Absolute cross section for the reaction $^3H(p,\gamma_0)^4He$ and a review of $^4He(\gamma, p_0)^3H$ measurements

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Accurate differential cross sections have been measured at 90° for the reaction $^3H(p,\gamma)^4He$ at $E_p=8.34$ and 13.6 MeV. Previously published results for both $^3H(p,\gamma)^4He$ and $^4He(\gamma,p)^3H$ are reviewed and compared with the present data. The theoretical implications of the results are briefly discussed.

[NUCLEAR REACTIONS $^3H(p,\gamma_0)^4He$, $E_p=8.34$ and 13.60 MeV, measured $\sigma(\theta)$ at 90°.]

I. INTRODUCTION

The comparison of mirror (γ,p) and (γ,n) cross sections provides a sensitive test of isospin mixing in the giant multipole resonances in self-conjugate nuclei. Following the original work of Barker and Mann[1] on the effect of isospin mixing on the (γ,p) and (γ,n) cross sections on ^{12}C, several theoretical works[2–4] have considered the possible effect of isospin mixing in ^4He and have attempted to calculate the (γ,p) and (γ,n) cross sections in the region $E_\gamma=20-50$ MeV.

Because of the emphasis on determining possible structure in the cross section and on measuring angular distributions in the reaction $^3H(p,\gamma_0)^4He$ in the giant $E1$ region, definitive measurements of the absolute cross sections have not been reported. In several cases where cross-section measurements have been given, an allowance for large systematic errors has been made. In this paper we report a measurement of the absolute cross section which is independent of the knowledge of both absolute target thickness and beam current integration and which we believe is more accurate and reliable than previous measurements. We have also reviewed the available literature on this reaction and the inverse (γ,p) reaction and compare our result to the more reliable published results. The status of the absolute cross section for the $^4He(\gamma,n)^3He$ reaction was recently reviewed, and the cross section remeasured, in a similar paper by Berman and co-workers.[5]

Previous values of the $^4He(\gamma,p)^3H$ cross sections have been obtained from three types of reactions: (1) radiative proton capture on ^3H, (2) photodisintegration experiments on ^4He in which both final state particles, p and ^3H, are detected in coincidence, and (3) photodisintegration experiments in which only one of the outgoing particles, either the p or the ^3H, is detected. If only the p is observed the measurement includes not only the two-body photodisintegration but also contributions from three- and four-body final states, and a correction must be applied to the data in order to obtain the two-body cross section. Earlier comparisons[6–8] of (γ,n) cross sections to (γ,p) cross sections were based either on a relative excitation function[9] for $^3H(p,\gamma)^4He$ normalized to measurements below $E_p=6$ MeV,[10] or on preliminary results from the present experiment. We give a comparison of all available data on this reaction.

The photodisintegration experiments have all used continuous incident photon beams from bremsstrahlung, relying on measurements of the outgoing particle energy. This is acceptable if both (all) outgoing particles are detected and their energies measured, but as we will see, severe discrepancies exist among various published results when only the proton is detected. If, on the other hand, the only particle detected is identified as a triton, then again the results are acceptable, since the other particle must be a single proton. No measurements on $^4He(\gamma,p)^3He$ exist for monoenergetic photons.

There have been two measurements[11,12] of the ratio of $\sigma(\gamma,n)$ to $\sigma(\gamma,p)$ obtained by observing the recoil ^3He and ^3H ions instead of the neutrons and protons. The first[11] utilized electrodisintegration and serial measurements of the ^3He and ^3H ions in a magnetic spectrometer. This work reported a cross section ratio essentially equal to unity above $E_\gamma\simeq30$ MeV. The second work[12] used bremsstrahlung and detected the recoil ions simultaneously by identifying them in a multicounter solid state telescope. Again the reported ratio is close to unity, although a significant deviation of about 15% is found in the region 35–40 MeV. Both of these ratio measurements were restricted to studying the region above $E_\gamma\simeq30$ MeV owing to the difficulty of detecting the low energy ^3He ions below this region.

Although these measurements indicate that

$$\sigma(\gamma,n)/(\gamma,p)\simeq1$$

above $E_\gamma\simeq30$ MeV, the measurements of (γ,n) and (γ,p) below 30 MeV give results anywhere between 1.0 and 0.5 for this ratio. Thus, it was decided to obtain a definitive measurement of $\sigma(\gamma,p)$ in the low energy region.

