = 10 would probably demand very stringent control of background gas contaminants unless additional hardware features were incorporated to shake loose periodically the undesired ions created from the background gas (Fig. 6).

Using these results and following the concept of an Electron Ring Accelerator for heavy-ions using magnetic acceleration only, we can derive the characteristics as follows: with a ring-forming cycle of less than a millisecond and a holding time for stripping of about 4 milliseconds the repetition rate would be limited to 200 Hz, which is technologically quite feasible. The peak flux of neon ions accelerated with $C = 5$ would then be $(200 \times 10^{11}/5) = 4 \times 10^{12}$ per second. For biomedical applications, the flux available exceeds by far what is needed. Separation of the ions from the carrier electrons is a simple matter, and full stripping of the ions is guaranteed at these energies.

The pulse of ions from an ERA will have the characteristic of short duration ($\approx$ 0.04 nanosecond) and large energy spread ($\simeq$ 0.0013 cp MeV FWHM, where p is the momentum in MeV/c. Thus at exit from the accelerator, the 200 MeV/neon ion beam would have a FWHM energy spreak of 1 MeV/u. For certain experiments the narrow time structure could be of advantage; e.g., in looking for very short-time activities or for time-of-flight measurements on reaction products. For other experiments it would be a disadvantage. Likewise, the broad momentum spread would be a handicap in certain cases. While one could always trade between better momentum definition and lower flux, a more reasonable solution is to use a debuncher. Note that the ion beam has high brightness in longitudinal phase-space ($\Delta p \cdot \Delta z$), which is simply partitioned in an unfamiliar manner.

In conclusion, by magnetic acceleration only an ERA should be capable of neon-ion fluxes in the region of 2×10^{12} per second. For biomedical applications this is far more than needed, and direct use of the short output ion pulses is envisaged. For application to experiments in nuclear chemistry a ring-magnet


ACCELERATION OF NEON IONS BY
MAGNETIC EXPANSION ACCELERATION
FIGURE 5.
Ne = 1.55 x 10^13
Ni=8.0x10^8
Ni= 3.0 x 10^10
(Above first quadrupole zone of instability.)
Ni= 2.17x10^10
Ni= 2.8 x 10^10
Ni=5.5 x 10^10
Ni= 1.0 x 10^11
Charge +10
Charge +5
Charge + 4
Charge + 2
KINETIC ENERGY (Mev/u)
Z, LENGTH OF SOLENOID (Meters)
330
300
200
100
0
5
10
15
20
25
30
35
40
45
50


DEVELOPMENT OF MULTIPLY-IONIZED NEON IONS
FIGURE 6.
Ne+
2+
3+
4+
5+
6+
7+
8+
9+
10+
10^{10}
10^{9}
10^{8}
ION NUMBER
1ms
10 ms
100 ms
TIME

debuncher is a desirable addition to give sharper momentum definition and a good duty cycle. Finally, while neon has been the only example species pursued in detail with respect to acceleration, there have been recent calculations by A. Salop on the progression of ionization states in krypton ($Z = 36$). He finds that in the 3 to 4 millisecond holding-time envisaged, the most likely charge state developed is $C \approx 12$; thus the flux and peak energy for this case would be somewhat less than for neon.

IV. HEAVY-ION RESEARCH AT LBL

A. Experimental Program at the SuperHILAC

The new SuperHILAC accelerator, with its ability to accelerate many kinds of heavy ions, is opening new fields of research both in nuclear and in atomic physics. The typical features associated with heavy ion reactions are the high nuclear charge and the large transfers of linear and angular momentum. Furthermore the presence of a large number of nucleons both in the target and in the projectile greatly enhances the collective and macroscopic behavior of the system. These features are exhibited in the research programs reported below.

Hydrodynamical Aspects of Heavy Ion Reactions

Unlike the reactions induced by light particles, the heavy ion reactions are expected to be strongly characterized by macroscopic and collective features which, to some extent might be interpreted in terms of classical hydrodynamics. In order to study these features a program has been started at the SuperHILAC to detect and identify the fragments emitted in heavy ion reactions. The detection and the identification of such particles is accomplished by means of telescopes formed by a thin transmission counter (ΔE counter) and by a total absorption counter (E counter). These telescopes provide information on the total energy of the particle and on its energy loss which can be used to determine the charge and sometimes even the mass of the particle. The reactions studied so far (Cu, Ag + ^{40}Ar) are characterized by an abundant production of particles whose atomic number ranges from 1 to 30 this last being the experimental limit of detection. The most probable kinetic energy of such particles is remarkably small. When transformed to the center of mass the kinetic energy is equal to or lower than the coulomb energy of two touching spheres. This kind of reaction seems to be highly inelastic and controlled by the potential energy of the system. The angular distribution of the particles are more forward peaked the lighter the particle. This seems to be correlated with the time of emission of the particles (longer for the lighter particles) from a rotating system. The overall picture is consistent with a strong relaxation of the system with a transfer of most of the initial kinetic energy into the internal degrees of freedom. In other words the system has very high viscosity. Complementary to this study is the off-line identification of the heavy fragments by means of x-ray γ-ray coincidences. This study has shown the existence of the expected partners of the light particles and has made it possible to determine their range.

Heavy Ion Coulomb Excitation

Since a single-step Coulomb excitation process depends upon Z^2 of the projectile (in perturbation theory) and for multiple processes upon Z^2 to the power of the multiplicity, all Coulomb excitation processes; but particularly multiple ones, are enhanced greatly by the use of heavy ions. With the use of Kr beams at the SuperHILAC the 18^+ and probably the 20^+ state in ^{238}U have been excited. The future use of Xe projectiles will enable the observation of states to 26^+ or 28^+. The spacing of such high-spin states and the values are important pieces of information to help resolve the problem of the nature of these states and the origin of the "back-bending" observed in some doubly-even nuclei. In addition, such multiple excitation experiments are a severe test of the Coulomb excitation theory, and on corrections to the semi-classical theory (polarization and quantal corrections, simultaneous excitation of target and projectile, etc.).

The large linear momentum imported to the resulting compound of Coulomb-excited nucleus leads to large Doppler shifts in the subsequent γ-ray de-excitation cascades when viewed at 0^o to the beam. These shifts can be used to measure lifetimes of states by the Doppler-shift recoil range method (10^{-10} - 10^{-12}s) or the Doppler-shift attenuation methosd (10^{-12} - 10^{-14}s). For example, ^{40}Ar beams have been used to study the lifetimes of the 8 → 6, 6 → 4, 4 → 2, transitions in $^{156, 158, 160}Er$ by (^{40}Ar, 4n) reactions and in $^{152, 154}Sm$ by Coulomb excitation. The results of the latter experiment (Nucl. Phys. A184, 481 (1972)) were accurate enough to show that ^{154}Sm followed the rigid rotor B(E2) values to a few percent, while those of ^{152}Sm indicated a possible centrifugal stretching of that latter nucleus.

The large amount of angular momentum brought into a compound nucleus by a heavy-ion reaction has a number of effects. The resulting γ-ray cascade shows states as high as 22^+ in the ground band of some doubly-even nuclei, and some of these show a strong "back bending" in a plot of moment-of-inertia vs. ω^2 ($\approx (\frac{\Delta E}{2})^2$). This phenomenon has not been satisfactorily explained yet, although it is a subject of great interest at present, and there are several physically different models in contention.

Production of Neutron Deficient Isotopes

The cleanest way to make a particular neutron-deficient isotope is to properly choose a projectile-target pair so that it is made as the first (HI, n) reaction above the barrier. More importantly, the use of heavy ions enables one to study a series of nuclei systematically, and one can sometimes learn more from the systematics than from an individual nucleus. For example, the decay schemes of the odd-mass La nuclei from A = 125 - 137 and have recently been studied found that each had a band based on an 11/2-state that corresponded very closely to the ground band of the neighboring doubly-even Ba core. This situation was not weak coupling, and to explain it a new coupling scheme was developed, rotation-aligned coupling, (Phys. Rev. Letters 29, 438 (1972)). This scheme appears to be quite general in occurence, and examples of it are to be seen in odd-mass Hg, Au, Re, and Gd nuclei.

Shape Effects on Nuclear Reaction Cross Sections

An outside user program at the SuperHILAC has initially concentrated on measuring threshold cross sections to produce simple transfer products with argon beams. So far, thick target cross section for ^{41}Ar and ^{39}Cl in the forward and backward hemispheres have been measured with ^{141}Pr (spherical) and ^{159}Tb (spheroidal) targets. Preliminary evidence is that transfer cross sections fall off more slowly with decreasing energy below the Coulomb barrier for the deformed target Tb than for the spherical Pr. Such behavior is expected theoretically.

