The Thick Target Yield of the Reaction $C^{12}(p, \gamma)N^{13}(\beta^+)C^{13}$*

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The yield of N^{13} from a thick carbon target bombarded with protons of energy up to 2.5 Mev has been studied by detecting annihilation quanta with a scintillation crystal. Resonances at 0.45 and 1.70 Mev are confirmed, and independent values are obtained for their relative and absolute intensities.

INTRODUCTION

THE thick target yield of the reaction $C^{12}(p, \gamma)N^{13}$ exhibits two resonances in the range $0<E_p<2$ Mev, at 0.45 Mev,[1] and at 1.70 Mev.[2] The ratio of maximum thick target yields is reported by Van Patter[2] as $Y(1.70)/Y(0.45)=1.3\pm0.2$, and the absolute yield of the lower resonance is reported by Fowler and Lauritsen[3] as $7.3\times10^{-10}\gamma/p$ (at $E_p=1.00$ Mev).

EXPERIMENTAL METHOD

The present investigation was undertaken to obtain a more precise value of the ratio of yields and an independent value for the absolute yield, and to check with a thick target the position and width of the 1.70-Mev resonance.

As in Van Patter's work, the (p, γ) yield was investigated indirectly, by measuring the $N^{13}(\beta^+)C^{13}$ activity built up in the target. Measurements of absolute yields of beta-particles are subject to uncertainties arising from self-absorption and back-scattering effects. These difficulties were avoided in the work reported here by detecting instead the annihilation quanta associated with absorption of the positrons. Satisfactory counting rates were obtained by taking advantage of the high sensitivity of a NaI scintillation counter to annihilation quanta. Absolute yields were computed from measurements on a Na^{22} positron source of known strength.

The targets comprised a series of identical discs machined (dry) from a block of Acheson graphite. They were mounted in quick-change probe, which permitted easy insertion into and removal from the target chamber of an electrostatic accelerator. The target assembly could be rotated to one side and the proton beam accurately aligned on a quartz window. After bombardment, the activated carbon targets were removed from the vacuum system and placed in a standard position on the aluminum light shield directly over a NaI crystal and photomultiplier. The targets were covered with a recessed block of aluminum so the positrons ($E_{max}=1.2$ Mev) were annihilated in the immediate vicinity of the target. Loss of N^{13} by diffusion out of the graphite was considered negligible at the moderate temperatures developed in the targets, as no build-up of activity was detected by a shielded Geiger counter placed in the exhaust line of the target pumping system.

N^{13} has a half-life of 10.1 minutes, and a corresponding decay constant $\lambda=1.142\times10^{-3}$ sec^{-1}. If the target is bombarded for a time t_b with a proton current i, the activity is allowed to decay for a time t_d, and is then counted for a time t_c by a counter whose effective efficiency is $f=2\epsilon_{0.51}\Omega$, then

$$\text{counts recorded}=\text{yield}\times f\times i\lambda^{-1}(1-e^{-\lambda t_b})\times e^{-\lambda t_d}(1-e^{-\lambda t_c}). \quad (1)$$

For $\lambda t_b\ll1$, the bombardment factor can be expanded in a rapidly convergent series, and (it_b) set equal to the total charge q collected by the integrator, so that the bombardment factor becomes

$$i\lambda^{-1}(1-e^{-\lambda t_b})=q[1-\tfrac{1}{2}(\lambda t_b)+\tfrac{1}{6}(\lambda t_b)^2+\cdots]. \quad (2)$$

In this application, the effect of rapid current fluctuations is smoothed out. Throughout this experiment, t_b did not exceed a few minutes, and the approximation made in obtaining the above equations was generally negligible. For an example of the quantities involved, bombarding at 1.00 Mev, collecting 222 microcoulombs in 200 sec, followed by a delay of 90 sec, and a counting period of 240 sec led to about 15,000 counts, about $\frac{1}{5}$ of

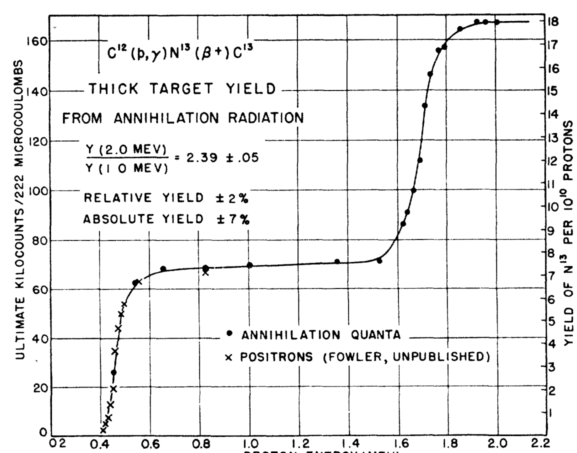

FIG. 1. Thick target excitation function for the reaction $C^{12}(p, \gamma)N^{13}(\beta^+)C^{13}$. The positron data for the shape of the lower resonance was supplied by Dr. W. A. Fowler (see reference 1, Fig. 1).

