Absolute Cross Section for the Reaction $C^{12}(\gamma,n)C^{11}$†

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The activation curve for the reaction $C^{12}(\gamma,n)C^{11}$ was obtained with the use of both the Mark II (38-Mev) and Mark III (630-Mev) linear accelerators, covering the energy range 18–260 Mev. Stacked foils of polystyrene detectors and tantalum and copper radiators were exposed to the direct electron beam and the resulting C^{11} activity was measured with a 4π scintillation counter. The photon flux was obtained from the measured electron flux by means of the Bethe-Heitler theory of bremsstrahlung, and the photon-difference method was applied to obtain the cross-section curve. This curve was found to be similar to some previous results, but with the addition of a high-energy tail extending beyond 38 Mev. The experimental accuracy does not permit a precise determination of the shape of this tail, but it cannot be accounted for by mesonic effects alone. The cross section has a peak value of about 8.3 millibarns at 22.5 Mev, and integrated values of 0.056 ± 0.003 and about 0.080 ± 0.01 Mev-barns when the integrals are carried up to 38 and 250 Mev, respectively. These numerical values were obtained from the data obtained by using a copper radiator. The corresponding results with a tantalum radiator are about 7 percent lower, indicating a possible failure of the bremsstrahlung formula for high atomic numbers.

INTRODUCTION

THE energy dependence of the x-radiation yield for the $C^{12}(\gamma,n)C^{11}$ reaction has been investigated extensively by using radiation from internal targets in circular machines.[1–7] A linear machine, while giving a relatively broad electron energy spectrum, makes it simple to use a Faraday-cup electron collector to measure the bombardment-flux directly. Two such monitors have been constructed and tested, and have been used in conjunction with a residual-activity technique to evaluate the yield of $C^{12}(\gamma,n)C^{11}$ over the energy range from threshold to 260 Mev. Previous results relied upon the calibration of ionization chambers.

The experimental method was basically the same as that described by Berman and Brown.[8] Pairs of closely matched polystyrene foils were used as detectors, while a tantalum or copper radiator foil placed between the detector foils produced the bremsstrahlung photons. The stack of foils was thin so that all of the electrons passed through them into the Faraday cup. Also, the area of the foils was large enough to intercept all of the bremsstrahlung produced by the electrons. The use of two detector foils enables one to correct for the undesired background reactions induced by electrons, neutrons, and gamma radiation. The corrected net difference in the reaction yield between the two foils is then due to the bremsstrahlung production in the effective radiator.

The Bethe-Heitler theory,[9] including screening effects, was used to calculate the number of photons in each quantum-energy interval. The degradation of the electrons and photons in passing through a thick target was calculated and corrected for by the method of Wilson.[10]

EXPERIMENTAL

The Mark II (38-Mev) and Mark III (630-Mev) accelerators were the sources of electrons. The Faraday-cup electron collector used in conjunction with Mark II has been described in a previous paper.[8] It has an absolute accuracy better than 2 percent. An evaluation of the performance of the high-energy Faraday cup has been made by Tautfest.[11] The absolute accuracy is better than $\frac{1}{2}$ percent. In each case the Faraday cup was used with an electronic integrating system which accumulated the total charge on a condenser having high leakage resistance. The voltage on the condenser was measured with a potentiometer. The capacity was determined with an accuracy of $\frac{1}{2}$ percent by feeding a known current into the system for a definite time and then measuring the voltage in the usual way. To compensate for the radioactivity lost during the bombardment, resistances were placed across the integrating capacitors to give an *RC* value close to the mean life of C^{11}. (The decay of the activity in the polystyrene was observed to be exponential over a period of 78 minutes, with a half-life of 20.26 ± 0.1 minutes. This is in agreement with other recent determinations of the half-life of the C^{11} decay.) These resistances varied slightly with time and temperature; hence the time constant was measured periodically, and small corrections were made to each value of the integrated voltage from the electron collector. There

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was no *RC* network available on the high-energy electron collector, so the values of the integrated voltage were read periodically during the bombardment and the correction for decay was calculated.

The presence of the foils and a vacuum-tight window in front of the mouth of the Faraday cup introduced an error due to secondary electrons being knocked out of the foils into the cup. The effect of the foil stack was determined experimentally by employing an ionization chamber in the beam ahead of the foils as a monitor. The test showed that the foil stack increased the Faraday-cup current by a constant amount of (1.5±0.2) percent over the energy range 18–38 Mev. The effect of the vacuum window was calculated to increase the current by an additional constant amount of (2.0±1.0) percent.

