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Radiative Capture of Protons in C^{13}†

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An excitation curve of the $C^{13}(p,\gamma)N^{14}$ reaction has been measured from 100 kev to 140 kev. The cross section ranges from $(7.7\pm1.8)\times10^{-34}$ cm^2 at 100 kev to $(9.8\pm1.2)\times10^{-33}$ cm^2 at 140 kev. The results are compared with those of previous measurements.

INTRODUCTION

The reaction $C^{13}(p,\gamma)N^{14}$ with which this report is concerned is one that is involved in the carbon-nitrogen cycle. It has been previously measured at 129 kev by Woodbury and Fowler.[1] It is of interest to measure the cross section at as low an energy as possible to permit more accurate extrapolation to stellar temperatures where these reactions are important in some classes of stars.[2]

EXPERIMENTAL ARRANGEMENT

The high-current ion injector at Livermore[3] was used to bombard high-density graphite targets. The 1.1% natural abundance of C^{13} in the graphite provided the target for the $C^{13}(p,\gamma)N^{14}$ reaction. The beam from the ion source was turned through a 90° analyzing magnet, passed through a 1-inch diameter collimator, and impinged upon a graphite target located $1\frac{1}{2}$ inches in front of a 4-in. ×4-in. NaI(Tl) crystal. A water-cooled block was mounted between the target and the counter. The 4-in. ×4-in. NaI(Tl) crystal was mounted outside the vacuum system. The NaI crystal and its mounting were coupled to a Dumont 6364 photomultiplier by means of a Celvancene grease seal to improve optical coupling. The output of the photomultiplier tube was fed into a linear amplifier whose output was registered in a twenty-channel pulse-height analyzer. The gain of the amplifier was periodically checked with a ThC″ 2.62-Mev gamma-ray source. See Fig. 1 for experimental arrangement.

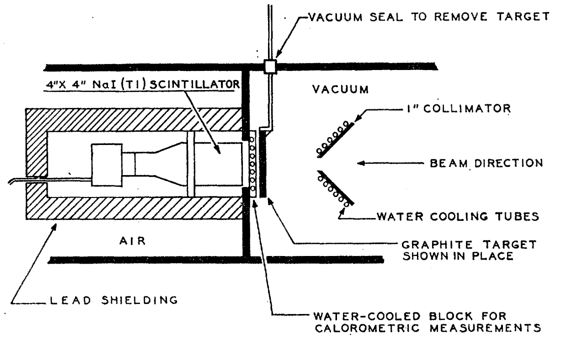

Fig. 1. Counter arrangement.

EXPERIMENTAL PROCEDURE

A. Counter Calibration

The photon efficiency of the counter was obtained by measuring an integral bias curve for the $C^{13}(p,\gamma)N^{14}$ reaction (see Fig. 2 for a typical bias curve) and extrapolating the straight-line portion of the curve to zero volts. The intercept at zero volts gives the total number of counts in the crystal. The number of counts can then be divided by the calculated total absorption of the crystal to give the yield. This method has been checked against known gamma-ray sources and gives agreement to better than 10%.[4] It can be seen in Fig. 2 that there are two breaks in the integral bias curve. These are due to cascade gamma rays in the reaction. The first break indicates a 3.7-Mev gamma ray, while the second break would indicate a 2.3-Mev gamma ray. The information derived from the integral bias curve plus a knowledge of the energy levels of the N^{14} compound nucleus[5] strongly suggested that about 86% of

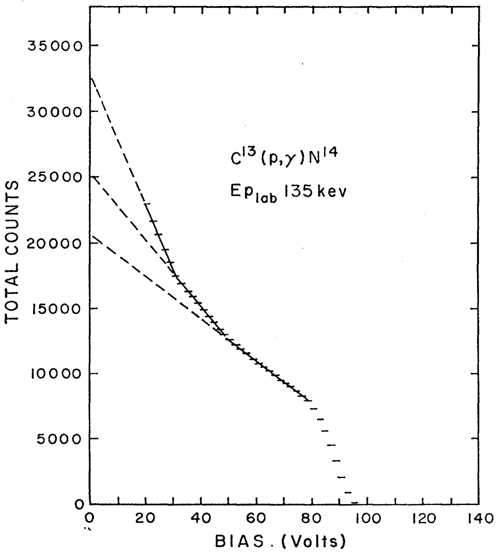

Fig. 2. Integral bias curve.

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[1] E. J. Woodbury and W. A. Fowler, Phys. Rev. **85**, 51 (1952).

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[3] W. A. S. Lamb and E. J. Lofgren, Rev. Sci. Instr. **27**, 907 (1956).

[4] T. Huus and R. B. Day, Phys. Rev. **91**, 599 (1953).

