Fragmentation of ^{14}N Nuclei at 29 GeV: Inclusive Isotope Spectra at 0°*

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We report the first results of a Bevatron heavy-ion experiment on the inclusive spectra of isotopically identified nuclei, $3 \leq Z \leq 7$, produced by the fragmentation of 29-GeV ^{14}N ions in carbon and hydrogen. The preliminary values of the partial differential cross sections at 0° give evidence that the modes of fragmentation of ^{14}N projectiles are independent of the target nucleus.

We report in this Letter the results of a Bevatron experiment on the single-particle inclusive spectra of secondary nuclei, $A \geq 6$, $Z \geq 3$, produced at 0° by the fragmentation of 29-GeV (2.1-GeV/nucleon) ^{14}N ions in carbon and polyethylene (CH_2) targets.[1,2] Isotopic identification of the nuclear fragments was obtained by measurements of magnetic rigidity, rate of energy loss, and velocity. The external beam transport system was used as a rudimentary magnetic spectrometer to analyze the rigidity of the fragments. An on-line computer-controlled counter telescope[3] consisting of nine 500-mm^2 lithium-drifted silicon detectors, 3 and 5 mm thick, yielded dE/dx and, hence, charge information. The time-of-flight measurements were made over the 40-m distance between the target and the counter telescope, which were located at the first and second focal points of the beam transport system, respectively. Salient properties of the spectrometer-detector system were (a) rigidity resolution $\sigma(R)/R \approx 1$ to 2% for $R \leq 6.7$ GV/c; (b) absolute charge resolution $\sigma(Z) = \pm 0.12e$; (c) time-of-flight resolution $\sigma(t) = \pm 0.5 \times 10^{-9}$ sec; and (d) acceptance cone angle of the spectrometer, 4 mrad, estimated from conventional beam-trace methods. The thicknesses of the carbon and polyethylene targets were 4.36 and 3.76 gm cm^{-2}, respectively.

Our initial observations demonstrated that the 0° fragments heavier than He ($Z = 2$) have velocities that differ little from the velocity of the primary ^{14}N beam.[2] Hence, the rigidity R (in GV/c) at which a secondary fragment is transmitted by the magnetic spectrometer is $R = M\beta\gamma c/Ze$, where M is the mass of the fragment in GeV/c^2, Z is its atomic number, and $\beta\gamma_{\text{frag}} = \beta\gamma_{\text{beam}} = 3.1$ for the 29-GeV ^{14}N beam. In the present experiment, the rigidity spectra of the 0° fragments were examined in the range $4.1 \leq R \leq 6.7$ GV/c at intervals $\Delta R = 0.1$ GV/c, minimum. The detection of nuclei was therefore limited to a range of charge-to-mass ratio $0.43 \leq Z/A \leq 0.71$. Within this range of Z/A *all* of the known nuclides that could be produced by the fragmentation of the ^{14}N nucleus *were in fact observed.* Furthermore, the maximum intensity of each nuclide (M, Z) occurred at the expected value of $R(\text{GV}/c) = 3.1Mc/Ze$. This is demonstrated in Fig. 1, which presents the rigidity spectrum of the carbon isotopes ^{9}C through ^{14}C. Where determined, the signal-to-background ratio was unity to within ±12% rms, independent of the rigidity of the isotopes. The most apparent feature of the spectrum is the predominance of ^{12}C. Relative to ^{12}C, the intensities of each carbon isotope diminish by about one decade per unit mass number. Illustrated in Fig. 1 is the complete separation of the isotopes by magnetic analysis alone, an observation verified by the time-of-flight data. Evidence that charge-exchange interactions occur between the incident ^{14}N and ^{12}C target nuclei is exhibited by the detection of ^{14}C. We also found tentative evidence for ^{13}O and ^{14}O, isotopes whose production also involves charge exchange. An upper limit of 10^{-2} is placed on the ^{14}O to ^{14}C production ratio.[4]

The central problem in obtaining the rigidity spectrum for each element of the type shown in Fig. 1 was the evaluation of background. There were two sources of background: First, a 1 to 5% beam contamination was produced by fragmentation at restrictive apertures in the Bevatron, and was extracted with (having a rigidity equal to) the ^{14}N beam. Second, and most important, was the background of beam fragments produced in the vicinity of the target and in the walls of the evacuated beam pipe.

