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Title

HEAVY ION BEAMS AT THE BEVATRON I: ACCELERATION OF HEAVY IONS AT THE BEVATRON.
/ II: FRAGMENTATION OF ^{14}N NUCLEI AT 2.1 GeV/NUCLEON. / III: RADIOLOGICAL PHYSICS
CHARACTERISTICS OF THE EXTRACTED HEAVY-ION BEAMS OF THE BEVATRON

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I: Acceleration of Heavy Ions at the Bevatron

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II: Fragmentation of ^{14}N Nuclei at 2.1 GeV/Nucleon

H. H. Heckman, D. E. Greiner, P. J. Lindstrom,
F. S. Bieser

III: Radiological Physics Characteristics of the Extracted Heavy-Ion Beams of the Bevatron

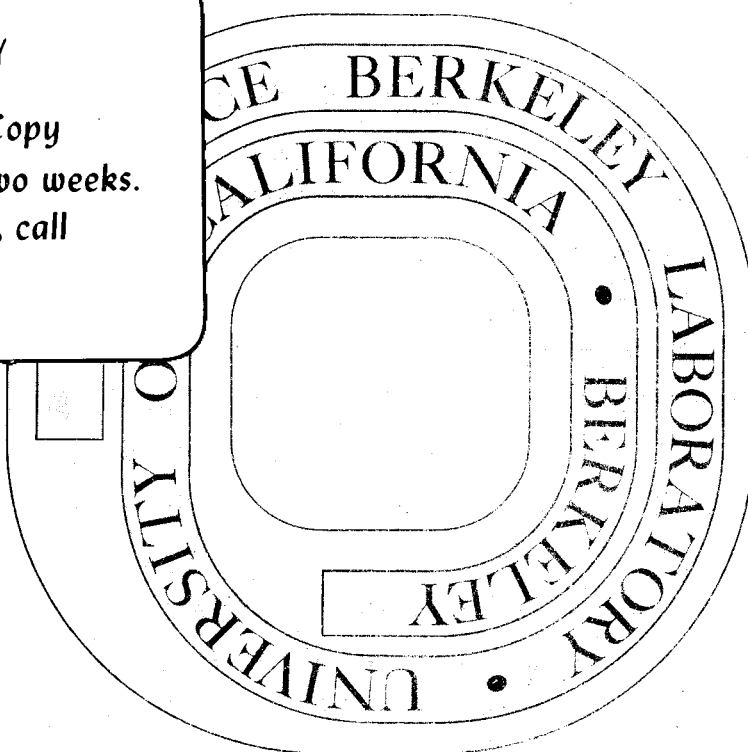
C. A. Tobias, J. T. Lyman, A. Chatterjee, J. Howard,
H. D. Maccabee, M. R. Raju, A. R. Smith, J. M.
Sperinde, and G. P. Welch

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ACCELERATION OF HEAVY IONS
AT THE BEVATRON

Abstract. Substantial beams of deuterons, alphas, and nitrogen ions have been accelerated to high energies (nitrogen to 36 BeV) in the Bevatron. Beams of various energies were successfully extracted for experimental use. Modifications of the ion source, the injector, and the main acceleration system made the production of high-energy heavy ions possible. Our computer control system played an important part.

The Bevatron, a proton synchrotron of 6.2 GeV energy with a long history of research in elementary particle physics, has recently been modified to accelerate heavy ions to very high energies. After a month of intensive exploration of the capability of this machine, we have verified the predictions that it has potential in several fields of physics, in biology, and in medical research. So far, deuterons, alpha particles, and nitrogen ions have been accelerated and extracted from the machine; experiments in radiobiology and in physics are under way using the nitrogen ions (1). Table I gives the energy and fluxes of the extracted heavy-ion beams. For comparison, the usual extracted proton beam is 3×10^{12} particles per pulse.

At the Princeton particle accelerator similar efforts are under way; they also have accelerated nitrogen ions to 0.280 GeV/nucleon.

The duoplasmatron source normally used to produce protons could be used without difficulty in forming the $^2\text{H}^+$ and $^4\text{He}^{+2}$ ions. But since these ions have only one-half the charge-to-mass ratio of protons, they are not accelerated in the usual ($1\beta\lambda$) mode in the injecting linear accelerator, which is designed for 20-MeV protons. Instead, they are accelerated in the $2\beta\lambda$ mode, which is only one-tenth as efficient, to 5 MeV/nucleon--or to one-half the velocity of protons. In the $2\beta\lambda$ mode, the ions take two rf periods to pass from one drift tube to the next; their lower velocity (compared with protons) requires that the starting frequency of the Bevatron accelerating system be reduced by one-half. Fortunately, this capability had already been built into the original conservative design.

Particles can be accelerated in the Bevatron to energies that are determined by the radius and magnetic field. For deuterons, this maximum is 5.2 GeV; for alpha particles, 10.4 GeV. Lower energies may also be obtained, presently down to about 280 MeV/nucleon, a limit imposed by the design of the extraction system.

Getting a beam of nitrogen ions was much more difficult (See Figure 1). Nitrogen ions are produced in the ion source in various charge states, in the ratios $N^{+a}/N^{+(a+1)} \simeq 0.1$ for charge states higher than +3. With a cold-cathode Penning discharge source (of the type developed for the Hilac), the highest charge state we can produce in useful quantities is N^{+5} ; the current of this ion species is about 40 μ A. The charge-to-mass ratio of 5/14 required that both the electrical gradient in the linac (injector) cavity and the quadrupole magnetic field in the drift tubes be increased by about 40% over their normal values. This was achieved, and gave a 2 μ A beam of 70-MeV N^{+5} ions.

However, it is not possible for N^{+5} ions to survive acceleration in the Bevatron; at the ambient pressure of 10^{-6} Torr, a change in charge state resulting in a loss of particles is almost certain. To overcome this problem, we converted the particles to N^{+7} , with an efficiency of about 50%, by passing them through an aluminum stripping foil of 40 μ g/cm². About 10^9 nitrogen ions per pulse were then available for injection into the Bevatron.

When this number is compared with the usual 10^{13} protons per pulse, it can be appreciated that this nitrogen beam current is too low to provide usable signals for operating the present closed-loop systems controlling the acceleration system of the Bevatron. We solved this problem by tuning up the Bevatron on alpha particles, whose

charge-to-mass ratio is the same (within 0.04% as that for $^{14}\text{N}^{+7}$, and storing on tape the frequency program and the settings for the 15 magnets used in the extraction. Nitrogen ions were then injected, and the Bevatron controlled entirely by computer, without beam signal. The last signal prior to acceleration is the Faraday-cup signal of the injected beam; the next signal is from the counter at the target.