II. EXPERIMENT AND DATA REDUCTION

The cross section measured for $^3H(p,\gamma)^4He$ in this experiment is based upon a simultaneous measurement of the yield for (p,γ) and that for proton elastic scattering from ^3H which has been accurately measured.[13,14] The proton beam was obtained from the Stanford FN tandem Van de Graaff accelerator. Photons from $^3H(p,\gamma)^4He$ were detected at 90° while protons from $^3H(p,p)^3H$, tritons from $^3H(p,t)^1H$, and deuterons from $^3H(p,d)^2H$ were detected at 30° on the opposite side of the beam line. The target consisted of tritium absorbed (one atom per atom of absorber) into 3 mg/cm^2 of erbium deposited on a backing

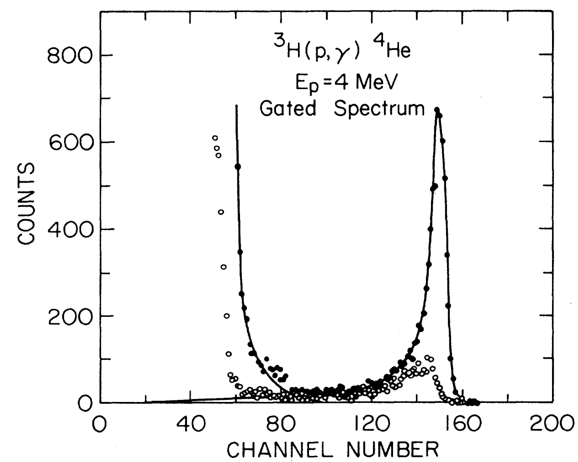

FIG. 1. Pulse height spectrum from ^{3}H(p,γ)^{4}He at $E_p=4.0$ MeV (laboratory energy) displaying the quality of the line shape fit to the NaI detector response function. The circles show the spectrum rejected by the anticoincidence cylinder of the spectrometer (Ref. 15).

of platinum 2 mg/cm^2 thick. The particles from the tritium were easily resolved from those from erbium and platinum.

The γ yields were measured with the 24×24 cm NaI spectrometer developed at Stanford.[15] The measurements were made in a carefully determined geometry without the use of paraffin absorbers between the target and detector. The geometrical solid angle, 0.333 sr, was measured to an accuracy of approximately 3%. The 90° angle of the spectrometer in the laboratory was determined with an error of about 1°, which produces an error of less than 1% in the total cross section as determined from the known angular distribution.[16] The absorption of photons in the wall of the scattering chamber, made of aluminum 0.15 cm thick, as well as in the plastic anticoincidence shield of the NaI spectrometer and the casing of the NaI crystal, was taken into account. The total attenuation was approximately 13%, with an uncertainty of about 1%.

The crucial question in determining the absolute γ yield lies in knowing the form of the γ-ray response function, or line shape, of the spectrometer. Figure 1 shows a pulse height distribution of photons obtained with a 4 MeV proton beam. At this energy the background produced by neutron induced events is appreciable only at low pulse heights; thus the line shape can be determined reasonably well over a wide range of pulse heights. Although it has not yet been possible to establish the line shape empirically all the way to zero pulse height, we believe that the shape shown in Fig. 1 is consistent with all current experimental and theoretical knowledge, and the uncertainty produced by lack of knowledge of the complete shape is approximately 10%. In other words, between 80% and 90% of the pulse height yield in Fig. 1 can be observed cleanly at pulse heights above the point where the neutron capture yield begins to dominate the spectrum, while an additional 10—20% of the area lies in the extrapolated tail, depending on whether it is extrapolated to zero at channel zero or whether a flat response is assumed. Figure 1 also shows the spectrum of pulses rejected by the anticoincidence ring of the spectrometer.[15]

Photon spectra were measured at $E_p=8.34$ and 13.60 MeV. Although the neutron induced yield extended to higher pulse height in these spectra, the line shape determined at $E_p=4$ MeV can be used to fit the γ_0 peak with approximately 75% of the counts being observed at pulse heights larger than those dominated by background. In analyzing these data, the cross sections were computed assuming that an extrapolation to zero counts at zero pulse height is correct. Thus our cross sections represent the minimum value, which we believe is more probable. The

TABLE I. Summary of cross section measurements on the reaction ^{3}H(p,γ_0)^{4}He made at two energies.

Measured quantity	Unit	Measurement I	Measurement II
E_p	MeV	8.34	13.60
$(d\sigma/d\Omega)_{90°}$	μb/sr	8.99	6.25
Error contributions			
γ-ray solid angle	%	±3.0	±3.0
γ-ray angle	%	±1.0	±1.0
γ-ray attenuation	%	±1.0	±1.0
Particle solid angle	%	±0.5	±0.5
Proton angle[a]	%	±2.5	±2.5
Proton statistics	%	±0.5	±0.5
γ-ray statistics	%	±2.5	±2.0
Combined error[a]	%	±6.7	±6.4
$(d\sigma/d\Omega)_{90°}$ with error	μb/sr	8.99±0.60	6.25±0.40
Line shape uncertainty[b]	%	+10.0 −0.0	+10.0 −0.0
Uncertainty[c] in $\sigma_{tot}/\sigma_{90°}$	%	±1.4	±1.5
Total cross section	mb	1.95±0.13	1.67±0.11

[a]Error contributions added in quadrature except for proton angle uncertainty, which was assumed to be systematic.

[b]Line shape uncertainty is not included in combined error.

[c]Derived from angular distribution measurements of Ref. 16.

