Lawrence Berkeley National Laboratory
Recent Work

Title
HIGH ENERGY HEAVY IONS

Permalink
https://escholarship.org/uc/item/7q55v9xb

Author
Thomas, Ralph H.

Publication Date
1971-10-01

eScholarship.org Powered by the California Digital Library
University of California

Submitted to Physics Bulletin

RECEIVED
LAWRENCE
RADIATION LABORATORY

LIBRARY AND
DOCUMENTS SECTION

LBL-367
Preprint c.1

HIGH ENERGY HEAVY IONS

Ralph H. Thomas

October 1971

AEC Contract No. W-7405-eng-48

For Reference

Not to be taken from this room

LBL-367
c.1

DISCLAIMER

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

0 0 0 0 3 7 0 1 7 3 7

HIGH ENERGY HEAVY IONS

Ralph H. Thomas, Ph. D, F Inst. P

Lawrence Berkeley Laboratory, University of California
Berkeley, California 94720

Introduction

In August 1971, N^{7+} ions were accelerated by the Bevatron to hitherto unprecedented energies in the laboratory (Grunder, Hartsough, and Lofgren, 1971). The Bevatron, a 6.2 GeV proton synchrotron, has a long and spectacular history of research in high energy physics. Among its more widely known discoveries have been the anti-proton, the anti-neutron, and particle resonances.

This summer yet another significant achievement was added to the record of this accelerator, (an old friend of physicists in the United Kingdom) which incidentally also restored it, if briefly, to its former position of being the highest energy accelerator in the United States, – 36 GeV when nitrogen is accelerated.

There has been a long standing interest in heavy-ion research at Berkeley. Three cyclotrons are available for the production of ions up to ^{4}He. The 27 in. cyclotron can accelerate ^{3}He to a maximum energy of 18 MeV, the 88 in. cyclotron can accelerate alpha particles up to 130 MeV (32.5 MeV/nucleon), while the 184 in. synchrocyclotron can accelerate alpha particles to 910 MeV. Heavier ions, as heavy as argon, are accelerated to energies of 10 MeV/nucleon in the Hilac.

In 1966 in an attempt to extend the energy of this research, the laboratory proposed unsuccessfully the construction of the Omnitron, a multipurpose accelerator with a capability of accelerating heavy ions, He through U, up to 500 MeV/nucleon.

During the past two years the Hilac has been converted to have the capability of accelerating ions as heavy as uranium to energies of 8.5 MeV/nucleon at an intensity of 10^{11} ions/s. One of the major missions of this new Super Hilac, expected to operate in 1972, will be to study superheavy element production.

Chapman (1969) and Hooton (1970) have summarized some of the heavy ion accelerators in operation or proposed for construction around the world. In general the maximum energy of heavy ion beams in the laboratory was, until the recent development described here, limited to about 100 MeV.

At the Princeton particle accelerator, efforts similar to those at Berkeley are under way, nitrogen ions having been accelerated to 0.280 GeV/nucleon.

Scientific interest in heavy ions

A previous article (Hooton 1970) has summarized some of the reasons for the intense interest in the use of heavy ions as projectiles: studies of coulomb excitation, nuclear structure, momentum effects, and the production of superheavy elements. [The latter given impetus by the report of the observation of element 112 in tungsten targets subjected to long exposure to 24 GeV protons (Marinov, Batty, and Kilvington, 1971). Since the production of element 112 was probably effected

0 0 0 0 3 7 0 1 7 5 8

by the interaction of an energetic tungsten nucleus recoil with a tungsten nucleus it seems highly probable that the bombardment of uranium with heavy ions energetic enough to surmount the coulomb barrier will be very effective in producing new elements.]

Further interest in the use of heavy ions derives from cosmic ray research and radiobiology. The composition of galactic radiation near the earth is determined first by the mechanism of its production and acceleration to high energies but ultimately from its fragmentation due to interaction with the interstellar gas (principally hydrogen) during its journey toward the earth. Reliable measurements of the fragmentation of light (C, N, O), medium ($9 \leq Z \leq 14$) and heavy (Fe) nuclei in hydrogen and air, particularly with respect to production of light nuclei (D, T, and ^{3}He), would provide means of testing theoretical models of the origins of the galactic radiation.

The use of heavy ions in radiobiology is of great interest both in a fundamental and practical sense. Radiation injury in mammals at the cellular level is strongly dependent upon the density of ionization of the incident and the presence (or absence) of oxygen during irradiation. Anoxic cells are about three times as resistant to radiations with low ionization density (e.g. x-rays, γ-rays, electrons). [This damage ratio has been designated the Oxygen Enhancement Ratio (OER).]

The central regions of large tumours are, in general, deprived of nutrients including oxygen. The presence of anoxic cells in a tumour can therefore lead to a substantial increase in the radiation

exposures necessary for therapy. Unfortunately, the most convenient and frequently used types of radiation presently used in radiotherapy are lightly ionizing.

Several techniques have been proposed for at least, redressing this unfortunate imbalance and improving the relative damage to the cancer cells. Work in the United Kingdom has been directed toward the use of hyperbaric chambers and high energy neutron therapy. Recently experimental radiobiological studies have started at the Rutherford laboratory exploring the possibilities of stopping π^- mesons following suggestions of workers at Bristol (Fowler and Perkins 1961).

As the density of ionization of radiation increases, the OER falls, reaching unity at $dE/dx \sim 1650$ MeV/g/cm^2. An alternative to producing densely ionizing particles within the body by nuclear interaction is to use primary radiation which itself has a high stopping power. Radiobiological experiments with beams of heavy ions of energy 10 MeV/nucleon are encouraging but it is vital that such studies be repeated with particles whose ranges are comparable to the dimensions of the human trunk. (The range of 200 MeV/nucleon nitrogen ions is 10g cm^{-2} of water). Physical studies of ion fragmentation in tissue-like materials, energy loss mechanisms as well as radiobiological studies will be necessary before any attempt on human treatment is undertaken. Theoretical studies are extremely encouraging in suggesting, however, that some specific tumours may respond well to irradiation by heavy ions, perhaps as heavy as neon. The production of energetic nitrogen-ion beams at the Bevatron makes such studies feasible.