Losses of ions during trapping and acceleration, and from the capture of electrons by fully stripped ions, left us with 7×10^5 nitrogen nuclei per pulse. We can increase this beam substantially in the near future.

Beams are extracted from the Bevatron by utilizing a resonance of the radial (betatron) motion of the particles, which is driven by a controlled magnetic-field perturbation. This method depends on the fact that a magnetic field causes the same deflection for all particles of the same rigidity $B\rho$ (the guidefield multiplied by the radius of curvature of the beam). Hence for an extraction scheme employing only magnetic fields, the setting of the currents is entirely prescribed by the rigidity of the particles. Therefore, once the extraction and beam-guiding system has been set up for protons or alphas, it will be equally correct for nitrogen ions of the same rigidity. Beams of energies above 1 BeV/nucleon can at present be extracted with 50 to 70% efficiency.

Heckman et al. have unambiguously identified the nitrogen ions by using a solid-state counter telescope (2). The quantity measured by this particle identifier is the profile of the energy loss along the particle's path through the detector system. We found the beam to have some contamination ($< 5\%$) of singly and doubly charged ions resulting from breakup of nitrogen ions by restrictive apertures.

Beam quality is characterized, in part, by the size of the beam-spot (see Figure 2). At the first focal plane (F1), 10 m downstream from the beam exit, the beamspot was 5 mm in diameter. Transporting the beam to the experimental cave resulted in a spotsize (at F2, 50 m downstream) of $2 \times 5 \text{ mm}^2$. In more precise terms, the beam emittance at 2.1 GeV/nucleon is 20 mm-mradians in the horizontal plane and 100 mm-mrad in the vertical plane.

We are now making a study to improve our high-energy heavy-ion facility. One possibility is to use the Hilac (Berkeley's heavy-ion linear accelerator) as an injector for the Bevatron. The Hilac, which soon will be capable of accelerating any ion species up to an energy of 8.5 MeV/nucleon, could provide fluxes of up to 10^{14} particles/sec. With this arrangement, we could produce beams of $^{20}\text{Ne}^{+10}$ of 10^{10} ions per pulse, $^{40}\text{Ar}^{+20}$ of 10^9 ions per pulse, and possibly beams of higher atomic mass numbers.

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References and Notes

1. See the following two reports by H. Heckman et al. and by C. Tobias et al.
2. See the following report by H. Heckman et al.
3. Work done under the auspices of the U. S. Atomic Energy Commission.

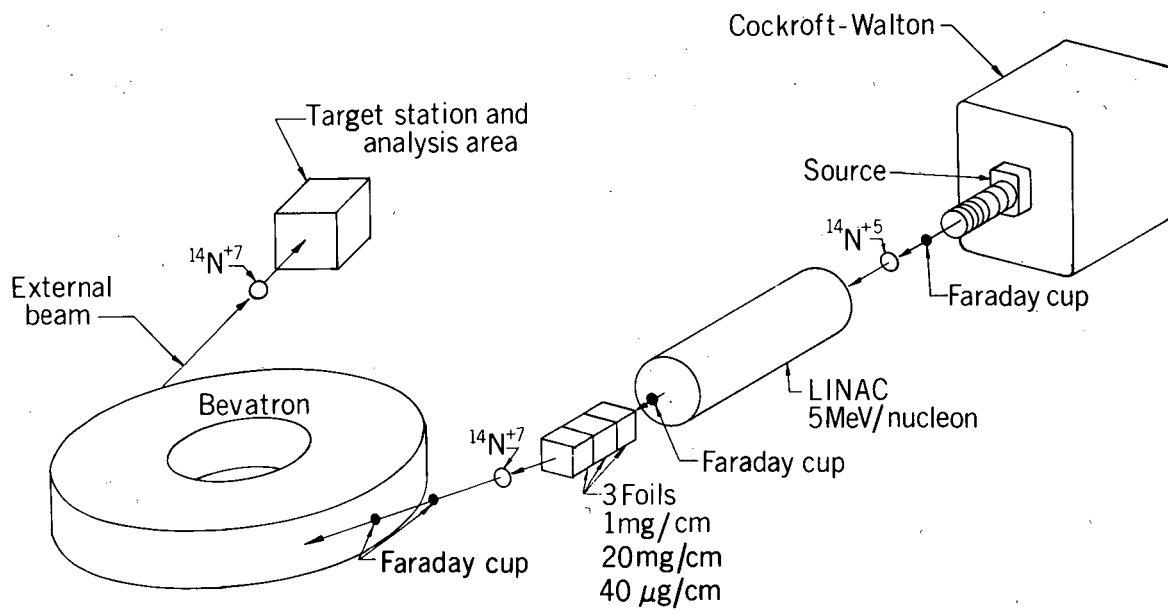
Table I. Extracted intensities (particles/pulse) for various extracted beam energies E (GeV/nucleon).

Particle	$E = 2.1$	$E = 1$	$E = 0.28$
Deuterons	10^{11}	not done	2×10^{10}
Alphas	5×10^9	5×10^9	10^9
Nitrogen ions	7×10^5	not done	1.4×10^5

Captions

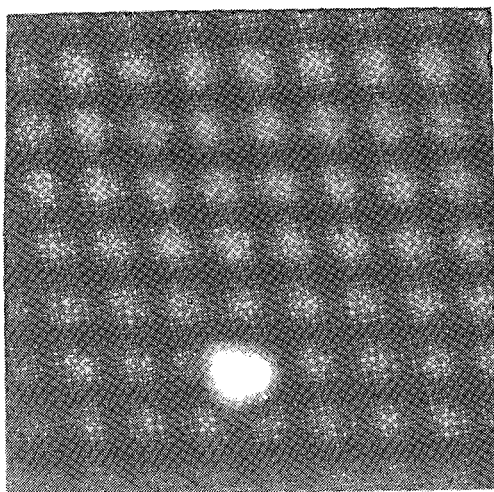
Figure 1. Schematic diagram of the Bevatron acceleration systems for heavy-ion work.

Figure 2. Quality of the heavy-ion beams accelerated at the Bevatron is indicated by the size of the beamspots at the two focal points.

