Three-Body Photodisintegration of He^3

H. M. GERSTENBERG AND J. S. O'CONNELL
National Bureau of Standards, Washington, D. C.
(Received 3 December 1965)

The $He^3(\gamma,n)2p$ cross section has been measured in 1-MeV steps from threshold to 30 MeV using the National Bureau of Standards betatron and a He^4 cryostat to produce a 40-cm^3 liquid-He^3 target. The measured cross section shows a broad peak between 14 and 20 MeV with a maximum cross section at about 0.90 mb. The cross section and bremsstrahlung-weighted cross section integrated up to 28 MeV give 12.1 $\pm 10\%$ MeV mb and $0.68 \pm 10\%$ mb, respectively. Theoretical calculations of the three-body photodisintegration cross section overestimate the experimental cross section by factors of 3 to 10.

I. INTRODUCTION

THE photodisintegration reactions provide a valuable source of data in the study of the three-nucleon problem. Since the electromagnetic-interaction operator is relatively well known, photodisintegration and electron-scattering reactions provide good tests of bound-state and continuum wave functions. The three-nucleon wave functions used so far in calculations of electromagnetic-reaction matrix elements have been simple analytical functions which are not related to the relatively complete phenomenological description of the two-nucleon interaction. Besides the static properties, the binding energies and rms radii of H^3 and He^3 and Coulomb energy of He^3, a successful three-nucleon bound-state wave function must account for a growing body of information on elastic and inelastic electron-scattering and photodisintegration data on the total and differential reaction cross sections. The results of the present experiment indicate that a simple three-nucleon wave function, which is relatively successful in predicting one reaction cross section, may fail for a similar reaction. In this paper we describe a measurement of the $He^3(\gamma,n)2p$ total cross section from threshold to 30 MeV. The experiment was done by measuring the bremsstrahlung-produced neutron yield curve, which was analyzed by the Penfold-Leiss and least-structure methods to give the cross section.

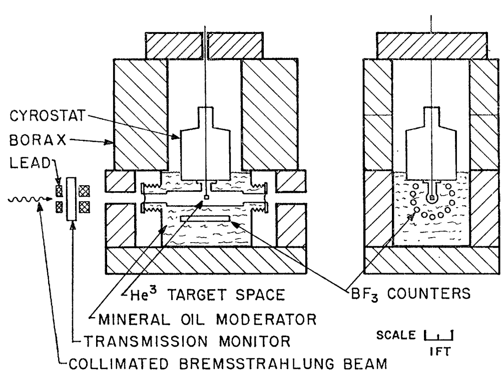

FIG. 1. A general view of the experimental arrangement. A collimated photon beam struck the liquid-He^3 target located in the center of the evacuated tube. Neutrons from the target were then moderated by the mineral oil before being detected by the eleven BF_3 counters.

Section II of this paper describes the apparatus and calibration procedures used in the experiment. In Sec. III the reduction of the yield curve to a cross section is described and the integrated and energy-weighted integrated cross sections to 28 MeV are given. In Sec. IV the results are compared with another cross-section measurement and with various theoretical calculations.

II. EXPERIMENTAL ARRANGEMENT

A schematic general view of the experimental arrangement is shown in Fig. 1. A collimated bremsstrahlung beam passed through a transmission monitor ion chamber before entering an evacuated beam tube which passed through the neutron detection system.

A He^4 cryostat was located above the beam tube and only the lower tail of the cryostat Dewar containing the He^3 target space extended into the beam tube. The evacuated beam tube was an integral part of the cryostat, i.e., the Dewar vacuum extended outside of the neutron detector to the 7-mil Mylar end windows on the evacuated tube. A massive neutron shield of borax with a minimum thickness of 12 in. completely covered both the neutron detector and the cryostat. The complete apparatus rested on a large steel plate which could be moved in any direction by means of jacks and screws and thus facilitated alignment of the He^3 target space with the collimated bremsstrahlung beam.

The neutron detection system was a modified "Halpern-type detector"[1] consisting of BF_3 counters immersed in a mineral-oil moderator. Eleven counters, each having a diameter of 2 in. and an active length of 15.7 in., were placed parallel and around the central 6.75-in. beam tube. The mineral-oil moderator thickness between the counter wall and central beam tube was 4.0 in. The BF_3 counters were connected into five groups, four of which had three counters per group and one of which had one counter. Each group had its own counting system consisting of a separate preamplifier, amplifier, discriminator, gate, and scalar. Care was taken to determine that the discriminator for each counter group was such that no pile-up pulses, produced by the x-ray Compton scattering in the target, were

[1] J. Halpern, A. K. Mann, and R. Nathans, Rev. Sci. Instr. 23, 678 (1952).

registered accidentally as neutron counts. During the experiment, the gate was opened to 10 μsec before the yield pulse and closed about 700 μsec later. Under these circumstances, the gate eliminated only about 2% of the pulses produced by neutrons from the target.