By replacing sums over angular momentum ℓ by integrals we have derived relatively simple analytical formulas for compound nucleus formation cross sections for heavy ions on spherical or deformed targets. The approximate formulas have been tested and are found to be accurate and much faster to compute than our earlier program for dedormed nucleus cross sections. These formulas have been incorporated into a general program for estimating optimum conditions for very heavy element production.

Analogous simple formulas are also being developed for transfer reactions. These formulas will be applied to angular distribution studies on transfer reactions near threshold.

Atomic Physics

This project is concerned with experiments to make direct tests of relativistic quantum mechanics and quantun electrodynamics using highly stripped ions at the SuperHILAC. The basic method is to pass the high-energy heavy-ion beam from the SuperHILAC through thin foils in order to create hydrogen-like and helium-like ions of high Z. Four experiments are in progress.

1) An experiment to measure with an accuracy of ±1% the lifetime of the 2^3S_1 of heavy helium-like atoms. Previous measurements on argon at the 7% level indicated a discrepancy between theory and experiment. Recent theoretical work has shown that radiative corrections to the rate should be of the order of 5% and may be responsible for the discrepancy. Hence experiments to improve accuracy will be made on Argon and it is hoped to extend the measurements to helium-like ion (Z = 25).

2) An experiment to make energy measurements to an accuracy of ±2 ev. Recent theoretical work shows that the Lamb Shift contribution to the ground state energy of hydrogen-like krypton is about 20 ev. Hence a measurement of this energy to 2 ev would correspond to a 10% measurement of the Lamb Shift. Such a measurement would be a significant new test of the theory of the Lamb Shift. New instruments are currently being constructed to make possible this measurement.

3) An experiment to measure the quenching of the hydrogen metastable state in hydrogen-like Si, S, and Argon. The quenching is very sensitive to the value of the Lamb Shift and it is hoped to obtain a 2% measurement of the Lamb Shift in these atoms.

4) An experiment to observe the ultraviolet radiation of the 2^3P - 2^3S_1 decay in helium-like argon. This decay is sensitive to relativistic effects in two-electron atoms, and should provide new tests of the theory of the Breit Interaction.

Search for Super-Heavy Elements

Isotopes of the elements 106 to 117 can eventually be produced by bombarding heavy element targets with heavy ions. Some of the isotopes produced ought to have half-lives long enough to permit a chemical separation but not so long that they will escape detection. These could then be separated chemically from the target material and other reaction products. A group separation is being planned where the elements are separated into eight fractions. The different violatilities from a HBr/Br_2 solution and the different degree of complexing with bromide ions gives an excellent separation from the actinides. The fractions are then counted for α and spontaneous fissions, which could indicate the presence of new elements. So far only one target has been processed where new elements could be expected and no evidence for the formation of new elements have been obtained.

The separated fractions are also suited for the identification and yield determination of many reaction products. Hence they are measured periodically with a Ge-detector and pulseheight analyzer. From gamma energies, peak areas and half-lives it was possible to identify and determine the yield of 136 different isotopes in uranium targets irradiated with ^{40}Ar ions. The products formed indicate that three main types of reactions occur, direct transfer of a few nucleons, fission of a neutron deficient composite system and fission of uranium and products around uranium. In the case of ^{82}Kr irradiated uranium the general picture looks similar, but many cross sections seem lower than for ^{40}Ar.

Heaviest Element Research

The purpose of this project is to synthesize new elements and to study their chemical, nuclear and physical properties. At present the project is centered around the SuperHILAC where a number of necessary pieces of experimental equipment are being developed. These are:

1) SASSY (Small Angle Separator System), the main instrument designed to detect the formation of superheavy nuclides, was extensively tested using ^{252}Cf fission fragments to simulate reaction products from heavy-ion bombardments.

2) The multiwire low-pressure proportional counters needed for SASSY were built and tested. Their present design uses pentane at a pressure of 0.5 to 1 torr as counting gas. The position signals from individual wires are separately amplified and digitized to obtain orbit position information.

3) A very successful device was built to manufacture the thin films (down to 3.5 micrograms/cm^2) needed for SASSY. We are now able to prepare these films routinely and to maintain excellent uniformity and leak tightness.

4) A rotating-wire beam scanner was developed and put to routine use in the SuperHILAC beam diagnostic program.

5) The problem of accurate energy measurement of the accelerated beam was solved by developing a system of mica-foil attenuators (holes a few microns in diameter were etched through the foils along tracks left by fission fragments which had been directed normal to their surface) so that it was possible to attenuate heavy ion beams to a level low enough to allow the placement of solid state energy detectors in the beam path and thus eliminate the use of scattering foils. It was found that the time of arrival of a particle relative to the radio frequency tank voltage could be measured to an accuracy of better than 100 picoseconds and thus its absolute velocity could be determined by making two determinations a known distance apart.

6) FAKE (Fast Automatic Chemistry Experiments) has been put into operation. This computer-controlled chemistry system is useful down to half-lives as short as 30 seconds. The methods are adaptable to several types of chemistry but the emphasis at the moment is on column procedures.

In addition a substantial effort was directed into developing a realistic computer code to analyze the collision between two liquid-drop nuclei including the effects of viscosity. This approach is expected to be of crucial importance in the problems relating to formation of superheavy nuclei.

References to above work can be found in the LBL Project Description Forms 189, attached, and in the LBL Nuclear Chemistry Annual Reports for 1971 (LBL -666) and 1972 (to be published).

The principal scientists responsible for the research projects illustrated above include: C. Alonso, J. Alonso, R. M. Diamond, A. Ghiorso, H. Gould, J. V. Kratz, J. O. Liljenzin, R. Marrus, L. G. Moretto, J. O. Rasmussen, G. T. Seaborg, S. G. Thompson.

B. Experimental Program at the 88-Inch Cyclotron

1. Heavy-Ion Studies using the Magnetic Spectrometer

For more than two years an intense heavy-ion program has been under way at the 88-Inch Cyclotron magnetic spectrometer facility. The 88-Inch Cyclotron coupled with the sepctrometer system, is uniquely suited for the study of high-energy heavy-ion-induced direct reactions. In the experiments to date we have attempted to utilize these capabilities.

Inelastic Scattering. Experiments involving the reactions $^{208}Pb(^{16}O, ^{16}O)^{208}Pb^*$ and $^{148,152}Sm(^{12}C, ^{12}C)^{148,152}Sm^*$ have been performed at energies of 104 MeV and 78 MeV, respectively. The objective for these studies has been to determine whether the heavy-ion properties of large Z_1Z_2 products and strong absorption can yield structure information not attainable with light ions. In the scattering on ^{208}Pb it was found that the comparable magnitudes of the contributions to the inelastic scattering eross sections from the Coulomb and nuclear interactions can be used to determine the relative phase between these forces. This has resolved ambiguities present in the measurement of deformations of excited states reported from Coulomb excitation and from light-ion inelastic scattering studies. In the study of scattering from Sm, we are also investigating the importance of coupled channel effects in inelastic heavy-ion scattering, in a mass region where the deformed structure is well understood. In addition, we are measuring the effect of large projectile size on the determination of the nuclear deformation parameters.

Single-Nucleon Transfer Reactions. Single-nucleon transfer reactions induced by ^{12}C and ^{16}O ions on several target nuclei have been studied. The most complete studies have been in the Pb region where the single-proton stripping and the single-neutron pickup reactions induced by ^{16}O at energies of 104, 140, and 218 MeV and ^{12}C at an energy of 78 MeV on ^{208}Pb have been investigated.

The objective of these studies was to understand the reaction mechanism in a situation in which the structure was well known. From these studies a j-dependence of heavy-ion-induced single-nucleon transfer reactions was observed, and the inadequacy of standard DWBA analysis noted. At present it appears that, with proper treatment of the DWBA analysis, reliable spectroscopic information can be extracted from the results of heavy-ion-induced experiments. Results from studies on ^{54}Fe, ^{62}Ni, and several Zr and Mo isotopes are now being analyzed to establish, together with the results on Pb, the systematics of heavy-ion reactions as a function of target mass, projectile, and bombarding energy.

Two-Nucleon Transfer Reactions. Studies of the two-proton transfer reactions (^{16}O, ^{14}C) and (^{12}C, ^{10}Be) on targets ^{54}Fe, ^{144}Sm, and ^{208}Pb have been performed at bombarding energies of 104 MeV and 78 MeV, respectively. These results indicate that there is a definite selectivity in which states are strongly populated depending on both the reaction dynamics and the structure of the final state. In particular, there is an observed enhancement of the low-lying 0^+ states indicative of the effects of pairing similar to that previously observed in light-ion two-neutron transfers.

