Radiative Capture of Protons in Carbon from 80 to 126 kev*

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An excitation curve has been measured for the reaction $C^{12}(p,\gamma)N^{13}$ in the energy interval 80 kev to 126 kev by utilizing beam currents of 30 ma to 50 ma from the high-current ion injector. The capture-gamma radiation was measured with a 4-in.×4-in. NaI scintillator which was arranged to count only gamma radiation of the energy appropriate to the reaction. The yield per incident proton ranges from $(7.0\pm2.3)\times10^{-18}$ at 80 kev to $(6.2\pm0.2)\times10^{-16}$ at 126 kev with corresponding cross sections of $(1.4\pm0.4)\times10^{-11}$ barn and $(6.8\pm0.8)\times10^{-10}$ barn. A value for the cross section of the reaction $C^{13}(p,\gamma)N^{14}$ has been obtained at two energies, namely: $(8.2\pm2.5)\times10^{-9}$ barn at 126 kev, and $(5.1\pm2.0)\times10^{-9}$ barn at 114 kev. The results are compared with previous measurements and with extrapolations from the resonance in this reaction at 456 kev by means of the Breit-Wigner single-level dispersion formula.

INTRODUCTION

THE reactions discussed here are the first two in the carbon-nitrogen cycle[1] and are involved in nuclear processes which are believed to be responsible for energy generation and element synthesis in some classes of stars.[2–4] The energies of protons used in this experiment are considerably higher than those which seem reasonable for stars burning hydrogen in the C—N cycle, but at the present time the energy range of from 10–30 kev is not accessible to experiment. The extrapolation from measured cross sections to cross sections at stellar energies can be done with more confidence if the appropriate relation between cross sections and energy can be demonstrated in regions which are accessible to experiment. The energetic protons in the high-energy tail of a Maxwellian distribution which make the major contribution to the reaction rate are only a factor of two or three from the energy range studied here; however, the cross section as extrapolated is some five orders of magnitude smaller.

DESCRIPTION OF APPARATUS

The high-current ion injector,[5] which was developed for the high-current linear accelerator[6] at Livermore, is capable of continuous currents of hundreds of milliamperes over a continuous range of voltage up to 130 kev. The beam from this machine was collimated and then analyzed by means of a large prismatic-pole electromagnet; the protons were turned 90° to the original direction of the beam and passed through another aperture and into the target tank (Fig. 1). The energy interval passed by this analyzing and collimating system was about 3 kev, and the interval to half the maximum intensity was typically ±1 kev. The collimator in front of the target was $1\frac{1}{4}$ in. in diameter.

The high-voltage power supply used for acceleration on the machine had an inherent 3-phase, 60-cycle ripple of about 2%.

The target used in this experiment was a $\frac{1}{8}$-in. sheet of high-density graphite, which was mounted on a shaft. This shaft passed through a sliding vacuum seal and permitted the target to be inserted or removed from the beam. With the target drawn aside the beam strikes a water-cooled copper block called the calorimetric collector, which was used to make a measurement of the beam power.

When the target was under bombardment it was cooled by radiation to the surrounding water-cooled surfaces. A little less than half of the total power radiated was intercepted by the calorimetric collector and provided a means of monitoring the beam power during a nuclear measurement. The output of a thermopile in the cooling-water circuit was fed to a recorder and continuously monitored during a run.

The equipment for measuring the power consisted of a calibrated flowmeter and thermocouples mounted on the cooling water in and out of the calorimetric collector.

The counting system consisted of a 4-in.×4-in.

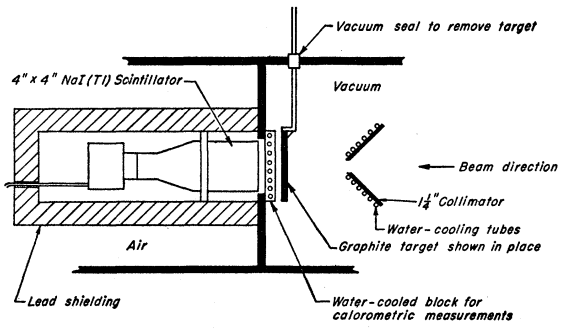

FIG. 1. Diagram of target and counting arrangement. The beam has previously been analyzed and turned 90° to the original direction. The graphite target is shown in place. Additional lead shielding used is not shown.