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[2] D. M. Van Patter, Phys. Rev. **76**, 1264(L) (1949).
[3] W. A. Fowler and C. C. Lauritsen, Phys. Rev. **76**, 314 (1949).

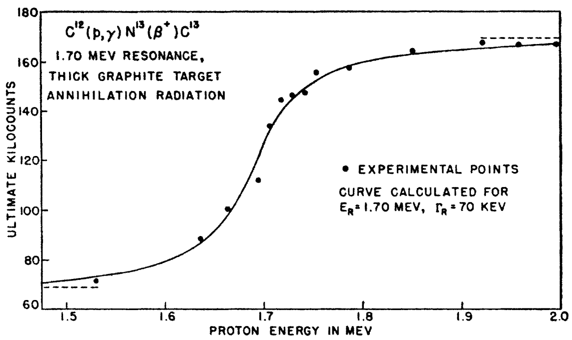

FIG. 2. Detail of the 1.70-Mev resonance. The curve is the integral of a single-level Breit-Wigner dispersion formula, taking into account the barrier for p-wave protons and other energy-dependent terms, assuming that $E_R=1.70$ Mev and $\Gamma_R=70$ kev.

the "ultimate" value obtained using Eqs. (1) and (2). and giving less than 1 percent random counting error,

THICK TARGET EXCITATION CURVE

The excitation function for the reaction was determined between 0.45 and 2.2 Mev with a single-channel differential pulse analyzer straddling the annihilation photopeak, and simultaneously with a discriminator set just below the peak. The integral data, corrected as outlined above, is shown in Fig. 1, and is believed to give the relative excitation function to within ± 2 percent. The 0.45-Mev and 1.70-Mev resonances are exhibited, and no other resonances of intensity > 2 percent that of the 0.45-Mev resonance appear below 2.1 Mev, or >15 percent between 2.1 and 2.5 Mev. In the upper region, irregularities in the operation of the Van de Graaff accelerator increased the error of using Eq. (2), and bombardment corrections could not be made with certainty. In particular, a possible weak resonance near 2.3 Mev could not be confirmed.

The 1.70-Mev resonance is shown in more detail in Fig. 2. The curve shown is based on a numerical integration of the single-level Breit-Wigner resonance formula with parameters $E_R=1.70$ Mev and $\Gamma_R=70$ kev, taking into account the energy dependence of the quantities involved. The barrier factor[4] for p-wave protons was used. The principal effect of these energy-dependent factors is to shift the half-maximum of the thick-target yield to some 5 kev below E_R, so from the observed half-maximum point at 1693 ± 5 kev we may calculate $E_R=1698\pm5$ kev. From the scatter of points about the curve, we take $\Gamma_R=70\pm10$ kev. These values are quite in agreement with Van Patter's values $E_R=1697\pm12$ kev, and $\Gamma_R=74\pm9$ kev.

The ratio of thick-target yield at 2.00 Mev to that at 1.00 Mev is found to be 2.39 ± 0.05. Since the yield at 2.00 Mev from a 70-kev resonance at 1.70 Mev is expected to be 4.5 percent short of the maximum yield (indicated by dotted lines in Fig. 2), we conclude that the total yield of the upper resonance is 1.45 ± 0.03 times that of the lower resonance (at 1.00 Mev), a result which is within the probable error given by Van Patter.

ABSOLUTE YIELD

The effective efficiency f was determined by comparison of the counting rate in the annihilation channel with that from a Na^{22} source of known strength placed in the standard position. A weak source of Na^{22} was prepared, and compared on a Geiger-tube "bench" with a "standard" Na^{22} source determined by T. Lauritsen in a β-spectrometer as 3.53×10^6 disintegrations/second (±5 percent) on 27 February, 1951. This value itself was determined by comparison of the 1.3-Mev Na^{22} line with a standard Co^{60} source. Allowing for a 3 percent decay (2.6-year half-life) since the time of determination, the weak source was found to have a strength of 3.0×10^4 disint/sec (±5.5 percent). This gave the efficiency $f=5.0$ percent. Two separate comparisons were made of the radiation in the annihilation channel from N^{13} at $E_p=1.00$ Mev and that from the Na^{22} source, and a systematic error due to radiation scattered into the annihilation channel from the 1.3-Mev line was found from the complete integral and differential bias curves to amount to 10 ± 1 percent. The yield of $C^{12}(p,\gamma)N^{13}$ was then computed as 7.7×10^{-10} N^{13}/proton (±10 percent) for normal carbon at $E_p=1.00$ Mev, which is in agreement with a value 7.3×10^{-10} previously reported.[3] Averaging these two independent measurements, we conclude that the yield is $7.5\pm0.5\times10^{-10}$ N^{13}/proton.