Multinucleon Transfer Reactions. Studies have been made of the reactions induced by ^{20}Ne ions on ^{27}Al at energies of 99 and 150 MeV, as well as reactions induced by ^{16}O on several nuclei, including ^{208}Pb. The objective of these studies was to investigate 4-nucleon cluster structure in the targets as well as the reaction mechanism of heavy-ion reactions at high energies. It is at present unknown what process or processes account for the large total cross sections measured at energies far above the Coulomb barrier. It has been suggested that at these high energies, where the large angular momentum brought in by the heavy ion might prevent the formation of compound states, there would be observed an enhancement of the direct-transfer processes. In our studies we have found no such enhancements in the direct-transfer cross section to the bound states; but a large cross section is observed for high excitations in the residual nuclei.

2. Studies of Nuclei Far from Stability

Heavy-ion beams are being employed to study the neutron-deficient and neutron-excess nuclei far from stability. Recently the (heavy-ion, xn) reaction has been used to discover beta-delayed alpha-particle (^{44}V) and proton (^{49}Fe) emitters in the $f_{7/2}$ shell, and experiments searching for other unknown nuclei in these mass series countinue. Further, initial evidence leading to the discovery of proton radioactivity was obtained via the $^{40}Ca(^{16}O, 2np)^{53}Co^{m}$ reaction. In-beam particle indentification experiments initiated by 80-MeV ^{6}Li and ^{7}Li beams are also being investigated. Studies of the two-proton pickup (^{6}Li, ^{8}B) reactions are in progress on targets from ^{12}C to ^{48}Ca, the latter permitting the mass measurement of ^{46}Ar ($T_z = 5$). In addition, such exotic heavy-ion-rearrangement reactions as $^{26}Mg(^{7}Li, ^{8}B)^{25}Ne$ have been observed, leading to mass measurements and spectroscopic studies of highly neutron-excess nuclei in the sd shell.

3. In-Beam Gamma-Ray Spectroscopy

Research during the past year has mainly been concerned with finding examples of a new coupling scheme for odd-mass nuclei. In the strong-coupling model of Bohr and Mottelson, the energy differences between states with different projections of the particle angular momentum along the symmetry axis are large compared with the energy difference among the rotational levels of the core. This model holds for nuclei with large values of the deformation parameter β (e.g. $\beta > 0.3$), and yields the well-known relationship that the energy of a level in a rotational band is proportional to $I(I + 1)$.

The opposite extreme is weak coupling, where the energy to change the particle's orientation is very small and the (vibrational) excitation of the core is large. Such a scheme may occur for $\beta < 0.08$, and results in multiplets at the energies of the core excitations.

Our new mode of coupling occurs for $0.1 < \beta < 0.25$ if the Fermi surface is near the $\Omega = 1/2$ single-particle level and if the odd particle is of high-j. Thus this scheme should take over when the Fermi surface is below the high-j subshell on the prolate side and above the subshell on the oblate side. Under these conditions the high-j particle couples not to the nuclear symmetry axis but to the nuclear rotation axis, and the particle contributes most efficiently to the total angular momentum of the nucleus.

Calculations based on a particle-rotor model show that the resulting energy-level diagram for the highest-spin states is just that of the doubly-even core but is based on the lowest state having $I = j$.

Studies at the HILAC of the odd-mass La nuclei with mass numbers 125, 127, 129, 131, 133, 135, and 137 showed that they fit this description amazingly well if they are prolate nuclei. At the 88-Inch Cyclotron, it was found that the neutron-deficient $^{189,193,195}Au$ and $^{195,197,199}Hg$ nuclei also show the new coupling scheme, and must be oblate. The bands built on 11/2 states in $^{135,137}Nd$ and $^{127,131,133,135}Ce$ do not follow the new scheme, and so must be prolate. We believe we have shown the generality of the new scheme; and now by determination of the type of coupling, one can make a decision as to the shape of the odd-mass nucleus.

4. Heavy-Ion Reaction Mechanism Studies

The traditional nuclear reactions can be classified as direct reactions and compound nucleus reactions. In the former case, one or several nucleons are exchanged between target and projectile; and individual single-particle levels of the target nucleus are involved. In the latter case, a complete fusion occurs between target and projectile, full equilibrium is attained among the nuclear degrees of freedom, and the decay of the system is controlled mainly by phase-space. The interaction between nuclei and heavy-ions illustrates an intermediate situation where the target and the heavy-ion strongly interact with a large dissipation of kinetic energy. The relaxation processes occur to a well-advanced but not complete degree and allow one to consider the overall phenomenon in terms of a macroscopic hydrodynamic picture.

These features are observed by bombarding various targets with heavy-ions (typically 160-MeV ^{14}N) and by detecting and identifying the various reaction products. Close to the grazing angle one observes the production of particles of various atomic number (we have indentified particles with $1 \leq Z \leq 20$ in ^{14}N bombardment). The kinetic-energy spectrum shows the relaxation phenomena by displaying high kinetic energies for atomic numbers close to that of the projectile and low kinetic energies for atomic number higher or lower than that of the projectile. Typically, the former kinetic-energy spectra show a high-energy component close to that of the projectile and a low-energy component close to the Coulomb barrier, while the latter kinetic-energy spectra contain only the low kinetic-energy component, close to the Coulomb barrier. At angles larger than the grazing angle, all the fragments show the low kinetic-energy component only. The kinetic-energy spectra close to the Coulomb barrier are, to a large extent, indistinguishable from those to be expected from compound nucleus evaporation. However, the large forward-peaked cross section indicates that the reaction is not due to the compound nucleus.

The strong relaxation phenomena, which are observed may be used to determine the nuclear viscosity and its relevance in the entire class of reactions involving a well-defined collective motion.

5. Biomedical Studies

Biomedical experiments have been performed with a number of light - and heavy-ion beams at the 88-Inch Cyclotron to study the effects of particle radiation on plant samples and small animals. A beam of particular interest was 250-MeV $^{14}N^{5+}$.

6. Cosmic-Ray Track Calibrations

Beams of very low intensity and high energy and charge state have been used to calibrate plastic track detectors used in cosmic-ray studies. An iron beam of about 200 MeV was useful since that is one of the dominant species in the cosmic rays.

References to the above work can be found in the LBL Project Description Forms 189, attached, and in the LBL Nuclear Chemistry Annual Reports for 1971 (LBL-666) and 1972 (LBL - 1666).

Principal scientists doing heavy-ion research at the 88-Inch Cyclotron are: B. G. Harvey, D. L. Hendrie, F. D. Becchetti, D. G. Kovar, J. Cerny, R. Gough, F. S. Stephens, R. M. Diamond, S. G. Thompson, L. G. Moretto, G. Welch, and P. B. Price.

C. Physics Research with High-Energy Heavy Ions

High-energy heavy-ions physics is a broadly based multi-disciplinary area of physics research encompassing the fields of elementary particles, nuclear physics, and astrophysics. Its rapid growth during the past few years can be directly linked to the successful development of the capability at the Bevatron to accelerate a wide variety of ions--deuterons up to neon--to energies between 0.250 to 2.5 GeV/nucleon. This field of research is sufficiently new that as yet there are few if any experts; rather, there is an active and enthusiastic group of physicists who are intrigued and stimulated by the scientific possibilities of this new experimental tool for high-energy research.

The experiments themselves bear on such topics as high-energy interaction mechanisms, fragmentation processes, particle production, nuclear and hypernuclear sturcture, and cross-sections for processes having astrophysical implications. Reference 1 is an internal report submitted to the Bevatron Group, outlining a heavy-ion research program for the Bevatron that reflects the multidisciplinary character of high-energy heavy-ion research. This list of experiments includes primarily first-generation experiments, although several of these will require extensive effort and time. (It is perhaps worth pointing out that for the purposes of this discussion the operational definition of a "heavy ion" is any nuclear species heavier than the proton.) A summary of the current Bevatron heavy-ion program is given in Reference 2. Major areas of study under way are: 1) fragmentation processes of relativistic heavy ions; 2) particle production (positive and negative) in heavy-ion collisions; 3) heavy-ion total cross-section measurements; 4) nuclear fragmentation of heavy target nuclei induced by high-energy heavy ions; 5) high-energy hypernuclear beams; and 6) production of tagged, monoenergetic neutron beams. From a technical point of view, an important contribution to cosmic ray research is the development and calibration of particle detection and identification systems for satellite and balloon experiments.

An important aspect of experiments utilizing relativistic heavy ions lies in the kinematic advantages to be gained in detecting energetic fragments rather than very slow fragments which often have difficulty in getting out of finite sized targets without appreciable interaction. For example, it is this factor which can provide information in a carbon (projectile) - proton (target) interaction which would be difficult or even impossible to obtain in the more conventional proton (projectile) - carbon (target) situation.

