gration can be found in terms of elliptic functions, which naturally include the possibilities of periodic solutions in time.

If dissipative effects are included, an oscillating structure of the solution for $n(t)$ will be expected to appear instead of the described solution. Besides, dissipation will affect the time scale of the problem so as to delay[12,15] the phenomenon and contribute to the saturation.

The authors would like to express their gratitude to professors B. B. Kadomtsev and A. G. Sitenko for discussions during the September 1972 meeting of the international working group on plasma theory in the Institute for Theoretical Physics, Academy of Sciences of the Ukrainian SSR, Kiev, U. S. S. R.

[1]B. B. Kadomtsev, A. B. Mikhailovskii, and A. V. Timofeev, Zh. Eksp. Teor. Fiz. 47, 2266 (1964) [Sov. Phys. JETP 20, 1517 (1965)].

[2]V. M. Dikasov, I. I. Rudakov, and D. D. Ryutov, Zh. Eksp. Teor. Fiz. 48, 913 (1965) [Sov. Phys. JETP 21, 608 (1965)].

[3]P. A. Sturrock, Phys. Rev. Lett. 16, 270 (1966).

[4]V. N. Tsytovich, Zh. Eksp. Teor. Fiz. 51, 1385 (1966) [Sov. Phys. JETP 24, 934 (1967)].

[5]R. L. Sagdeev and A. A. Galeev, *Nonlinear Plasma Theory* (Benjamin, New York, 1969).

[6]E. G. Harris, in *Advances in Plasma Physics*, edited by A. Simon and W. B. Thomson (Interscience, New York 1969), Vol. 3, p. 157.

[7]V. N. Tsytovich, *Nonlinear Effects in Plasma* (Plenum, New York, 1970).

[8]R. C. Davidson, *Methods in Nonlinear Plasma Theory* (Academic, New York, 1972).

[9]B. Coppi, M. N. Rosenbluth, and R. N. Sudan, Ann. Phys. (New York) 55, 207 (1969).

[10]F. Engelmann and H. Wilhelmsson, Z. Naturforsch. 24a, 206 (1969).

[11]L. Stenflo, Plasma Phys. 12, 509 (1969), and Phys. Scr. 2, 50 (1970).

[12]H. Wilhelmsson, L. Stenflo, and F. Engelmann, J. Math. Phys. 11, 1738 (1970).

[13]H. Wilhelmsson and K. Östberg, Phys. Scr. 1, 267 (1970).

[14]K. S. Karplyuk, V. N. Oraevskii, and V. P. Pavlenko, Ukr. Phys. J. 15, 859 (1970).

[15]H. Wilhelmsson, Phys. Rev. A 6, 1973 (1972).

[16]J. Fukai, S. Krishan, and E. G. Harris, Phys. Rev. Lett. 23, 910 (1969).

[17]C. T. Dum and R. N. Sudan, Phys. Rev. Lett. 23, 1149 (1969).

[18]S. Hamasaki and N. Krall, Phys. Fluids 14, 1441 (1971).

[19]M. Caponi and R. C. Davidson, Phys. Fluids 14, 1463 (1971).

[20]A. G. Bonch-Osmolovsky, V. G. Makhankov, V. N. Tsytovich, and B. G. Shchinov, to be published.

[21]H. Wilhelmsson, Phys. Fluids 4, 335 (1961).

[22]V. I. Karpman, *Nonlinear Waves in Dispersive Media* (Novosibirsk, U. S. S. R., 1968).

[23]P. K. C. Wang, J. Math. Phys. 13, 943 (1972).

Absolute Cross Section for Producing ^{11}C from Carbon by 270-MeV/Nucleon ^{14}N Ions*

L. Skoski,† M. Merker, and B. S. P. Shen
Astrophysics Laboratory, Department of Astronomy, University of Pennsylvania, Philadelphia, Pennsylvania 19104
(Received 30 October 1972)

The cross section for producing ^{11}C from carbon irradiated by 270-MeV/nucleon ^{14}N has been found to be 90.0 ± 4.6 mb. The measurement was made using internal counting in plastic scintillators of three different thicknesses; the nitrogen beam was monitored by nuclear emulsions.

The recent successful acceleration of nitrogen ions to several hundred MeV/nucleon at both the Princeton Particle Accelerator (PPA)[1] and the Berkeley Bevatron[2] has ushered in a new era of research using these high-energy heavy ions. In this paper, we report an absolute determination of the cross section for producing ^{11}C from carbon irradiated by 270-MeV/nucleon ^{14}N ions. The process under study is an interesting one not only because it illustrates the collision between two typical medium nuclei but also because it will very likely be used as a convenient primary monitor for the intensity of nitrogen beams.

