Fragmentation of Nitrogen-14 Nuclei at 2.1 Gev per Nucleon

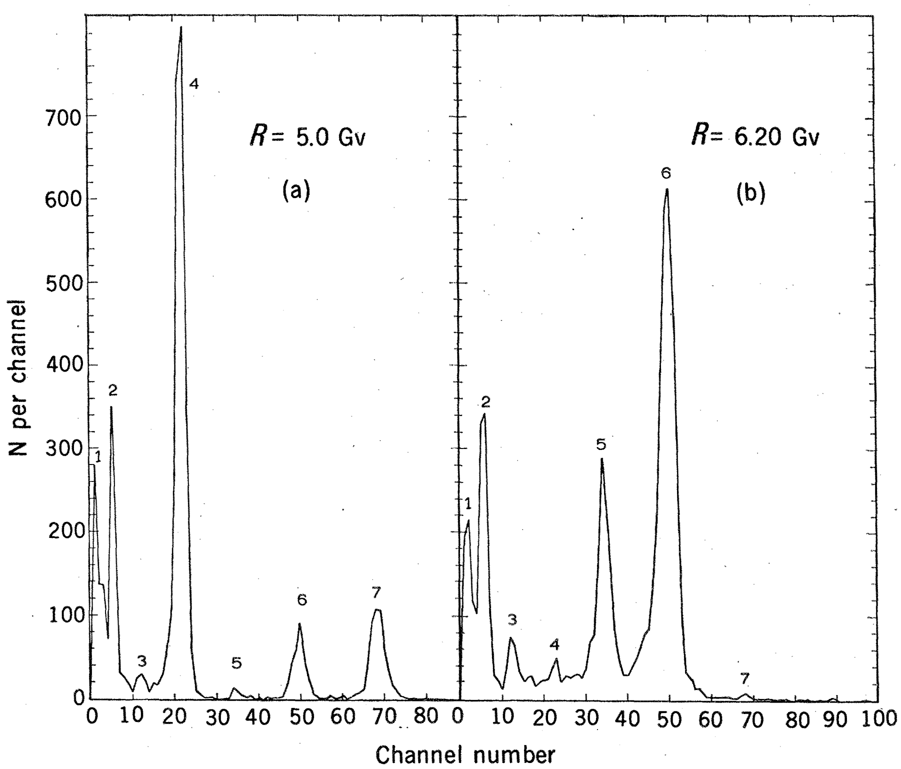
Abstract. *An experiment has been carried out at the bevatron on the nuclear fragmentation of nitrogen-14 ions at an energy of 2.1 billion electron volts (Gev) per nucleon. Because of the near equality of the velocities of the nitrogen-14 beam and the fragmentation products at an angle of 0°, we find it possible to identify the nuclear fragments isotopically.*

Concurrently with the successful acceleration and extraction of 2.1-Gev/nucleon ^{14}N ions from the bevatron, a program of measurements was begun (i) to determine the energy and composition of the beam and (ii) to use the beam to study the fragmentation of energetic heavy ions in matter. The fragmentation of nuclei is not only of basic interest to nuclear physics, it is of key importance to the central problems of cosmic-ray physics, namely the sources and initial compositions of cosmic rays, their acceleration mechanisms, and their transformation by fragmentation in the interstellar gas. It is from the latter phenomenon that the age or ages of cosmic rays are deduced.

The particle-identification system has been developed in a joint effort by the Lawrence Berkeley Laboratory and the Space Sciences Laboratory, both of the University of California at Berkeley. The particle identifier is a nine-element counter telescope consisting of lithium-drifted silicon detectors, 3 and 5 mm thick and 2.5 cm in diameter. The pulse height (that is, energy loss) information obtained from each detector is recorded on magnetic tape and processed initially by an on-line PDP-8 computer. The data undergo final analyses on the CDC-6600 computer, from which charge, mass, and energy information are obtained. The detector we used in these experiments is a prototype for a forthcoming satellite (orbiting solar observatory) 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 percent ^{14}N and 5 to 10 percent traces of helium, lithium, boron, and carbon. The background ions have the same rigidity, that is momentum per unit charge, as the primary beam—and are 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 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 carbon, polyethylene, and lead, 4 to 7 g cm^{-2}) at focus F1 (*1*) and the particle identifier at focus F2, and to use the external beam channel as a magnetic spectrometer to examine the rigidity spectra