Figure 2 shows a schematic drawing of the cryostat with its various pumping systems. The cryostat, obtained commercially,[2] was essentially a modified He^4 Dewar having a central sphere with a liquid-He^4 capacity of 18 liter and an outer jacket with a liquid-N_2 capacity of 53 liter. The tail of the cryostat contained primarily the target surrounded by two $\frac{1}{16}$-in. thick copper heat shields; the inner shield was in thermal contact with the He^4 bath space and the outer shield was in contact with the N_2 bath space. In order to keep the neutron counting background at a tolerable level, holes were cut in the heat shields to allow for passage of the bremsstrahlung beam. These holes were then covered with $\frac{1}{4}$-mil aluminized Mylar in such a way as to leave a narrow viewing slot through which the He^3 target face could be observed. The target was in thermal contact with the bottom plate of the He^4 bath space and consisted of a copper cylinder having a wall thickness of 0.125 in., an inside diameter of 1.75 in., and a width of 0.875 in. The target windows, through which the 1.0-in. diameter bremsstrahlung beam passed, were of 7-mil Mylar.[3] Filling of the target with He^3 gas took place through a long stainless steel tube which passed out through the top of the cryostat. The level of the condensed He^3 liquid was determined visually by observing, through the viewing slots, the meniscus on the transparent Mylar target windows.

The typical experimental run with the cryostat began by transferring about 15 liter of liquid helium into the He^4 bath space; the bath space was then pumped down from atmospheric pressure to about 110 Torr. The 30 liter (STP) of He^3 gas in the storage tank were then slowly pumped into the target space where condensation of He^3 liquid was visually observed at a pressure of about 525 Torr. The target continued to fill until the He^3 gas in the storage tank was depleted. The He^4 pump speed was then adjusted with a throttle valve to keep the He^4 bath space pressure as constant as possible. Typical operating pressures and temperatures for the He^4 bath space and He^3 target space were 110 Torr and 2.69°K, 450 Torr and 2.70°K, respectively, with a temperature difference between bath space and target space always less than 0.1°K. The temperature of the He^3 and He^4 was determined by measuring their respective vapor pressures and using tables[4,5] which gave the relationship between pressure and temperature. Corrections for thermomolecular pressure differences[6] were unnecessary for the range of pressures and temperatures used in this experiment.

The target was considered usable until a meniscus appeared at the Mylar window of the target; this would occur anywhere from 1 to 5 h after filling the target space. The cause as well as the time difference of the occurrences was not completely understood. The target was visually checked at least every 10 min for signs of a meniscus and, once found, a usable target was remade by simply recycling the He^3 back to the storage tanks and then allowing it to recondense in the target space. This process could be repeated any number of times as long as liquid He^4 was still present in the cryostat.

In order to obtain an absolute cross section from the He^3 yield points, it was necessary to determine the peak betatron energy at which the points were taken, the total beam energy in the bremsstrahlung spectra at these points, and the absolute neutron detection efficiency of the detector. The peak photon energy of the betatron was controlled by a system[7] based on the determination of the average magnetic field in the vicinity of the electron orbit at the instant of x-ray production. The field was sampled by means of a small search coil whose signal was proportional to the time

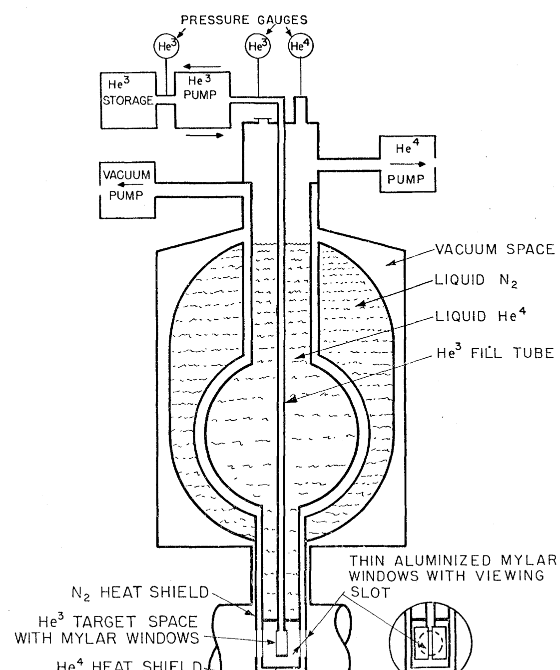

FIG. 2. Schematic of the cryostat. The He^3 gas was contained in a closed system and could be pumped from the storage tank into the target or from the target into the storage tank. The He^4 pump reduced the vapor pressure of the bath space and cooled the He^3 target space to about 2.74°K. Visual observation of the liquid-He^3 level in the target space was made through the viewing slots and observing the meniscus on the Mylar windows of the target space.