0 0 0 0 3 7 0 1 7 3 9

Preparations for acceleration

Based on experience at the 33 GeV proton synchrotron of the Brookhaven National Laboratory, Piccioni (Lander et al. 1963) suggested that neutron beams of good momentum resolution could be obtained by bombarding heavy targets with energetic deuterons. In 1970, the Bevatron scheduling committee urged this be attempted. At the time of the Chicago Particle Accelerator Conference (March 1971) (which stressed the interest of ionizing particle acceleration for radiotherapy), discussions between A. Ghiorso, director of the Hilac, and E. J. Lofgren, director of the Bevatron, gave birth to the idea of the Bevalac in which the Super Hilac would be used as an injector for the Bevatron, in the production of heavy ions in the GeV/nucleon energy range. (The Bevatron is a complex of three separate accelerators and fig. 1 schematically illustrates the acceleration and detection system used in the experimental program.)

The logistics of a program designed to successfully accelerate deuterons in the Bevatron suggested that all particles with $e/m = 1/2$ might also be accelerated. Nitrogen ions at intensities of $\sim 10^5$ ions per pulse were anticipated. Several factors led to this conclusion. The age of the Bevatron (17 years) was a decided advantage in this instance because it has permitted a deep and thorough understanding of the accelerator by the operations and development team. The Bevatron has been developed until its operation is extremely stable in all phases from injection to extraction–a fact of paramount importance as we shall show later. Finally, advances in accelerator technology,

particularly in the uses of on-line computers to control the radio-frequency supply and extraction field, played an extremely important role.

In planning for the acceleration of heavy ions several departures from the operational modes used to accelerate protons were necessary. The logical progression was to attempt to accelerate ions in the relative order of the intensities in which they could be produced by the ion sources.

Ion source The ion normally used at the Bevatron is a duoplasmatron. Such sources yield high currents of ions in low charge states and it was therefore possible to use the normal source to produce $^{2}H^{+}$ and $^{4}He^{2+}$ ion beams for the acceleration of deuterons and alpha particles. However, extremely small ion currents of high charge states are produced. It was therefore necessary to construct a cold-cathode Penning discharge source of the type already developed at Berkeley for the Hilac. Figure 2 shows the output of the various charge states of such a source as determined by a mass spectrometer.

Nitrogen ions are produced in intensities which decrease by a factor of approximately 3 for each integral increase in charge number. Approximately 40 μA of N^{5+} ions could be produced by the ion source and this represented the lowest current that would produce an acceptable intensity of extracted energetic heavy ions. It was ncessary, therefore, to accelerate N^{5+} ions through the linear accelerator.

No changes were necessary in the Cockroft-Walton preinjector.

0 0 0 0 3 7 0 1 7 6 0

Linac injector The linac injector is designed to accelerate protons (e/m = 1) along its drift tube structure to energies of 19.2 MeV using the fundamental frequency of a 200 MHz rf supply (the so-called $\beta\lambda$ mode). It is possible, however, to accelerate particles of smaller e/m ratios on subharmonics of the fundamental frequency, albeit with less efficiency. Thus particles with e/m = 1/2 can be accelerated in the 2 $\beta\lambda$ mode to velocities half those attained by protons accelerated in the 1 $\beta\lambda$ mode. In consequence, particles with e/m = 1/2 may be accelerated to energies of about 5 MeV/nucleon in this manner with an efficiency of about 10% compared to the 1$\beta\lambda$ mode.

As the charge-to-mass ratio decreases below the value of 1/2 it is necessary to correspondingly increase the electrical field gradient, $\mathcal{E}$, to maintain synchronism in acceleration. The parameter ($\mathcal{E} \cdot$ e/m) must be conserved. Thus for $^{14}N^{5+}$ ions with e/m = 0.357 the field gradient must be increased by a factor of 1.4 while for $^{12}C^{4+}$ ions with e/m = 0.333 the increase required is a factor of 1.5.

Such an increase in field gradient on a linear accelerator is obtained only by a prolonged period of "baking-in", in which the voltage is gradually increased and spark-gaps are added to the system to rapidly absorb the energy in any unduly large breakdown. The 50% increase in field gradient required, militated against an attempt to accelerate $^{12}C^{4+}$ ions although they are produced more abundantly than N^{5+} ions by the source.

After the event it became clear that a voltage gradient adequate to accelerate $^{12}C^{4+}$ could indeed be obtained. It is anticipated that

attempts to accelerate carbon ions will be made early in 1972.

Identification of the accelerated particles at the high energy end of the linac was achieved by range separation. A foil of density 1 mg/cm^2 was adequate to remove low energy particles that drift along the accelerating structure, and a 24 mg/cm^2 foil stopped $^{14}N^{5+}$ ions at 5 MeV/nucleon but would not stop, if they were accelerated, protons, deuterons, or alpha particles. Simple difference measurements with a Faraday cup and two absorbers were therefore capable of demonstrating the acceleration of nitrogen to 5 MeV/nucleon.

Stripping foil To be accelerated by the same Bevatron rf program used for deuterons and alpha particles it was necessary to convert the N^{5+} ions ($e/m \approx 1/3$) to ions with $e/m = 1/2$. (It might have been possible to accelerate $e/m = 1/3$ particles on the third harmonic of the rf system but this was judged to present some difficulties.) Furthermore, ions in a high charge state, but not fully stripped (e.g. $^{14}N^{5+}$ ions) have a high recombination cross section at low velocities. The pressure in the Bevatron vacuum tank is 10^{-6} torr and theoretical estimates showed that with the acceleration cycle of the Bevatron it would not be feasible to accelerate $^{14}N^{5+}$ ions injected at 5 MeV/nucleon. $^{14}N^{7+}$ ions were needed for injection for there to be any significant beam survival. Estimates of loss varied from a factor of 3-10. An aluminum stripping foil of density 40 μg/cm^2 was therefore used at the high energy end of the linac to convert the particles to $^{14}N^{7+}$ with an efficiency of about 50%.

0 0 0 0 3 7 0 1 7 6 1

After stripping the nitrogen ions will have e/m = 1/2 and will behave in a similar fashion as deuterons or alpha particles in the injection channel into the synchrotron. Approximately 10^9 nitrogen ions per pulse were available for injection.

Bevatron proper (synchrotron) The first few turns of the ions in the Bevatron vacuum chamber are crucial to their survival. As we have discussed, at their injected energy of 5 MeV/nucleon the probability of electron capture is quite high. However, the particles are rapidly accelerated and because the recombination cross section is roughly inversely proportional to β^7 (β is the particle velocity), their recombination rapidly becomes unlikely. Of the particles injected and selected as suitable for acceleration only about one-third survive recombination. Reduction of this loss may be achieved by either improving the vacuum conditions within the accelerating chamber or by increasing the injection energy.

Loss of ions from trapping and acceleration, and from ion recombination reduced the high energy beam intensity to 7×10^5 nitrogen ions per pulse.