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[1] H. A. Bethe, Phys. Rev. **55**, 103, 434 (1939); Astrophys. J. **94**, 37 (1940).
[2] W. A. Fowler, Mém. soc. roy. sci. Liège **14**, 88 (1954).
[3] Bosman-Crespin, Fowler, and Humblet, Bull. soc. roy. sci. Liège **9**, 327 (1954).
[4] Burbidge, Burbidge, Fowler, and Hoyle, "Synthesis of the Elements in Stars," Revs. Modern Phys. (to be published).
[5] W. A. S. Lamb and E. J. Lofgren, Rev. Sci. Instr. **27**, 907 (1956).
[6] E. O. Lawrence, Science **122**, 1127 (1955).

NaI(Tl) crystal and a 5-in. multiplier phototube surrounded by a 2-in.-thick cylinder of lead except on the front. The counter, which was outside the vacuum, was placed as close to the target as possible to optimize the solid angle. The front face of the crystal was approximately $2\frac{1}{4}$ in. from the target. The output of the phototube was fed into a 20-channel pulse-height analyzer from which the data were taken.

EXPERIMENTAL PROCEDURE

A. Counter Calibration

It is necessary to know the absolute efficiency of the photon counter in order to determine the number of nuclear events taking place in the target. The efficiency was measured at two energies, namely, at 1.3 Mev using a Na^{22} source and at 2.8 Mev using a Na^{24} source.

A Na^{22} source whose activity is believed known to about 5% was placed in the position of the graphite target and a pulse-height spectrum was taken under conditions with which measurements were taken. This source was physically smaller than the 1-in. to $1\frac{1}{2}$-in. diameter beam spot and so the effect of the larger source was simulated by moving the sample to several positions of the beam spot with the result that the geometry differences were negligible.

A Na^{24} source was prepared for each calibration by bombarding a sodium salt such as NaOH in the Livermore reactor until its activity was sufficient to permit a measurement of the gamma radiation with a 0–5 mr full-scale ion chamber which was calibrated against standard sources. This sample was too active to be used in the position of the target and so it was dissolved in water and aliquots taken. The samples were made by putting aliquots of the solution on blotting paper which was cut to the diameter of the beam spot. Usually three equal aliquots were taken and the chemical technique was checked by their reproducibility.

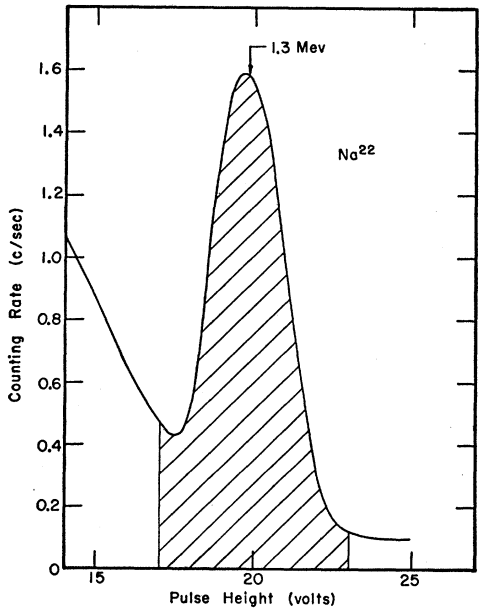

FIG. 2. Pulse-height spectrum of Na^{22} 1.3-Mev gamma ray. The shaded portion was used to determine the "photofraction" efficiency. A similar measurement was made on the 2.8-Mev gamma ray of Na^{24}.

Figure 2 shows typical pulse-height distributions from these radioactive samples. The gamma-ray energy interval or window used in making the measurement was also used on the calibrations. A typical interval is shown shaded in Fig. 2, and is what could be called the "photofraction." One can calculate these "photofraction" efficiencies as a function of energy[7–9] and geometry, and the results obtained by experiment at the two energies used are in substantial agreement. With the counting geometry determined in this way, and a calibration of the efficiency at two photon energies, the efficiency of the counter for a similar photon energy interval is calculated for the particular gamma ray under study.

B. Accelerating Voltage Measurement

The average accelerating voltage was measured by means of a 100-megohm resistor arranged as a voltage divider and measured with a potentiometer. The resistor used as a standard was borrowed from the California Institute of Technology where it was previously used in a similar measurement.[10] This resistor was further checked by constructing a similar resistor by means of the technique of measuring the resistors first individually, and then in parallel, which should lead to accuracy of better than 0.1%.

C. Beam Current Measurement

The beam current is deduced from a measurement of the beam power calometrically with the graphite target removed and then dividing the power by the average high voltage. The graphite target is then inserted in front of the calorimetric collector and the relative power maintained during the run. The graphite target was removed from time to time and the beam level checked during a run if the relative power level appeared to change. The calorimetric measuring apparatus was checked periodically with an immersion electric heater and precision electrical instruments.