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[6] T. R. Roberts and S. G. Sydoriak, Phys. Rev. **102**, 304 (1956).
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rate of change of field. This signal was integrated and the integrator output was a voltage analog of the field, i.e., proportional to the electron's momentum. A dc offset voltage was applied to the integrator, by means of a potentiometer, such that a discriminator would fire when the sum of the off-set voltage and the integrator output voltage was zero. The ejection pulse to the expander coils of the betatron was timed such that the betatron pulse and discriminator pulse from the integrator were coincident in time: this condition ensured that x-ray production occurred at the predetermined magnetic field value.

The energy control was calibrated in terms of the (γ,n) thresholds for H^2 at 2.22 MeV, Cu^{65} at 9.91 MeV, and the well-known break in the $O^{16}(\gamma,n)$ yield curve at 22.2 MeV. These three points were then used to establish a straight line relating the potentiometer setting to the peak energy of the bremsstrahlung spectra. From the reproducibility of the counting rates it has been estimated that the betatron energy can be reset and maintained to within 60 keV at 20 MeV.

The total beam energy in the bremsstrahlung spectra was determined by measuring the ionization charge collected from the transmission monitor and comparing it with the ionization charge collected from a standard NBS chamber. The standard chamber was calibrated[8] so that a measurement of the ionization charge collected during an x-ray exposure determined the total beam energy incident on the front face of the chamber.

The detector efficiency for counting neutrons was determined with a calibrated RaDBe(α,n) source as well as with a comparison of the actual and calculated yield for the photodisintegration of deuterium. The results, which were consistent with previous measurement made in this laboratory on similar detectors,[9,10] gave a detector efficiency of 0.053 ± 0.003 for the system of eleven BF_3 counters. Detectors of this type, when used with photonuclear sources, have been shown[9] to have an efficiency independent of neutron energy to within $\pm5\%$.

During the course of the experiment, a number of checks were made of the stability of the neutron detection system and the transmission monitor ion chamber. The neutrons for the RaDBe(α,n) source were counted at least once a day in order to determine the stability of the neutron detection system. The daily counting rates were found to reproduce to better than 0.3%. The sensitivity of the transmission-monitor ion chamber was checked by placing a Co^{60} source near the chamber in a standard position and measuring the time required for a charge, produced in the chamber by the source, to reach a given value. This charge was measured by means of a vibrating-reed electrometer. Daily changes in the sensitivity of the chamber were found to be less than the 0.5% uncertainty in the measurement itself.

III. DATA REDUCTION AND RESULTS

The reaction yield Y is defined as the number of neutrons detected per unit of charge registered in the standard ion chamber. The yield as a function of betatron end-point energy E_0 is called the activation curve $Y(E_0)$. This function was measured in approximately 1-MeV intervals from 8 to 30 MeV. Each yield point was measured an average of 11 times over a period of 5 weeks. The statistical accuracy of the final activation curve varied over the range 0.3% at 28 MeV, 1.1% at 16 MeV, and 3.3% at 12 MeV. The statistical accuracy was limited by the cost of the liquid-He^4 refrigerant and by the available accelerator time. The empty target background yield data were taken interspersed with the He^3 yield data. The foreground to background counting rate ratio varied from 10.0 near threshold to 2.7 at 28 MeV. The data were analyzed in the following manner: At each energy E_0 the cosmic ray background was subtracted from both the total and background yield points; this was necessary because the runs were for different lengths of time. The average background yield at each energy was subtracted from each corresponding total yield point to produce the foreground yield. A density correction for each 10-min run was then applied. This correction, which was always less than 5%, took into account the fact that liquid-He^3 density slowly varied during the course of the experiment. The density was known from the relationship between vapor pressure and density.[11] The average density of the liquid He^3 was 0.070 g/cm^3 with a corresponding vapor pressure of 423 Torr and temperature of 2.68°K. The foreground yields were then averaged at each energy. The foreground activation curve was analyzed in two ways; the standard Penfold-Leiss[12] method and by the least-structure analysis of Cook.[13] The first method consisted of calculating and smoothing the running integral of the reduced cross section $\Omega(E_\gamma)=\eta f\sigma(E_\gamma)/E_\gamma$, where η is the number of target nuclei, f is the attenuation due to photon absorption by the target (a constant for this experiment), and E_γ is the photon energy. The cross section σ was obtained by taking first differences. The running integral $\int_0^{E_\gamma}\Omega(E_\gamma)\,dE_\gamma$ and the derived cross section are shown in Fig. 3(a). Figure 3(b) shows the resulting cross section when the activation curve was analyzed by the least-structure method. In this method the cross section was smoothed over an energy interval determined by errors in the yield curve. This smoothing reduced the error in the resulting cross section at the expense of the

