Cross Section of the C^{12} $(p, \gamma)N^{13}$ Reaction at Low Energies

CARL L. BAILEY
Concordia College, Moorhead, Minnesota

AND

WILLIAM R. STRATTON
Department of Physics, University of Minnesota, Minneapolis, Minnesota

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The efficiency of the nuclear reaction $C^{12}(p, \gamma)N^{13}$ has been measured over the energy range from 125 kev to 200 kev, with results which are in good agreement with those recently published by Hall and Fowler. The cross section ranges from 1.0×10^{-33} cm² at 128 kev to 23×10^{-33} cm² at 194 kev. The thick-target yield of the reaction was measured, by detecting the N^{13} positron activity with an absolutely calibrated counter, and the cross sections were obtained by differentiation of the thick-target yield curve.

THE efficiency of the nuclear reaction

$$C^{12}+H^1\rightarrow N^{13}\rightarrow C^{13}+\beta^+,$$

which is of interest in connection with the theory of stellar energy,[1,2] has recently been determined by Hall and Fowler[2] in the neighborhood of 88 to 128 kev bombarding energy. We have extended this measurement over the energy region between 125 and 200 kev, with results which are in good agreement with those of the above authors.

In our experiments, the yield of the reaction was measured by detecting the N^{13} activity. This method is feasible because N^{13} has a convenient half-life (10 minutes) and because no other activity is produced when carbon is bombarded by low energy protons.

A target of pure, natural isotopic carbon (graphite), 0.5 mm thick, was fastened to a hollow copper cylinder, by electroplating the back side of the carbon with copper and soldering to the cylinder. A mica-window β-ray Geiger counter (Radiation Counter Laboratories Mark 1, Model 2) was mounted so that the carbon could be placed 2.5 mm from the mica window, and so that the bombarding protons struck a spot 180° opposed to the position of the counter. The copper cylinder was filled with water to cool the carbon, and the whole assembly mounted on the target end of a 200-kev accelerator.

The experimental procedure was as follows: The target was bombarded for 20 minutes (two half-lives of N^{13}) by protons of a specified energy from the accelerator. Then the beam was shut off, the target rotated through 180°, and the total β-ray count (n^*) during the next 20 minutes determined (n^* equals gross count minus background). Under these conditions, it can easily be shown that the thick-target yield of the reaction, in disintegrations per proton, is given by

$$Y=\int_0^{E_B}(\sigma/\epsilon)dE=16\lambda en^*/9FI. \qquad (1)$$

In this expression, σ is the reaction cross section; $\epsilon=(1/N)dE/dx$ is the stopping cross section of carbon for protons, and N is the number of carbon nuclei per cm³; E_B is the bombarding energy; λ is the decay constant of N^{13}; e is the electronic charge; F is the over-all efficiency of the β-ray counter (the number of counts recorded divided by the number of N^{13} nuclei which decay); and I is the average proton current. Small corrections were made to Eq. (1), to account for drift of the proton current and for the delay between the end of the bombardment and the beginning of the counting. Enough time was left between the successive bombardments to insure that residual N^{13} activity was negligible.

Background in the β-ray counter was important, because in some of the runs the intensity was below background. It was lowered by a 4-inch lead shield, and was further reduced by arranging eleven large Geiger counters in a semicircle in the hemisphere above the β-ray counter, and connecting them all in anti-coincidence with the latter. Accidental coincidences between the shielding counters and the β-ray counter were taken into account.

In determining the fraction F, it was not necessary to consider stopping of the electrons in the counter window or in the carbon target, because the counter window was only 2 or 3 mg/cm² thick and the range of protons in the target is less than 0.2 mg/cm², while the β-rays of N^{13} have an end-point energy of 1.2 Mev[3] and an energy spectrum[3] such that less than 1 percent have ranges of less than 10 mg/cm² of aluminum. The counter was calibrated by placing a RaD-RaE standard β-ray source (obtained from the National Bureau of Standards) at the same distance as the carbon target from the counter. By covering this source with lead sheet having holes of various sizes, it was determined that the efficiency F was sensibly independent of the size of the active deposit, as would be expected for distances as small as 2.5 mm. This circumstance made it unnecessary to make any correction for variations in the diameter of the proton beam.

