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BEVALAC: STATUS OF THE MACHINE AND OF THE PHYSICS RESEARCH PROGRAM

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BEVALAC: STATUS OF THE MACHINE AND OF THE PHYSICS RESEARCH PROGRAM*

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Abstract

The Bevalac is briefly described and its schedule for completion is given. The Physics Research Program to be carried out with heavy ion beams with energy in the range 0.250 to 2.1 GeV/nucleon is described.

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1. Introduction: The Bevalac

The Bevalac represents the union of two accelerators at the Lawrence Berkeley Laboratory (LBL) to achieve the acceleration of heavy ion beams to relativistic energy {1}. The SuperHILAC, which is designed for acceleration of ions of any mass up to an energy of 8.5 MeV/nucleon, - which ions are used for a wide variety of research studies in this energy range - is to be used also as an injector for the Bevatron, a proton sychrotron used thoughout most of its research life from 1954 to 1974 for the acceleration of protons to 6 GeV. The Bevalac project consists of the addition of a beam transfer between the two accelerators and of the installation of machine modifications, including computer control, to permit synchronized operation of the SuperHILAC and the Bevatron. Acceleration of d, α, C, N, O has been demonstrated previously in the Bevatron {2} with ions produced in its own ion source. Use of the SuperHILAC as injector permits development of greatly intensified beams of C, N, O and Ne. See Table 1. Above mass 20 there is a rapid fall off in beam intensity but intensities of Ar and of somewhat heavier elements will be sufficient for some experimental purposes. With improvements in the accelerator tank vacuum the intensity of such ions could increase dramatically.

The transfer line and most machine modifications will be complete by the end of the summer 1974 and initial experiments with the SuperHILAC should be started in the fall and winter months. Computer controlled time-share operation to permit acceleration of one selected beam at the SuperHILAC for experiments at 8.5 MeV/nucleon interspersed with acceleration of a different heavy ion for injection into the Bevalac will be complete in the third or fourth quarter of 1975. The Bevatron requires an injection pulse only once every 6 seconds, whereas the SuperHILAC pulse rate is hundreds per second, so this time-share operation will allow use of the SuperHILAC for its own research program at 8.5 MeV/nucleon with negligible interference by its use as Bevatron injector.

The full energy of the Bevalac beam particles at ejection will be 2.1 GeV/nucleon. Operation at lower energies down to 250 MeV/nucleon will be possible.

Financial support for the Bevalac comes from the U.S. Atomic Energy Commission and the program is reviewed by a committee of experts from all parts of the USA. Experimental facilities are open to all qualified U.S. scientists. Participation by scientists from other countries is welcomed.

2. Biological and Medical Interest

The initial interest and scientific justification for the Bevalac project came from researcher workers in Biology and Medicine. The large ranges and the radiation deposition characteristics of heavy ions of relativistic energy makes them exceedingly interesting for eventual use in medical diagnosis and therapy for many diseases, including cancer. An extensive research program is planned in radiation chemistry, radiation biochemistry, molecular-cellular radiobiology and genetics, tumor kinetics, tissue radiobiology and carcinogenesis diagnostic radiology (imaging of internal structures), plant radiobiology, neuroradiobiology, and therapy for tumors, pituitary malfunction, and other diseases.

3. Physics Interest

The Bevalac will for the first time provide a variety of heavy ion beams at relativistic energy with sufficient intensity for the application of a variety of experimental techniques for the study of the nature of the interaction of such projectiles with simple and complex nuclei. It is a virgin field in which the experimental phenomena will be of great interest to nuclear physicists, particle physicists, astrophysicists and nuclear chemists. Theoretical prediction of the mechanism and resulting phenomena is such interactions is a severe challenge to nuclear and particle theorists. A summer study was held at LBL in July 1973 and another is scheduled for July 1974 to develop theoretical ideas on relativistic heavy ion physics. The possibility of qualitatively new and unexpected phenomena lends excitement to this virgin field of study. General statements on this new field of heavy ion physics have been written by Heckman {4} and by Steiner {5}.

4. Some Expectations from Past Results

One can apply to relativistic heavy ion reactions the same experimental techniques that have provided so much experimental information on the interaction of GeV protons with simple and complex nuclei. These techniques include radiochemistry, nuclear emulsions, off-line and on-line mass spectroscopy, semiconductor particle detection systems based on rate of energy loss, total energy, and time-of-flight measurements, track detectors of mica or plastics, plus all the techniques used to measure pions, kaons, and hyperons. One can also ask what part of the detailed understanding of reaction mechanisms in the case of GeV proton interactions can be taken over for the relativistic heavy ion case. We recall that the wave length of GeV protons is short compared to internuclear distances in nuclei and that the initial interaction of the incoming proton is with a single nucleon, almost as if the collision occurred in free space. This initial encounter sets off a chain of nucleon-nucleon collisions calculated most readily by Monte Carlo mathematical techniques. In an ensemble of struck nuclei, there is left an extremely broad distribution of excitation energy. Meson production and reabsorption can play a strong role. The struck nuclei are de-excited in a variety of ways including evaporation of nucleons or light nuclear fragments, by fission, or by an asymmetric two-body breakup with special properties resembling fast asymmetric fission. Final products vary greatly in Z, A and yield. For a general review see {6}.