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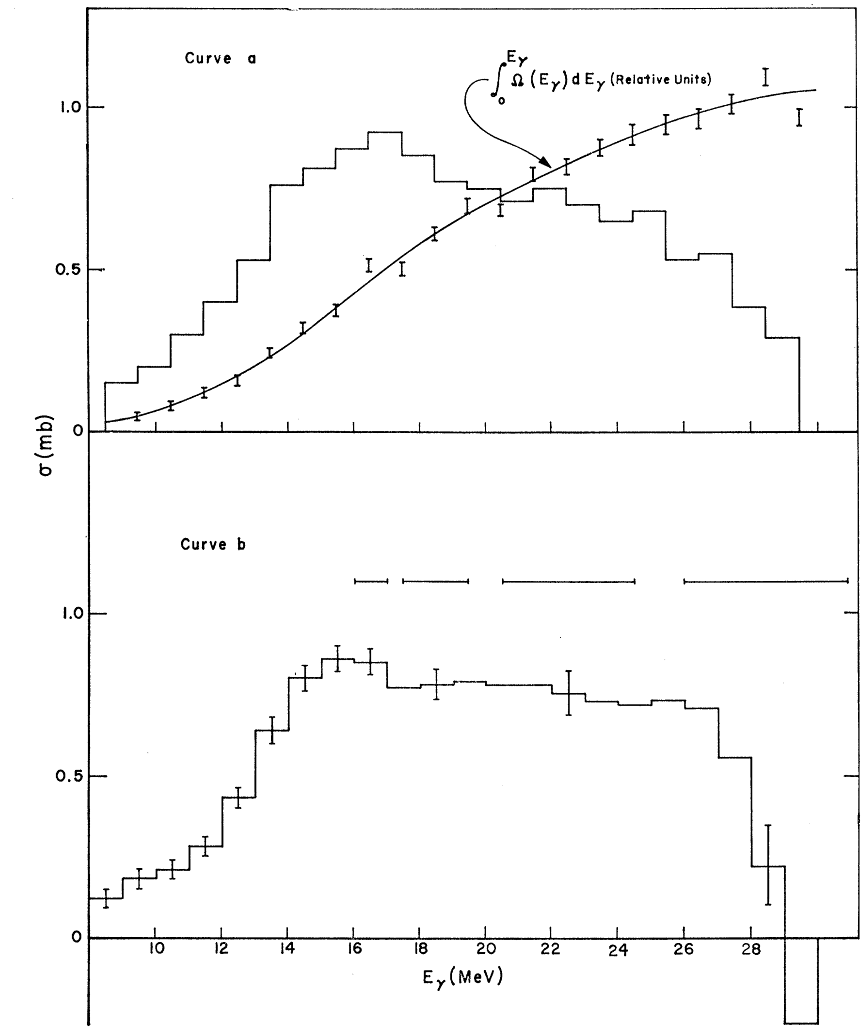

FIG. 3. Total cross section of the reaction $He^3(\gamma,n)2p$ as obtained by an analysis of the neutron yield curve. Figure 3(a) was obtained by smoothing the running integral of the reduced cross section and taking first differences to obtain the cross section. Figure 3(b) was obtained using the "least-structure analysis" of Cook. The horizontal error bars indicate the energy interval over which the data are smoothed.

energy resolution. The width (full width at half-maximum, of the resolution function is indicated by the energy error bars in Fig. 3(b). The results using the two methods of analysis seem to differ only in their high-energy behavior. The rapid falloff of the cross section beyond 28 MeV is considered doubtful; it is possible, although there is no direct evidence, that the energy control of the betatron may not have been linear over the last few MeV of the yield curve.