The results obtained during the first heavy-ion experiment on the fragmentation of 29 GeV nitrogen ions indicated that the nucleus-nucleus interaction exhibits features characteristic of high-energy single particle inclusive reactions. Subsequent fragmentation experiments with other relativistic ions under a variety of kinematic conditions gave further support to the conjecture that inclusive reaction theory is applicable to high-energy heavy-ion interactions. Briefly, the present state of our knowledge of the fragmentation process can be summarized as follows:

a) The modes of fragmentation are independent of target nucleus, H through Cu (the principle of factorization).
b) The distributions of the longitudinal and transverse momentum of secondary fragments produced at 0^o (E = 2.1 GeV/nucleon) appear to be independent of the Z and A of the fragment, as well as the target nucleus.
c) In the projectile frame (incident beam particle at rest) the longitudinal and transverse momentum distributions can be approximated well by Gaussian functions with $\sigma \cong m_\pi c$ = 140 MeV/c. To the present accuracy of the experiments, $\Delta p \cong m_\pi c$ appears to be an invariant property of high-energy fragmentation.
d) The total inelastic cross-sections are geometric; i.e., vary as $A^{2/3}$, whereas the fragmentation cross-sections vary as approximately $A^{1/3}$.

In a very general sense, fragmentation products include π and K mesons, even antiprotons, as well as nuclei. Studies of pion production at 2.5^o (Lab) by means of p, d, and He^4 at 1.05 and 2.1 GeV/nucleon on targets of Be, C, Cu and Pb have begun with preliminary results that indicate:

1) The shape of the observed pion momentum distribution cannot be reproduced by a model in which the production is attributed solely to single collisions between individual nucleons inside the projectile with the target nucleus. Either multiple scattering terms, or equivalently some kind of coherent mechanism

in which several nucleons in the projectile are involved, seem to be necessary to explain the observed spectra.

2) The positive pion spectra are in accord with the negative pion results.

3) The shape of the production spectrum for pions of energy greater than about 1 GeV is independent of the target.

4) The production cross-section for these pions is proportional to $(A_{Target})^{1/3}$, indicating that peripheral effects are dominant.

It is also interesting to note that the fragmentation of 1.05 GeV/nucleon alpha particles by Be, C, Cu and Pb targets yields protons: deuterons: He^3:H^3 in the ratio of approximately 1:1:1/2:1/2, indicating that there are strong nucleon correlations inside the He^4 nucleus. Here again the kinematical advantages of having high-energy projectiles makes possible very clean separation and identification of the fragments. The foregoing examples show how fragmentation and particle-production experiments with energetic ions yield potentially interesting new information not only about the underlying mechanisms responsible for these processes, but also about nucleon correlations inside nuclei and other nuclear structure effects. Further details about recent experimental results are contained in References 3 and 4.

It has been pointed out by Chew (Reference 5), and others, that similarities in the high-energy interactions between the various "elementary" particles and between nuclei are inherent features of the strong interactions, and that common theoretical considerations should apply to all of these processes. For example, why shouldn't Regge Poles couple to nuclei just as strongly as to nucleons? High-energy heavy-ion interactions provide a new domain of applicability of concepts which heretofore were used almost exclusively in high-energy "elementary" particle reactions. Three aspects of heavy-ion interaction in this regard are particularly tantalizing: (1) The availability of a large variety of possible projectiles and targets makes possible new kinds of detailed tests of high-energy interaction models (e.g., Regge Pole models) as a function of baryon number. (2) It may well be that in a certain sense experiments with $\sim$ 2 GeV/nucleon heavy ions on complex targets come closer to fulfilling asymptotic criteria than corresponding experiments with more "elementary" particles at much higher energies. An example

of a possible energy scale might be the ratio of bombarding energy to the characteristic spacing of energy levels of the colliding particles.
(3) The observed similarities of the shapes of the momentum distributions of inelastically scattered particles in reactions of the type $A + B \rightarrow A$ + anything for different A and B suggest that the dominant characteristics of these spectra may be a consequence primarily of the energy level density, and not of any other more complicated considerations. Experiments with relativistic heavy ions can also be used to test various predictions based on parton models, and such concepts as limiting fragmentation and scaling.

The use of energetic heavy-ion beams to produce hypernuclei offers an interesting new probe of nuclear structure. The time dilation associated with relativistic hypernuclei may make possible detailed studies of decay parameters and lifetimes. It should be possible to produce superstrange hypernuclei with energetic beams of heavy ions. Tagged beams of hypernuclei might be achieved by detecting K^+ mesons in coincidence.

Neutron beams of well-defined momentum and small momentum spread have been achieved by stripping energetic deuterons. By detecting the stripped proton in coincidence, tagged monoenergetic neutron beams can be produced. A number of interesting experiments become possible using these techniques (e.g., $np \rightarrow d\chi^0$, np scattering in all of its many incarnations, etc.). By dissociating heavier projectiles, other types of secondary projectiles can be produced which conceivably could find experimental applicability. Possible correlations experiments involving rescattering of several nucleons from dissociated projectiles might yield interesting new information about nucleon correlations. For example, if both neutron and proton from such a dissociated deuteron could be rescattered, there should be a definite correlation between the scattered neutron and scattered proton directions reflecting the $^3S_1$ nature of the deuterons.

Measurements of cross-sections involving energetic heavy ions will provide important new data in relating cosmic ray abundances to various astrophysical and cosmological models. The development, and especially the testing of new techniques for identifying heavy particles in cosmic rays, will be greatly facilitated through the availability of beams of these particles at high-energy accelerators.

It seems likely that as more experience is gained in experiments with energetic heavy ions, further ideas and programs will evolve. But it is already clear that physics research with high-energy heavy ions has opened a new and interesting area of scientific study.

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D. Biomedical Research with Heavy Ions

The action of heavy ions on living cells and tissues is different from that of other penetrating radiations in several important respects. Briefly, these are:

(1) Molecular lesions in genetic material (e.g., double-strand scissions in DNA) are different in quantity and/or quality from those produced by low linear-energy-transfer (LET) radiation. These lesions lead to irreversible effects, lethality or mutation, and are produced as a consequence of interaction with a single heavy ion of appropriately high LET.

(2) As far as we know, the lesions are permanent in the sense that intracellular enzymatic repair mechanisms, so effective for low-LET radiation, are partially or completely ineffective.

(3) Unlike the case for low-LET radiations, these lesions are not altered by the known chemical and physical radiation modifiers and are independent of the presence or absence of molecular oxygen dissolved in tissue.

(4) In tissues, heavy accelerated particles can produce well-defined and exceedingly well-localized lesions. This is due to the sharply defined range of the particles and to the depth distribution of ionization, the Bragg ionization curve.[1] Radiolesions approximately the dimension of 1/60 of the particle range can be produced at will, without undue damage to intervening tissues. Lesions of this type cannot be produced with surgery or with other types of radiations.

(5) It is possible to produce beams of accurately controlled energy spread in synchrotrons, and to scan or focus these beams to cover almost any desired area and depth-dose distribution.

(6) The fragmentation of the accelerated nuclei, as demonstrated in experiments at Berkeley,[2] results in the possibility of producing beams of radioactive particles. The use of these may have special advantages.

(7) The exploration of very high-LET particles (above $Z = 18$) has not yet begun and may lead to unexpected new information in biology.

We know of most of the above types of biological effects of heavy-ion beams, chiefly because of research done by various local and external groups. This work was carried out during the past twenty-five years using heavy accelerated particles produced at the HILAC, the 88-Inch and 184-Inch Cyclotrons, and (more recently) at the Princeton Particle Accelerator and the Berkeley Bevatron.

As a result of our experience, the characteristics of beams necessary for further work have become better defined. Applications in cancer therapy and diagnosis will require particles with ranges up to 40 cm (or energies up to 1 GeV/u); charges up to $Z = 26$; and moderate intensities, by nuclear physics standards, of $\sim 10^{10}$ ions/sec. Such beams will be provided by the Bevalac--an integrated HILAC-Bevatron system--now under construction. Other accelerator systems capable of providing these beams in the future are being developed. Such accelerators, based on electron ring acceleration (ERA), could conceivably result in a medical heavy-ion facility at moderate cost.

The advantages of the above-listed properties of heavy accelerated particles and the availability of these particles at Berkeley have led to plans for an extensive research program that will in all probability involve participation of national and international groups of scientists. The major fields of interest are discussed below.