One may expect a considerable fraction of the experimental phenomena, of the nucleonic cascade effects, and of the de-excitation by evaporation and nuclear breakup to be reobserved in the case of heavy ion reactions, but many notable differences will certainly occur. A crucial question is whether the projectile nucleons in a central collision will interact independently on target nucleons or whether coherent effects will play an important role: Will clusters of nucleons in the projectile undergo knock-on collisions with clusters in the nucleus? Year ago, Igo Nansen and Gooding {7} observed $\alpha,2\alpha$ reactions in complex target nuclei. Can similar knock-on reactions be induced by C, N, O, projectiles? Will coherent effects give rise to enhanced production of pions? Will the struck nuclei be so much more highly deformed and excited by the heavy projectile, compared to the proton case, that the pattern of residual nuclear de-excitation and breakup will be considerably different?

5. Experiments in Progress on in Planning Stage

5.1 <u>Summary</u>

A list (not exhaustive) of experiments is given in Table 2.

5.2 <u>Projectile Fragmentation</u>

The most interesting study done so far with Bevatron generated heavy ions is the investigation of the fragmentation of ^{14}N and ^{16}O nuclei at 2.1 GeV/nucleon energy by diffractive dissociation on Be, C, CH_2 and heavier targets {4,8}. A kinematical fact of great importance is that the fragments travel at high energy and are confined to a small forward cone in the lab system, even though the fragments have little or no energy with respect to the projectile. Figure 3 is a diagram of the 0^0 heavy ion magnetic spectrometer used for the 0^0 fragmentation experiments. The spectrometer focuses magnetically analyzed beam fragments on to charge-measuring solid-state detector telescopes located on the focal plane of the spectrometer. With proper tuning all possible projectile fragments can be identified and their cross sections measured. A typical spectrum for the carbon isotopes is shown in Figure 4. A remarkable characteristic of the momenta spectra is that the maximum for each isotope occurs at a momentum corresponding to the beam velocity. When the distributions for individual isotopes are transformed to the projectile frame, a near universal curve for the momentum distribution is obtained as shown in Figure 5. Measurements of transverse momenta distributions by wire chamber techniques showed that the momenta distributions perpendicular to the beam were similar to those parallel to the beam.

Projectile fragmentation increases with atomic number of the target, but the distributions in momenta and in relative cross sections for various products remain constant and give evidence for the applicability of the principle of factorization; i.e., the modes of fragmentation are independent of the target nucleus. Factorization states that in the reaction A + B → X + anything the partial cross sections factor according to the rule $\sigma_{AB}^{x} \rightarrow \gamma_A^x \gamma_B$, where the function γ_A^x depends only on the beam nucleus and γ_B only on the target nucleus.

These results pose interesting challenges to theory. Future experimental studies will include a broader distribution of projectile and target nuclei and some variation in projectile energy. Further tests of factorization and scaling will be made. It will be interesting to find whether heavier projectiles (Ar,Fe,etc.) fragment as completely as do ^{16}O and ^{14}N, or whether there is a limit set by energy transfer in the grazing collision. Future experiments will investigate the coincident emission of a second projectile fragment or possibly of a target fragment.

5.3 Coherent Effects in Pion Production

One of the open questions about reactions induced by relativistic heavy ions is whether production of pions, kaons, and hyperons can occur only via the interaction of single nucleons within the projectile acting independently on target nucleons, or whether cooperative effects of several nucleons can be involved in production of such particles. Measurement of production cross sections and secondary particle characteristics in reactions involving a variety of targets and projectiles will be made. Particular interest will be associated with measurements with beam energies varying from the maximum available down to values where the energy of individual projectile nucleons is below the meson production cross section. One group of high energy physicists at LBL {5,9} has already made some preliminary studies of energetic negative pions emerging at forward angles from targets of Be, C, Cu and Pb bombarded with 1.0 and 2.1 GeV/nucleon protons, deuterons and helium ions. It was found that pions are produced more copiously by deuterons and helium ions than by protons and that the pion spectra extend to higher momenta when the pions are produced by deuterons and helium ions. The internal Fermi momenta of the nucleons in the complex projectiles can account partially for this effect, but the results suggest the possibility of some collective process in the pion production. This study will continue with heavier projectiles when the Bevalac becomes operational.