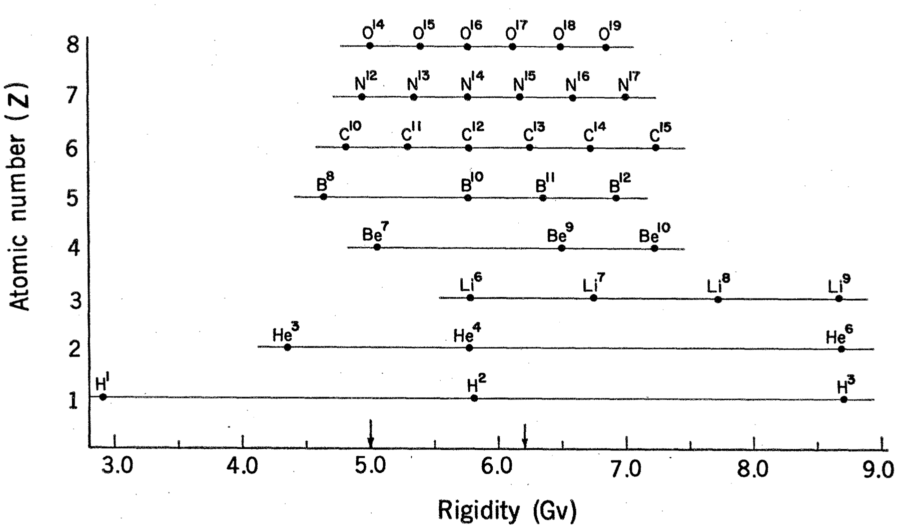


Fig. 1 (top). Spectra of the rates of energy loss of the fragmentation products of 2.1-Gev/nucleon ^{14}N ions. The ordinate N is the number of counts observed in each channel; one channel corresponds to 6.8 Mev. The values of the rigidity (momentum per unit charge) are (a) 5.0 Gv and (b) 6.2 Gv. The elements hydrogen (Z = 1) through nitrogen (Z = 7) are indicated by their atomic numbers Z. These data are the direct readouts of the particle identifier and are unprocessed. The target material was carbon. Fig. 2 (bottom). Diagram of the rigidities 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 were taken.

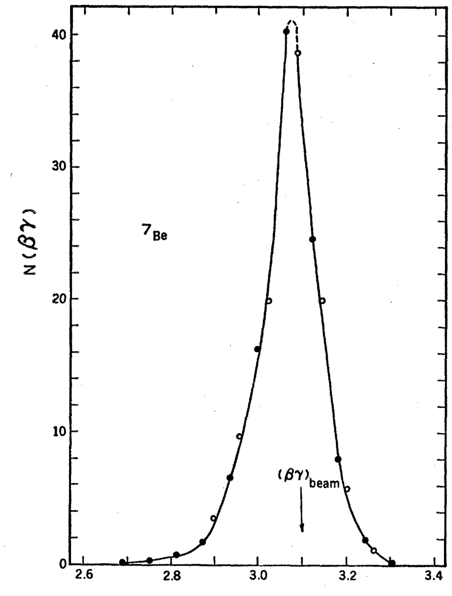


Fig. 3. Spectral line of the ^{7}Be isotope, uncorrected for energy loss in the target and resolution of the detector-spectrometer system. The arrow indicates the value of $\beta\gamma$ for the incident ^{14}N beam. The symbol β represents the velocity of the particle divided by the velocity of light, and γ is defined by the equation $\gamma = (1 - \beta^2)^{-1/2}$. The ordinate N is the number of counts observed as a function of $\beta\gamma$.

of the fragmentation products. The distance between the target and the particle identifier was approximately 40 m. Our first observations demonstrated that the 0° fragmentation products are predominantly due to the distintegration of the ^{14}N nucleus. This characteristic feature of the fragmentation process has been documented in studies of the interactions of cosmic-ray heavy ions by use of the nuclear emulsion technique (*2*). Virtually all the fragments heavier than helium (atomic number 2) have velocities that differ very little from the velocity of the beam. Qualitatively, the ^{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 exhibits a sharp maximum when $R = (M/Ze)\beta\gamma$, where $\beta\gamma = \beta(1 - \beta^2)^{-1/2} \equiv (\beta\gamma)_{beam}$. In these equations, e is the electron charge and β is the velocity of the particle divided by the velocity of light. 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 Fig. 1, where we show the spectra of elements produced in a carbon target at an angle of 0° when R was set at 5.0 and 6.2 Gv. (The rigidity of the 2.1-Gev/nucleon ^{14}N beam is 5.8 Gv.) In Fig. 1a, the prominent feature is the $Z = 4$, or beryllium, peak. Assuming that it is due to ^{7}Be, we find that the $\beta\gamma$ of this nuclide is 3.06, which is only slightly less than $(\beta\gamma)_{beam} = 3.10$. When R is 6.2 Gv (Fig. 1b) the intensity of beryllium vanishes and carbon, $Z = 6$, dominates. Because 6.2 Gv is greater than the rigidity of the beam, no ^{14}N ions are observed. It follows 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 rigidity 6.2 Gv is therefore due to ^{13}C, which has, at this rigidity, a $\beta\gamma$ of 3.07—again equal to that of the incident ^{14}N beam.

These and subsequent measurements can be interpreted in terms of Fig. 2, where we have plotted the values of rigidity R for several isotopes of atomic numbers 1 through 8 under the assumption that their velocities are equal and hence that their $\beta\gamma$'s are equal to $(\beta\gamma)_{beam}$ or 3.1. For orientation purposes, we indicate by arrows the points $R = 5.0$ and 6.2 Gv, appropriate for Fig. 1. An examination of the raw data has revealed the production of all the isotopes shown in Fig. 2 with mass number $A \leqq 14$ nucleons, excepting oxygen, 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 the target nuclei.

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

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References and Notes

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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 million electron volts per nucleon at the bevatron (*1, 2*) have given us an opportunity to investigate the radiological 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 synchrocyclotron at Berkeley in 1947, we have conducted biophysical investigations with accelerated protons, deuterons, and helium ions, and also, since completion of the heavy ion linear accelerator (Hilac) about 14 years ago, with low-energy (less than 10 Mev/nucleon) heavy ions, including argon beams. These studies indicate 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 linear energy transfer radiations, that is, 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 ioniza-