Particles can be accelerated to energies determined by their radius of curvature in the magnetic field: for deuterons, this maximum is 5.2 GeV; for alpha particles, 10.4 GeV. Energies as low as 280 MeV/nucleon may presently be obtained–a limit imposed by the design of the extractor system.

Synchrotron radiofrequency system When accelerating protons, the initial oscillator frequency is 0.494 MHz increasing with particle energy by a factor of five to a maximum value of 2.47 MHz. When accelerating particles of e/m = 1/2, the velocity of the injected particle is reduced requiring an initial frequency roughly a factor of two lower than normal.

Two alternatives were therefore open: Either to initially to accelerate on the second harmonic of the rf system, switching back to the first harmonic at an appropriate point in the acceleration cycle and suffering an inevitable loss of beam at the change-over, or to extend the frequency swing of the rf system by a factor of two and accelerate on the first harmonic. The latter alternative is preferable because it avoids the loss of beam involved in the former. It is fortunate that the original design of the rf system was sufficiently conservative that such a requirement could be accommodated.

Beam control system Under normal operation, with intensities of $\sim 10^{13}$ protons per pulse, the acceleration cycle parameters (e.g. magnetic field rise, oscillator frequency) are controlled by a closed-loop system which obtains information from beam-sensing electrodes. The amplitude of the signal from these electrodes was adequate when accelerating deuterons (2×10^{11} particles circulating) but marginal with alpha particles (10^{10} particles circulating).

When attempting to accelerate nitrogen ions it was therefore necessary to tune the accelerator with alpha particles (which may also

0 0 0 0 0 7 0 1 7 6 2

be obtained from the ion source). The frequency program and the settings of the fifteen magnets used in the extraction system were then stored on magnetic tape. The great stability of the accelerator then made it possible to go "open loop". Nitrogen ions were injected and the acceleration controlled completely by computer; the last signal observed prior to acceleration being the Faraday cup signal at injection. No signals monitoring the beam were then obtained until it was observed, after extraction, in the experimental detectors.

Particle extraction from the synchrotron Two systems of proton extraction are in use at the Bevatron, either the energy loss (or Piccioni) extraction or the resonant extraction in which a resonance of the radial motion of the particles is excited by a controlled perturbation in the magnetic field. The former system depends, as its name suggests, upon producing a small energy loss in the circulating beam by a thin target. It is vital in the acceleration of nitrogen ions that the accelerator to first tuned with alpha particles; however, (dE/dx) of the alpha particles differs from that of the nitrogen ions, the energy loss system is impracticable and therefore, the resonant extraction system is utilized.

Beams energy greater than 1 GeV/nucleon may be extracted with an efficiency of 60% by this method, which equally deflects all particles of the same rigidity, $B\rho$ (B = guidefield intensity, ρ = particle radius of curvature). Thus once the extraction and beam guiding system has been tuned for protons or deuterons it will be equally correct for nitrogen ions of the same rigidity.

Acceleration of heavy ions – August 1971

During August an attempt was made to demonstrate the feasibility of accelerating heavy ions in the Bevatron: On August 2 deuterons were readily accelerated and within only 8 hours from the initial attempt, they were extracted at an energy of 2.1 GeV/nucleon intensities of ~ 3×10^{10} (subsequently increased to ~ 10^{11}) deuterons per pulse.

On August 6, alpha particles at the same energy were extracted at an intensity of 5×10^{9} particles per pulse, followed by a reduction in energy to 1 GeV/nucleon on August 12. August 17 saw the successful acceleration of nitrogen ions to 2.1 GeV/Nucleon at an intensity of 2×10^{5} particles per pulse. At this point in the program it was necessary to investigate the accelerator parameters for particle extraction at 250 MeV/nucleon. On August 22 alpha particles were extracted, and by August 24, nitrogen ions. Table 1 summarizes the intensities of the heavy ion beams extracted from the Bevatron.

Identification of nitrogen ions after acceleration The process of acceleration imposes such a stringent set of constraints upon particles that, after confirmation that $^{14}N^{7+}$ ions are injected into the Bevatron, it is extremely unlikely that unwanted particles could be inadvertantly produced. Nevertheless it is prudent to directly confirm that $^{14}N^{7+}$ ions were indeed accelerated.

Ilford G-5 nuclear emulsions were exposed to the beam. The track densities observed, immediately showed that the incident particles were more heavily ionizing than proton, deuteron, or alpha particles of the same energy. Detailed grain counting can positively

identify the tracks as having been produced by $^{14}N^{7+}$ ions. Interactions in the emulsion are most spectacular, as may be seen from Fig. 3.

Emulsion scanning is a laborious process and more immediate evidence was necessary. It was most fortunate that a particle identification system had been developed in a joint effort by the Lawrence Berkeley Laboratory and the Space Sciences Laboratory (both of the University of California, Berkeley) for use in satellite flights. The system consists of 9 lithium drifted silicon detectors (all 2.5 cm in diam and 3 or 5 mm thick) placed end to end (Heckman et al). Figure 4 shows the telescope used in these experiments. The passage of a charged particle through the telescope produces a set of pulse heights from each detector, which is characteristic of the charge of the incident particle. Should the particle stop in the detector system, its energy and mass can also be determined.

This detector was applied to an examination of the purity of the beam extracted from the Bevatron. Measurements showed that 90-95% of the beam consisted of $^{14}N^{7+}$ ions, while the impurities, helium, lithium, boron, and carbon, probably were produced by fragmentation of the nitrogen ion during the extraction process.

The beam purity was found to depend initially upon the quantity of material in the beam path. Reduction of intensity by the use of either constricting collimators or an absorber was shown to be inadvisable, such adjustments being better made by changes in the time of injection into the synchrotron.

Brief survey of experimental program, August 1971 At each stage of the production of extracted beams some experimental work was performed (Cagle et al. 1971, Heckman et al. 1971, Tobias et al. 1971):

Preliminary investigation of the feasibility of producing neutron beams by stripping high energy deuterons is encouraging. From data obtained in a short run it appears practicable to produce neutron beams of $\sim 10^7$ neutrons per pulse with momentum spread of ~6% from 4 GeV deuterons.