A 4π scintillation counter using two anthracene crystals[8] measured the positron activity from C^{11}. The counter background was approximately 80 counts per minute at the operating discriminator setting.

It was necessary to know the electron energy, and thereby the maximum photon energy incident on the foils. This was accomplished by an energy calibration done on the Mark II deflecting-magnet system, which has a relative accuracy of 0.2 percent and an absolute accuracy of 2 percent.[8] The Mark III calibration employed a floating-wire method with an absolute accuracy of $\frac{1}{2}$ percent.[11]

ACTIVATION CURVES

The yield, as a function of the maximum electron energy E_0, is given by

$$Y(E_0)=N_C\left(N_{eff}\cdot\frac{Z+1}{Z}\right)\int_0^{E_0}\phi(E_0,k,t)\sigma(k)dk, \quad (1)$$

where $Y(E_0)$ is the number of radioactive atoms produced per electron; N_C is the number of C^{12} atoms per cm²; N_{eff} is the number of atoms per cm² in the effective radiator; $(Z+1)/Z$ is an approximate correction for the radiation produced in the field of the atomic electrons; $\phi(E_0,k,t)$ is the thick-target bremsstrahlung cross section (except for the region near the end point, the thick-target formula was accurate to $\frac{1}{2}$ percent as used in this experiment); $\sigma(k)$ is the reaction cross section; and k is the photon energy.

This yield was obtained from the observed activity in the foils after the data were corrected. The raw data were first corrected for: (a) any residual activity; (b) dead time of the 4π counter; (c) background; (d) C^{11} decay; (e) difference in thickness of the two detector foils; and (f) variations in the effective radiator thickness (the tantalum radiator plus the mean thickness of the front foil was 2.855×10^{-2} radiation length). The net difference activity of each individual run was then corrected for: (a) multiple scattering of the electrons in passing through the foils, thus giving more activity in the rear foil ($\frac{1}{2}$ percent); (b) the fact that the electron-induced activity is not the same in the two foils due to electron-energy degradation in the effective radiator (2.8±1.3 percent); (c) the setting of the discriminator of the 4π counter. A curve of discriminator setting *vs* counting rate was made in order to extrapolate to zero discriminator setting (4.5±1.0 percent); (d) the self-absorption of the C^{11} beta rays in the foil. For the absolute result, thin (8×10^{-3} g/cm²) polystyrene foils were used (6.0±2.5 percent).

The yield was investigated in some detail in the region from 18 to 38 Mev using the Mark II accelerator. Data were taken at 1- and 2-Mev intervals for both tantalum and copper radiators. The two radiators gave similarly shaped activation curves, but the absolute values at the high-energy limit were not consistent with the Z-dependence of the bremsstrahlung formula, corrected for screening.[12] The tantalum result was 7 percent lower than copper, indicating a possible failure of the formula for high-Z elements.[13]

From the reproducibility of the results at a given energy, the relative accuracy of the points was calculated to be $\frac{1}{2}$ percent. Figure 1 shows the corrected yield curves from these Mark II data, using the tantalum radiator of 169.77 mg/cm².

The points taken on the Mark III accelerator covering the range 35–260 Mev, were taken at different times, some with the same tantalum radiator as was used in obtaining the data of Fig. 1, and some with a 0.1-radiation-length copper radiator. Those taken with the copper radiator were marked with a subscript C, and have been arbitrarily normalized to fit the tantalum points. There were few runs on Mark III using both tantalum and copper radiators at the same energy and conditions. This corrected activation curve is shown in Fig. 2. The density of points and their statistical

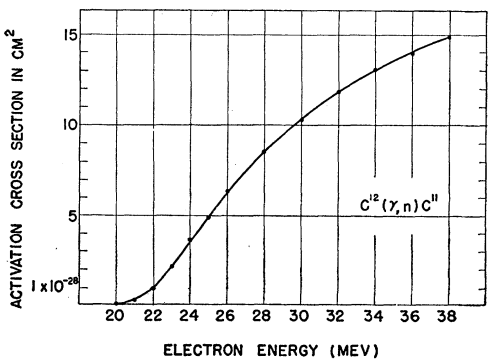

FIG. 1. Yield curve for the reaction $C^{12}(\gamma,n)C^{11}$. The data shown as dots were taken with a tantalum radiator of 169.77 mg/cm². However, the yield as expressed by Eq. (1) has been divided by N_C and by the thickness of the radiator in radiation lengths so that the ordinate scale represents the cross section for the reaction induced by the bremsstrahlung of one electron in a unit radiator.