5.4 Target Fragmentation Studies

Some of the most detailed information on the breakup of complex target nuclei resulting from bombardments with GeV energy protons has come from measurements with semiconductor detector telescopes {10-12}. By measurements of rate of energy loss and total energy or of total energy and velocity it was possible to identify individual isotopes of light element fragments (from helium to nitrogen) and to measure energy spectra at several angles to the beam as well as total production cross sections for these fragments. A sample particle identification spectrum from this work is shown in Figure 6. The energy and angular distributions indicated a formation mechanism resembling evaporation from a struck target nucleus but several features were not fully explained. A broad distribution in excitation energies was evident. The effective Coulomb barrier was less than 0.5 of the expected value. There was some favoring of forward emission in the center-of-mass frame. An appreciable forward peaked, high-energy component indicated some fragment formation during the initial high energy cascade of nucleons or nucleonic clusters. Another feature of interest was the production of exotic nuclei of high neutron excess not previously reported; e.q. ^{11}Li, ^{14}B, ^{15}B, ^{17}B, ^{14}Be.

Application of these experimental techniques to Bevalac reaction systems should result in highly interesting data on target fragmentation and on the participation of projectile and target sub-structure nucleon clusters in the initial stage of the reaction. The fast and more extensive distortion and fracturing of the struck nucleus by heavy ion projectiles should lead to target fragment characteristics grossly different from those observed with GeV proton projectile. Opportunities for the production and identification of exotic nuclei should exist.

5.5 Astrophysics Interest

Bevalac beams will provide unprecedented opportunities for experimental measurements useful to astrophysics, particularly with reference to heavy components in the cosmic rays. First, there is the obvious possibility of calibration of all detection techniques. The composition of cosmic rays observed near our planet does not correspond to the composition at the source, because of transformations by fragmentation in the interstellar gas (mostly H and He), in the earth's atmosphere, and in the walls of the instruments of detection. These fragmentation cross sections can be obtained by Bevalac experiments and used to determine the initial cosmic ray composition at the source. Measurements of production, interaction, and electron attachment cross section of ^{10}Be and ^{53}Mn (unstable K - capturing species) would be useful for the determination of cosmic ray lifetimes.

6. Theoretical

The theoretical description of nucleus - nucleus interactions in the GeV/nucleon energy region is in its infancy, but is attracting interest from nucleon and particle theorists {13}. One can make a rough classification under the titles macroscopic, microscopic and particle theory. Under the macroscopic heading falls the geometric description of two colliding spheres which partially overlap according to the impact parameter between them. Parameterization can be taken from geometrical or liquid drop descriptions of nuclei. Matter may be sheared off by "abrasion" in the overlap region. The highly distorted and excited residual target de-excites by "ablation". An interesting possibility is the penetration of a projectile by boring a hole through the center of a massive nucleus. The dynamics of such a deformed residual nucleus could be highly instructive. Other macroscopic models are statistical and thermodynamic or optical in character.

Microscopic models are based on the premise that important features of the interaction of two nuclei can be computed in a straightforward way from the scatterings of the various constituents out of which the nuclei are constructed. Elaborations of the Glauber model are promising. Other calculations making use of nucleon - nucleon cross section data can be made by the Monte Carlo technique to describe the cascade of collisions within the interacting nuclei. A major uncertainly is how to allow for coherent effects in which several nucleons participate in a collision.

Particle theorists suggest the application of Regge pole ideas to these heavy ion reactions. There might exist strong resemblances between objects with small and large baryon number. The interesting possibility is raised that nuclear reactions at a few GeV/nucleon might show features of particle reactions at hundreds of GeV.

Highly interesting papers on the possible existence of shock waves in reaction systems at Bevalac energies have been published by two groups of theorists {14,15}. These papers discuss the possibility of production of nuclear matter at several times normal density and the consequences of this abnormal density for pion production. The most startling and fascinating theoretical prediction to be made in the past few months is that of Lee and Wick {16,17} who predict that interaction of complex nuclei such as Pb + Pb at GeV/nucleon energy could lead to the production of new states of highly-dense nuclear matter never observed heretofore.

Acknowledgment

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Table 1

Expected Fluxes of Particles at Bevalac

Particle	Particles Per Pulse
^{1}H	4×10^{12}
^{2}H	5×10^{11}
^{3}He	10^{10}
^{4}He	3×10^{10}
^{12}C	6×10^{10}
^{14}N	3×10^{10}
^{16}O	3×10^{10}
^{20}Ne	10^{10}
^{40}Ar	5×10^{8}

Table 2

Physics Experiments Planned at Bevalac

Projectile Fragmentation

- Single particle inclusive spectra at forward angles for variety of projectiles and targets.
- Coincidence experiments, i.e. exclusive spectra at forward angles.
- Development and study of secondary beams.