Preliminary data on the fragmentation of 1- and 2-GeV/nucleon alpha particles in a variety of targets [$(CH_2)_n$, C, Si] at 0° were obtained with no magnetic analysis. Studies of the fragmentation products from 2.1-GeV/nucleon nitrogen ions at 0° in $(CH_2)_n$, C and Pb targets were performed. The experimental target was placed at the first focus of the extracted beam and the external proton beam channel used as a magnetic spectrometer to analyze the fragments produced. Preliminary measurements show that the heavy fragment ($Z > 2$) production is at a maximum when the velocity of the fragment is very close to that of the incident nitrogen ion. In consequence, the intensity of a particular fragment of mass M charge Ze exhibits a sharp maximum as the rigidity of the particles transmitted by the magnetic spectrometer is varied. The maximum intensity is observed at a rigidity R_{max} given by: $R_{max} = (M/Ze)\beta\gamma$ and $\beta\gamma$ takes on the value for the incident beam. This is illustrated in Fig. 5 where the spectra for fragments produced in the forward direction from a carbon target

0 0 0 0 3 7 0 1 7 6 3

are shown at settings of 5.0 and 6.2 GV for the rigidity of fragments transmitted by the spectrometer. At R = 5.0 GV ^{7}Be is seen to be predominantly produced with a $\beta\gamma = 3.06$ to be compared with 3.10 for the beam. At R = 6.2 GV the production of particles with Z = 6 dominates and simple arguments show the peak to be due to $^{6}C^{13}$ (with $\beta\gamma = 3.07$). Figure 6 shows the detailed shape of the variation of intensity for the production of ^{7}Be with $\beta\gamma$. Figure 7 shows a schematic representation of the rigidity of fragments of Z = 1 to 8 assuming $(\beta\gamma)_{beam} = 3.10$. Such preliminary experiments have provided identification for the production of all the nuclides shown in Fig. 7 with $A \leq 14$, $Z \leq 7$ in the rigidity range 4.1 to 6.7 GeV set by the spectrometer.

Incidental to these measurements are the important experimental checks on theoretical calculations of the range and energy loss of heavy ions in silicon, which derive from the calibration of the particle telescope. Emulsions (both plates and a large stack) were exposed to alpha particles and nitrogen ions. Subsequent analysis will permit determination of the interaction mean free path, interaction characteristics and Coulomb-scattering parameters in emulsion.

In the field of nuclear chemistry, track registration techniques were used to study the binary (and higher order) fission cross section for 2 GeV/N nitrogen ions in heavy targets (U, Au, Ta, and Ag). In addition, a search is being made for the production fragments with $Z > 10$ and energy greater than 5 MeV/N produced by ^{14}N bombardment of Au and U targets.

Some preliminary activation studies by 250 MeV/N nitrogen ions in Be targets showed the production of ^{11}C and ^{13}N. These radionuclides are observed at well-defined depths in the target suggesting that they were produced in a completely ionized state as the result of fragmentation of the primary ions and are then stopped in the target at a depth corresponding to the charge state of the fragments. Other target materials are being investigated.

Typical of the radiobiology experiments is one carried out by a team the Ames Laboratory of NASA in which some 56 pocket mice (Perognathus longimembris) were irradiated by the 250 MeV/N nitrogen ion beam. In most cases the Bragg peak was located in the brains of the animals or in adjacent tissue. Both animals that were examined were found to be radioactive after irradiation.

A wide range of tissues were irradiated and will be studied for pathological conditions. The biological end points that will be studied include glycogen accumulation, nerve cell pyknosis, nerve cell injury or loss and glial reaction. Four irradiated animals were injected with tritrated thymidine and will be used to study DNA repair. Some mice with radiation detectors implanted in the scalp were irradiated and attemps will be made to relate any observed lesions to particle tracks in these detectors.

Other experiments included

(a) Study of chromosmal damage to irradiated leucocytes.

(b) Effects of irradiation by heavy ions on the skin and the retina of small animals.

(c) Determination of the OER for cultured mammalian cells.

Incidental to these experiments, was the confirmation of the theoretical predictions of energy loss of nitrogen ions in water.

Perhaps one of the more dramatic experiments was related to space missions. Following the reports of the observation of flashes of light by the astronauts of the Apollo 12 and 13 missions, several attempts have been made to reconstruct these effects in the laboratory. Hitherto subjects have exposed themselves to x rays, neutrons, pions, and alpha particles. It has been postulated that the reported flashes are due to the interaction of heavily ionizing particles in the retina of the eye. The production of nitrogen ions by the Bevatron provided an ideal opportunity to study the mechanism of "eye flash" production. All the subjects whose retinas were irradiated observed the flashes, but attempts to stimulate visual sensations by irradiating the aqueous humour of the eye or the occipital lobe of the brain (visual cortex) failed. In addition, preliminary measurements were made of the efficiency of production of light in the uv and visible region by heavy ion interaction with tissue-like material.

Conclusions

The production of high energy nitrogen ion beams at the Bevatron has opened up exciting possibilities. Significant experimental information has already been obtained. Further experiments are planned early in 1972. A study to improve the heavy-ion facility at the Bevatron is now underway. If the Hilac were used as an injector to the Bevatron,

beams of $^{20}Ne^{10+}$ and an intensity of 10^{10} ions per pulse or $^{45}Ar^{20+}$ at an intensity of 10^{9} ions per pulse could be obtained.

This brief discussion of the scientific interest in the use of heavy ion beams is by no means exhaustive. There is much interest in studying the ionization processes of heavy ions, in particular the electron-recombination cross sections. Nuclear chemists wish to study the fission cross sections for incident heavy particles; activation studies are of great interest, and the availability of energetic heavy ion beams will provide a reliable means of calibrating the mineral and plastic track registration detectors now being applied to the study of geophysical phenomena. Studies of the radiation damage to rocks taken from the lunar surface may yield information on the history of cosmic radiation. There seems to be no doubt that the availability of heavy ion beams opens up many exciting avenues!

Acknowledgments

The author is privileged to be able to report this work that involved the direct participation of something like 100 people. More detailed descriptions of the modifications in Bevatron operations will appear in the proceedings of the conference held in October in Gatlinburg, Tennessee on heavy ion acceleration.

It is a pleasure to acknowledge the helpful advice and comments of Harry Heckman, Fred Lothrop, and Emery Zajec on the form and content of this paper.

Work done under the auspices of the U. S. Atomic Energy Commission.