D. Nuclear Measurements

Figure 3 shows the pulse-height distribution with the cosmic-ray background subtracted at 126 kev with the shaded portion encompassing events from 1.75 Mev

[7] R. W. Kavanagh, thesis, California Institute of Technology, 1956 (unpublished).
[8] R. S. Foote and H. W. Koch, Rev. Sci. Instr. **25**, 746 (1954).
[9] G. R. White, National Bureau of Standards Report No. 1003, 1952 (unpublished).
[10] R. N. Hall and W. A. Fowler, Phys. Rev. **77**, 197 (1950).

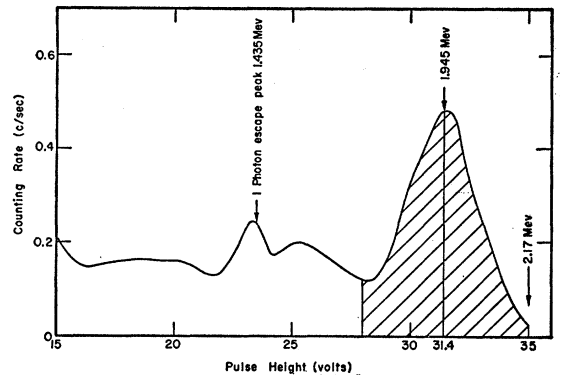

FIG. 3. Pulse-height spectrum of $C^{12}(p,\gamma)N^{13}$ at a proton energy of 126 kev. The shaded portion was used to determine yields.

to 2.17 Mev, which was used in determining the yield of the reaction $C^{12}(p,\gamma)N^{13}$. In this case all of the nuclear events result in a ground-state transition in N^{13} of 1.945 Mev.[11] The same window was utilized in determining the yields at the lower accelerating voltage where the lower counting rate made the position of the gamma line less obvious.

The background was normally taken with the beam turned off; however, this was compared with runs on blank targets made of copper with the beam on and no systematic difference was observed. It was impossible to take backgrounds with the beam striking the calorimetric collector for example, because of the presence of sublimed carbon on the components inside the vacuum after running the beam on the graphite.

RESULTS—$C^{12}(p,\gamma)N^{13}$

Figure 4 shows the thick-target yields per incident proton for energies from 80 kev to 126 kev in the laboratory frame of reference, and was obtained by substituting in the following expression:

$$Y_t=\frac{\text{net counts/sec}}{\text{beam current in ma}\times 6.24\times 10^{15}\times f}, \quad (1)$$

where f is the absolute efficiency of the counter including geometry for the interval used.

The thick-target yield is related to the cross section by the following expression:

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

where ϵ is the stopping cross section per nucleus and $\sigma(E)$ is the nuclear cross section which is a function of energy.

If the stopping cross section is considered to be constant over the energy interval covered by this measurement, and the cross section is a steep function of energy,[10] then the thick-target yield Y_t can be related to the cross section by the following expression:

$$\sigma\cong 3Y_t\left[\frac{\epsilon}{E^{\frac{3}{2}}}\right]\left[1+\frac{E^{\frac{1}{2}}}{6}+\cdots\right], \quad (3)$$

where ϵ is in Mev-cm^2 and E is in Mev.

If one uses for the atomic stopping cross section for carbon 1.62×10^{-20} Mev-cm^2,[12] then for C^{12}, $\epsilon=1.62\times 10^{-20}/0.989$, where the factor 0.989 is the correction for the isotopic abundance. One has finally

$$\sigma\cong 3Y\left[\frac{1.63\times 10^{-20}}{E^{\frac{3}{2}}}\right]\left[1+\frac{E^{\frac{1}{2}}}{6}+\cdots\right]. \quad (4)$$

The values for the cross section shown on Fig. 5 were derived using this expression.

Also shown in Fig. 5 are points derived from the Breit-Wigner single-level dispersion formula[10,13] by extrapolating from the resonance at 456 kev, namely,

$$\sigma=\frac{1.4\times 10^{-3}}{E}\exp\left[-\frac{6}{E^{\frac{1}{2}}}\right]\text{barn}, \quad (5)$$

where E is in Mev.