Total cross section measurements

Target Fragmentation

- Radiochemistry
- Particle detector techniques
- Emulsion studies
- Track detector (mica, plastics)

Correlation between target and Projectile Fragmentation

- Emulsions
- Counter systems

Positive and negative particle production.

- Studies with p, d, α projectiles
- Studies with heavier ions

Production and study of high energy hypernuclei

- Search for super strange nuclei

Calibration of particle detection and identification systems for satellite and balloon flight experiments.

Range and ionization studies.

Figure Captions

Fig. 1	Sketch of Bevalac
Fig. 2	Layout of SuperHILAC, Bevatron and Beam Transfer Line.
Fig. 3	Magnetic spectrometer for O^{0} projectile fragmentation experiment {4,8}. Fragments of heavy ion beam $\left({}^{14}N \text{ or } {}^{16}O\right)$ produced within 12.5 mr of beam direction are focused along guide rail according to charge and mementum {4}.
Fig. 4	Momentum spectrum for the carbon isotopes produced by fragmentation of ${}^{16}O$ nuclei at 2.1 GeV/nucleon {4}.
Fig. 5	Longitudinal momentum distributions in projectile frame of fragments from ${}^{16}O$.
Fig. 6	Particle spectrum of fragments from target fragmentation in uranium targets bombarded with 5.5 GeV protons. Identification made with semiconductor telescope {10}.