Cancer Research and Therapy. It is well known that tumor cells that are deprived of oxygen are about three times as resistant to conventional radiations as are normal cells with a good oxygen supply; that is, the oxygen enhancement ratio (OER) = 3. Initial studies using 260-MeV/u oxygen beams[1] have encouraged the belief that particles with atomic numbers $10 \leq Z \leq 20$, neon to calcium, may depress the OER to values near unity. Therefore, plans have been forwarded to the National Cancer Institute for an ambitious pretherapeutic radiobiology program which could be followed by full-scale therapeutic trials. The pretherapeutic program includes:

(1) Cellular radiobiology of accelerated heavy ions ($Z \leq 26$, $E \leq 1$ GeV/u)

(2) Acute and long-term effects of heavy ions on normal tissues, including carcinogenesis

(3) Cell population kinetics of radiation effects on rodent tumor systems.

Helium ions of 900 MeV/u have been used in this Laboratory for eighteen years in medical procedures. These ions have yielded excellent results in the treatment of acromegaly and in treating certain classes of Cushing's Disease.[3]

Additional exploratory work is under way on management of local lung metastasis with helium ions.[4]

The therapy research is part of a national program oriented toward exploring the possible usefulness of high-LET radiations: neutrons, pi mesons, and heavy ions.

Diagnostic Uses of Heavy Ions. The exact range-energy relationship, relatively low multiple-scattering, and special properties for detecting individual heavy ions have very recently resulted in initial experiments[5] that point to the potential future usefulness of heavy ions in radiographic diagnosis. The use of heavy ions will allow detection of small differences in soft-tissue density. X-rays, while excellent for determining differences between bone and soft tissue, are largely unsuited for soft-tissue radiography; and the need has existed for a long time to visualize structures in soft tissue. The new technique being developed will utilize mainly boron or carbon beams; it probably has even greater potential than another new technique, proton radiography.

In addition, work is under way to utilize heavy ions for laminography;[6] it should become possible to obtain quantitative information on the tissue distribution in the various sections of the human body using this technique.

The production of a heavy-ion radiograph requires a dose of about one rad. Initial applications of heavy-ion radiography will be directed at:

(1) Diagnosis of soft-tissue tumors

(2) Diagnosis of sclerosis of the aorta

(3) Diagnosis localizations for heavy-ion therapy.

Additional instrumental developments are necessary in order to make these techniques useful in human radiotherapy.

The autoradioactive beams also have diagnostic potential[2,6]. It will be possible to measure the location of therapeutic beams in the body during and after therapy by techniques of nuclear medicine. Autoradioactive beams may also open a new chapter of radioactive tracer investigations. The fate and turnover of instantaneously administered radioactive particles, localized in any predetermined part of the body, can be studied. Several definite applications have been suggested:

(1) Determination of blodd flow through heart valves immediately following millisecond bursts of a beam depositing radioactive ^{11}C or ^{15}O in the chambers of the heart

(2) Determination of brain-blood flow by similar techniques

(3) Diagnosis of specific types of hydrocephalus (draining or not draining).

Such applications await completion of the Bevalac, and successful separation of pure radioactive beams of appropriate intensity.

Space Radiobiology. The presence of heavy galactic and solar cosmic rays may prove to be a serious limitation to prolonged space travel by man to other planets. A committee of the National Academy of Sciences has recently outlined the needs for research in this field[7]. It has already been shown that individual fast heavy ions produce visible stars and streaks,[8,9] and there is initial evidence that oxygen particles have a high RBE in producing vascular and cellular lesions in the eye[10]. We estimate that a single heavy ion is able to produce permanent degeneration of the outer segment of a visual rod.

Exploration of the effects of heavy accelerated particles on cells and tissues of the nervous system is of particular interest to NASA.

Other Pertinent Fields. It is anticipated that many other fields of biology and medicine will profit from research with heavy ions. At this time, we wish to list a few of these without detailed elaboration. Proposals for specific research have been made in each of these fields:

- Radiological physics
- Radiation chemistry
- Radiation biochemistry
- Basic radiobiology
- Radiation genetics
- Studies on nervous system with localized radiolesions
- Studies on development and differentiation with local lesions
- Aging research
- Research on preparation of vaccines.

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E. Theoretical Support

A distinguishing feature of the wide range of heavy ion research activity at Berkeley is the substantial amount of local theorteical support. Coupled channel methods of dealing with higher order processes in direct reactions (developed earlier in connection with alpha scattering) are of critical importance in the interpretation of heavy ion particle transfer reactions. Similarly the knowledge gained in past studies of the fission process now finds application in studies of macroscopic aspects of heavy ion processes. Knowledge of the collective ptoential energy surface is being extended and new information gained about inertal prameters, viscosity and the damping at large scale collective motion into intrinsic excitation. Locally performed experiments stimulated much of this theoretical activity and the theoretical work suggests important experiments, aids in their interpretation and helps to establish the relationships that exist between this field and nuclear physics as a whole. The interaction between theory and experiment has resulted in more efficient utilization of the existing experimental facilities.

Descriptions are given below of some of the major theoretical programs. The 189 forms from which some of these have been extracted are also included in this report. The original forms should be consulted for additional details, descriptions of many closely related programs, and lists of current references.

Investigation of the Mechanism of Particle Transfer in Heavy Ion Reactions

As a natural extension of earlier investigations here into the importance of higher order processes in direct reactions, we have turned our attention to particle transfer in heavy ion reactions. Here also because of the high probability of exciting collective states, we expect that higher order processes in heavy ion transfer reactions, going through such intermediate states, will be important. If so, then the reactions offer the opportunity of studying the spectroscopy of that set of nuclear states which have a large parentage based on excited collective states of the core. As such they add a new dimension to spectroscopic studies since in light nuclide reactions such as (d,p) these processes are not very important (except in deformed nuclei) and produce mainly those states having parentage based on the ground state of the core nucleus. Although semi-classical treatments of heavy ion reactions have been proposed, we believe the full advantages of these reactions can be obtained only through a careful quantum mechanical treatment. At this early stage in heavy ion physics, one aim is to suggest to the experimentalist what special features of the cross sections to look for, under what circumstances, and to what physical phenomena they should be associated. To this end our task is to formulate the theory of the reaction dependent upon the details of nuclear models, to set up computer programs based on such a formulation, and then to compute cross sections under various conditions such as bombarding energy, reaction Q-value, nuclear collectivity and structure. At a later stage our task will involve the analysis of data in terms of detailed nuclear structure calculations.

Theory of Particle Transfer in Heavy Ion Induced Reactions

There has been, in recent years, an extensive accumulation of data on single and multinuclear transfers in reactions induced by heavy ions. The interest has been due to the possibility of studying high spin states of nuclei due to the large angular momenta which can be easily transferred from the heavy ion to the target, as also the possibility of studying nuclei with neutron and proton excess. The improvement in the detection and identification of the resulting nuclei has allowed one to study individual nuclear states. The large Coulomb repulsion between the interacting ions allow the possibility of treating their relative motion classically. At bombarding energies below the Coulomb barrier, the probability of nuclear transfer can be calculated by describing the relative motion of the heavy ions by pure Coulomb orbits. The predictions of the transfer cross sections and their angular dependence on the basis of the semiclassical theory have been found to agree very well with the experimental data. Due to the fact that at these low energies the uncertainties in the theory due to the nuclear distortions are absent, the details of nuclear structure could be studied with high accuracy. However, the cross sections at these low energies are small. Recently, experiments have been performed at higher energies. At bombarding energies greater than the Coulomb barrier, the effect of nuclear distortions became significant. Indications are that even at these energies, the nuclear optical potential behaves as a strongly absorbing potential and thus the transfer of nucleons is confined to a small region around the distance of closest approach of the interacting ions. One would therefore expect the semiclassical theories to be valid even at these energies, with the Coulomb orbits being perturbed by nuclear distortions. The transfer cross sections being found to be small compared with the elastic cross sections, one could treat the transfer process in a Born approximation. The aim of this project is to compare the predictions of a semiclassical theory with that of a quantum mechnical distorted wave Born approximation theory.