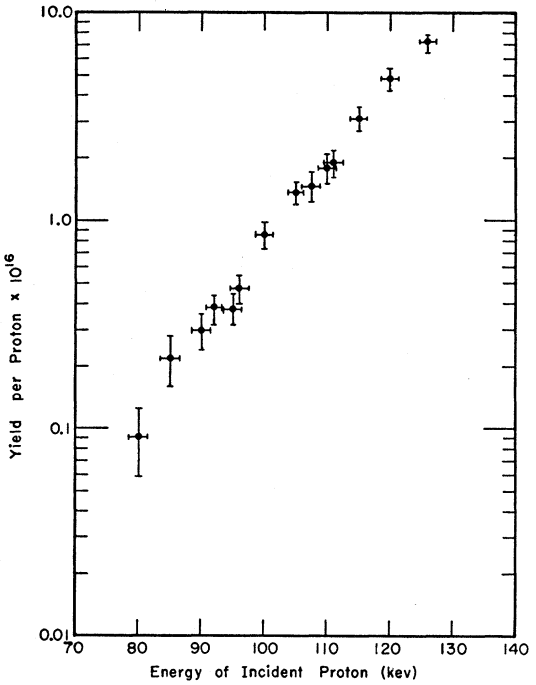

FIG. 4. The thick-target yield per incident proton is shown as a function of energy. The errors shown are rms errors in counting statistics plus estimated systematic errors.

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[12] R. Fuchs and W. Whaling, California Institute of Technology "Compilation of Stopping Cross Sections" (private communications).

[13] J. M. Blatt and V. F. Weisskopf, *Theoretical Nuclear Physics* (John Wiley and Sons, New York, 1952).

DISCUSSION OF ERRORS

There are many sources of error in a measurement of this kind, but one can place reasonable limits on the major ones enabling an evaluation of the errors on the cross sections given. The principal errors on the thick target yield are: (1) counter calibration, $\pm 5\%$; (2) accelerating-voltage measurement, (average) $\pm 1\%$; (3) beam-power measurement, $\pm 5\%$; (4) counting statistics, ranging from $\pm 5\%$ to $\pm 40\%$. Hence, the rms error on the thick target yield ranges from $\pm 8.7\%$ to $\pm 41\%$.

It is believed that the reduction to cross section introduces an additional error of perhaps 10% because of errors in the stopping cross section and approximation in the formulations, hence, the rms errors range from about $\pm 13\%$ to $\pm 41\%$ at the extreme lower and higher energies. These errors are indicated on Figs. 4 and 5. The results shown in Fig. 5 are in substantial agreement with those given in Hall and Fowler.[10]

$C^{13}(p,\gamma)N^{14}$

A by-product of the measurement discussed above are values at two energies for the cross section of $C^{13}(p,\gamma)N^{14}$. These thick-target yields and cross sections were obtained on the assumption that each photon counted in the interval between 2.5 Mev and 7.5 Mev[11] is due to one nuclear reaction in C^{13}. An average counting efficiency was used for this interval. The counting statistics are poor because of the 1.1% abundance of C^{13} in normal graphite. The results are:

$$126 \text{ kev}\begin{cases} Y_t = 7.9\times 10^{-15} \pm 40\%, \\ \sigma = (8.2\pm 2.5)\times 10^{-9} \text{ barn}, \end{cases}$$

$$114.2 \text{ kev}\begin{cases} Y_t = 4.5\times 10^{15} \pm 35\%, \\ \alpha = (5.1\pm 2)\times 10^{-9} \text{ barn}. \end{cases}$$

The errors given are derived similarly to those quoted for the $C^{12}(p,\gamma)N^{13}$ measurement and do not include the uncertainty about the mode of decay of N^{14} from its excited states. With this uncertainty, the values for the cross sections are perhaps within a factor of two or so. These results are somewhat higher than those given previously by Woodbury and Fowler[14]; however, because of the uncertainties the differences are thought to be insignificant.

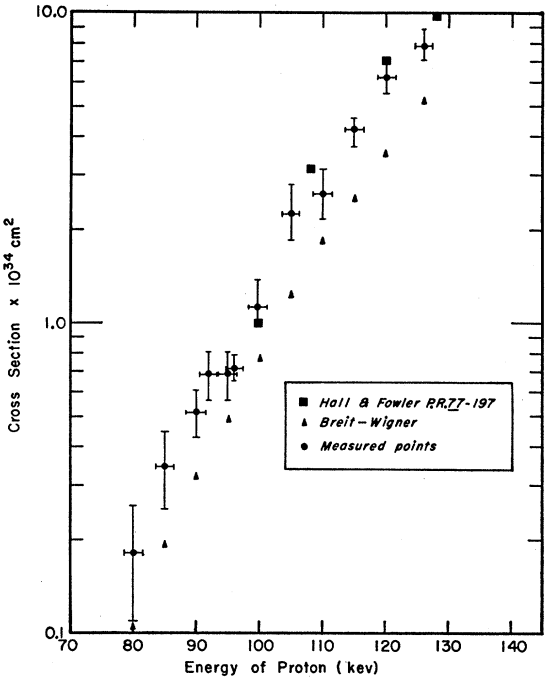

FIG. 5. The cross section is shown as a function of proton energy in the laboratory system.

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