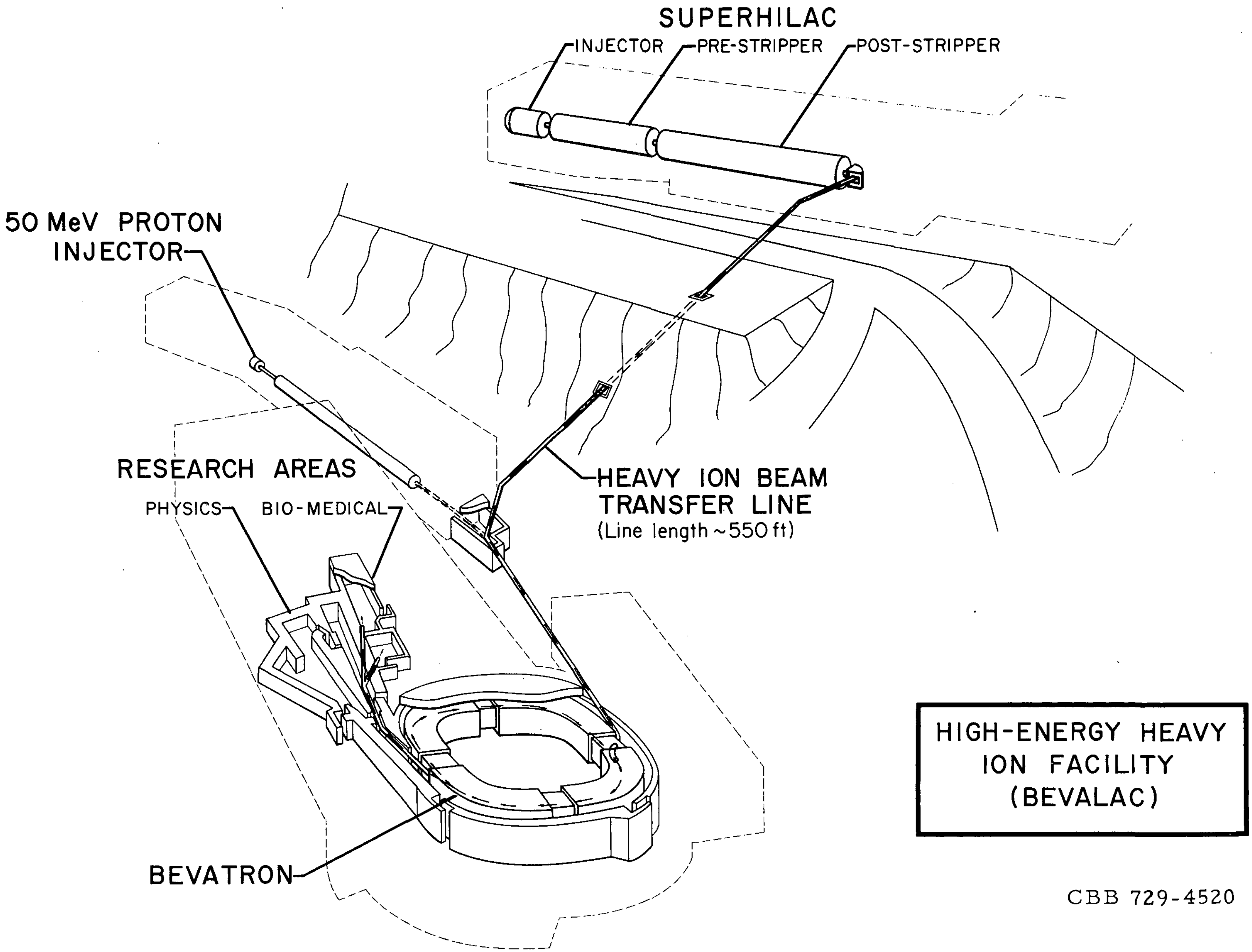

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Fig. 1

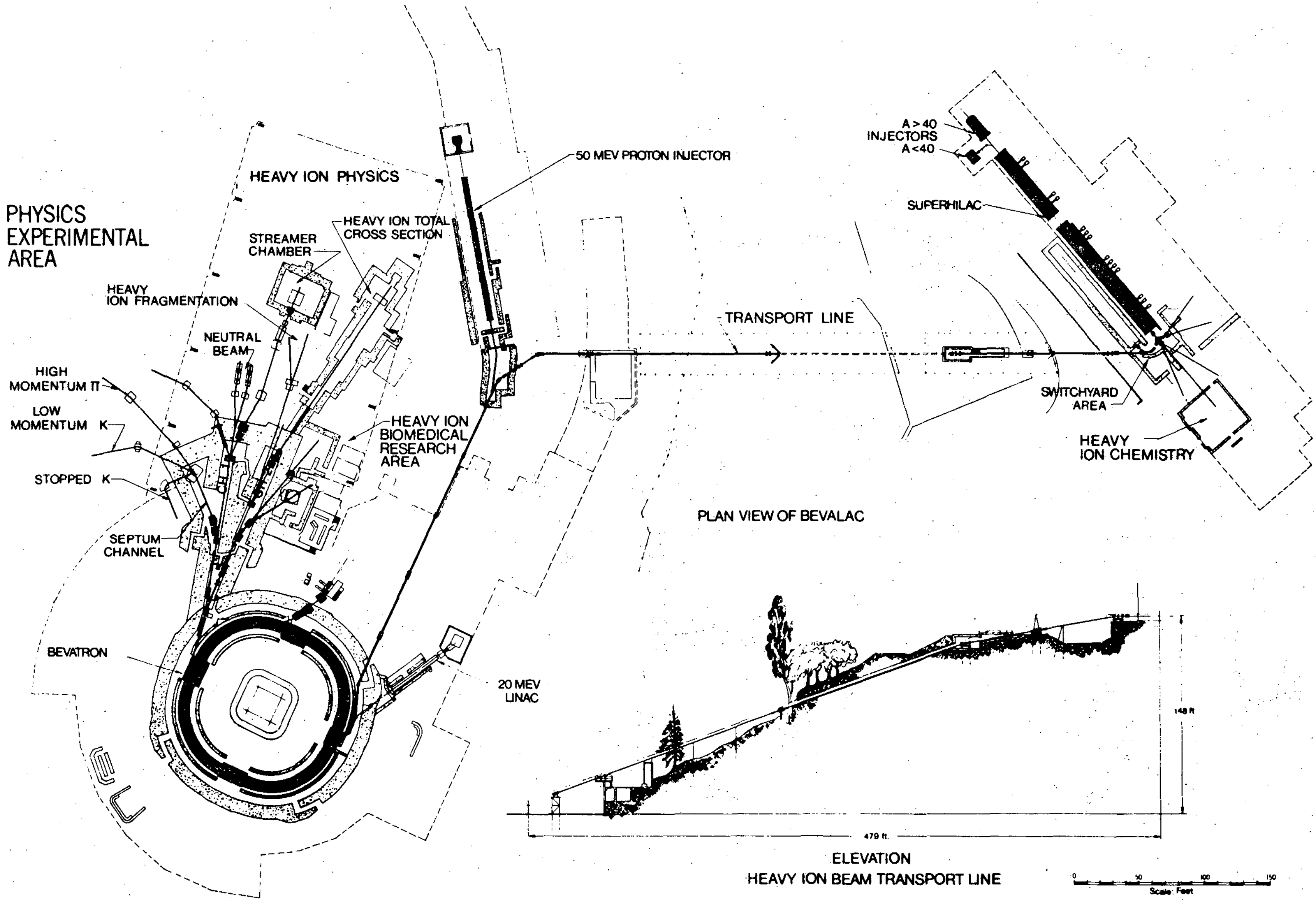

