98° Differential Cross Section for the Reaction $^4He(\gamma, n)^3He$†

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The 98° differential photoneutron cross section for ^4He has been measured for excitation energies between 22 and 33 MeV with a liquid ^4He target at its normal boiling point and for excitation energies between 23 and 37 MeV with a ^4He gas target at a pressure of 51.6 bars. The cross-section values obtained with the gas target were approximately a factor of 1.9 greater than those obtained with the liquid target. This apparent dependence of the cross section upon the physical state of the ^4He target may explain the large values for the ratio $\sigma(\gamma, p)/\sigma(\gamma, n)$ obtained by comparing photoneutron and photoproton cross sections obtained with targets in different physical states.

Recent measurements of the $^4He(\gamma, n)^3He$ cross section are in disagreement. Data from Livermore[1] and Yale[2] indicate a total cross section of approximately 0.7 mb at 29.8 MeV, while the work of Dodge and Murphy[3] gives a value of 1.54 ± 0.34 mb which is essentially in agreement with the earlier work of Gorbunov.[4] Dodge and Murphy also obtained the (γ, p) cross section. Their ratio $\sigma(\gamma, p)/\sigma(\gamma, n)$ is approximately unity, while a combination of the liquid target data[1,2] with the (γ, p) cross section obtained from the proton capture work of Meyerhof, Suffert, and Feldman[5] gives a ratio of approximately 1.9, nearly double the ratio obtained by Dodge and Murphy. This discrepancy needs resolution, particularly as it has been suggested[1,6] that the larger values of this ratio may be due to charge symmetry breaking of the nuclear force. Therefore we have carried out two measurements of the 98° $^4He(\gamma, n)^3He$ differential cross section, one using a liquid target at its normal boiling point and the other using a gaseous target.

The two cross-section measurements were carried out using the same experimental facility and under as nearly identical circumstances as possible. The neutron time-of-flight facility used has been described previously.[7] Although the two measurements were performed in the same manner, there was a difference in the treatment of the data from the two experiments because of the large background present in the gas target experiment. Details of the two experiments follow.

A liquid ^4He target at its normal boiling point was irradiated with pulsed bremsstrahlung. The pulsed electron beam characteristics were 0.42 A, 15-ns pulse width, 360 pulses per second, and 35 MeV. The bremsstrahlung target was 0.20-cm tungsten followed by a 4.45-cm aluminum beam stop. The helium was contained in a thin aluminum-walled Dewar. The neutron detector was collimated so that the full detector could see a circular area with diameter approximately equal to the 5-cm diameter of the helium Dewar. Background neutrons constituted approximately 60% of the total count rate.

Runs were carried out
(a) with the Dewar full of liquid helium;
(b) with the Dewar empty;
(c) with the Dewar at room temperature filled with D_2O;
(d) with the Dewar at room temperature filled with H_2O;
(e) with a 0.64-cm thickness of D_2O in a target holder with 0.013-cm Mylar walls; and
(f) with H_2O in the same holder.

(a) minus (b) gives the helium photoneutron spectrum. (e) minus (f) gives a deuterium photoneutron spectrum and thus the bremsstrahlung shape. This shape was then normalized to the helium data using (c) minus (d). Before using (c) minus (d), (c) and (d) had to be corrected for neutron self-scattering in these targets. This was done using the results of a Monte Carlo program which calculated the neutron scattering in a 5-cm-diam sphere of H_2O or D_2O for neutrons emerging from this sphere which were produced uniformly over the volume of the sphere. This amounted to a correction of approximately 20% at a neutron energy of 13 MeV. Once the bremsstrahlung shape was normalized to the helium data it was a simple matter to find the 98° differential cross section relative to the calculated deuterium cross section of Partovi.[8] It should be noted that in the helium case a similar self-scattering takes place, but its effect is considerably smaller ($\lesssim 5\%$). This correction has not been made.

Because of the possibility that beam-induced bubbling might reduce the effective density of the liquid target, the measurement was repeated with a gas target. A gaseous ^4He target at 51.6 bars (absolute) was irradiated with pulsed bremsstrahlung. The pulsed electron beam characteristics were 0.33 A, 7-ns pulse width, 480 pulses per second, and 38.5 MeV. The bremsstrahlung target was 0.05-cm tungsten followed by a 7.60-cm aluminum beam stop.

The ^4He target chamber was a stainless-steel cylinder of 20-cm diameter with 0.32-cm walls and 0.64-cm stainless-steel end plates. The beam core saw only the 0.32-cm walls, and the neutron detector viewed the target through one of the end plates. Neutron collimation was arranged so that the detector did not see the bremsstrahlung-irradiated 0.32-cm walls.