An Interpretation of Very High Energy Heavy Ion Collisions

Heavy ions of very high energies have been found in cosmic rays. Due to the obvious limitations of low intensity, high background, and difficult-to-control experimental conditions, only restricted measurements have been made (mainly using emulsion techniques). The recent availability of heavy ion beams in the GeV region at the Berkeley Bevatron opened an area of research essentially unexplored up to now. On the experimental side, recent results of Heckman and coworkers represent the most complete set of data in this area. On the theoretical side, several diverse approaches have been proposed to understand what goes on in a high energy heavy ion reaction. One approach employes the S-matrix theory which has been widely studied in connection to Elementary Particles and their collisions.*) There are no conditions in the foundation of S-matrix theory to prevent it from being applied to processes involving heavy ions. A second approach considers the nucleus in its cluster expansion, i.e., it can be considered as represented by different cluster combinations of its constituents with characteristic spatial and momentum distributions. The third approach, in which this project is concerned, assumes that in the high energy collision, part on the nucleus is chopped away and the cross sections can be calculated on a simple geometric picture. These three approaches are not exclusive of each other. They may well be complementary. If these approaches yield similar results it will be extremely interesting to study the relation between them. In particular, an understanding of S-matrix theory originated in high energy hadron physics in terms of low energy nuclear physics represented by the second and third approaches may prove very valuable. A more detailed approach which we use is as follows. Since the collision energy is higher than the average binding energy of nucleons in a nucleus by a factor of about 200 in the projectile frame, the projectile nucleus loses all its nucleons that are in the way of the target nucleus. Thus what remains is the spherical projectile nucleus with a groove cut by the target nucleus. The

*)See also Ref. IV-C5.

number of nucleons knocked off as a function of impact parameters can easily be calculated from the geometry. Further nucleons are boiled off when the remaining projectile nucleus de-excites to a spherical shape. It is hoped that this model will explain, without any adjustable parameters, the main features of the experimental results and provide a simple background against which experimental data can be discussed.

Survey of Heavy Ion Reactions

With the completion of the Super-Heavy-Ion-Linear-Accelerator at Berkeley (and other heavy ion accelerators in Europe) a whole new field is opened in the study of the process of heavy ion reactions. Thus depending on the impact parameter in the collision of various heavy ions with a target nucleus, several phenomena may occur: 1) few-nucleon-transfer reactions, 2) reactions in which the projectile and target nuclei get stuck together, but fission without any equilibrium state being attained for the combined system, 3) reactions in which the compound nucleus is formed, but is unstable toward fission, and 4) the formation of the compound nuclei in its ground state. It is the goal of this project to understand the general dynamic features of these phenomena. We aim at the physics of the processes rather than detailed quantitative predictions of specific experiments. Such an understanding is crucial in attempts to produce superheavy nuclei by heavy ion reactions. Many physical effects will have to be carefully considered, including rotational effects, fusion-fission ("vibrational") inertia, competition between neutron emission and fission at high excitation energies, contact forces, and viscosity of nuclear matter flow in fission and fusion.
The problem is being attacked in three directions. First, existing experimental data, such as Coulomb barriers, multi-nucleon-transfer cross sections, and fission probabilities are analyzed against simple models to bring out unexpected features and their physics. Second, a model calculation of the extreme viscous limit will be made to understand the role of viscosity in heavy ion reactions. Even though viscosity has been speculated to be a deciding factor in the fusing of two nuclei, very little is known about it and accurate calculations are very difficult. Such a model calculation coupled with the well known non-viscous results will give us an idea how viscosity affects the processes. The third line of attack will be to make more fundamental mocroscopic calculations on various physical effects, such as rotational moment of inertia and effects of

angular momentum on shell energies, and then incorporate the results in the understanding of these reactions. It is hoped that this project will throw light on what actually is happening in heavy ion reactions, and to suggest the optimum conditions whereby superheavy nuclei may be produced.

Electron Transfer in Heavy Ion Reactions

In heavy ion reactions one normally studies the properties of the nucleus. The high energetic ion beam of an accelerator can also be used to detect the electronic structure of the atom. In a collision between a positive-charged projectile and a neutral target one observes electron capture by means of dipole radiation. Experiments where an electron is transferred from the target to the projectile are not new but they have been confined to low collision energies. With the advent of high-energetic beams, the collision energies are considerably increased: during the transfer the electron changes its kinetic energy by an amount comparable to the binding energies of K shell electrons in heavy atoms. This fact allows a test of the wave functions of inner electrons. Generally speaking, a theoretical treatment of the transfer requires the use of many-electron wave functions because the exchange interaction between the electrons plays an important role in the formation of the band states of an atom. As a first step it will be sufficient to use the single-electron approximation as given by a Hartree-Fock calculation being the pioneering methods of Slater. The kinematical part of the transfer is described by well-established methods: The Landau-Zener formula governs the region of low collision energies whereas the Brinkman-Kramers approximation applies to high collision energies. Both methods are quantum mechanical. There is also a classical theory due to Thomas which like the other methods has been revived recently.

Effects of Nuclear Deformation on Heavy Ion Reactions

A new formalism and computer program applicable to heavy ion reactions on spherical or deformed nuclei was developed at Yale. Unlike optical model calculations, this theory requires no time-consuming radial integrations, hence may be more easily extended to heavy ion reactions, where a very large number of angular momentum partial waves are involved. Our current calculations show that the classically expected lower barriers at the tips of deformed nuclei (rare earths and actinides) are not appreciably exploited by nuclear reactions until projectiles as heavy as argon hence, classical in behavior, are used. In Berkeley a multi-faceted program is being mounted to measure reaction differences between nearby spherical and spheroidal target pairs.

Nuclear Rotational Band Theory

A major program begun at Yale and continued here is the measurement and interpretation of long rotational band level sequences. In the course of this work theoretical attention has been focused in two main directions: 1) semi-microscopic treatment of even-even rotors, including Coriolis anti-pairing and effects of other collective degrees of freedom and 2) Coriolis band mixing effects in odd-mass rotors. We plan to continue these theoretical studies, complementary to and in support of the strong experimental program of the Heavy Ion Coulomb Excitation group here.

Atomic Electron Processes in Heavy Ion Collisions

The prospect of intense beams of ions in any mass range at the SuperHILAC raises exciting possibilities for study of electron cloud behavior. It is tantalizing, though not certain of realization, to consider gaining knowledge of electron binding in the trans-fermium region without forming compound nuclei. That is, if one can observe x-ray emission on internal conversion processes while the colliding nuclei are closer than electron orbital distances, unique information of electron binding in a new high-charge regime is afforded. Emission lifetime-collision duration considerations appear to make such high Z measurements difficult or impossible. Furthermore, the ionization probabilities for deep shells in very high Z collision systems may be very low. We intend, however, to explore such processes theoretically beginning with projectiles such a krypton, looking for resonant transfer of electrons with targets where K or L binding energies match the K binding energy of krypton. Of the myriad processes in the electron clouds of colliding ions, we will initially concentrate theoretical and experimental effort on yield and mechanisms of inner-shell ionization with full energy krypton ions at the SuperHILAC. Barat-Lichten promotion mechanisms will be tested especially on targets near $Z = 36$, where K-binding energies match, and near $Z = 79$ where the L binding energies match the krypton K-binding energy. A distant goal is the design of experiments to measure electronic binding energies at near impact of heaviest ions, and the foregoing work will be necessary to provide insight on production of deep vacancies. Theoretical calculations are being made on the possibility of using deviations from Rutherford scattering to measure electronic binding energies.

Residual Force Effects in Nuclear Level Systems

We have long been concerned with the profound effects on nuclear structure of residual nucleon-nucleon interactions. Multinucleon transfer reactions in heavy ion collisions will be strongly influenced by the pairing interactions, just as is alpha decay to which we have given much theoretical attention in the past. Ions hitherto available have not been heavy enough for simple pairing theory to apply. One must go above mass ∿100, where protons and neutrons are filling separate shells. Furthermore, with sufficiently classical very heavy ions it is conceptually feasible to explore the pairing behavior in various latitudes of deformed target nuclei.

We are currently conducting theoretical studies of the n-p residual interaction as it affects nuclear level systems in deformed as well as spherical regions (esp. ^{176}Hf and ^{213}Ra regions, where we have recent data on nuclear isomeric properties). The studies may be extended to predict radioactivity properties in regions, such as, ^{100}Sn and the superheavy region, accessible only with very heavy ion reactions.

Equilibrium Configurations of Rotating Charges Liquid Drops with Surface Tension

The theory of rotating liquid masses with a surface tension and a uniform electric charge arose in nuclear physics in connection with the study of nuclei endowed with large angular momenta. The major part of the binding energy of a nucleus is well represented by the model of a uniformly charged liquid drop with a surface tension, and the addition of a rotational energy to the conventional volume, surface, and electrostatic energies of the liquid drop model constitutes an interesting generalization.

It has been pointed out that the nuclear problem of a rotating charged drop may be made to go over smoothly into the astronomical problem of an idealized rotating gravitating mass by imagining the electrostatic energy of the drop to be gradually decreased in magnitude, to go through zero, and to continue on to negative values, at which stage it becomes the energy of attractive Newtonian gravitation. In this way a continuous formal connection is established between the classic equilibrium configurations of idealized rotating astronomical masses and the various equilibrium configurations of an idealized nucleus.