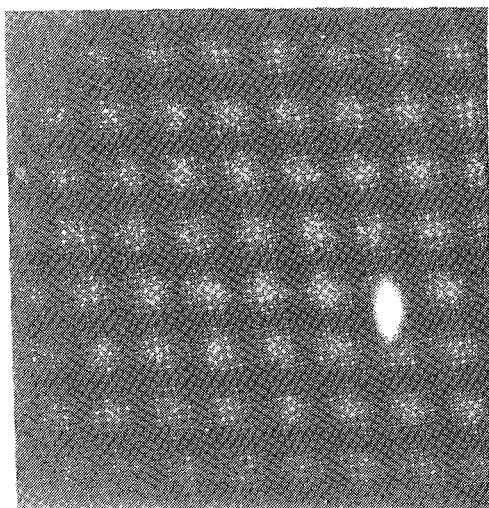


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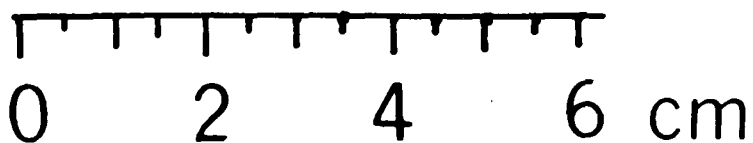
Fig. 1



1st focal plane (F1)



2nd focal plane (F2)



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Fig. 2

Fragmentation of ^{14}N Nuclei at 2.1 GeV/nucleon

Abstract. We present the first results of a physics experiment carried out at the Bevatron on the nuclear fragmentation of ^{14}N ions at 2.1 GeV/nucleon energy. Because of the near equality of the velocities of the ^{14}N beam and the fragmentation products at 0° , we find it possible to identify the nuclear fragments isotopically.

Concurrent with the successful acceleration and extraction of the 2.1 GeV/nucleon ^{14}N ions from the Bevatron, a program of measurements was begun (a) to determine the energy and composition of the beam, and (b) to undertake preliminary experiments using this beam to establish a basis for a high-energy heavy-ion physics research program. It was clearly evident to us that experiments of highest priority are those concerned with the fragmentation of the energetic heavy ions in matter. The fragmentation of nuclei is not only of basic interest to nuclear physics, but it is of key importance to the central problems of cosmic-ray physics: namely, the sources and initial composition of the cosmic rays, their acceleration mechanisms, and transformation by fragmentation in the interstellar gas. It is from the latter phenomenon that the "age(s)" of cosmic rays are deduced. An important aspect of such a program of research is that it inter-relates more closely accelerator physics with cosmic-ray research and high-energy astrophysics. The experimental results we report here are, of course, a very modest beginning in this new area of physics research.

The particle-identification system that was used to carry out the experiments is one that has been recently developed in a joint effort by the Lawrence Berkeley Laboratory and Space Sciences Laboratory, both of the University of California, Berkeley. Briefly, the particle identifier is a 9-element counter telescope consisting of lithium-drifted silicon detectors, 3 and 5 mm thick, 2.5 cm. in diameter. The pulse-height (i.e., energy-loss) information obtained from each detector is recorded on magnetic tape and processed initially by an on-line PDP-8

computer. The data subsequently undergo final analyses on the CDC-6600 computer, yielding charge, mass, and energy information. The detector we used in these experiments is, actually, a prototype for a forthcoming satellite (OSO-J) experiment on the high-energy proton component of the inner Van Allen radiation belt.

The composition of the extracted ^{14}N beam at 2.1 GeV/nucleon energy was found to be approximately 90 to 95% ^{14}N , with traces of helium, lithium, boron, and carbon in total amounts 5 to 10%. The background ions have the same rigidity, i.e., momentum per unit charge, as the primary beam -- and are most probably produced by the fragmentation of the ^{14}N beam during the extraction process. For this reason, the levels of the background were sensitive to the operational procedures used to extract the ^{14}N beam.

Within an hour after the first extraction and identification of the 2.1 GeV/nucleon nitrogen ions, we began the first measurements on the fragmentation products of ^{14}N nuclei at 0° . The experimental approach was to place a target (we used C, CH_2 , and Pb, 4 to 7 gm/cm^2) at focus F_1 (1), the particle identifier at focus F_2 , and to use the external beam channel as a magnetic spectrometer to examine the rigidity spectra of the fragmentation products. The distance between the target and particle identifier was approximately 40 meters.

Not unexpectedly, our first observations clearly demonstrated that the 0° fragmentation products are predominantly due to the disintegration of the ^{14}N nucleus itself. This characteristic feature of the fragmentation process has been well documented in studies of the interactions of cosmic-ray heavy ions by use of the nuclear-emulsion technique (2).

Striking in the present experiment was the observation that virtually all of the O^0 fragments heavier than helium ($Z=2$) have velocities that differ very little from the velocity of the ^{14}N beam. Qualitatively, the fragmented ^{14}N nucleus appears to simply "fall apart", with the resultant nuclear products proceeding on with little or no change in velocity. The consequence of this fact is that as one varies the rigidity R of the particles transmitted by the magnetic spectrometer, the intensity of a fragment of mass M and atomic number Z exhibit a sharp maximum when $R = \frac{M}{Ze} \beta\gamma$, where $\beta\gamma = \beta(1 - \beta^2)^{-1/2} \equiv (\beta\gamma)_{\text{beam}}$. The atomic number of the fragment is measured by the ion's rate of energy loss in traversing the counter telescope. The rigidity R has units GV when the mass M is expressed in GeV.

We illustrate this in Figure 1 ab, where we show the spectra of elements produced in a carbon target at O^0 when the rigidity R of the fragments transmitted by the spectrometer was set at 5.0 GV and 6.2 GV. (The rigidity of the 2.1 GeV/nucleon ^{14}N beam is 5.8 GV.) In Figure 1a, the prominent feature is the $Z=4$, or Be, peak. Assuming that it is due to 7Be , we find that the $\beta\gamma$ of this nuclide is 3.06, which is only slightly less than $(\beta\gamma)_{\text{beam}} = 3.10$. By "tuning" the spectrometer to accept particles with $R = 6.2$ GV, Figure 1b, we observe that the intensity of Be vanishes and that carbon, $Z=6$, now dominates. Because 6.2 GV is greater than the rigidity of the beam, no ^{14}N ions are observed. It follows, therefore, that no ^{12}C can be present, since these ions have the same rigidity as ^{14}N at equal velocities. The $Z=6$ peak at $R = 6.2$ GV is therefore ^{13}C , which has, at this rigidity, a $\beta\gamma = 3.07$ -- again equal to that of the incident ^{14}N beam.

These, and subsequent measurements, can be interpreted in terms of Figure 2, where we have plotted the values of rigidity R for several isotopes of the elements $Z=1$ through 8 under the assumption that their velocities, hence, $\beta\gamma$'s, are equal to $(\beta\gamma)_{\text{beam}} = 3.1$. For orientation purposes, we indicate by arrows the points $R = 5.0$ and 6.2 GV, appropriate for Figure 1 ab. Excepting oxygen, an examination of the raw data has revealed the production of all isotopes shown in Figure 2 with $A \leq 14$ nucleons within the rigidity interval 4.1 to 6.7 GV --- a limitation set by the spectrometer system. The observation of ^{14}C is evidence that charge exchange interactions also occur between the incident ^{14}N and target nuclei.