The experimental technique is similar to that used by Cumming and co-workers,[3] Poskanzer *et al.*,[4] and Radin.[5] Briefly, a packet consisting of a plastic scintillator and a pellicle of nuclear emulsion was exposed to the PPA nitrogen beam, with the beam axis perpendicular to the emulsion surface. The pellicle monitored the nitrogen

TABLE I. Experimental data and results.

	Run 2	Run 3	Run 6	Run 4	Run 5
(1) Scintillator thickness (cm)	0.4	0.4	0.4	2.5	5.1
(2) Scintillator weight (gm)	4.270	4.323	4.291	30.010	59.863
(3) No. of ^{11}C nuclei in scintillator at end of exposure	4.25×10^4 1%[a], 2%[b]	1.34×10^5 1%[a], 2%[b]	4.09×10^4 1%[a], 2%[b]	1.99×10^5 1%[a], 2%[b]	4.01×10^5 1%[a], 3%[b]
(4) No. of sampling areas on emulsion	139	197	259	146	163
(5) Total No. of tracks counted	4382	19089	9999	4369	3470
(6) Flux through scintillator (^{14}N ions)	26.6×10^6 6%[a], 3%[b]	81.9×10^6 3%[a], 3%[b]	26.2×10^6 5%[a], 3%[b]	16.8×10^6 6%[a], 3%[b]	15.8×10^6 7%[a], 3%[b]
(7) Track overlap correction	(0.9±0.9[b])%	(2.8±2.8[b])%	(0.9±0.9[b])%	(0.6±0.6[b])%	(0.6±0.6[b])%
(8) Measured ^{11}C production cross-section (mb)	92.3 6.1%[a] 4.2%[b]	91.2 3.2%[a] 5.0%[b]	89.7 5.1%[a] 4.2%[b]	97.7 6.1%[a] 4.2%[b]	106.4 7.1%[a] 4.7%[b]
(9) ^{11}C production cross-section in thin target	90.0 ± 4.6 mb				

[a]Random-error estimate. [b]Systematic-error estimate.

flux while the carbon constituents of the scintillator served as the target. After exposure, the scintillator was mounted on a photomultiplier and the induced activity counted for 2 to 3 half-lives of ^{11}C. Table I gives the relevant experimental data and results.

For all five successful runs of the experiment, the cylindrical scintillators used had a diameter of 3.81 cm; their thicknesses are given in Table I, row 1. The scintillators (Pilot B)[6] were of an almost pure hydrocarbon containing 91.5% carbon by weight.

The emulsions used were Ilford L-4 pellicles, 100 μm thick. Each emulsion was firmly wrapped in a single layer of light-tight paper, and the scintillator was fastened to the paper with double-sided Scotch tape. The circular outline of the scintillator was then traced on the paper causing the emulsion underneath to be "pressure exposed" along the outline. This outline later served to indicate the position of the scintillator on the developed emulsion. Before each run, a Polaroid film was exposed in order to determine the position of the beam. The scintillator-emulsion packet was then placed on the beam image; centering was not required for the experiment.

The exposures, each lasting several seconds, were made in the PPA 0° external beam cave, with the emulsion at the upstream side of the packet. The counting of the induced radioactivity in the scintillator was undertaken at a site approximately 100 m from the cave, starting about 10 min after the end of each exposure.

After exposure, the scintillator was detached from the emulsion, optically coupled to the photomultiplier using a small contour-fitted light pipe, and counted within a shield constructed of low-activity Pb. An ^{241}Am source was used to set the discriminator of the multichannel analyzer at the 60-keV photopeak. After the ^{241}Am source had been removed, counts were continuously recorded and tallied at one-minute intervals. Background was low and remained constant for each run; it amounted to 4%, 1%, 4%, 6%, and 6% of the total counts in the first 20 min of counting for runs 2, 3, 6, 4, and 5, respectively. The decay curves were analyzed using standard least-squares techniques to obtain the activity of the scintillator at the end of exposure. The effect of the short but finite exposure time was taken into account in the analysis. The calculated value for the activity was then corrected for light outputs below the 60-keV photopeak by interpolating from the efficiencies of Cumming, Friedlander, and Katcoff[3]; this correction never exceeded 6% for our scintillators.