0 0 0 0 3 7 0 1 7 6 4

FURTHER READING

Cagle D, Lothrop F, Grunder H and Thomas R H 1971 Lawrence Berkeley Laboratory Monthly Report for August (Bev-2031) Sept. 1

Chapman K R 1969 Physics Bulletin 21 415

Fowler P and Perkins D H 1961 Nature 189 524

Grunder H A, Hartsough W D and Lofgren E J 1971 "Heavy ion beams at the Bevatron I Acceleration of heavy ions at the Bevatron" Lawrence Berkeley Laboratory Report LBL-345. Submitted to Science for publication

Heckman H H, Greiner D E, Lindstrom P J and Bieser F S 1971 "Heavy ion beams at the Bevatron II Fragmentation of ^{14}N nuclei at 2.1 GeV/nucleon" Lawrence Berkeley Laboratory Report LBL-345. Submitted to Science for publication

Hooton B W 1970 Physics Bulletin 21 389

Lander R L, Piccioni O, Xuong N H, and Yager P M 1963 Proc. Sienna Int. Conf. on Elem. Particles Vol I Bologna, Societa Italiana di Fisica 1963 651

Marinov A, Batty C J and Kilvington A 1971 Nature 229 464

Tobias C A, Lyman J, Chatterjee A, Howard J, Maccabee H, Welch G, Smith A R and Sperinde J 1971 "Heavy ion beams at the Bevatron III Radiological physics characteristics of the extracted heavy-ion beams of the Bevatron" Lawrence Berkeley Laboratory Report LBL-345. Submitted to Science for publication

Table 1. Extracted intensities (particles/pulse) for various extracted beam energies

Particle	Energy (GeV/ Nucleon) E = 2.1	E = 1	E = 0.28	Ion source used
Deuterons	10^{11}	not attempted	2×10^{10}	D
Alphas	5×10^{9}	5×10^{9}	10^{9}	D, P
Nitrogen ions	7×10^{5}	not attempted	1.4×10^{5}	P

D - Duoplasmatron

P - Penning

0 0 0 0 3 7 0 1 7 6 5

FIGURE CAPTIONS

Figure 1 Schematic diagram of the Bevatron acceleration systems for heavy-ion work

Figure 2 Output of various charge states from ion source

Figure 3 At a point above the scale marker an incident $^{14}N_7$ ion fragments into two He and three H isotopes. Beam energy is 2.1 GeV/nucleon. (Ilford 6.5 emulsion).

Figure 4 Silicon solid-state detector counter-telescope

Figure 5 Spectra of the rates of energy loss (1 channel = 6.8 MeV), of the fragmentation products of 2.1 GeV/nucleon ^{14}N ions. Rigidities (momentum per unit charge) are 5.0 GV and 6.2 GV. The elements hydrogen (Z = 1) through nitrogen (Z = 7) are indicated by their atomic numbers Z. These data are the direct read-outs of the particle identifier, and are unprocessed. The target material was carbon

Figure 6 The observed spectral shape of the ^{7}Be isotope, uncorrected for energy loss in the target and resolution of the detector-spectrometer system, versus $\beta\gamma$. The arrow indicates the $\beta\gamma$ of the incident ^{14}N beam

Figure 7 Diagram of the rigidities R at which various isotopes of hydrogen through oxygen will be observed when their velocities are equal to that of the 2.1 GeV/nucleon ^{14}N beam. At this energy, ^{14}N ions have a rigidity R = 5.78 GV. The arrows indicate the rigidities at which the data shown in Fig. 5 were taken

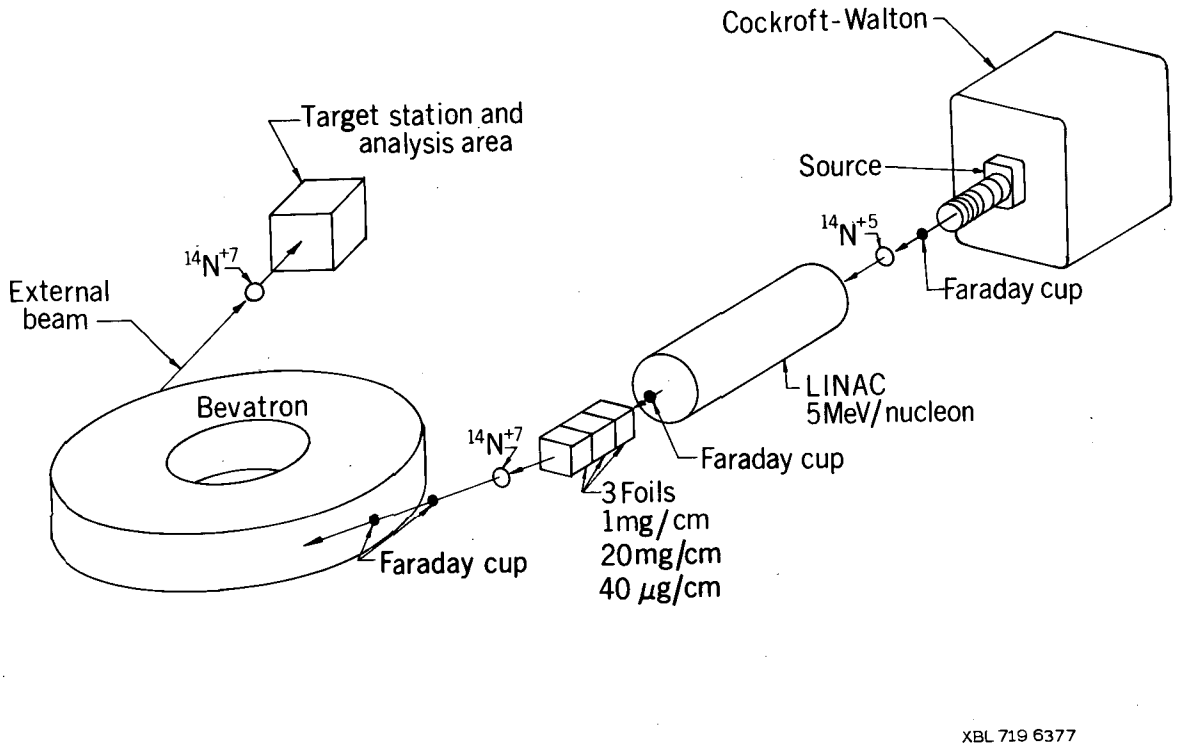

Cockroft-Walton
Target station and analysis area
Source
$^{14}N^{+5}$
$^{14}N^{+7}$
External beam
Faraday cup
LINAC
5MeV/nucleon
Bevatron
$^{14}N^{+7}$
Faraday cup
3 Foils
1mg/cm
20mg/cm
40 μg/cm
Faraday cup
XBL 719 6377