To demonstrate the shape of a "spectral line" of an isotope, we show in Figure 3 the measured intensity of ^7Be as a function of $\beta\gamma$. The maximum intensity occurs at $(\beta\gamma)_{\text{beam}} = 3.1$ to the accuracy of these measurements. The width of the distribution is an upper limit to the natural width since these preliminary data have not been corrected for the resolution of the detector-spectrometer system.

These initial findings indicate to us that a broad range of new and varied areas of physics research has now become available with the introduction of beams of relativistic heavy ions to the laboratory.

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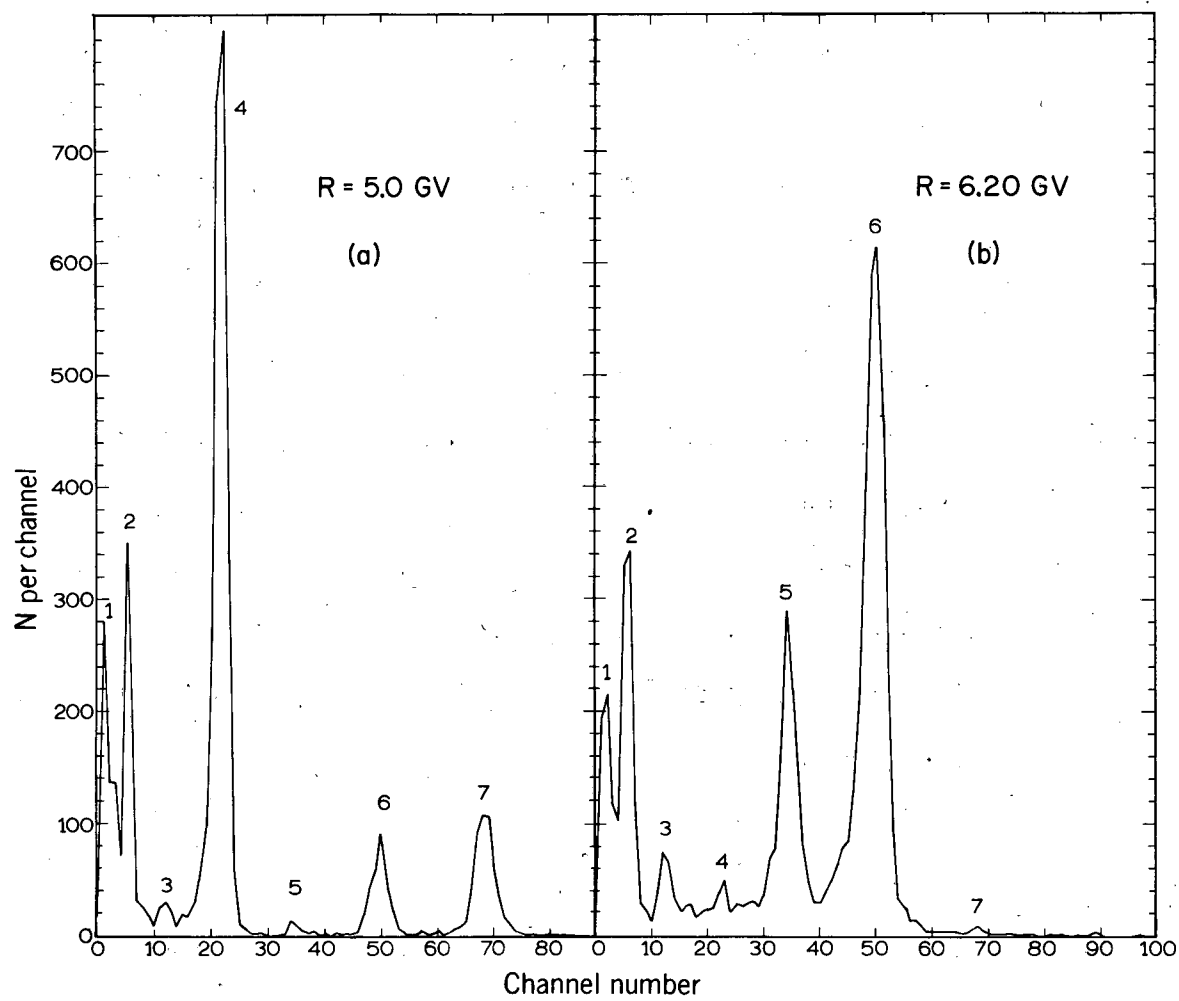
Berkeley, California

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2. C. F. Powell, P. H. Fowler and D. H. Perkins, The Study of Elementary Particles by the Photographic Method (Pergamon Press, New York, (1959), pp 579-640.
3. Work done under the auspices of the U.S. Atomic Energy Commission and National Aeronautics Space Administration Grant NGR-05-003-405.