DISCUSSION

Investigators at Wisconsin[5] have studied elastic scattering of protons by carbon up to 4 Mev, and find in addition to the 0.45-Mev resonance a pronounced anomaly near 1.7 Mev which has been interpreted[6] as indicating the existence of two closely spaced levels, with $J=\frac{3}{2}$ and 5/2, respectively. The observation of only one resonance for gamma-radiation is consistent with this hypothesis, since the intensity of radiation from a $J=5/2$ level either to the ground state (presumably $J=\frac{1}{2}$) or to the 2.4-Mev level may be expected to be at least an order of magnitude weaker than radiation from a $J=\frac{3}{2}$ level to the ground state. However, a marked discrepancy does exist between the width found for the radiating level and those proposed by Jackson and Galonsky,[6] who have fitted the (p,p) data with a 45-kev $P_{\frac{3}{2}}$ level at approximately the position of the (p,γ) resonance, and a $D_{\frac{5}{2}}$ level also about 45 kev wide, some 50 kev higher. From the thick target data alone, it is not possible to exclude a small contribution from a second resonance, since within certain limits, the data

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[5] G. Goldhaber and R. M. Williamson, Phys. Rev. 82, 495 (1951).

[6] We are indebted to H. L. Jackson and A. I. Galonsky for making available to us their paper in advance of publication [Phys. Rev. 84, 401 (1951)].

may be "fitted" by superposition of two resonances, making appropriate adjustment of widths, positions, and intensities. If the widths and positions are constrained to the values suggested by Jackson and Galonsky, the upper resonance would have to show a gamma intensity not less than half as strong as the lower. Were this the case, both resonances should appear in thin target data. Van Patter has obtained a curve[7] for positrons with a 10-kev target, and gamma-ray curves have been obtained at this laboratory for several targets with thicknesses between 16 and 50 kev. All of these curves point to a single radiating resonance. If there are two which radiate, they are separated by less than 20 kev, and at least one of them has a width greater than 60 kev. It may be remarked that radiation from a weak, narrow resonance above 1.76 Mev might have been obscured by the strong radiation due to C^{13} which appears at that energy[8] but no evidence appeared in the positron data.

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The Scattering of Slow Electrons by Atoms

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A new approximation is proposed for calculating cross sections for the scattering of slow electrons by atoms. Although the proposed approximation embodies the essential feature of Born's approximation it is compatible with the exclusion principle for electrons, and yields nonvanishing cross sections for the excitation by electron impact of intersystem transitions in normal-coupling atoms. Unlike Oppenheimer's approximation it yields unambiguous results when approximate atomic wave functions are used in the calculation of excitation cross sections, provided that these wave functions belong to a single hermitian operator that differs from the exact hamiltonian only through a term in the potential energy.

1. INTRODUCTION

Many astrophysical and geophysical problems require for their solution accurate estimates of cross sections for the excitation of atoms by collision with slow electrons. Unfortunately, the simplest and most successful of the approximation methods available for calculating scattering cross sections, that of Born,[1] is least reliable in the low-energy domain. There are two reasons: (a) Born's approximation is a first approximation in the sense of the perturbation theory. Hence the smaller the perturbation suffered by an incident electron in exciting a particular atomic transition, the more accurately should Born's approximation predict the corresponding cross section. But the cross section itself is a measure of the perturbation. Since scattering cross sections increase with decreasing impact energy (except in the immediate neighborhood of the threshold energy), Born's approximation should deteriorate with decreasing impact energy. (b) Born's approximation is based, in part, on the simplifying assumption that the colliding electron is distinguishable from the atomic electrons. But the effects on scattering cross sections of the exchange interaction between the colliding electron and the atomic electrons, which are thereby neglected. are known to be significant in the low-energy domain,

Of particular importance in astrophysical and geophysical applications is the excitation by electron impact of optically forbidden transitions. Since, in general, cross sections for this type of excitation are intrinsically small, it seems likely that for these transitions the principal source of inaccuracy in the cross sections calculated on Born's approximation is the neglect of exchange, not the neglect of second- and higher-order perturbation effects. If this view is correct, a first approximation compatible with the Pauli exclusion principle would suffice for the calculation of many cross sections of astrophysical and geophysical importance that cannot be accurately calculated on Born's approximation. In any event it would constitute a reasonable point of departure for further refinements.

An approximation resembling that of Born but compatible with the exclusion principle was proposed by Oppenheimer in 1928,[2] and has since served as the basis for many calculations. Recently, however, Bates, Fundaminsky, Leech, and Massey[3] have presented convincing evidence that Oppenheimer's approximation is actually far less reliable than Born's. Among their results are the following:

(a) Where a comparison is possible, cross sections calculated on Born's approximation are found to agree far better with experiment than those calculated on

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[2] J. R. Oppenheimer, Phys. Rev. 32, 361 (1928).

[3] Bates, Fundaminsky, Leech, and Massey, Trans. Roy. Soc. (London) 243, 117 (1950).