[5] F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. **27**, 77 (1955).

the transitions were those from 7.65 Mev to the ground state, while the remaining 14% predominantly were a triple cascade. Integral bias curves were made at 135 kev and 120 kev to look for energy dependence in the decay scheme of the N^{14} compound nucleus. Within statistical errors no energy dependence was observed. These bias curves were obtained by bombarding targets prepared in the Oak Ridge National Laboratory electromagnetic isotope separators, which targets contained about 15% C^{13}. The targets were not uniform in thickness and tended to erode, making them undesirable for use in obtaining cross-section data; however, they served very well for bias curves.

To reduce the background the counter was arranged to count only those counts registering in the "escape peak" of the 7.65-Mev gamma ray. The "escape peak" consisted of all total absorption events and pair-production events with either one or two positron annihilation gamma rays escaping from the NaI crystal. The fraction of counts falling in this peak was deduced from the bias curve, and an efficiency of 2.8±0.3% established for the counter.

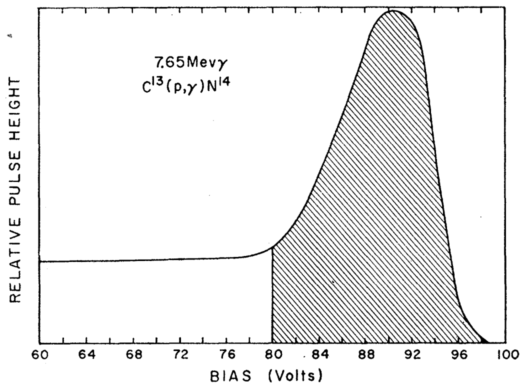

FIG. 3. Pulse-height distribution.

B. Accelerating-Voltage Measurement

The accelerating voltage was measured by means of a precision voltage divider and a potentiometer. The voltage divider was calibrated against the $B^{11}(p,\gamma)C^{12}$ resonance at 163 kev. The voltage measurements are believed to be accurate to ±1%.

C. Beam-Current Measurements

Immediately before and after a run the graphite target was removed from the beam path, allowing the beam to strike the water-cooled block. In this manner the beam power was measured by a thermopile in the cooling circuit of the water-cooled block. The thermopile was calibrated by means of an immersion heating unit and precision electrical instruments. With a knowledge of the accelerating voltage the beam current was then calculated with an estimated accuracy of ±5%. During bombardment the graphite targets were at sufficiently high temperature to be incandescent. This produced a large flux of secondary electrons, which rendered electrical beam readings meaningless; however, a sizeable fraction of the heat radiated from the target was absorbed by the water-cooled block, giving a convenient means of monitoring the beam level during bombardments.

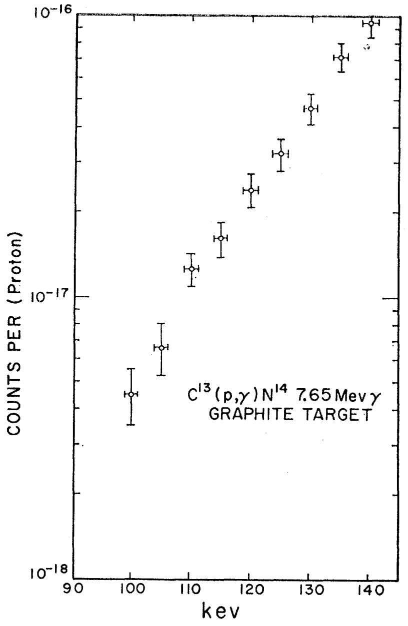

FIG. 4. Thick-target yield per incident proton as a function of energy, for the 7.65-Mev gamma ray.

D. Counting Measurements

The pulse-height distribution of the 7.65-Mev gamma ray is shown in Fig. 3. The shaded portion shows the "escape peak" of the ground-state transition in the $C^{13}(p,\gamma)N^{14}$ reaction. This portion of the pulse-height distribution was used to determine the excitation curve for the ground-state transition from 100 kev to 140 kev. The counter resolution, "poor geometry," a one-inch diameter gamma-ray source, and scattering of the high-energy radiation into the crystal combine to present the "escape peak" as one large peak rather than resolving it into its three components of total absorption and the two annihilation-radiation escape peaks.

The background data were taken with the beam on but unanalyzed and striking a blank target several feet from the counter. The large amount of sublimed carbon in the vicinity prevented taking the background data with the beam striking the water-cooled block located in front of the counter. Bombardment of clean blank targets $1\frac{1}{2}$ inches in front of the counter did indicate our method of obtaining background data was justified, and in either case no systematic difference in background was detected with the beam on or off.