Despite this collimation, background neutrons were a serious problem, constituting 80% of the total count rate. This background comes mainly from two sources: (1) neutrons produced externally to the ^4He and scattered in the target chamber end plates; and (2) neutrons produced externally to the ^4He and scattered in the ^4He.

The cross section for ^4He was again obtained by comparison with the Partovi calculation of the deuterium photoneutron cross section.[8] A comparison of the photoneutron spectra from an oxygen gas target and a liquid H_2O target was employed as an intermediate step in determining the helium cross section.

Runs were therefore carried out
(g) with a 0.64-cm thickness of D_2O in a target holder with 0.013-cm Mylar walls;
(h) with H_2O in the same holder;
(i) with the same holder empty;
(j) with O_2 at 50.5 bars (absolute) in the high pressure gas target;
(k) with ^4He at 51.6 bars (absolute) in the gas target; and
(l) with the gas target evacuated.

All runs were carried out under the same electron beam conditions. In all subsequent discussions it will be assumed that beam-independent background and the contributions of (i) and (l) (normalized to beam current) have been removed where applicable.

Comparison of (h) and (j) showed that the apparent ratio of the yields from the two oxygen targets varied with neutron energy, but became constant above 8 MeV (see Fig. 1). The reason for this variation is the large contribution of neutrons produced in the stainless-steel walls of the target chamber and scattered off the oxygen gas (compared with those produced in the gas itself). The constancy above 8 MeV indicates that scattering is negligible above this energy in the case of gaseous oxygen.

The ^4He spectrum (k) was also contaminated by scattered neutrons. The helium spectrum was corrected for these scattered neutrons in the following manner. (h) was normalized to (j) so that the ratio of the two yields was unity in the region above 8 MeV. (This was necessary because of the different geometries of the two targets.) The normalized (h) was then subtracted from (j) to yield the spectrum of neutrons scattered from the oxygen. Calculation of the scattered spectrum to be expected based on a Maxwellian distribution of neutrons typical of that from an iron photoneutron target (nuclear temperature 1.71 MeV)[9] and the scattering cross section for oxygen[10] gave good agreement between 2 MeV $< E_n <$ 11 MeV in spectral shape with that obtained by experiment from runs (h) and (j). Comparison with the observed spectrum of scattered neutrons gives the magnitude of the incident neutron flux. The neutron flux can then be combined with known ^4He scattering cross sections[10] to give the expected scattered neutron spectrum for the ^4He. Subtraction of this from (k) [less, as always (l)], gives the ^4He photoneutron spectrum.

The difference between (g) and (h) when normalized to the same photon dose yielded a deuterium photoneutron spectrum which was used to obtain the shape of the bremsstrahlung spectrum and fix an absolute value on the differential cross-section measurement by assuming the theoretical $^2H(\gamma, n)$-^1H cross section of Partovi.[8] In order to correct for different target geometries used, the deuterium data had to be normalized to the helium data by way of the high-energy region of the oxygen spectra (h) and (j).

Once these manipulations had been performed it was a simple matter to obtain the $^4He(\gamma, n)^3He$

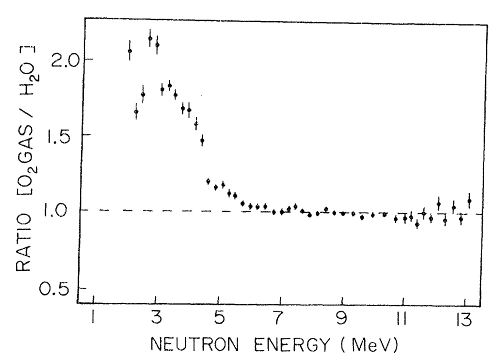

FIG. 1. Ratio obtained by dividing the oxygen gas spectrum by the oxygen spectrum obtained using a liquid H_2O target. The ratio has been normalized to unity in the region above 8 MeV. The divergence of the ratio from unity at low energies indicates contamination of the oxygen gas spectrum by scattered neutrons.

differential cross section by dividing the helium spectrum as a function of photon energy by the properly normalized photon spectrum.

Errors on the resulting cross section increase with decreasing energy because of the above scattering correction. Above 29 MeV the correction due to neutrons produced externally and scattered in the helium is less than 5% of the gross yield and the resulting errors in the cross section may therefore be neglected, but by 25.3 MeV the correction is 50% of the gross yield, and errors in the cross section due to this cause may be expected to be ±15% at this energy. Below this energy the possible error could be expected to increase rapidly. However, the shape of the cross section which is obtained deviates by no more than 15% at any point from the shape of the cross section obtained using the liquid target.