To determine the signal-to-background ratios,

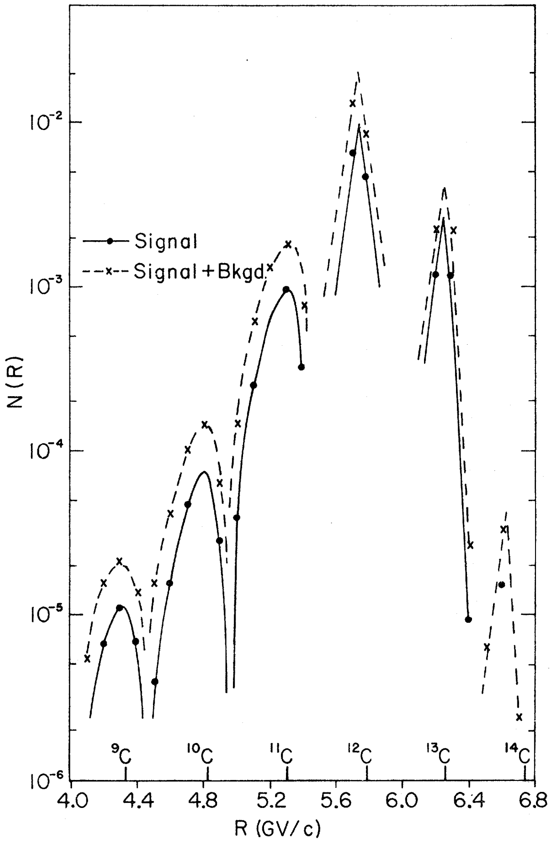

FIG. 1. Rigidity spectrum of carbon isotopes produced by the fragmentation of 29-GeV ^{14}N nuclei. The differential intensity has been normalized to give the observed count-rate per incident ^{14}N beam particle on the carbon target (4.36 g cm^{-2}).

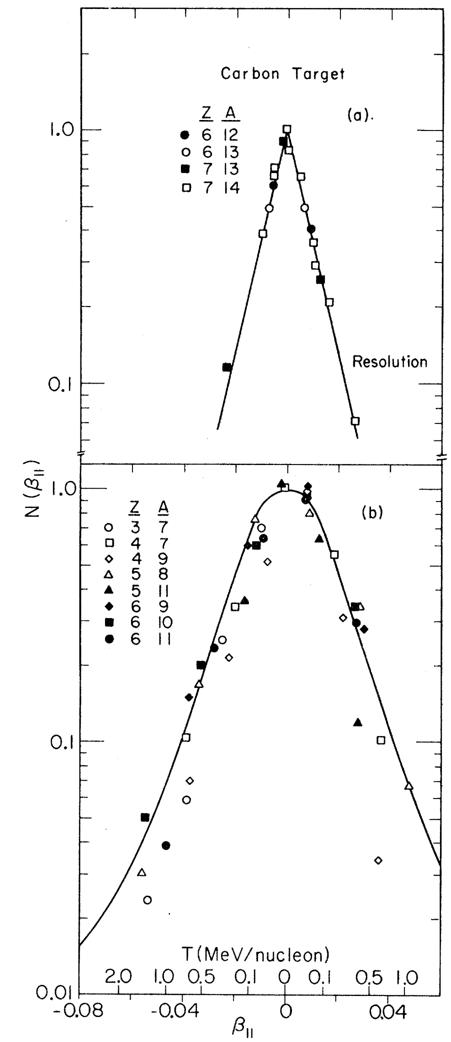

FIG. 2. Distribution of longitudinal velocities and energies/nucleon of ^{14}N fragmentation products in the projectile frame. (a) Nuclei with mass numbers $12 \leq A \leq 14$. The resolution function is the apparent $N(\beta_{\parallel})$ for the monoenergetic ^{14}N beam. (b) Nuclei with mass numbers $7 \leq A \leq 11$. Solid curve drawn through data represents a composite of the $\beta_{\parallel}$ spectra for these nuclei.

we measured at each rigidity setting the Z (i.e., dE/dx) and time-of-flight (TOF) spectra, with and without the target in place. The shape of the observed Z spectra at any given rigidity was independent of target, whether C, CH_2, or background target material. The target-in, target-out TOF data exhibited conspicuous spectral differences, however, and made possible the separation of background (a broad TOF spectrum) from target-produced fragments (a narrow TOF spectrum consistent with the resolution of our TOF measurements).

Because of the near equality of the beam and fragment velocities, a natural frame of reference to examine the fragmentation process is one at rest with respect to the ^{14}N beam, i.e., the projectile frame of reference. We illustrate in Fig. 2 normalized spectral distributions of the longitudinal velocities $\beta_{\parallel}$ for the fragments of ^{14}N nuclei in the projectile frame. Two distinct velocity distributions are obtained when the masses of the fragments are grouped as follows: (a) $12 \leq A \leq 14$ and (b) $7 \leq A \leq 11$. The $N(\beta_{\parallel})$ spectra are, within our experimental errors, the same for CH_2 and C targets, the carbon target data being used for Figs. 2(a) and 2(b).