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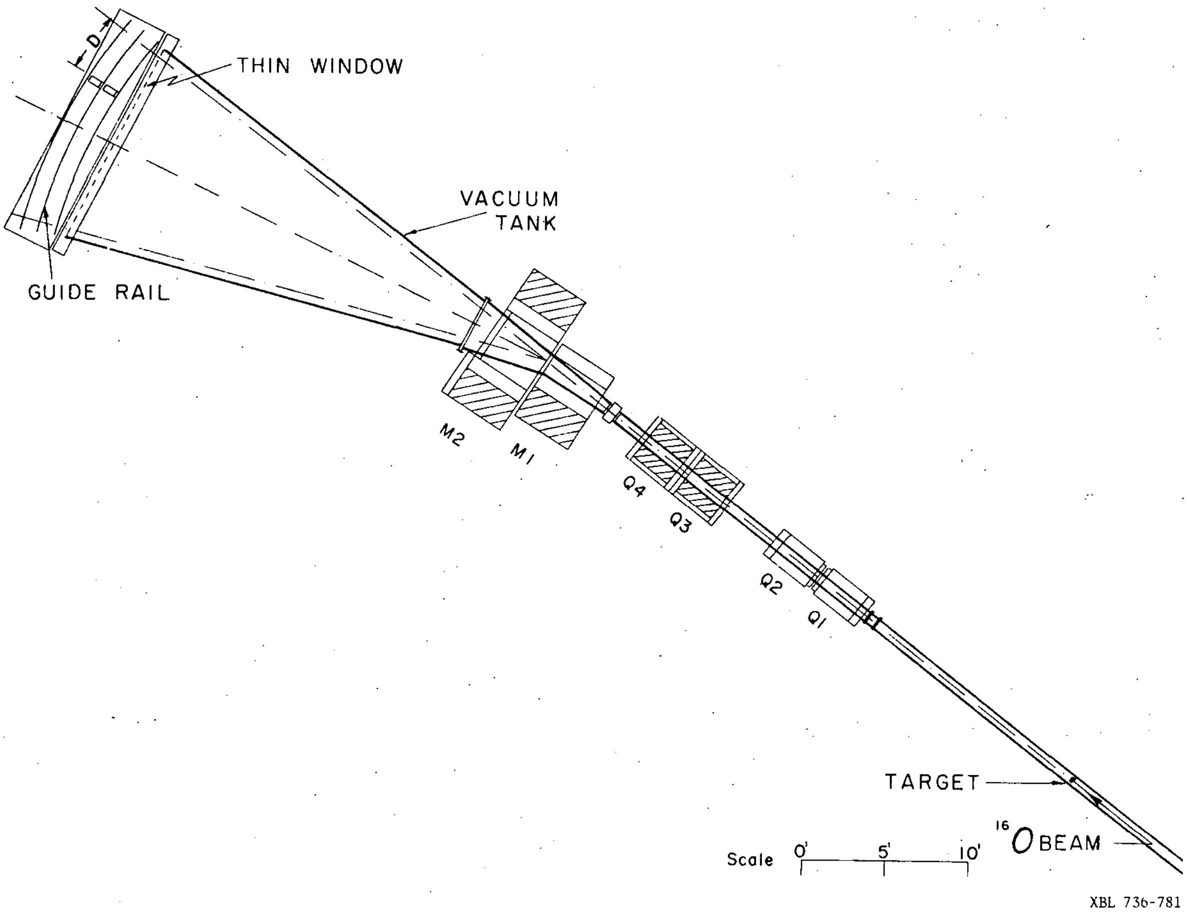
Fig. 2