Thus a problem of irresistible scope presents itself: to discuss in a unified manner the equilibrium shapes of rotating masses representing at one extreme idealized atomic nuclei and at the other idealized heavenly bodies. The current work is an attempt in this direction.

In the case of static (nonrotating) systems the relation between the nature of the stationary points and the stability or instability of a system is simple and direct: a maximum in one or more degrees of freedom indicates instability. In the case of systems in uniform rotation (i.e., gyrostatic systems) the configuration of gyrostatic equilibrium may still be located by making stationary an effective potential energy (the potential energy augmented by a centrifugal potential), but the relation between the nature of the stationary points (maxima, minima or saddles) and the stability or instability of the system is more subtle. The conventional view is that a maximum in one or more degrees of freedom indicates instability of motion in the presence of dissipative forces (secular instability) but not necessarily otherwise. In any case the first step is a listing of the configurations for which the potential energy or effective potential energy is stationary, together with an indication of the number of degrees of freedom with respect to which the energy is a maximum.

Studies on the Statistical Properties of Excited Nuclei

The aim of this research project is to gain in-depth understanding of the statistical properties of nuclei as a function of excitation energy and angular momentum. The foundation of the statistical functions describing the nucleus is chosen to be the independent particle model (shell model) in conjunction with a short range attractive residual interaction (pairing interaction). The shell structure and the superfluid effects are naturally accounted for in such an approach and their disappearance with increasing excitation energy can be easily studied. The ground state deformation of nuclei finds its physical explanation in the shell model. Similar information is retained in the statistical functions. A deformation probability function for the various excitation energies can be obtained and the effect of the disappearance of shell effects on the nuclear deformation can be described. Such an approach to the problem of nuclear deformation has interesting applications to the fission process. The superfluid properties of nuclei depend characteristically on two variables: excitation energy and angular mementum. At the same time the shell structure of the nucleus strongly affects the superfluidity and alters its dependence on those variables. A transition from the superfluid to the normal phase can be induced by raising the excitation energy and/or the angular momentum above their respective critical values. Such transitions introduce discontinuities in the specific heat of the nucleus. The disappearance of the superfluid properties with angular momentum is responsible for an interesting anomalous behavior of the nuclear moment of inertia. As the angular momentum increases, the moment of inertia becomes larger and approaches its rigid value. Due to this phenomenon, the angular velocity of the nucleus does not increase linearly with angular momenta and, in certain instances, remains constant or even decreases. This formalism has proven to be very powerful because of the large amount of physical information which it contains. It should be particularly suitable to describe the behaviour of nuclei with moderate amounts of excitation energy and angular momentum. A complementary approach to the statistical properties of excited nuclei has been devised to describe highly excited systems decaying by the emission of complex fragments. In this approach the liquid drop potential energy is employed in association with temperature dependent statistical distributions. A critical state (transition state) is singled out which corresponds to a saddle point in the potential energy as a function of all but the mass asymmetry mode and which controls the decay rate. The formalism can be made almost model independent and predicts the decay width as well as the final kinetic energy distribution. In the case of neutron emission, the spectrum is Maxwellian, as expected, while for large charged particles the spectrum is more gaussian. Emission below the nominal Coulomb barrier is predicted as well as very large widths in the kinetic energy spectrum. Such a formalism yields the mass distribution associated with the statistical decay of the compound nucleus, and unifies in a single description, the phenomenon of fission and that of particle evaporation.

Droplet Model

The development of the droplet model is a major continuing project. The object of current work is to formulate the model in the most useful way and to determine the best values for the adjustable parameters. Because of the wide applicability of the droplet model approach to nuclear properties, the data base relevant for the determination of these parameters consists not only of the experimental ground state masses of nuclei but also the quadrupole moments, fission barriers, charge radii, isotope shifts and effective shell model well parameters. Progress in this work depends upon the simultaneous progress of a number of related projects. For example, consider the fact that experimental nuclear masses must be corrected for "shell effects" and for the so called "Wigner term" before they are compared with droplet model predictions. As a concrete objective of this work, a printed table is planned which will contain, for all nucleon stable nuclei with $A \lesssim 360$, the predicted values for such quantities as the mass, deformation, fission barrier, radius, isotope shift, neutron skin thickness, and single particle potential well parameters. The droplet model mass formula will permit more reliable extrapolation of nuclear properties away from the region of stable nuclei. Consequently, it will be useful for studying super-heavy nuclei and nucleo-synthesis. Perhaps the most significant contribution of the method will be the improved accuracy obtained in the determination of parameters such as the volume energy coefficient, the surface energy coefficient, the symmetry energy coefficient, and the nuclear radius constant. This improvement will result from the improved treatment of the higher order terms in the statistical theory of nuclei. On the basis of Thomas-Fermi studies currently in progress the droplet model will also be generalized to cover high excited systems. The present formalism will be adequate once the temperature dependence of the various coefficients has been determined. Another generalization envisioned is to nuclei immersed in a neutron gas. Such a droplet model mass formula would be useful in calculations of the properties of neutron stars.

Thomas-Fermi Method

A continuing program is underway for the calculation of nuclear properties using the Thomas-Fermi method. These calculations are being pursued for the support they provide for the development of the droplet model and for the insight they give into the relationships between various statistical properties of nuclei. Because of the statistical basis the Thomas-Fermi method is much simpler to employ than are microscopic methods such as Hartree-Fock. Consequently a wider range of situations can be investigated and calculations of special limiting cases such as those of nuclear matter and semi-infinite nuclear matter can be carried out with elementary mathematical methods. The list of inter-relationships between nuclear properties that can be studied with the Thomas-Fermi method is endless but some of the more interesting ones can be cited as examples: The dependence of the surface energy on such properties as surface thickness, nuclear compressibility, or neutron excess can be investigated. The relationship between the nuclear density distribution and the corresponding single particle potential well can be displayed. And, the effect of bulk properties of finite nuclei can easily be determined. The main objectives of the Thomas-Fermi work are understanding of the interrelationships just mentioned and the calculation of quantities needed in the development of the droplet model. An example of the latter sort of application is the calculation of nuclear matter properties such as compressibility, the relation between compressibility and neutron excess, and the value of coefficients describing higher order effects of the neutron excess on the binding energy. The properties of finite nuclei are related to those of the infinite and semi-infinite systems by means of a variational calculation. An integral equation, which is solved numerically, is obtained for the nuclear density distribution by performing a functional variation on the total energy with respect to the density. Because of the calculational simplicity various unusual cases can be considered such as nuclei with thousands of particles of nuclei immersed in a neutron sea. This latter application is of special interest for the calculation of properties to be expected of nuclei in the crust of neutron stars. In addition to the applications already listed, the Thomas-Fermi method may prove useful in studying the stability of neutron excess nuclei, and in studying the possible influence of higher order curvature effects on the properties of fission barriers. The thermodynamics of nuclear matter and finite nuclei can also be studied with the Thomas-Fermi method. Of particular interest is the temperature dependence of collective properties. Such information is needed for calcualtions of the decay modes of highly excited nuclei whether they be formed by high-energy protons or by heavy-ion reactions.

Geometric Properties of Nuclei

The geometric properties of the nuclear density distribution have been studied since nuclear physics began. Indeed, Rutherford,s discovery of the nucleus was simply a measurement of its size. These days the size, shape, and surface diffuseness of the proton density distributions of nuclei are quite well known. To a lesser extent the same is true for the neutron density distributions. A great deal is also known about the geometrical properties of single particle and optical model potential wells. Our study of these quantities has two specific goals. The first is to obtain simple algebraic predictions for those geometric properties of nuclei to which the droplet model can be applied. The second is to obtain relationships (of a purely geometric nature) between the different ways of describing the density distributions and potential wells. The approach is in terms of the droplet model and the assumption that the distributions of interest are leptodermous. This allows many of the desired relationships to be obtained from straightforward application of solid analytic geometry. The results of this study are formulae for the prediction of the geometric properties of interest and various special applications such as the isotope-shift anomaly. In addition purely geometric constraints have been discovered between the properties of the density distributions and the potential wells that were previously unknown. The success obtained so far stimulates us to apply the approach to geometric questions that arise in heavy-ion scattering. It is expected that this will be one of the most important uses of this work because many features of heavy-ion reactions seem to be dominated by geometric and kinematic considerations.