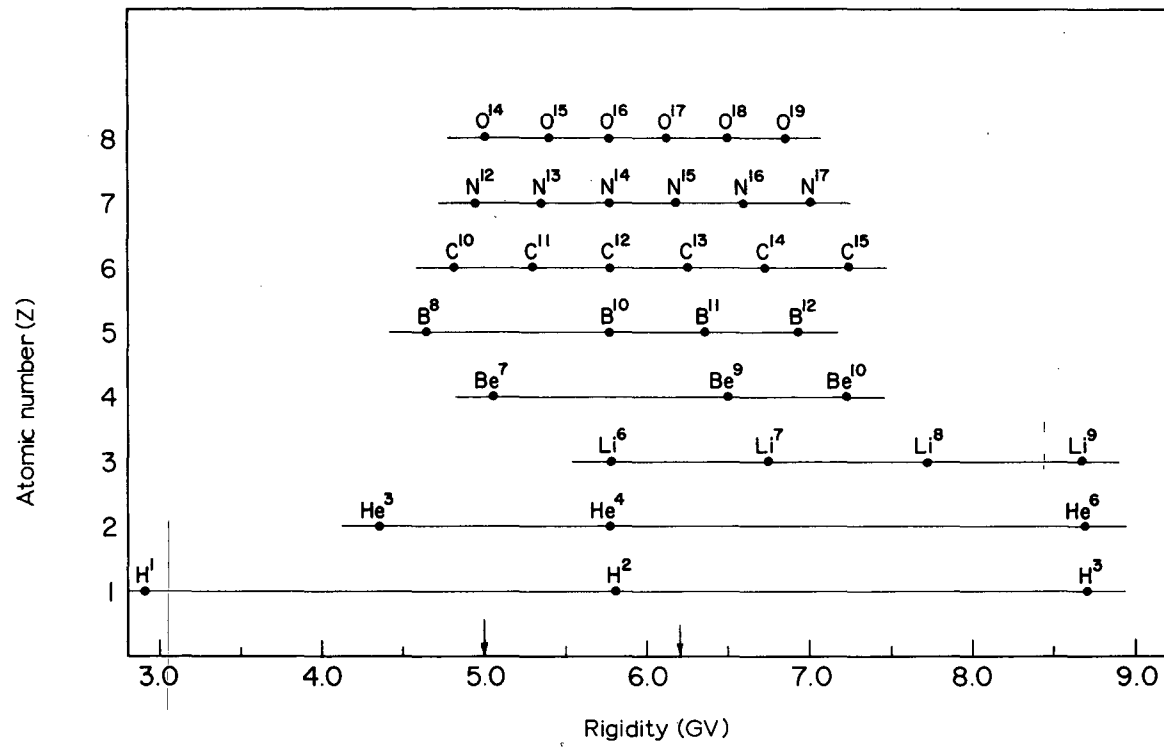
Figure Captions

- Fig. 1 ab, 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 (a) 5.0 GV and (b) 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.
- Fig. 2. 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. 1 ab were taken.
- Fig. 3 The observed spectral shape of the ^7Be 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.



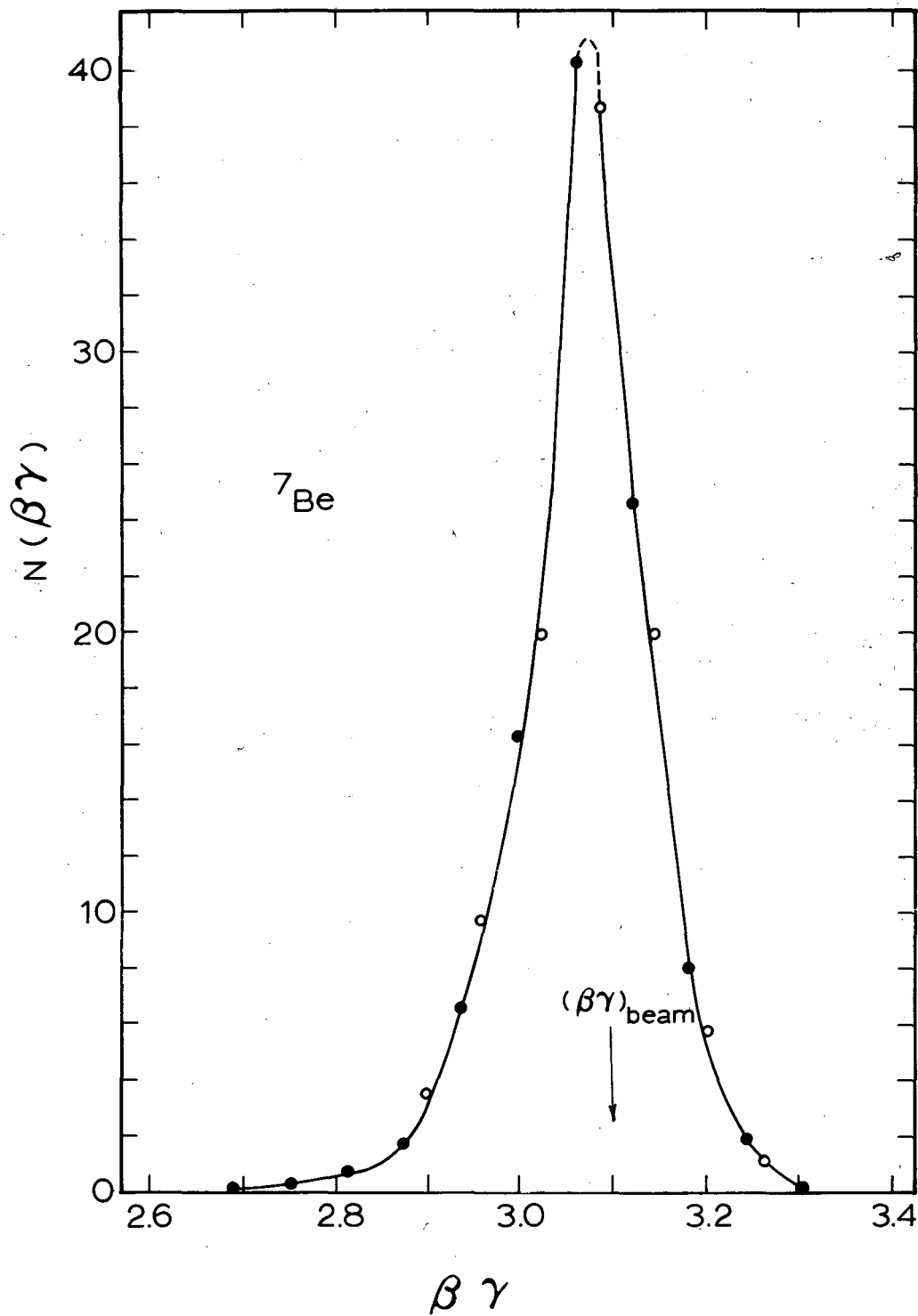
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Fig. 1ab



XBL718-4173a

Fig. 2



XBL 719 6389

Fig. 3

Radiological Physics Characteristics of the
Extracted Heavy-Ion Beams
of the Bevatron

Abstract: Studies of the depth-ionization properties and the biological effects of heavy-ion beams produced at the Bevatron have extended work previously done with less energetic beams from other sources. Results indicate that heavy-ion beams are suitable for tumor therapy, studies relating to space biology, and fundamental radiobiology.

Recently achieved nitrogen beams of a few hundred MeV/nucleon at the Bevatron have given us an opportunity to investigate the radiological physics properties of these particles and make an initial assessment of the potential usefulness of still heavier ions for future biological investigations in medical therapy. Since the completion of the first synchrotron at Berkeley in 1947, we have conducted biophysical investigations with accelerated protons, deuterons, and helium ions, and also with low-energy (smaller than 10 MeV/nucleon) heavy ions, including argon beams, since completion of the Hilac accelerator about 14 years ago. These studies have yielded information that the high linear energy transfer of the particles might be particularly suitable for therapy of certain types of tumors since they produce similar effects on anoxic tumor cells and on oxygenated normal cells. This is unlike low-LET radiations, i.e., x-rays, which kill normal oxygenated cells preferentially. Furthermore it was predicted that the depth-ionization properties of heavy-ion beams producing a peak (Bragg ionization curve) make penetrating monoenergetic beams particularly suitable for producing well localized radiolesions in multicellular organisms thus avoiding surgical trauma and bleeding (1,2,3). The recently accelerated penetrating nitrogen particles allowed a test of these ideas.