THIN WINDOW
D
VACUUM
TANK
GUIDE RAIL
M2
M1
Q4
Q3
Q2
Q1
TARGET
^{16}O BEAM
Scale
0'
5'
10'
XBL 736-781

Fig. 3

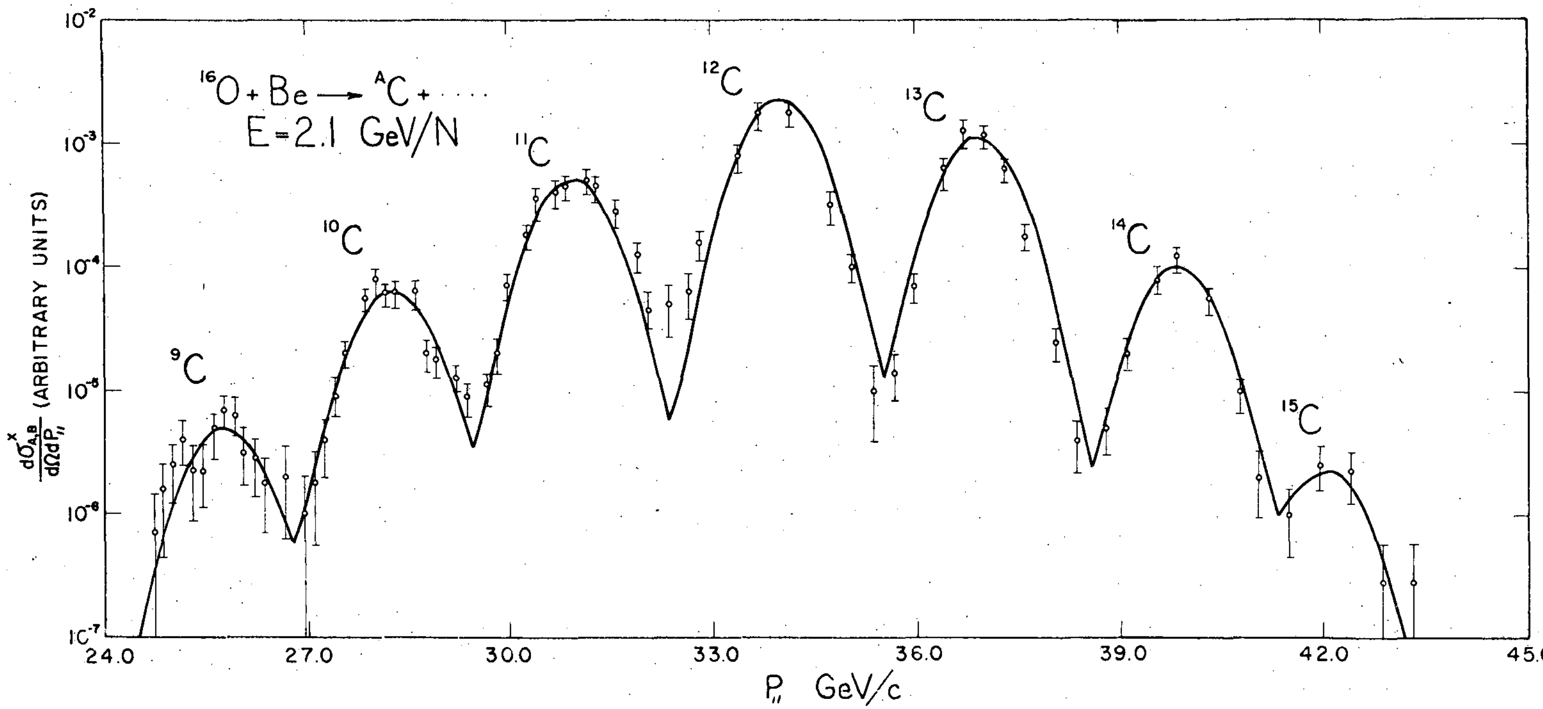


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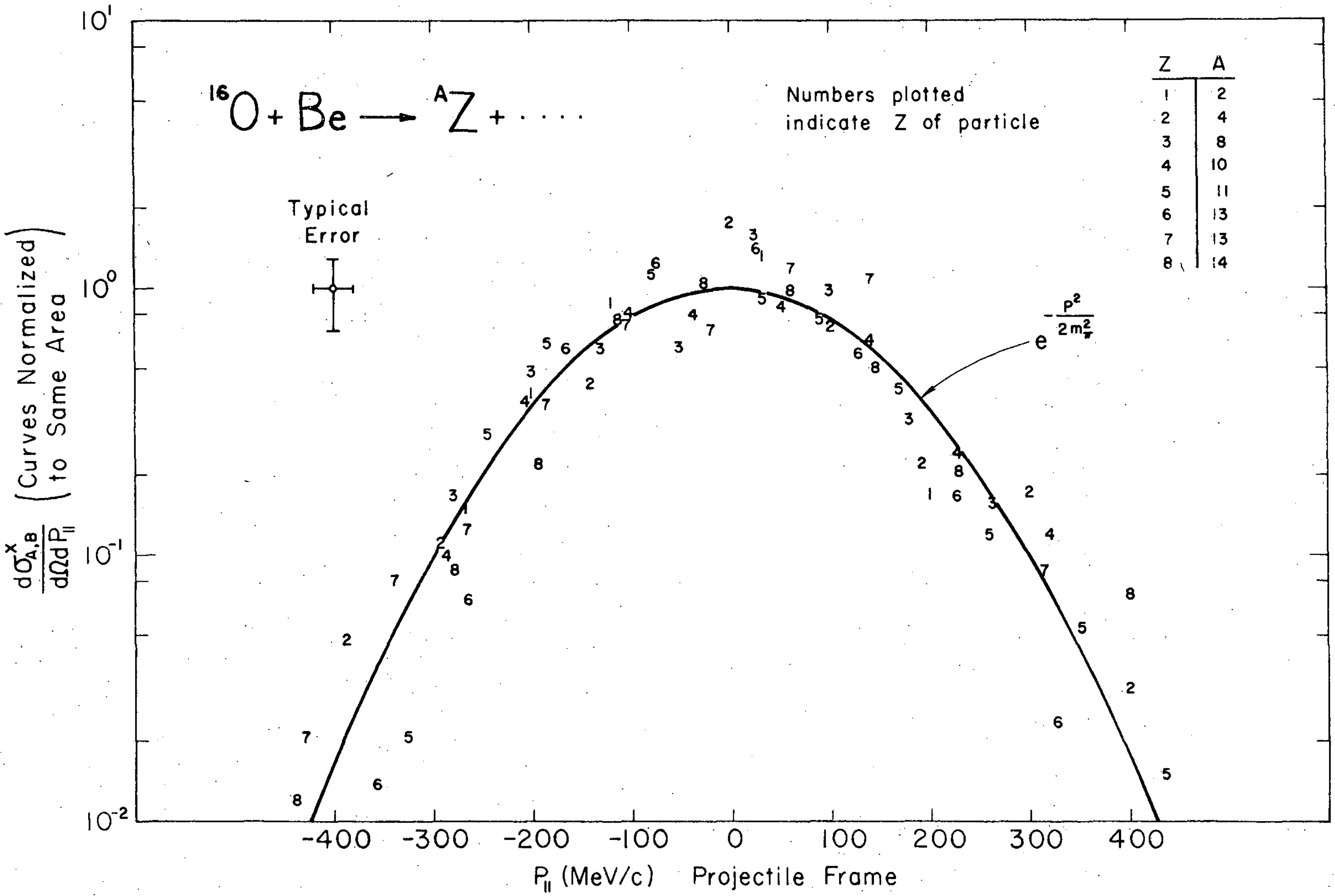
Fig. 4