The values obtained for the cross section and the bremsstrahlung-weighted cross section integrated to 28 MeV were:

$$\int_0^{28\ \mathrm{MeV}} \sigma\, dE_\gamma = 12.1\ \mathrm{MeV\ mb} \pm 10\%,$$

$$\int_0^{28\ \mathrm{MeV}} \frac{\sigma}{E_\gamma}\, dE_\gamma = 0.68\ \mathrm{mb} \pm 10\%,$$

where the quoted errors include estimates of systematic errors and random statistical errors.

IV. DISCUSSION

Our three-body breakup cross section can be compared with a previous measurement by Gorbunov and Varfolomeev.[14] In Fig. 4 our cross section is seen to be consistently lower than that of Gorbunov and Varfolomeev whose integrated cross section to 28 MeV is 30% larger than the present experimental results.

A number of theoretical calculations[15–19] have been made for the $H^3(\gamma,p)2n$ and $He^3(\gamma,n)2p$ cross sections, which apart from a small Coulomb correction, are assumed to be equal in the electric-dipole approximation. These cross sections are shown in Fig. 4. It is seen that these calculations overestimate the experimental cross

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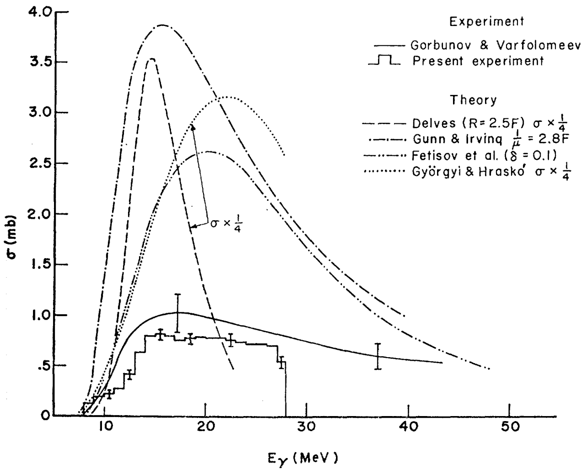

FIG. 4. Total cross section of the reaction $He^3(\gamma,n)2p$ compared to another measurement (Ref. 14) and to four theoretical calculations (Refs. 16–20). Note that two of the cross sections are reduced by a factor of 4 for presentation. The number following the names of the theoretical papers identify a particular parameter of the theory.

section by factors of 3 to 10. We will discuss two of these calculations.

The Gunn and Irving[16] calculation uses a ground-state wave function of the form $\exp[-\mu R]/R$, where $R=(\sum_{i<j} r_{ij}^2)^{1/2}$, and r_{ij} is the internucleon coordinate with μ as radius parameter. The electric-dipole operator is taken as the dominant interaction, and the final state is taken as the s- and p-wave parts of plane waves for the final nucleons. Gunn and Irving have also calculated the two-body breakup $He^3(\gamma,d)p$ using the same assumptions except the bound deuteron wave function is used in the final state. The two-body cross section is found to give reasonable agreement with experiment.[20] This ground-state wave function also gives a good fit to the elastic-electron-scattering form-factor data[21] (for a slightly different radius parameter μ). The failure of the Gunn and Irving three-body breakup cross-calculation to fit the data might be due to the neglect of the s-state final-state interaction which is present in the three-body breakup case, but not in the two-body breakup case. However, since the nucleon-nucleon s-state interaction is attractive, a cross-section enhancement might be expected.

The s-wave final-state interaction has been taken into account in a calculation by Fetisov, Gorbunov, and Varfalomeev.[18] These authors used as a ground-state wave function a sum of two terms of the form $\exp[-\mu R^2]$, i.e., Gaussians in the interparticle coordinates. This wave function has been used previously by Eichmann[22] in a calculation of the two-body breakup cross section and was found to give good agreement with experiment.[20] Fetisov *et al.* used a square-well potential as the interaction between the two nucleons in the final relative s state. This interaction had the effect of shifting the energy of the peak of the cross section, but not reducing its magnitude as is needed to obtain agreement with experiment. The final-state interaction did give a good prediction of the energy distribution of the final nucleons.

Thus, the problem of an accurate calculation of the cross section for the reaction $He^3(\gamma,n)2p$ remains open. It is pointed out in Ref. 20 that all the photodisintegration theories of H^3 and He^3 give integrated cross sections which exceed the electric-dipole sum rules by large factors and thus have an inconsistency.

ACKNOWLEDGMENTS

The design of the He^4 Dewar and initial planning of this experiment were done by E. G. Fuller and T. Stovall; the least-structure analysis of the data was done at Iowa State University under the direction of B. C. Cook. The authors wish to thank Alfred Lopez and Robert Martin for their help in operating the betatron.

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