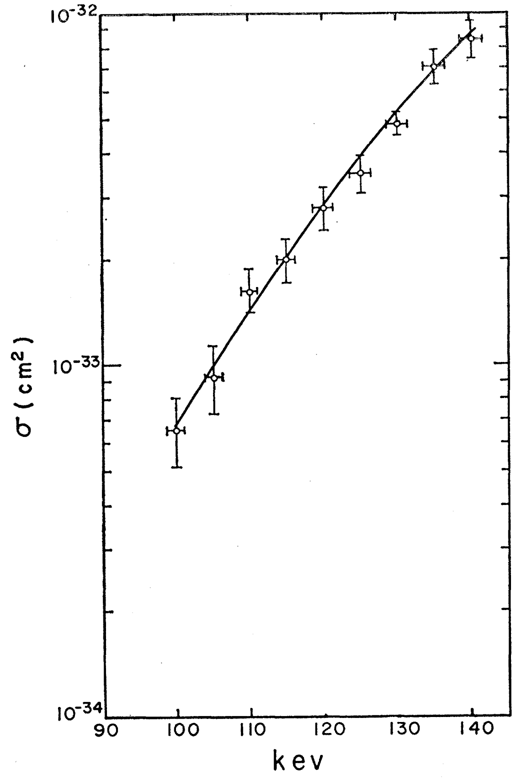

FIG. 5. Excitation curve for the 7.65-Mev gamma ray, calculated from Eq. (3).

REDUCTION OF THE DATA

Figure 4 shows the thick-target yield per incident proton as a function of energy from 100 kev to 140 kev for the 7.65-Mev gamma ray. The thick-target yield is calculated from

$$Y_t = \frac{\text{net counts/sec}}{\text{beam current in ma} \times 6.24 \times 10^{15} \times F}, \tag{1}$$

where F is the appropriate counter efficiency.

It can be shown that the thick-target yield is related to the cross section by

$$Y_t = \int_0^E \frac{\sigma(E)dE}{\epsilon}, \tag{2}$$

where ϵ is the stopping cross section per target nucleus and is approximately constant in the energy interval used. Since the cross section is a steep function of energy, the cross section can be related to the thick-target yield after the manner of Hall and Fowler[6] by the expression

$$\sigma \simeq 3Y_t \left[\frac{\epsilon}{E^{\frac{3}{2}}}\right]\left[1 + \frac{E^{\frac{1}{2}}}{Z_0} + \cdots\right]. \tag{3}$$

The value of ϵ used was 1.62×10^{-20} Mev-cm², and the appropriate correction was made for the isotopic abundance of the target nuclei.[7]

Figure 5 shows the excitation curve for the 7.65-Mev gamma ray as calculated from Eq. (3).

Since interest in the carbon cycle as a source of energy generation in some stars was part of the stimulus for measuring this cross section, it is of interest to compute the cross-section factor $S(E)$, which can be expressed by (2),

$$S(E) = \sigma(E_1)E_1 \frac{A_0}{A_0 + A_1} \exp(31.28 Z_1 Z_0 A_1^{\frac{1}{2}} / E_1^{\frac{1}{2}}),$$

where $S(E)$ is expressed in kev-barns in center-of-mass system, $\sigma(E)$ is expressed in barns, Z_1 and Z_0 are the charges of the reacting particles in units of proton charge, A_1 and A_0 are the masses in units of atomic mass, and E_1 is the energy of the incident proton in kev in the laboratory system. When far from a resonance, $S(E)$ is expected to be an approximate constant over a limited energy range. A value of 10.6±1.5 kev-barns is computed for $S(E)$ from the excitation curve of Fig. 5 when the appropriate correction is made for the cascade gamma rays.

COMPARISON OF RESULTS WITH PREVIOUS MEASUREMENTS

The $C^{13}(p,\gamma)N^{14}$ reaction cross section had been previously measured by Woodbury and Fowler,[1] who quoted a cross section of $(5 \pm 1) \times 10^{-33}$ cm² at 129 kev. The present measurement would indicate a cross section of $(5.8 \pm 1) \times 10^{-33}$ cm² at 129 kev. This is excellent agreement; however, the two values were arrived at in different ways. Woodbury and Fowler quote their cross section on the basis of two-step cascade for the soft radiation, while our data indicate a three-step cascade. If Woodbury and Fowler quote their results on the basis of a triple cascade for the soft radiation, the value is $(4.6 \pm 1.0) \times 10^{-33}$ cm², which is still in agreement with these results within the limits of the experimental error.

A previous preliminary measurement[8] at 126 kev by the authors gave a value for the cross section which was about 40% higher than the present measurement would indicate, but the experimental error was large to imply any serious disagreement.

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[6] R. N. Hall and W. A. Fowler, Phys. Rev. **77**, 197 (1950).

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[8] W. A. S. Lamb and R. E. Hester, Phys. Rev. **107**, 550 (1957).