Although the data are limited, the $N(\beta_{\parallel})$ distributions for ^{13}N, ^{13}C, and ^{12}C, Fig. 2(a), are consistent with the experimentally determined resolution function. Thus, within the precision of the measurements, these secondary nuclei have dynamic properties indistinguishable from the primary beam. We conclude from this that the total cross sections for the fragmentation of ^{14}N into ^{13}N, ^{13}C, and ^{12}C are being observed, since these nuclei are apparently confined to forward angles within the acceptance cone of the spectrometer. We note that these isotopes are produced by the removal of a neutron, a proton, or both, from the ^{14}N nucleus—a fragmentation that figuratively leaves intact the ^{12}C "core."

For product nuclei with $7 \leq A \leq 11$, the ^{12}C "core is disrupted and we observe the $N(\beta_{\parallel})$ distribution shown in Fig. 2(b). Here, the standard deviation of the distribution is 3 times the experimental resolution, indicating the presence of larger momentum transfers and, possibly, of final-state interactions.[5]

The detected number of the ith isotope, corrected for background, is

$$n_i = \kappa N n \int [d\sigma^2/d\beta_{\parallel}\, d\Omega]\, d\beta_{\parallel}\, d\Omega,$$

where κ is the transmission of the magnetic spectrometer, N is the number of ^{14}N incident on the target during the sensitive time of the counter telescope, and n is the number of target nuclei per centimeter squared. The value of the integral is, except for a normalization factor, equal to $\int N_i(\beta_{\parallel})\, d\beta_{\parallel}$. The spectral shape of $N_i(\beta_{\parallel})$ used to carry out the integration appropriate to the ith isotope was either the resolution function, Fig. 2(a), or the curve representing the mean of the composite data, Fig. 2(b).

Table I lists in columns 1 and 2 the measured partial differential cross sections at 0° for the fragmentation of ^{14}N nuclei in carbon and hydrogen (obtained by CH_2-C differences) integrated over the solid angle of acceptance. Errors in the cross sections are typically ±30% rms, external error, and are due to uncertainties in the corrections for background and counter telescope dead time, and in the evaluation of the integral $\int N(\beta_{\parallel})\, d\beta_{\parallel}$ for each isotope. Column 3, σ_H^*, shows the semiempirical estimates of the partial total cross sections by Silberberg and Tsao[6]; and column 4 gives previously measured values of the partial total cross sections of the inverse reaction $p + {}^{14}N \rightarrow$ radioactive nucleus for energies above 1 GeV, tabulated in Ref. 6. But for several exceptions, a comparison of the hydrogen cross sections (columns 2, 3, and 4) reveals that the cross sections measured in this experiment are about one half of the total for ^{7}Li through ^{11}C, and are compatible with the total cross section for ^{12}C, ^{13}C, and ^{13}N. If we assume that the fragments are produced isotropically and possess a

TABLE I. Fragmentation cross sections for ^{14}N nuclei in carbon and hydrogen targets. Cross sections at 0° are from the present experiment; the σ_H^* are semiempirical estimates of the total cross sections given by Silberberg and Tsao; and σ_H(expt) are existing total-cross-section data obtained by proton bombardment above 1 GeV (see Ref. 6).

	$\sigma_C(0°)$ (mb)	$\sigma_H(0°)$ (mb)	σ_H^* (mb)	σ_H(expt) (mb)
^{6}Li	<2.9		10.2	
^{7}Li	9.1 ±1.3	4.5 ±1.0	10.8	
^{7}Be	8.0 ±1.0	6.6 ±1.3	10.3	12±2
^{9}Be	3.0 ±0.3	1.5 ±0.3	3.2	
^{8}B	5.1 ±0.6		2.9	
^{10}B	14.4 ±2.9		9.7	
^{11}B	10.7 ±1.3	6.2 ±1.2	12.5	
^{12}B	1.9 ±0.4	1.3 ±0.4	3.0	
^{9}C	0.14±0.02		0.44	
^{10}C	0.96±0.12		3.4	
^{11}C	11.3 ±1.1	5.2 ±0.9	13.0	25±6, 11±4
^{12}N	0.63±0.13	0.43±0.09	3.0	
^{12}C	46 ±9		22.2	
^{13}C	9.2 ±1.8	4.5 ±1.5	17.8	
^{13}N	7.7 ±1.5	3.6 ±0.7	4.2	4.5±0.5

Gaussian momentum distribution in the projectile frame, we deduce from these cross section results that the characteristic transverse momenta $\langle P_{\perp} \rangle$ of the ^{7}Li through ^{11}C nuclei are ≈ 25 to 30 MeV/c and <12 MeV/c for $^{12,13}C$ and ^{13}N.