The deflected nitrogen and helium-ion beams from the Bevatron were collimated by magnetic focusing to a slowly divergent cone yielding a beam cross-section of $0.6 \times 1.5 \text{ cm}^2$ at the apex. The apex is located where the experimental studies were performed. The depth-ionization properties of the beams were studied by means of ionization chambers and fast plastic scintillators. As shown in Figure 1, a beam was monitored by thin-blade

plastic scintillators and an ion chamber (11) constructed of thin parallel aluminum foils. This apparatus is similar to that used in therapeutic investigations with heavy charged particle beams (4). The beam was then passed through a variable thickness water column with lucite windows, in which energy transfer is similar to that in tissue. The thickness of the water absorber could be remotely controlled during the measurements. A second ionization chamber immediately adjacent to the water absorber monitored ionization due to the particles after they passed through the water column. The normalized ratio of charge collected simultaneously in 12 and 11 when the nitrogen beam passed through them was measured as a function of the thickness of the water absorber.

Thus we obtained the Bragg ionization curve for nitrogen, plotted in Figure 1. The range of particles calculated from these data corresponds to a monoenergetic nitrogen beam of about 278 MeV/nucleon. The shape of the ionization curve corresponds very closely to predictions made in this laboratory by Palmer Steward (5) and Jerry Litton (6). The measured ionization values are proportional to the distribution of dose in soft tissue. From a plateau, the ionization rises near the end of the range of the particles to a peak of about 5.82 before it drops to a low level of about 15% of the plateau. The sharp rise of the Bragg ionization peak will allow us in the future to produce deep lesions at specific locations inside the human body, as required by therapeutic need, with minimal hazard for hemorrhage. The Bragg ratio (ratio of ionization peak to plateau) is significantly better than that of high-energy protons, deuterons, or helium ions currently available in some laboratories.

We have reached an interesting conclusion that ionization due to generated secondary particles, predominantly fast protons and helium ions and less frequent heavier fragments, is quite low and should not diminish the usefulness of nitrogen beams in research or in therapeutic applications. It appears that calculations made by Stan Curtis (7) for neon ions are also valid. We expect that in the future the use of combinations of nitrogen-particle beams of several energies can yield depth-dose distributions that are flexible and controlled, and suitable for tumor therapy.

The stopping of the particles was also studied by a method in which the particles were individually counted. The general layout for this experiment is shown in Figure 2. It consists of the plastic scintillators for monitoring the impinging high-energy beam, the variable water absorber, and two thin scintillation monitors (of equivalent stopping power of about 3.5 mm water each). At various absorber thicknesses, we obtained single counts of the monitor (S-1), coincidence between S-1 and S-2, and triple coincidences between S-1, S-2, and S-3. Figure 2 contains a plot of some of the data obtained, which are normalized and corrected for additional absorbers in front of the experimental setup within the beam. Pulse-height discrimination was applied in such a manner that most of the lighter secondary fragments, protons, and helium ions, which usually have a lower rate of ionization than primary nitrogen particles, were not recorded. Some of the heavier fragments, e.g., boron and carbon, are probably included in the measurements. The initial slope of the curve and the exit portion are strongly affected by discrimination settings. But the rapid drop at

the end of the range is not affected. More detailed studies are planned with this technique and with lithium disc detector to analyze the spectrum of secondary particles. Most of the nitrogen particles stopped very abruptly at 12.55 cm water-equivalent absorber. The shape of Figure 1 and Figure 2 are in good agreement with theoretical results predicted earlier (5,6).

Figure 2 also gives a differential-stopping-data curve, which indicates the number of particles that stop in scintillator S-2. This is obtained by subtracting triple coincidences (S-1, S-2, S-3) from double coincidences (S-1, S-2).

Inelastic collisions of the high-speed nitrogen beam produce nuclear fragmentation. The fragments of the nitrogen particles keep traveling forward with about the same velocity as particles of the primary beam. This was clearly shown in the experiments of Heckman et al. (see the above report) with nitrogen beams of 2 GeV/nucleon.

Using the 278 MeV/nucleon nitrogen beams, we have obtained evidence that the fragments of nitrogen sometimes are radioactive nuclides. Because of the speed of the fragments, this radioactivity becomes deposited near the end of the range of the nitrogen beam, unlike the radioactivity produced in target nuclei by the beam, which is approximately uniformly distributed along the entire beam path. Using pure metallic beryllium as absorber for the nitrogen beam and also as catcher for the radioactivity, we have obtained some measurements of the distribution of radioactive ^{11}C and ^{13}N in the nitrogen beam. Since the radioactivity induced in beryllium is negligibly small, almost all of the radioactivity deposited is due to breakdown of the moving nitrogen nuclei. Some data are shown in Figure 3;

more details will be published (8). Thus we obtain the obvious result: that radioactivity produced by heavy particles in matter is representative not only of the composition of the target, but also of the bombarding projectile. This statement has geophysical implications. For example, we expect that heavy primary cosmic rays (oxygen and heavier) have produced radioactive ^{14}C and other long-lived isotopes over long time periods in the earth's atmosphere and beneath the lunar surface at depths related to the penetration of the primary particles. Similarly, continuous creation of ^{40}K may occur by breakdown of cosmic-ray nuclei in the calcium-iron groups. The deposition of carrier-free ^{11}C fragments at the end of the range, its stopping distance, and hence its possible isolation may also have practical implications for medical research: external measurement of the location of the autoradioactive deposit might provide a convenient means for finding out (e.g., in patients in vivo) where the beam has stopped.

Initial Biological Experiments: Most of the studies described were performed in parallel with physical improvements on the Bevatron for nitrogen-beam acceleration. The beam intensity was relatively small, nevertheless it was possible to carry out a few bioexperiments demonstrating the effects of small groups of particles. Working with T. Budinger it was shown that the individual nitrogen particles can produce a sensation of light flashes and streaks when they aim on the human retina; whereas elsewhere in the occipital lobes of the brain, where visual sensations are elaborated, the particles fail to elicit light sensation (9). The effects observed are quite similar to those reported by the astronauts in lunar flights. Special studies were made by T. Budinger et al. on the fluorescence yield of various

fluids placed in the nitrogen beam -- including rabbit vitreous fluid and retina. We have also exposed the skin of black mice (C57-B) to small bursts of nitrogen particles which were allowed to stop in the skin. The development of bleached hair as a consequence is an indication of the profound effects of individual nitrogen particles on the pigment cells of the hair follicles (J. Leith, W. Schilling, et al.)