By fitting the decay curves with the half-lives of both ^{13}N (10.0 min) and ^{11}C (20.4 min), we found that at the end of exposure the number of ^{13}N nuclei in each of the three 0.4-cm-thick scin-

tillators amounted to $(0 \pm 1)\%$ of the number of ^{11}C nuclei present. Corresponding values for the 2.5 and 5.1-cm-thick scintillators were $(1 \pm 1)\%$ and $(2 \pm 2)\%$, respectively. Thus, little or no ^{13}N was present. Now ^{13}N, if present, would include the ^{13}N ions which resulted from the breakup of ^{14}N ions and which happened to stop in the scintillator. Since little or no ^{13}N contribution to the scintillator activity was found, the contribution to the scintillator activity by stopped ^{11}C ions from the breakup of ^{14}N ions cannot be much greater. In any event, the extrapolation to thin target to be discussed later removed any possible contamination due to ^{11}C produced as a result of the breakup of the ^{14}N ions. The number of ^{11}C nuclei in the scintillators at the end of exposure along with the estimated errors are given in Table I, row 3.

The pellicles were mounted on glass slides and developed in Kodak D-19. The number of tracks in many "sampling areas" on each emulsion was then counted under a microscope. These sampling areas, each a square with (38.6 ± 1)-μm sides, were distributed fairly uniformly within and slightly beyond the scintillator contour on the emulsion surface; their number within the contour per emulsion (i.e., per run) ranged from 139 to 259, as given in Table I, row 4. The use of a large number of sampling areas was desirable because the flux in the beam was neither uniform nor perfectly symmetrical. The track counts of the scanners were cross checked repeatedly and were found to agree to within 1%. The emulsions were also analyzed by the Joyce-Loebel microdensitometer of Yale University Observatory, and digitized isodensity contours obtained. This improved the interpolation between the sampling areas and served as a confirmation of the relative counting rates among them. Table I, row 6, gives the total flux of nitrogen ions through the scintillator. The estimated random error is based mainly on the total number of tracks counted and on the uncertainties introduced by the smoothing between adjacent sampling areas. The estimated systematic error is based on the track-scanning efficiency and on minor changes in the shape of the emulsions during processing. Table I, row 7, gives the percentage correction for track overlap, made on the assumption that tracks whose centers are separated by less than the track radius have been erroneously counted as a single track.

The diameter of foreshortened ^{14}N tracks in the developed emulsion was 1.0 ± 0.1 μm. On the basis of dE/dx, we estimate that tracks of foreshortened He (down to 200 MeV/nucleon) and H (down to 30 MeV/nucleon), if present, would be easily distinguishable from those of ^{14}N. We looked for such tracks in all the emulsions but found none. This is consistent with the fact that upstream matter totaled only ~ 0.5 g/cm^2 (6 mils of Al, 10 mils of paper, and 69 mils of plastic at the beam portal; 4.6 m of air between the portal and the experimental packet).[7] Based on the collision cross section of Bradt and Peters,[8] we estimate that only about 3% of the initial beam suffered inelastic nuclear collision of some kind in this matter and in the wrapped emulsion. Among the secondary ions thus produced, only Li, Be, and possibly B could have had an effect (second-order effect at that) on the measured ^{11}C production cross section, whereas C, N, and O secondaries would have cross sections very close to that of ^{14}N. Furthermore, although local irregularities of the emulsion surface caused the beam to strike slightly nonperpendicularly in various regions of the emulsion, the tracks in any given region always showed the same direction of incidence, indicating the virtual absence of highly scattered particles in the beam. However, the 0.5 g/cm^2 of upstream matter did cause the 280-MeV/nucleon nitrogen beam from the PPA to be slowed down to approximately 270 MeV/nucleon, the actually incident energy of this experiment. Since beam contamination by protons was negligible down to at least 30 MeV, the same must be true of contaminating neutrons. In any case, the reaction $^{12}C(n, 2n)^{11}C$ has a high practical threshold of about 20 MeV, and its cross section does not rise much above 20 mb out to at least 300 MeV, except for a possible peak between 40 and 80 MeV.[3] We estimate that beam contamination of all kinds introduced a systematic error of $\pm 2\%$ to the measured cross sections.

Table I, row 8, gives the ^{11}C production cross sections obtained from the five successful runs, using scintillators of various thicknesses. The cross sections are seen to increase with thickness. This increase can be due to ^{11}C produced by secondary interactions in the targets and to stopped ^{11}C from the breakup of ^{14}N ions. In order to remove these unwanted contributions, the cross sections obtained with the 0.4- and 2.5-cm-thick scintillators are used to linearly extrapolate the cross section to zero thickness. The correction to zero thickness amounted to $(0.32 \pm 0.1)\%$ per 100 m/cm^2 of scintillator; this is to be compared with Radin's value[5] of $(0.26 \pm 0.1)\%$ per

100 m/cm^2 using 230-MeV/nucleon α particles. The extrapolated thin-target cross section for producing ^{11}C from carbon irradiated by 270-MeV/nucleon ^{14}N ions is therefore found to be 90.0 ± 4.6 mb. As noted earlier, within the cited error this cross section does not include any contribution from the ^{11}C ions which resulted from the breakup of the moving ^{14}N ions themselves.