Modified Definition of the Surface Energy in the Liquid-Drop Formula

The rapidly increasing experimental information on heavy-ion scattering data makes it desirable to find a unified description of fission, fusion, and elastic scattering processes in the frame-work of the same model. Recently considerably progress has been made in the theoretical description of several aspects of induced fission reactions by adding shell corrections to the liquid-drop deformation-energy surfaces. An extension of these methods to collective motion beyond the fission saddle-point meets several problems. Calculating the potential energy for the collective motion of strongly necked-in configurations one finds a spervious sensitivity to the details of the shape in the scale region.

This is a consequence of the assumed sharp nuclear surface in the liquid-drop model. An improvement of the liquid-drop model to avoid this problem is investigated. The surface-energy term is replaced by the self-energy of a drop caused by a short-range two-particle interaction. For a Yukawa potential the self-energy integral can be evaluated analytically for a few important symmetrical configurations and it can be transformed into a three-dimensional integral for arbitrary axial-symmetric figures. A numerical calculation of the new term in the liquid-drop formula is therefore not more complicated than the usual treatment of the Coulomb energy. The term contains two phenomenological parameters, the strength and the range of the Yukawa potential, compared to the single surface parameters in the conventional liquid-drop formula. The new parameters have to be fitted together with the unchanged terms in the Bethe-Weizsäcker formula to experimental fission and Coulomb-barrier heights and ground state masses throughout the periodic table. Once the parameters are fitted one can calculate deformation energy surfaces and derive fission and fusion barriers for known and unknown nuclei off the valley of β-stability. Classical trajectories in the space of deformation parameters can be calculated in those parts of the collective variable space where reliable inertial and viscosity parameters are available. In heavy-ion reactions this presently restricts the calculation of trajectories to Coulomb and sub-Coulomb reactions.

Nuclear Viscosity

In the hydrodynamical treatment of nuclear fission the coupling between the collective motions and the particle hole excitations is usually disregarded. However, the effect of these interactions may become important in a more detailed study of fission or in the study of heavy-ion collisions. A particularly simple way to include this coupling between macroscopic and microscopic degrees of freedom is provided by the hydrodynamical concept of viscosity. The transverse viscosity coefficient determines how fast the kinetic energy of collective motion is irreversibly dissipated into particle-hole excitations, which can be interpreted in terms of the macroscopic statistical concept of heat. This dissipation is proportional to the amount of shear in the macroscopic velocity field. The viscosity of nuclear matter is expected to depend on its temperature. A reliable prediction of this dependence has not yet been made, but there are some rough estimates that may be readily improved upon an alternative approach would be to try to extract an empirical estimate of the viscosity coefficient and its temperature dependence from the relevant experimental data by making a comparison with the predictions of hydrodynamical calculations. This method is especially simple if the viscosity is small enough that a perturbation approach can be used. In this case the unperturbed mass flow could be used to calculate the amount of energy which is converted to heat. For such a calculation the Navier-Stokes equations of hydrodynamics must be solved for a set of suitable shape parameters. Then the unperturbed motion of the system from saddlepoint to fission must be determined. If the flow is assumed to be imcompressible and irrotational, a symmetric friction matrix can be derived which is similar to the inertial matrix. The rate of energy dissipation can then be calculated for various assumptions about the strength and temperature dependence of the coefficient of viscosity. These results can then be compared with experiment. Another problem is to determine the proper transition of these semi-classical concepts into quantum mechanics. The proper quantum treatment of a dynamical system under the influence of an irreversible force like viscosity is not known. To obtain some insight into this problem simple one-dimensional systems might be considered.

Hartree-Fock Calculations of the Angular Shapes of Neutron and Proton Distributions in Deformed Nuclei

The first determination of the details of the shape of nuclei beyond the long known quadrupole component was made five years ago at this laboratory through a collaboration involving an experimental team at the 88-inch cyclotron and a member of the theory group. The analysis of the data led to values of the hexadecapole component (Y_4) in the shape of a number of rare earth nuclei. More recently Coulomb excitation experiments have yielded measurements of the 4-pole electric moment for several of the same nuclei. Unfortunately, among the groups reporting such measurements there are disagreements. Several groups report Coulomb excitation measurements in agreement with the alpha scattering experiments, while several others repsort significantly larger values.

The two types of experiments do not in fact measure quite the same quantity. The alpha particles feel the nuclear field of both protons and neutrons while the Coulomb excitation measurements concern the charge distribution. Moreover, the finite size of the alpha particle was not unfolded from the alpha measurements, and there is no known prescription having a sound basis, for unfolding the alpha size. Notwithstanding these reservations, there is a suggestion that the angular shape of neutron and proton distributions in deformed nuclei may be different. The difference could arise because of the Coulomb repulsion amongst protons, not experienced by neutrons, and because neutrons and protons fill quite different shells. On the other hand the neutron-proton interaction will tend to encourage equal distributions.

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[redacted]

FIGURE 10 TOP

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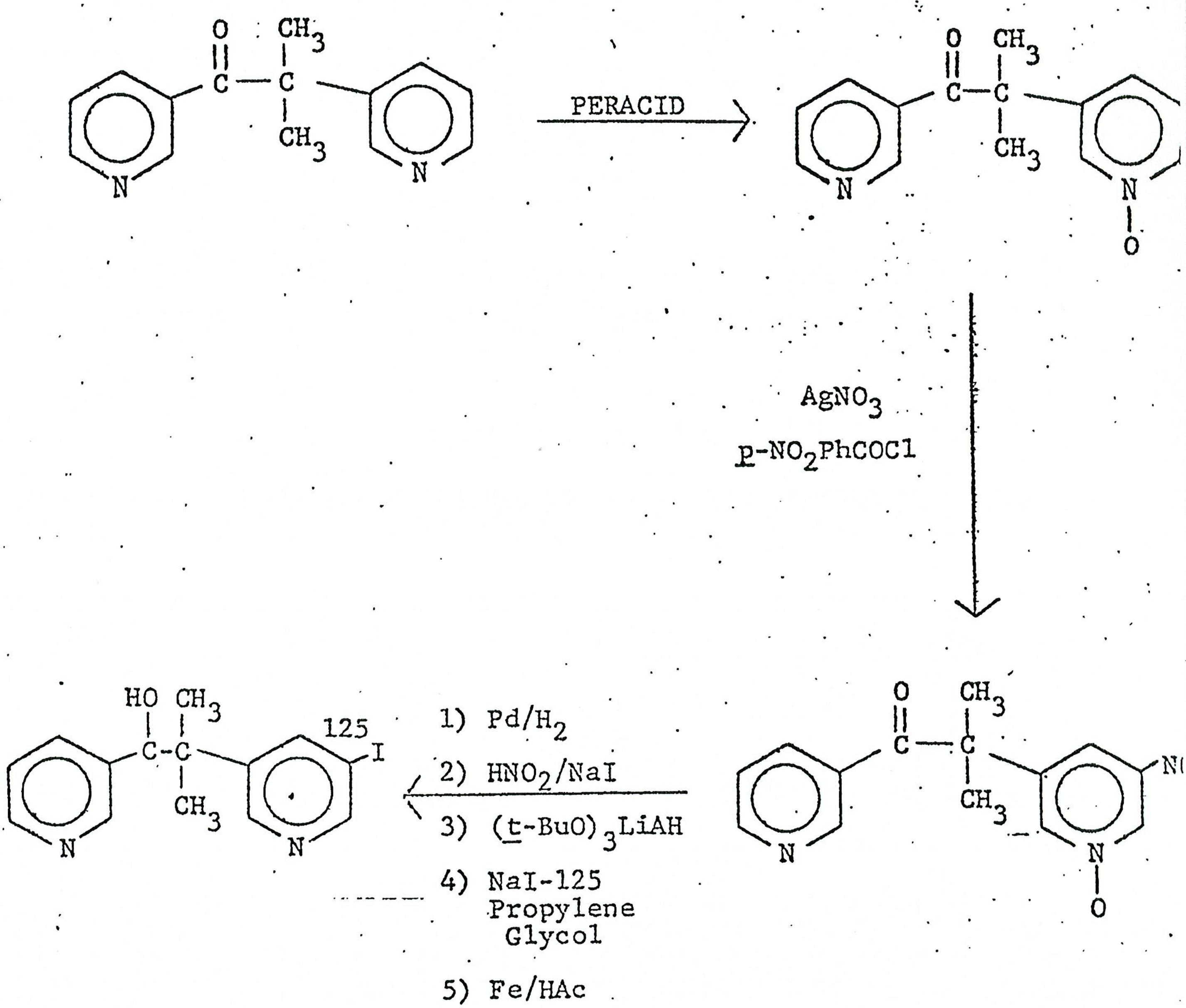
ADRENAL IMAGING AGENTS



NOTE: Figure 10 is in the process of being professionally drawn and photographed. It will be forwarded to Dr. Blaufox on completion (2 weeks).