Of particular interest is the observation that the ratios of the differential cross sections for the production of the ith isotope in carbon and hydrogen targets are, within their errors, constant. Figure 3 presents the ratios $\sigma_H(0°)/\sigma_C(0°)$ for the respective isotopes. The mean ratio, 0.62±0.07, is in accord with the ratio of the geometric cross sections of the (p, ^{14}N) and (^{12}C, ^{14}N)

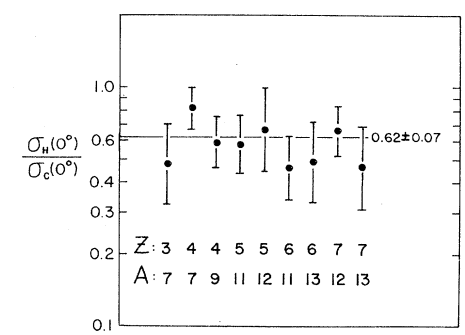

FIG. 3. Plot of the measured ratios of the partial differential cross sections, $\sigma_H(0°)/\sigma_C(0°)$, for the production of isotopes by the fragmentation of 29-GeV ^{14}N nuclei in hydrogen and carbon targets.

systems. The ratio is sustained though the magnitude of the cross sections varies by a factor of 20. We thus have evidence that the modes of fragmentation of the ^{14}N nucleus are the same in hydrogen and carbon.

A possible interpretation of this result comes from the theory of multiparticle reactions at high energy.[7] Applicable to single-particle inclusive spectra are the concepts of limiting fragmentation (scaling) and factorization of cross sections. Limiting fragmentation states that, at high energy, the production cross section for the ith fragment is independent of energy.[8] Factorization states that $\sigma_{ab} \propto C_a C_b$, i.e., the total cross section for interaction between a and b can be factored into quantities that are functions of a and b only. A direct consequence of factorization in the region of limiting fragmentation is the prediction that the modes of fragmentation of the projectile (^{14}N in our case) are independent of the target nucleus.

The underlying result of this experiment, then, is the implication that the concepts of limiting fragmentation and factorization are applicable to hadron systems of large baryon number.

We thank the Bevatron operations staff under H. A. Grunder and W. D. Hartsough, and R. H. Thomas for giving us their unlimited support and effort during the experiment. We also thank G. F. Chew for his helpful and extremely fruitful discussions, and H. M. Steiner for the loan of his time-of-flight equipment. The authors benefitted greatly from the encouragement and active participation of E. M. McMillan throughout the experiment.

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[1]H. A. Grunder, W. D. Hartsough, and E. J. Lofgren, Science 174, 1128 (1971).

[2]H. H. Heckman, D. E. Greiner, P. J. Lindstrom, and F. S. Bieser, Science 174, 1130 (1971).

[3]D. E. Greiner, University of California Report UC-SSL Series 12, Issue 100, 1972 (to be published).

[4]This result may be interpreted by noting that the mass difference $M(^{14}\mathrm{O}) - M(^{14}\mathrm{C}) = 5.0$ MeV, the production of ^{14}O relative to ^{14}C thereby being inhibited by the requirements for energy conservation.

[5]Although incomplete, data on the $N(\beta_{\parallel})$ distributions for the He isotopes extend to $\beta_{\parallel} \approx 0.1$ to 0.2, corresponding to 5 to 20 MeV/nucleon. Such energies are Coulombic, and suggest that final-state interactions may be an important contributor to the spectra.

[6]R. Silberberg and C. H. Tsao, "Partial Cross-Sections in Hgih Energy Nuclear Reactions for Targets with $Z \leq 28$" (to be published).

[7]For a general review, see W. R. Frazer, L. Ingber, C. H. Mehta, C. H. Poon, D. Silverman, K. Stowe, P. D. King, and H. J. Yesian, University of California at San Diego Report No. UCSD 10P10-83, June 1971 (to be published).

[8]On the basis of existing data, cited in Ref. 6, the total cross sections for fragmentation of heavy nuclei are approximately constant for energies greater than 0.5 GeV/nucleon.

New Approach to Perturbed γ-Ray Angular Distributions from Heavy Nuclei Recoiling into Vacuum*

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Time-differential attenuation coefficients of the γ-ray angular distribution of Coulomb-excited Hf nuclei recoiling into vacuum have been measured using a plunger technique. The data have been interpreted in terms of a new model which assumes a stochastic process with Gaussian probability distribution of the perturbing magnetic field strengths and arbitrary correlation times. Reasonable fits to all existing applicable measurements are obtained with a correlation time considerably larger than previously assumed.

In a first attempt to understand the perturbation of the γ-ray angular distribution in the decay of heavy nuclei recoiling into vacuum, Ben Zvi *et al.*[1] applied the theory of Abragam and Pound[2] (AP) for randomly fluctuating interactions. In a recent investigation[3] we found some evidence that