The results of both differential cross section measurements are shown in Fig. 2. The error bars show statistical errors. For both measurements there is a possible over-all error of approximately ±20% arising mainly from the uncertainty in the Partovi cross section and uncertainties in the detector efficiency. It should be noted, however, that this same deuterium cross section was used in the calculation of both the present results and also in the calculation of the earlier Yale results[2] and so errors in the Partovi cross section cancel out in a comparison of these results. The possible error in the gas target cross section resulting from uncertainties in the neutron scattering corrections is indicated by the solid lines in Fig. 2. For the gas target results there is an additional uncertainty of no more than $^{+7\%}_{-14\%}$ due to a possible $^{+1\%}_{-2\%}$ error in the normalization of the background run to the helium run.

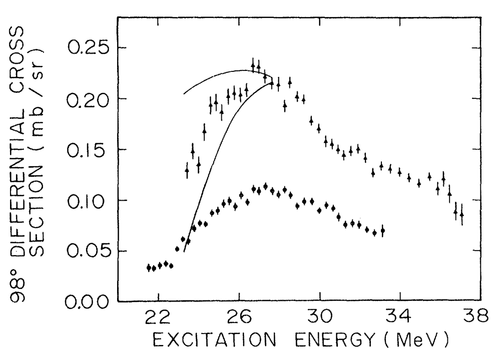

FIG. 2. 98° ^{4}He(γ, n)^{3}He differential cross section. Circles (lower curve) denote results obtained with the liquid target. Triangles (upper curve) denote results obtained with the gas target. The solid lines indicate the limits of the uncertainty in the gas target cross section due to the correction for scattered neutrons.

The values of the cross section obtained using the gas target agree with the values obtained by Dodge and Murphy[3] and the values of the cross section obtained using the liquid target agree with those obtained in a similar experiment at Yale[2] (see Fig. 3). The Yale results were measured at a lab angle of 90°, whereas the present results were measured at a lab angle of 98°. Measured angular distributions[11] show that this difference in angle is insignificant. However, the two measured cross sections disagree with one another, the gas target cross section being approximately a factor of 1.9 greater than the liquid target cross section. For the present we must leave the reason for this discrepancy unresolved; however, there is a suspicion that the density of the liquid target was reduced below the 0.125 g/cm^3 (density at the normal boiling point) used in the calculation by bubble formation in the liquid helium. Similar but less drastic density reductions in liquid hydrogen targets have been reported (see, for example, Ref. 12).

The two experiments performed at Toronto, one using liquid helium target at its normal boiling point and the other using a high-pressure helium gas target, show that both the previously reported[2,3] cross-section results can be obtained. Because of this apparent dependence of the value obtained for the cross section on the physical state of the target used, one can see how erroneous results for the ratio $\sigma(\gamma, p)/\sigma(\gamma, n)$ could be obtained by comparing cross sections which were obtained using targets of different physical properties. It must therefore be concluded that measurements of the (γ, p) and (γ, n) cross sections using

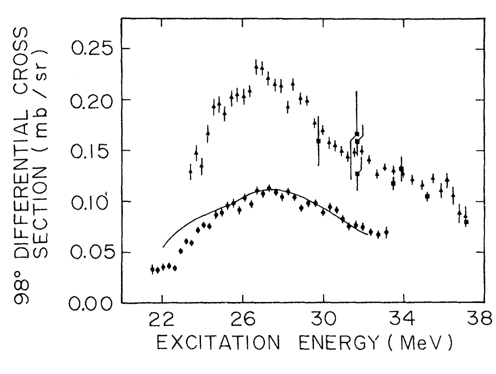

FIG. 3. ^{4}He(γ, n)^{3}He differential cross section as a function of excitation energy. Present results: Circles (lower curve) denote liquid target; triangles denote gas target. The squares are the results of Dodge and Murphy obtained at a center-of-mass angle of 101° (see Ref. 3). The solid line was obtained by drawing a line by eye through the Yale results obtained at 90° using a liquid target (see Ref. 2).

the same target and experimental equipment should give more meaningful values for the ratio $\sigma(\gamma, p)/\sigma(\gamma, n)$; all such measurements[3,4,13] show that the ratio in the energy range from 27.2 to 65 MeV is approximately unity. Best of all are simultaneous measurements.[4,13]

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