[1] H. A. Bethe, Phys. Rev. **55**, 434 (1939).

[2] R. N. Hall and W. A. Fowler, Phys. Rev. **77**, 197 (1949); see also Phys. Rev. **74**, 1558A (1948), and Phys. Rev. **75**, 1462A (1949).

[3] Hornyak, Dougherty, and Lauritsen, Phys. Rev. **74**, 1727 (1948).

A correction was necessary for the back-scattering of β-rays, from the carbon target and from the silver disk on which the standard was mounted. The size of this correction was determined experimentally by depositing a thin film of uranyl nitrate on a 1.5 mg/cm^2 Nylon foil and placing this source at the standard 2.5-mm distance from the counter window. Then the counting rate of the uranium β-rays was determined with and without the carbon target behind the source, and also with and without a clean silver disk of the same size as that on which the RaD-RaE calibrating source was mounted. While the spectrum of the uranium β-rays is not the same as that of the RaD-RaE standard or that of the N^{13}, Burt[4] has shown that the β-ray reflecting power is independent of energy over the range which we need consider. The values of F finally obtained were 0.385 $\pm$0.016 for one counter, and 0.365$\pm$0.015 for another.

The scattering of β-rays is, in general, a quite serious factor[4] in absolute β-ray counting; in this auxiliary experiment we observed that the carbon (plus copper backing) increased the counting rate by 31 percent, and the silver disk increased it by 37 percent.

The proton energy was measured by a high resistance voltmeter, reliable to 2 percent. In measuring the proton current, care was taken to prevent errors due to secondary electron emission.

The thick-target yields are shown in Fig. 1. The two sets of data shown by the dots and crosses were obtained with different counters and different sets of beam energies. In the first set, a thick-target yield was obtained at 121 kev, and then others were taken at higher energies separated by intervals of 13 or 14 kev. In the second set, the same procedure was followed except that the first point was taken at 126 kev.

The cross sections were calculated by subtracting successive measured values of Y and dividing the differences by $\Delta E/\epsilon$. They are shown in Fig. 1 and tabulated in Table I. The two sets of thick-target yields were analyzed independently, so that there are two sets of cross sections.

In the calculations, the constant value $\epsilon = 20\times 10^{-15}$ cm^2 volt was used, in accordance with the proton range-energy measurements of Parkinson *et al.*,[5] and with the value 0.97 for the atomic stopping power of carbon relative to air. Included in the adopted value of ϵ is a 1 percent correction for the fact that the target was only 99 percent C^{12}.

TABLE I. Measured cross section of the $C^{12}(p, \gamma)N^{13}$ reaction at various energies. The two sets of data were taken independently.

Bombarding energy (Kev)	σ (in 10^{-33} cm^2 unit) First set	Second set
128	1.0$\pm$0.2	
133		1.7$\pm$0.2
141	1.8$\pm$0.2	
147		2.5$\pm$0.2
155	3.8$\pm$0.3	
161		5.0$\pm$0.3
168	7.2$\pm$0.5	
175		9.6$\pm$0.6
181	16$\pm$1	
189		14.2$\pm$0.9
194	23$\pm$2	
202		20$\pm$1

[4] B. P. Burt, Nucleonics 5, 28 (1949).

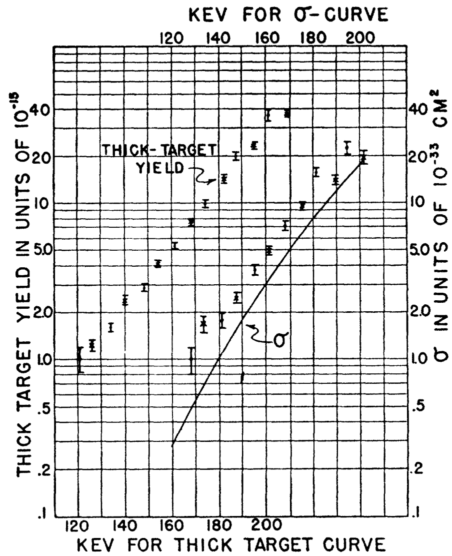

FIG. 1. Thick-target yield and cross section for the reaction $C^{12}(p, \gamma)N^{13}$. The left ordinate and lower abscissa refer to the thick-target yield; the right ordinate and upper abscissa refer to the cross section.