[12] Further experiments to measure the Z-dependence of bremsstrahlung are in progress in this laboratory.

[13] C. D. Curtiss, Phys. Rev. **89**, 123 (1953).

accuracy were limited by the running time available on the large accelerator, and by the difficulty of getting high beam intensities in the low-energy region.

CROSS SECTION AS A FUNCTION OF PHOTON ENERGY

The cross-section curve in Fig. 3 was obtained from the corrected activation curve of Fig. 1 by the photon-difference method.[1] The photon spectrum was calculated for the tantalum radiator, but the absolute value of the cross section was everywhere increased by 7 percent to give agreement with the results obtained with the copper radiator. The copper result is thought to be more accurate because errors due to the Born approximation used in deriving the bremsstrahlung formula are expected to be proportional to Z^2. The oscillations characteristic of the photon-difference method are quite evident by 38 Mev, and application of the method to still higher energies would require an activation curve of considerably greater accuracy than we have achieved. This cross-section curve is similar to those of previous experimenters in many respects. It has the usual sharply-peaked resonance; this one centered at 22.5 Mev with a peak of 8.3 millibarns, but with the addition of a high-energy tail extending at least to 38 Mev.

In order to get information about the shape of the cross-section curve above 38 Mev, different high-energy tails were fitted to the curve of Fig. 3 and the corresponding activation curves were computed by numerical integration of Eq. (1). The results are shown in Fig. 2. Referring to this figure: (1) Circled E is the contribution that comes from the cross-section curve of Fig. 3 cut off at 36 Mev. It is far outside of experimental error, proving that a considerable part of the cross-section curve is beyond 36 Mev. (2) Circled A is the same as E, but with a symmetrical bump added to the cross-section curve, centered at 50 Mev, and of

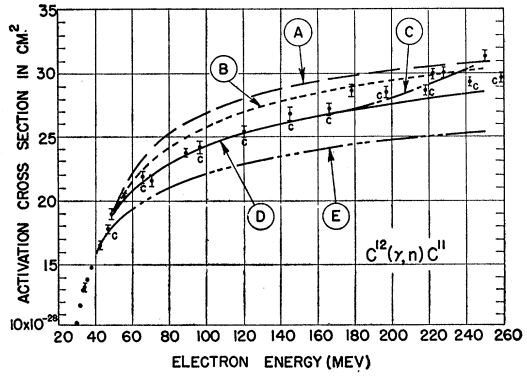

FIG. 2. Yield curve for the reaction $C^{12}(\gamma,n)C^{11}$ extended to high energies. Absolute points taken with the tantalum radiator are shown as plain dots, while the points labeled with a subscript C, taken with a thick copper radiator, have been arbitrarily normalized. The ordinate scale is the same as for Fig. 1. The curves A to E are computed yield curves assuming various cross-section curves described in the text.

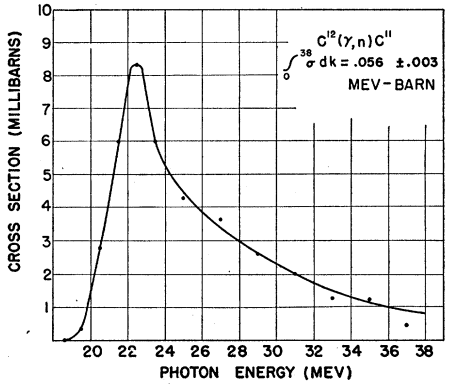

FIG. 3. Cross-section curve for the reaction $C^{12}(\gamma,n)C^{11}$. The shape of the curve was determined by the photon-difference analysis of the yield curve of Fig. 1, but the absolute value of the ordinate scale was determined from the data with a copper radiator. The smooth curve shown is consistent with the data, but because of the insensitivity of the method the detailed shape of the high-energy portion is uncertain.