It is important to realize that there are two parts to the cross section of the reaction $C(^{14}N, X)^{11}C$. We propose that the first part, the part we measured, be called the cross section for producing ^{11}C *from C* interacting with ^{14}N, or the cross section of the reaction $C(^{14}N, X)^{11}C[C]$. The second part, the part we did not measure, may be called the cross section for producing ^{11}C *from* ^{14}N interacting with C, or the cross section of the reaction $C(^{14}N, X)^{11}C[^{14}N]$. Distinctions of this kind will become important as experiments using high-energy heavy ions proliferate.

Prior to our experiment, Schimmerling and co-workers had, in the first days of the PPA ^{14}N beam, made an independent preliminary measurement of the $C(^{14}N, X)^{11}C[C]$ cross section at 270 MeV/nucleon at the PPA using Lucite targets of a single thickness (0.6 cm), and they quoted a preliminary result of 103 ± 9 mb.[9] Their nitrogen beam was monitored by a counter telescope, and the Lucite target was counted by γ-γ coincidence using two NaI scintillators.[9] We believe that our experimental technique, which is similar to that used in previous definitive determinations of ^{11}C production cross sections,[3-5] is more likely to lead to results with a small percentage error estimate.

The cross section of $^{12}C(p, pn)^{11}C$ is 36 mb at 270 MeV (and 28 mb at 3.8 GeV).[10] The cross section of $^{12}C(\alpha, \alpha n)^{11}C$ measured by Radin has been revised,[11] and is 48.9 ± 1.8 mb at 230 MeV/nucleon. Our experiment now finds the cross section of $C(^{14}N, X)^{11}C[C]$ to be 90.0 ± 4.6 mb at 270 MeV/nucleon (or 3.8 GeV total energy). Calculations based on our Monte Carlo code RENO[12] for nucleus-nucleus reactions show that the cross sections of $C(\alpha, X)^{11}C$ at 230 and 270 MeV/nucleon are equal to within a few percent. If we assume this equality, then it can be seen that the various ^{11}C production cross sections just cited increase as $A^{0.4}$ for incident particles having 270 MeV/nucleon.

We thank J. Radin for his advice and for the use of some of his equipment, G. Reimer for providing time and assistance on the emulsion microscope, and B. Hrivnak for assistance in the data reduction. The cooperation of M. G. White, W. Schimmerling, and their staff at the Princeton Particle Accelerator is gratefully acknowledged. Thanks are also due to S. A. Korff, R. B. Mendell, and R. S. Sanna for their advice. E. B. Newell and R. Zinn kindly allowed us to use the Yale University Observatory microdensitometer in an interesting cooperation between astronomy and nuclear physics.

---

*Research supported in part by National Aeronautics and Space Administration under Grant No. NGR-39-010-114 and Contract No. NAS 1-10282.

†Cosmic Ray Project, Department of Physics, New York University, University Heights, New York, N. Y. 10453.

[1]M. G. White, M. Isaila, K. Prelec, and H. L. Allen, Science 174, 1121 (1971).

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

[3]J. B. Cumming and R. Hoffman, Rev. Sci. Instrum. 29, 1104 (1958); J. B. Cumming, G. Friedlander, and S. Katcoff, Phys. Rev. 125, 2078 (1962).

[4]A. M. Poskanzer, L. P. Remsberg, S. Katcoff, and J. B. Cumming, Phys. Rev. 133, B1507 (1964).

[5]J. Radin, Phys. Rev. C 2, 793 (1970).

[6]Pilot Chemical Company, 36 Pleasant St., Watertown, Mass.

[7]W. Schimmerling, private communication.

[8]H. L. Bradt and B. Peters, Phys. Rev. 77, 54 (1950); G. Alexander and G. Yekutieli, Nuovo Cimento 19, 103 (1961).

[9]W. Schimmerling, private communication.

[10]J. B. Cumming, Annu. Rev. Nucl. Sci. 13, 261 (1963).

[11]J. Radin, Phys. Rev. C 4, 1010 (1971).

[12]W. Schmitt, Ph. D. thesis, University of Pennsylvania, 1970 (unpublished).