The statistical fluctuations, plus the uncertainty in F and the uncertainty involved in subtracting thick-target yields, allow an assignment of 5 percent to 10 percent error to each value of σ; the 10 percent uncertainty in ϵ imposes an additional latitude which is not indicated in the graph or table. The proton energy calibration does not introduce serious error, except as it effects ΔE, because a change in the energy calibration would just imply a shift of the thick-target yield curve along the energy axis.

At the highest energy the measured yield is very likely affected by evaporation of N^{13} from the target due to heating under bombardment, although we looked for such an effect by varying the proton current and found no clear-cut evidence.

The agreement with the results of Hall and Fowler is satisfactory. For example, at 120 kev they give the value 0.6×10^{-33} cm^2 for σ, and at 95 kev they give 0.1×10^{-33} cm^2. Examination of Fig. 1 shows that these values agree with an extrapolation of our results.

The solid cross-section curve in Fig. 1 is an extrapolation from the well-known 456-kev resonance in this reaction,[6] calculated using the one-level Breit-Wigner

[5] Parkinson, Herb, Bellamy, and Hudson, Phys. Rev. 52, 75 (1937); F. T. Rogers and M. M. Rogers, Phys. Rev. 53, 713 (1938).

[6] Fowler, Lauritsen, and Lauritsen, Rev. Mod. Phys. 20, 236 (1948); W. A. Fowler and C. C. Lauritsen, Phys. Rev. 76, 314 (1949).

formula,

$$\sigma=\pi\lambda\!\!\!^{-2}[\omega\Gamma_P\Gamma_\gamma/(E-E_R)^2+\tfrac{1}{4}\Gamma^2], \tag{2}$$

where $\lambda\!\!\!^{-}$ is the de Broglie wave-length in the center-of-mass system, ω is a weight factor, Γ_P is the proton width, Γ_γ is the γ-ray width, E is the center-of-mass energy, E_R is the resonance energy, and Γ is the total width. At resonance, one has $\sigma=\sigma_R$, $\lambda\!\!\!^{-}=\lambda\!\!\!^{-}_R$, $\Gamma_P=\Gamma_{PR}$, and $\Gamma=\Gamma_R$, so that

$$\sigma_R=4\pi\lambda\!\!\!^{-}_R{}^2\frac{\omega\Gamma_{PR}\Gamma_\gamma}{\Gamma_R{}^2}. \tag{3}$$

Dividing (2) by (3), and using the fact that $\Gamma^2\ll(E-E_R)^2$ in our energy region,

$$\sigma=\frac{1}{4}\frac{E_R}{E}\frac{\Gamma_P}{\Gamma_{PR}}\frac{\Gamma_R{}^2}{(E-E_R)^2}\sigma_R, \tag{4}$$

assuming that Γ_γ and ω are independent of energy. The constants are:[6] $\sigma_R=1.2\times10^{-28}$ cm^2, $E_R=421$ kev (center-of-mass energy), $\Gamma_{PR}=35$ kev, $\Gamma_\gamma=0.63$ ev, $\Gamma_R\cong35$ kev. The ratio of proton widths is involved, and if we take Γ_P to be of the form $\Gamma_P=$const. penetrability, it is only necessary to find the ratio of the penetrabilities in order to evaluate Γ_P/Γ_{PR}. The penetrabilities were read from the curves of Christy and Latter.[7]

If the theoretical expression used by Bethe[1] in his calculations on stellar energy is used to calculate the cross section in the energy region covered by our measurements, a result approximately 100 times smaller than the measured value is obtained. This discrepancy does not alter the main points of the stellar energy theory, but only the calculations of lifetimes and relative abundances of elements in stars. A detailed discussion of this matter is given by Hall and Fowler.[2]

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[7] R. Christy and R. Latter, Rev. Mod. Phys. **20**, 185 (1948).