Fig. 1

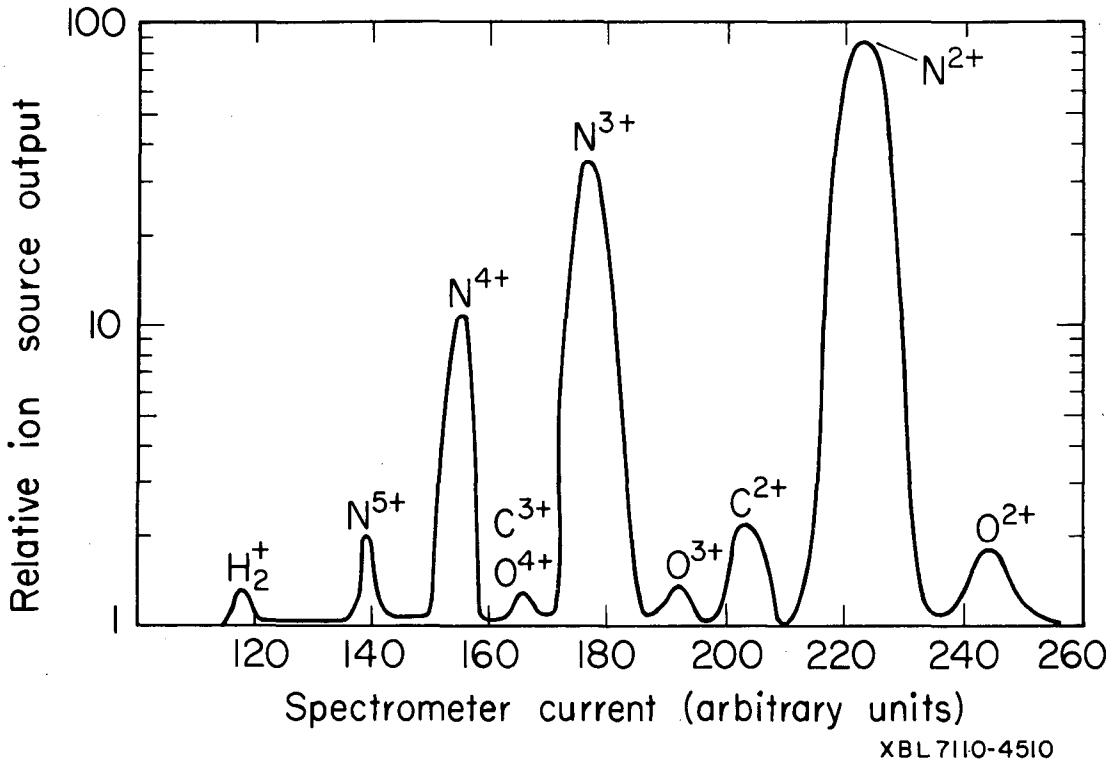

100
10
1
Relative ion source output
H_2^+
N^{5+}
N^{4+}
C^{3+}
O^{4+}
N^{3+}
O^{3+}
C^{2+}
N^{2+}
O^{2+}
120
140
160
180
200
220
240
260
Spectrometer current (arbitrary units)
XBL 7110-4510

Fig. 2

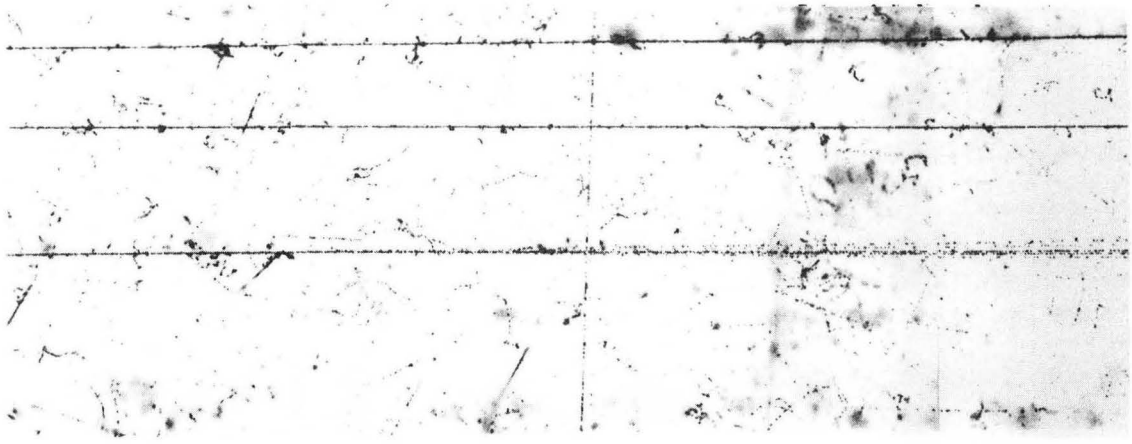
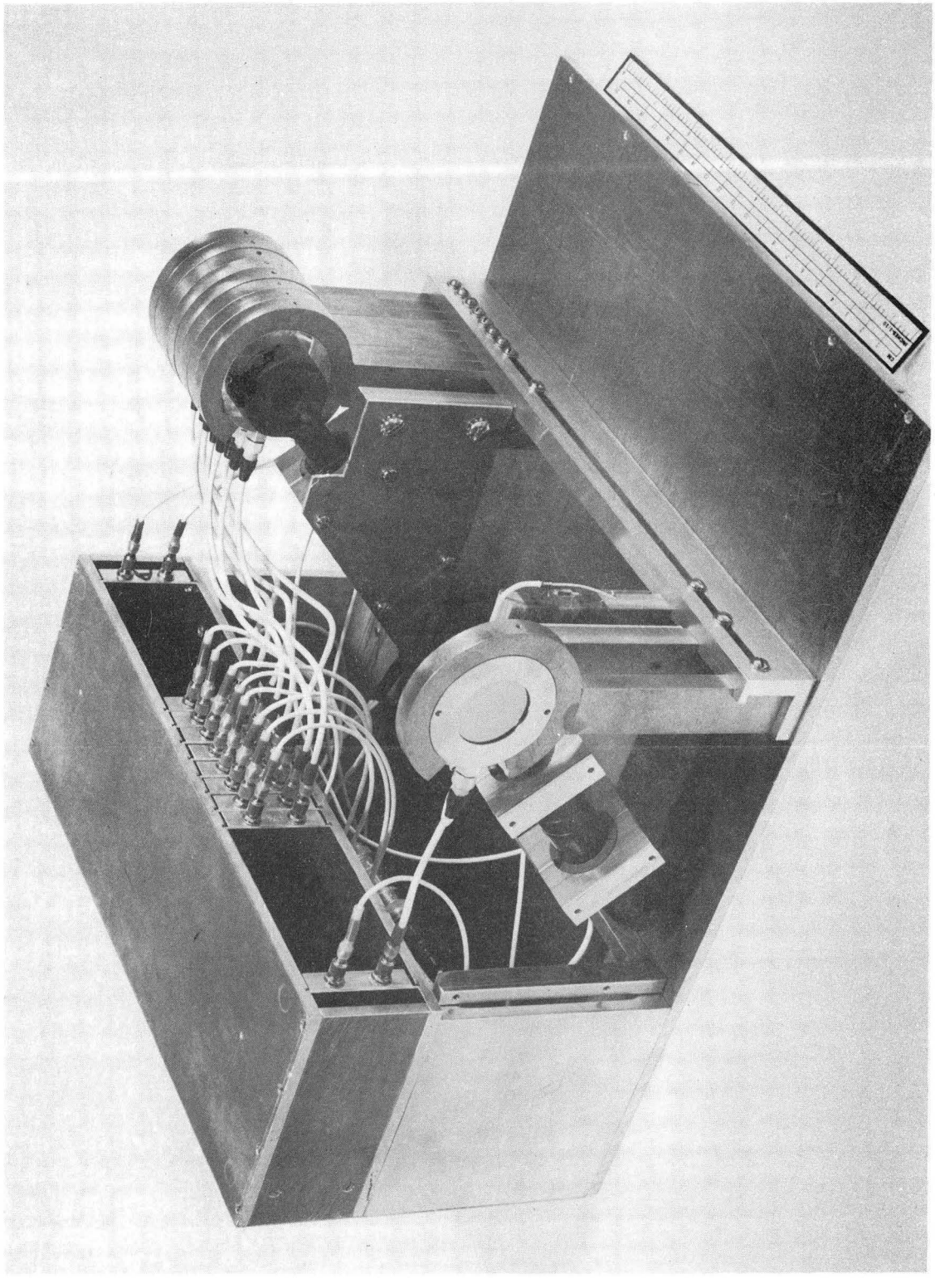