XBL 736-779

Fig. 5

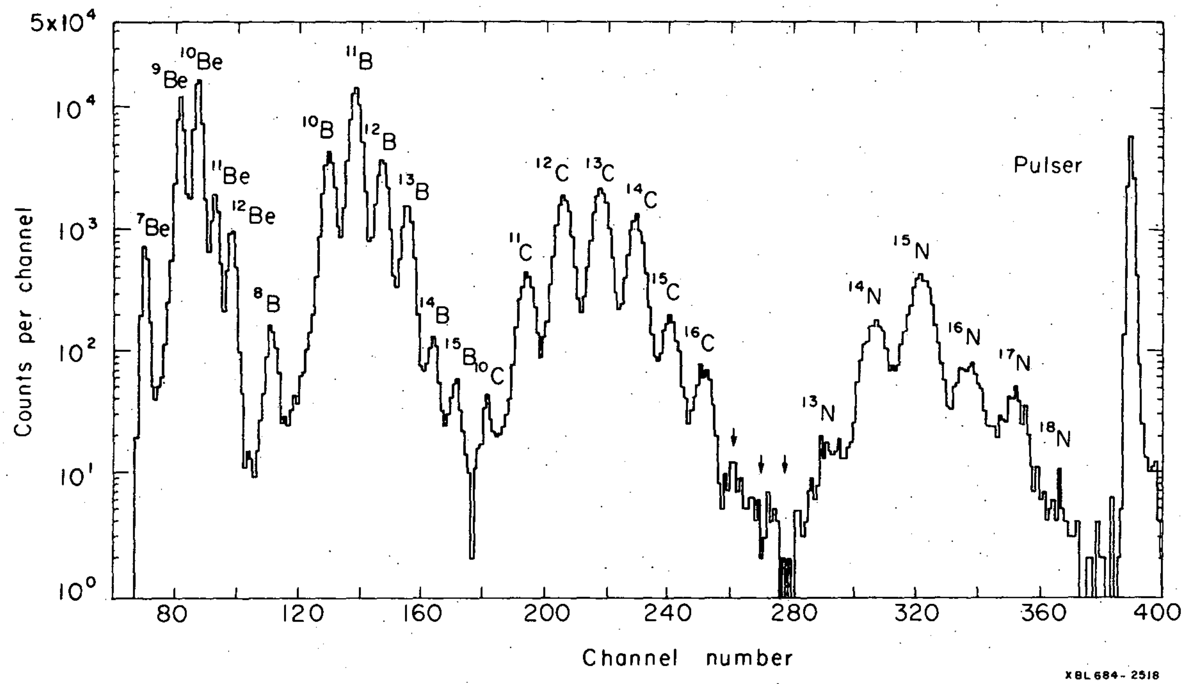

5x10⁴
10⁴
10³
10²
10¹
10⁰
Counts per channel
80
120
160
200
240
280
320
360
400
Channel number
⁷Be
⁹Be
¹⁰Be
¹¹Be
¹²Be
⁸B
¹⁰B
¹¹B
¹²B
¹³B
¹⁴B
¹⁵B
¹⁰C
¹¹C
¹²C
¹³C
¹⁴C
¹⁵C
¹⁶C
¹³N
¹⁴N
¹⁵N
¹⁶N
¹⁷N
¹⁸N
Pulser
XBL 684-2518

Fig. 6

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