A group from Ames Research Center-NASA, led by Webb Haymaker, made a number of exposures of portions of the nervous system of pocket mice for histological studies. M. Raju, R. Roissman, and B. Martins conducted studies on mammalian cells in culture with an aim in determining the magnitude of the oxygen effect in various energies of nitrogen ions. Some experiments on the effects of nitrogen ions on the membranes of red blood corpuscles were carried out by Rod McGregor and Jack Resius. Seed and embryo of developmental organisms were exposed by T. Yang and W. Heinze. T. Budinger exposed human leukocytes and lymphocytes in order to investigate chromosome aberrations induced by the beam.

The radiological physics data reported here and initial biological investigations indicate that as predicted these particles have interesting properties for biological investigations and for therapy. The technology is available to produce penetrating beams not only of nitrogen but of other heavier particles as well. We feel that if this can be achieved we shall have particles in the laboratory with the properties of cosmic rays which could previously be studied only in spaceflight by use of rockets, balloons, and satellites.

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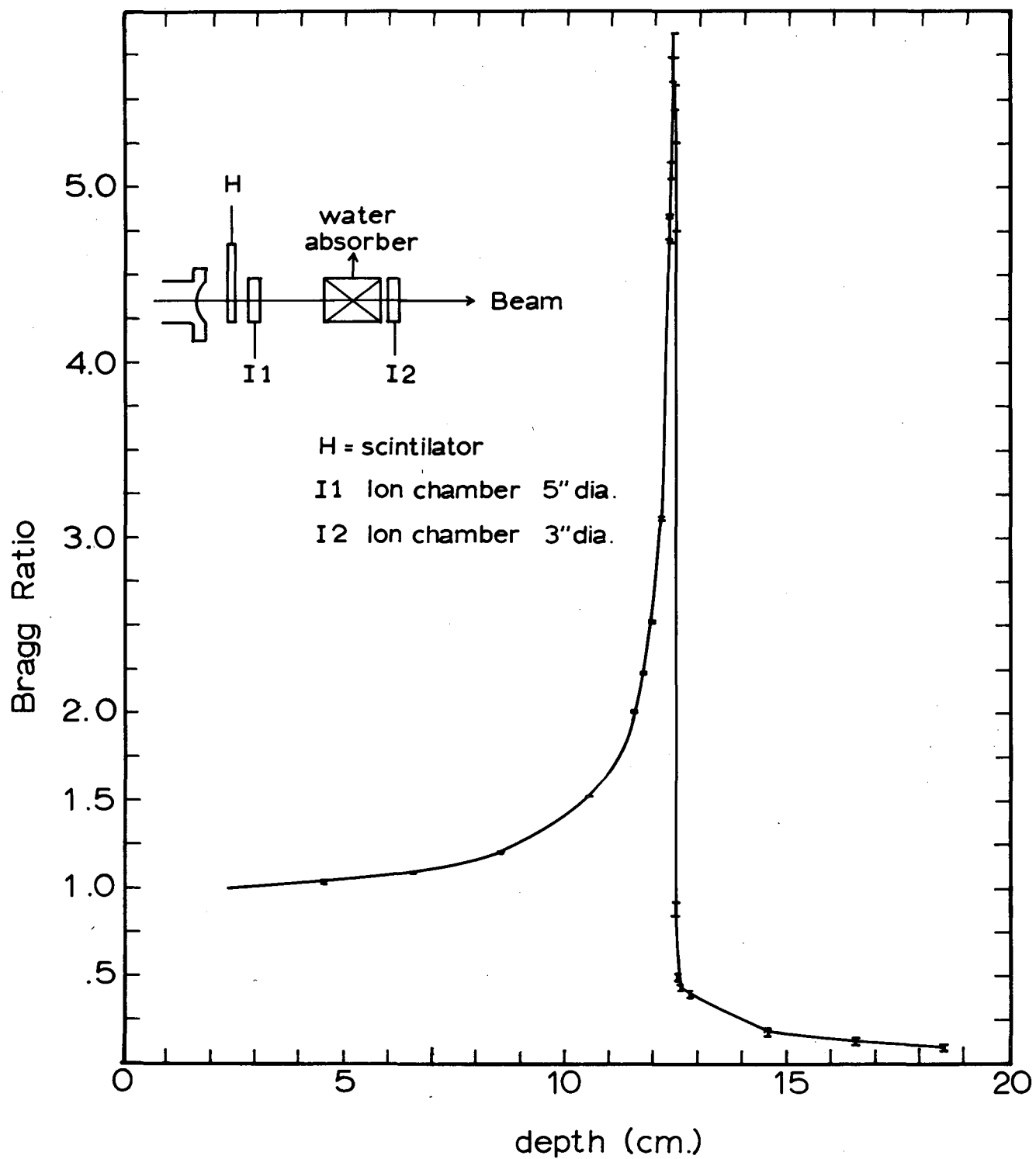
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Figure Legends

Fig. 1. Sketch shows the apparatus used to obtain the Bragg ionization curve (for details refer to text). It also presents the Bragg ionization curve for the 278 MeV/nucleon ^{14}N beam in water.