base-width 12 Mev. The shape of the bump was chosen arbitrarily, but the magnitude gives the correct contribution to the yield at 250 Mev. The curve A is definitely too high in the region from 60 to 200 Mev, indicating that the cross section is finite at energies beyond 56 Mev. (3) B is the contribution from Fig. 3 with a tail inversely proportional to the cube of the photon energy beginning at 44 Mev with a value of 1.27 millibarns. A flat portion closes the gap between 34 and 44 Mev. (4) D is the contribution from Fig. 3 with the addition of a k^{-3} tail fitted at 34 Mev, again with the value of 1.27 millibarns. B and D enclose most of the experimental points between them and any cross-section curve of gross shape between those assumed in deriving B and D would be compatible with the data. (5) C contains a contribution, additional to D, of a possible meson rise in the cross section. The rise was calculated from particle kinematics and experimental data on the production of π^0-mesons from low-Z elements. The calculation is expected to be correct only to an order of magnitude because it is not known how often the production of a π-meson is accompanied by the emission of only a single neutron. For this reason, the production of C^{11} by other processes such as $(\gamma,\pi^- p)$ was not included in the calculation.

The result for the expected activation cross section can be expressed as

$$\frac{Y'(E_0)}{N_C\cdot(t/t_0)}=2.2\times10^{-28}\frac{\int_{150}^{E_0}(k_{eff}^2-\pi^2)^{\frac{3}{2}}(dk/k)}{\int_{150}^{320}(k_{eff}^2-\pi^2)^{\frac{3}{2}}(dk/k)}\text{cm}^2, \quad (2)$$

where (t/t_0) is the thickness of the radiator in radiation lengths, and $k_{eff}^2=k^2[1-(2k/M)+(M_\pi^2/Mk)]$. The plotted values, curve C, are three times those obtained

TABLE I. Comparison of some parameters of the $C^{12}(\gamma,n)C^{11}$ cross section as determined by different investigators.

Reference	Mean energy (Mev)	Energy at peak of cross section (Mev)	$\int_0^{\sim 25}\sigma(k)dk$ (Mev-barns)	$\int_0^{>50}\sigma(k)dk$ (Mev-barns)
This paper	34	22.5	0.032±0.003	0.080±0.01
4	···	21.3	0.029	···
5	···	22.0	0.027	···
6	27	···	···	0.090±0.022
7	23–32	···	···	0.086±0.02

from Eq. (2). Curve C is a good fit to the data, but this fact alone does not prove the existence of a meson rise. The data would rule out a meson rise greater than ten times the increase calculated by Eq. (2).

Gell-Mann *et al.*[14] derive the sum-rule result in a general form which makes no restrictive assumptions as to multipolarity of the transitions or the nature of nuclear forces and wave functions. By making use of experimental data on photomeson production, they obtain

$$\int_0^{M_\pi}\sigma_T(k)dk = \frac{2\pi^2e^2\hbar}{Mc}\frac{NZ}{A}\left(1.0+0.1\frac{A^2}{NZ}\right)\text{ Mev-barns} \quad (3)$$

for the integral up to the meson threshold. In Eq. (3), $\sigma_T(k)$ is the total cross section for gamma absorption, and the constant 0.1 on the right-hand side is evaluated from experimental data with a stated accuracy of about 30 percent.

From the present experiment the value of the integrated cross section to 38 Mev was found to be 0.056±0.003 Mev-barns. The value up to 250 Mev depends on the shape of the high-energy tail and is therefore more uncertain. Using cross sections proportional to k^{-3} fitted at energies 34 and 44 Mev corresponding with yield curves D and B, respectively, one finds integrated cross sections to 250 Mev of 0.073 and 0.091 Mev-barns. The value predicted by Eq. (3) for C^{12} is 0.25±0.03 Mev-barns, and therefore the totality of other reactions must contribute about twice as much as the (γ,n) reaction alone. This is not improbable because the (γ,p) and (γ,pn) reactions are likely comparable with the (γ,n) while a host of less probable reactions, such as (γ,α), (γ,γ), and $(\gamma,2n)$, are each expected to make some contribution.

A comparison of the results of this paper with those of some other investigators is shown in Table I. The comparison reveals how some of the large discrepancies in the reported values of the integrated cross section are accounted for by the existence of the tail on the cross-section curve. This relative prominence of the tail is not a general feature of the (γ,n) reactions. For example, Berman and Brown,[8] using basically the same technique as described herein, found no contribution to the cross section beyond 30 Mev in the case of Cu^{63}. However, Sagane[3] has pointed out the existence of a high-energy tail in the case of (γ,n) reactions on C^{12} and O^{16}, and its occurrence may be relatively common in reactions on the light elements.

ACKNOWLEDGMENT

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[14] Gell-Mann, Goldberger, and Thirring, Phys. Rev. **95**, 1612 (1954).