Fig. 3

0 0 0 3 7 0 1 7 7



XBB 717-3457

Fig. 4

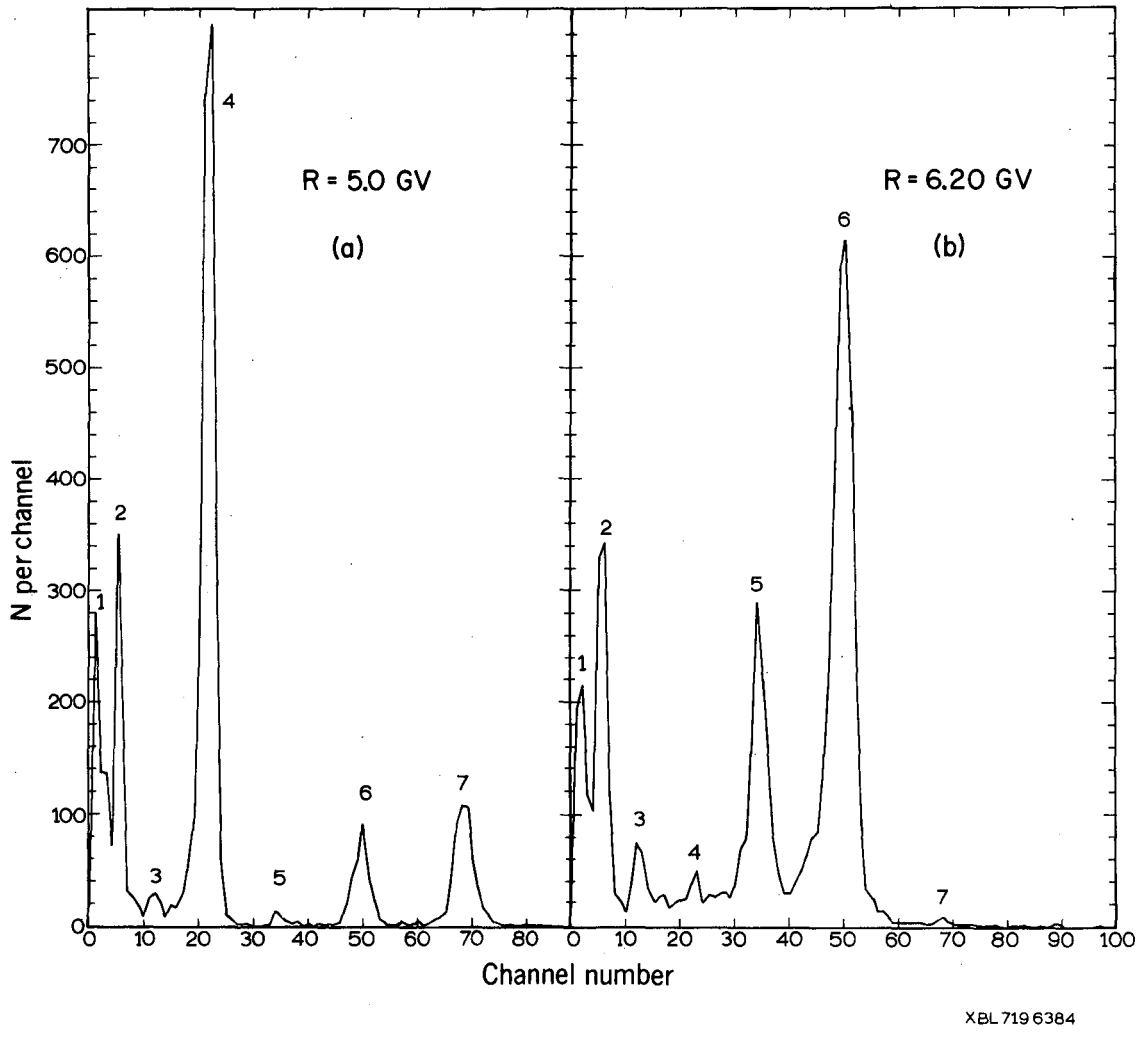


Fig. 5

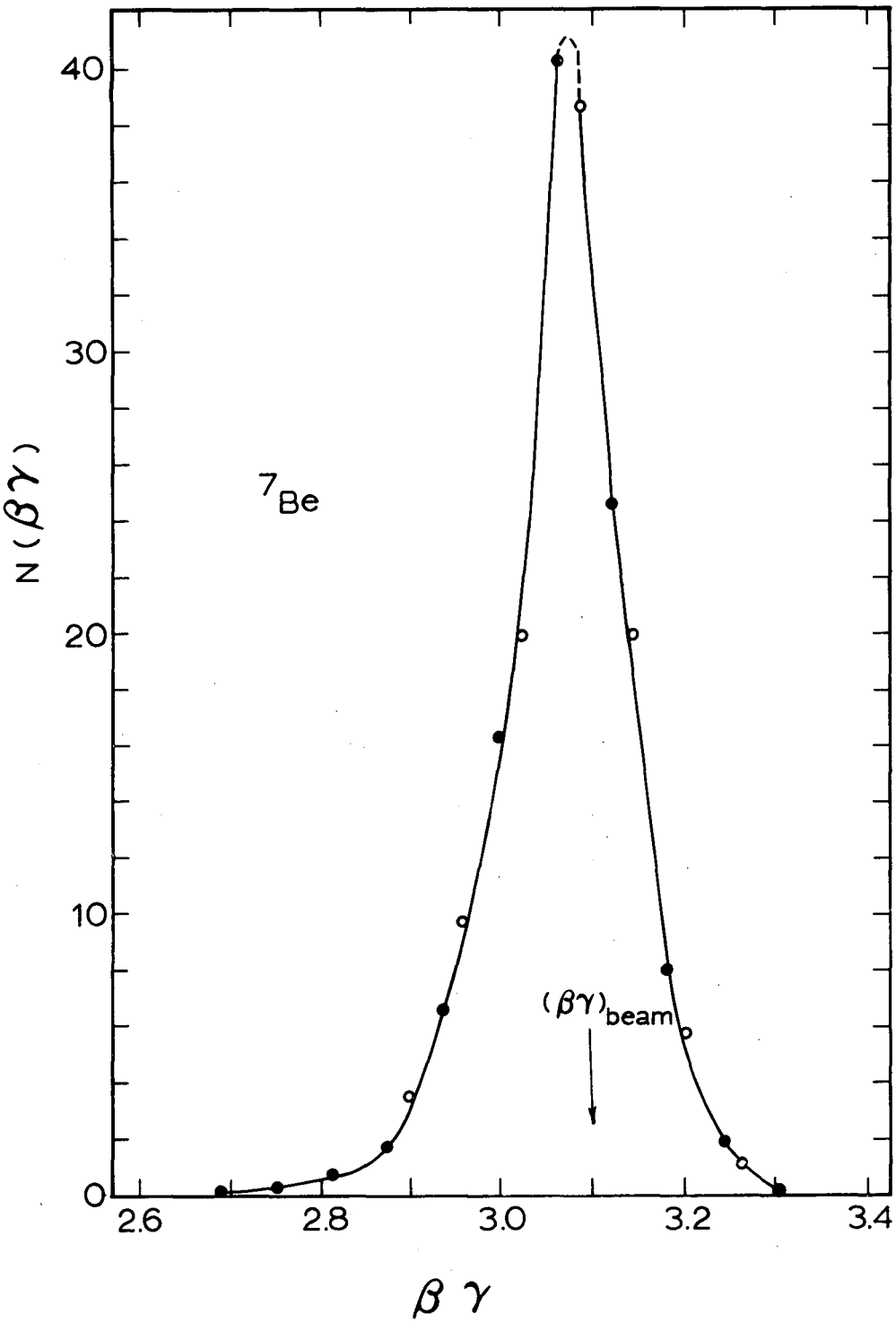


Fig. 6

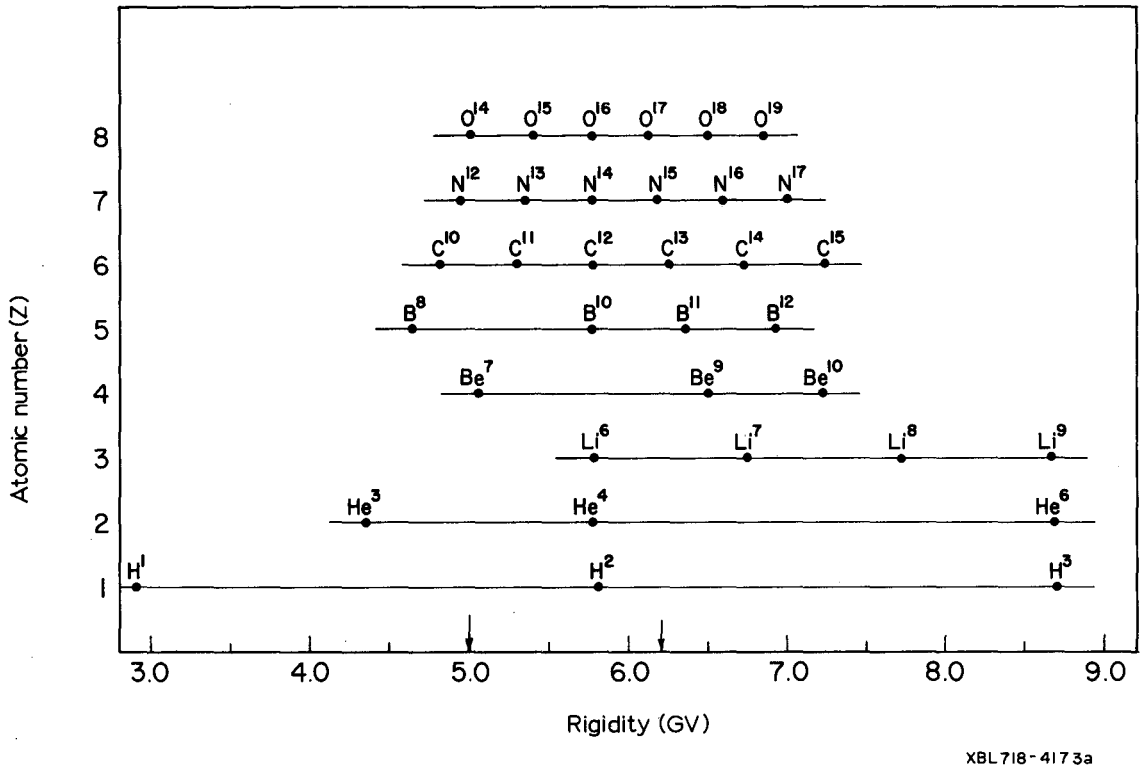

Atomic number (Z)
8
7
6
5
4
3
2
1
O14 O15 O16 O17 O18 O19
N12 N13 N14 N15 N16 N17
C10 C11 C12 C13 C14 C15
B8 B10 B11 B12
Be7 Be9 Be10
Li6 Li7 Li8 Li9
He3 He4 He6
H1 H2 H3
3.0
4.0
5.0
6.0
7.0
8.0
9.0
Rigidity (GV)
XBL718-4173a

Fig. 7

LEGAL NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Atomic Energy Commission, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

TECHNICAL INFORMATION DIVISION
LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720