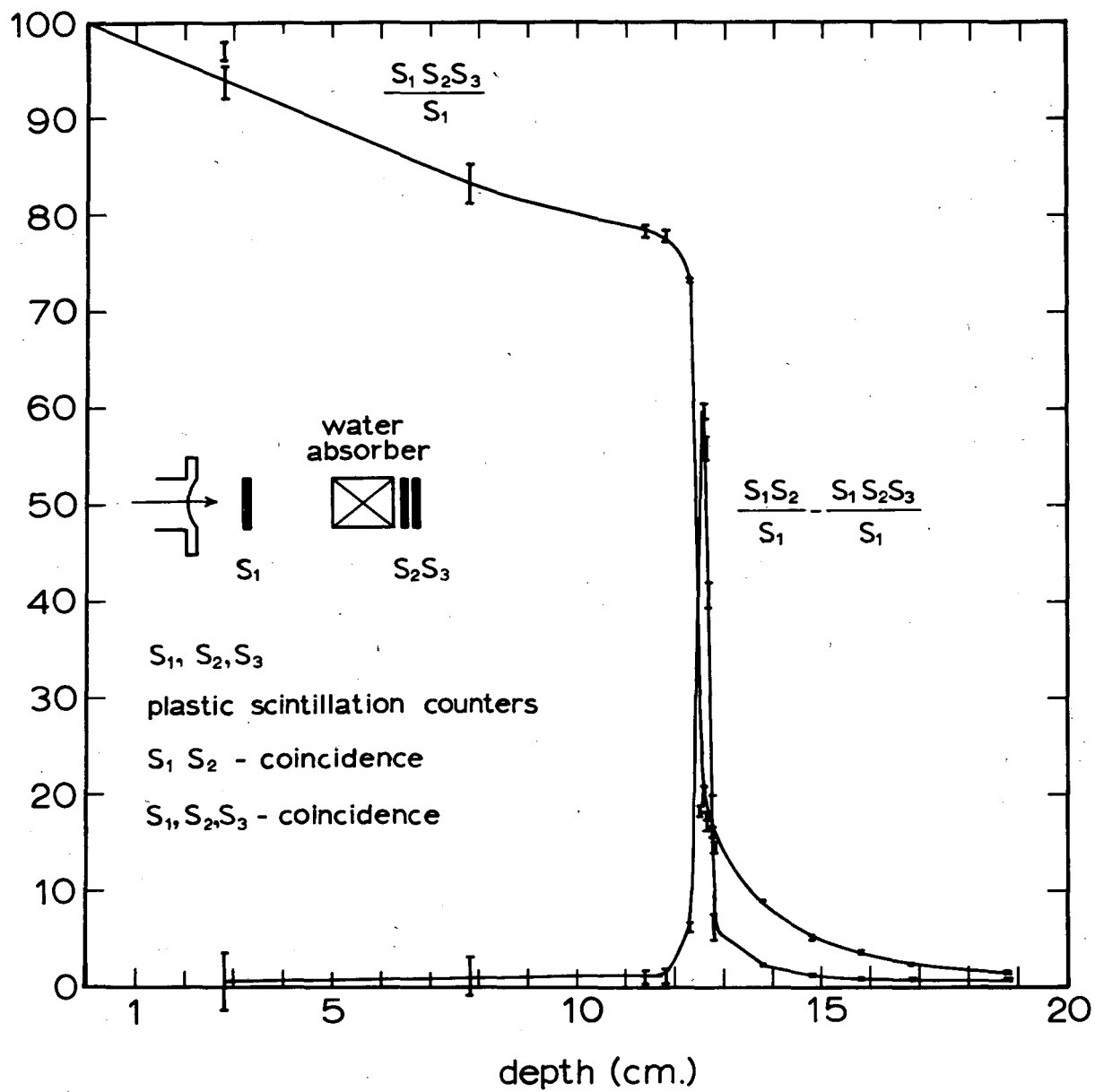
Fig. 2. Layout shows the experimental arrangements for the study of the stopping of the ^{14}N beam (details in text). The differential-stopping-data curve is given as well as the number-distance curve for 278 MeV/nucleon ^{14}N ions in water.

Fig. 3. Curve shows that ^{11}C , resulting from the fragmentation of ^{14}N ions impinging on a Beryllium target, is deposited mostly at a particular depth. The length of the Beryllium target was long enough to stop the beam.



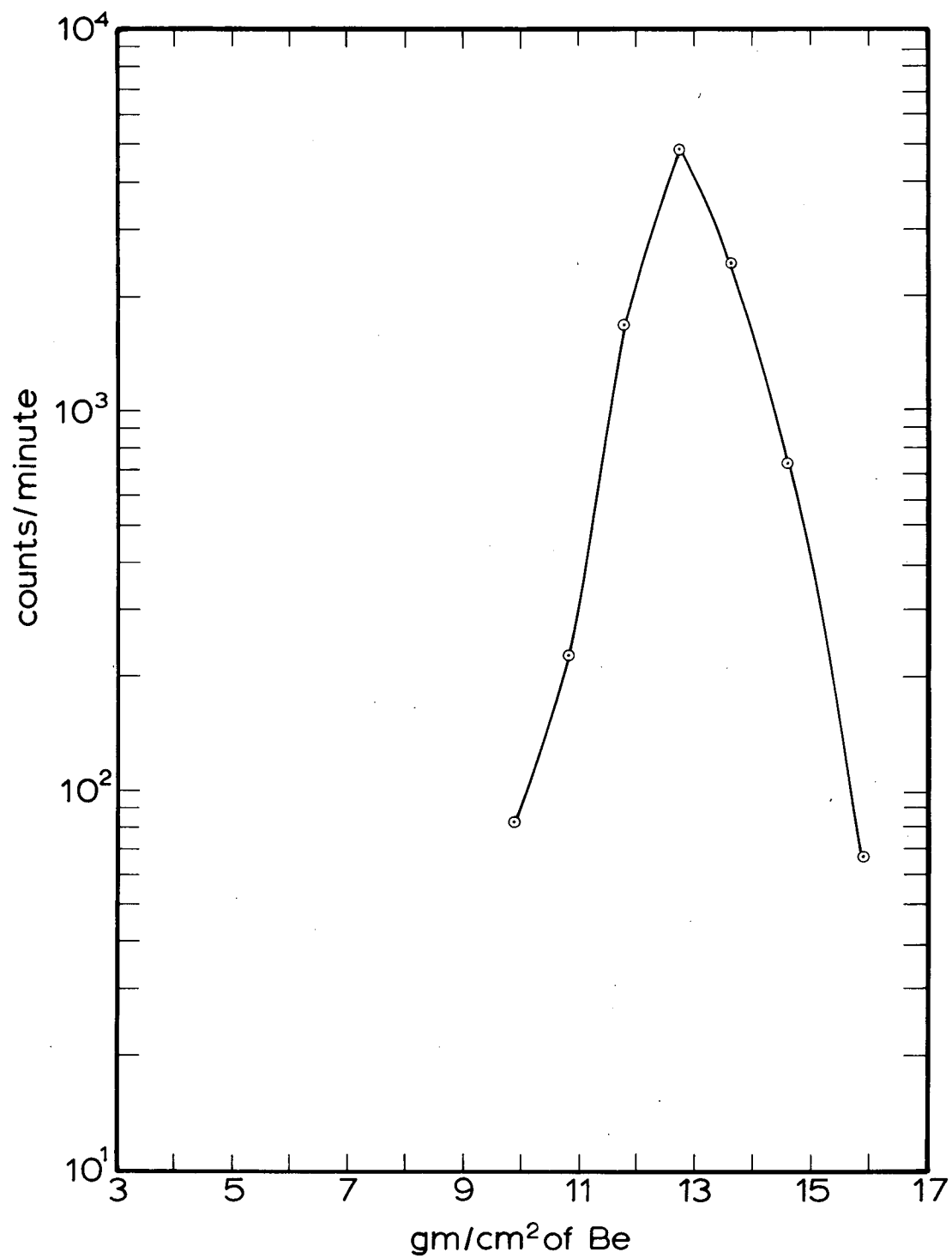
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Fig. 1



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Fig. 2



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Fig. 3

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