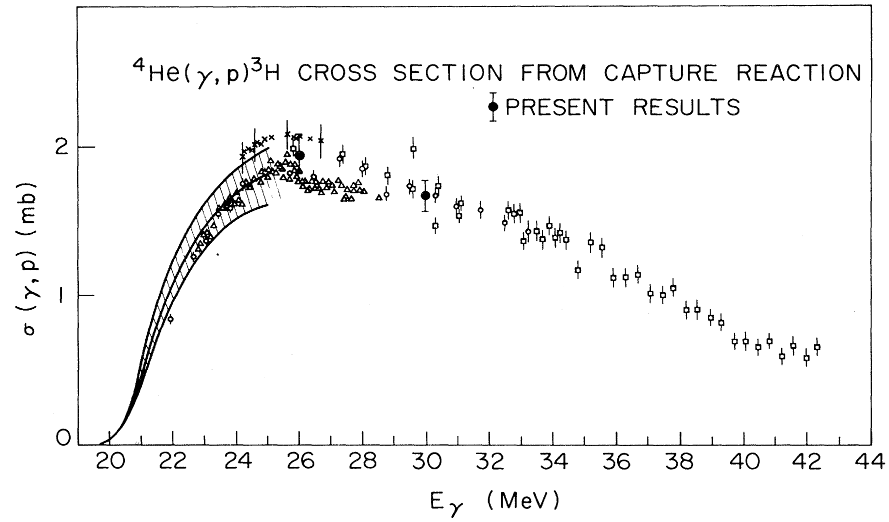

FIG. 2. Comparison of the results for ^{4}He(γ,p)^{3}H as derived by detailed balance from capture reactions. The shaded error band is the original work of Perry and Bame (Ref. 10). The present results are given by the solid circles. The other results are the following: open circles, Meyerhof *et al.* (Ref. 9); open triangles, Gemmell and Jones (Ref. 17); $\times$'s, Gardner and Anderson (Ref. 18); open squares, McBroom *et al.* (Ref. 19).

uncertainty arising from the line shape extrapolation is therefore 0–10%.

The γ yield was normalized to the yields of elastically scattered protons and recoil tritons measured simultaneously by means of a standard ΔE-E two-counter telescope of silicon surface barrier detectors. A double collimator was used in front of the telescope. The first aperture was inserted to eliminate a tail on the line shape of detected charged particles which was due, possibly, to scattering from the wall of the arm which housed the detector. The second aperture defined the solid angle of the telescope to be 22.1 msr as determined from a measurement of the diameter of the aperture with a traveling microscope. The error in the solid angle was judged to be $\pm 0.5\%$. The error introduced by a possible systematic uncertainty in the angle of the particle detector was estimated to be $\pm 2.5\%$.

The (p,γ) cross sections were computed by relating them to the precision cross section measurements of Brolley *et al.*[13] at $E_p = 8.34$ MeV and by Detch *et al.*[14] at $E_p = 13.60$ MeV for ^{3}H(p,p)^{3}H at the corresponding angles. In fact, the measurement of the yields of both protons and tritons at a single laboratory angle provides two independent points in the angular distribution of the elastic scattering. The two points are in agreement with the results of Ref. 13 and 14 within statistics ($\sim 1\%$). A further check was provided by a comparison with the yield of deuterons from the reaction ^{3}H(p,d)^{2}H.[14] Again the agreement was well within statistical uncertainties, although the statistics associated with this reaction are significantly poorer than for elastic scattering.

Table I lists all the data, the derived cross sections, and the estimated errors (both systematic and statistical), except for the uncertainty associated with the γ-ray line shape discussed earlier. The final results of our measure-

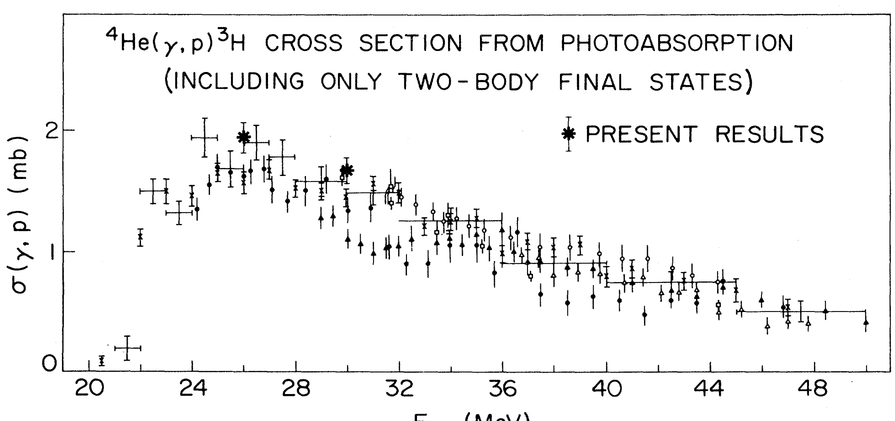

FIG. 3. Comparison of the present results (shown by an asterisk) with those from photoabsorption measurements where either the triton or both particles were observed. The data shown are the following: $\times$'s, Arkatov *et al.* (Ref. 22); crosses, Gorbunov (Ref. 20); solid circles, Balestra *et al.* (Ref. 24); solid triangles, Clerc *et al.* (Ref. 25); open triangles, Denisov and Kul'chitskii (Ref. 23); open circles, Wait *et al.* (Ref. 21); and open squares, Dodge and Murphy (Ref. 11).

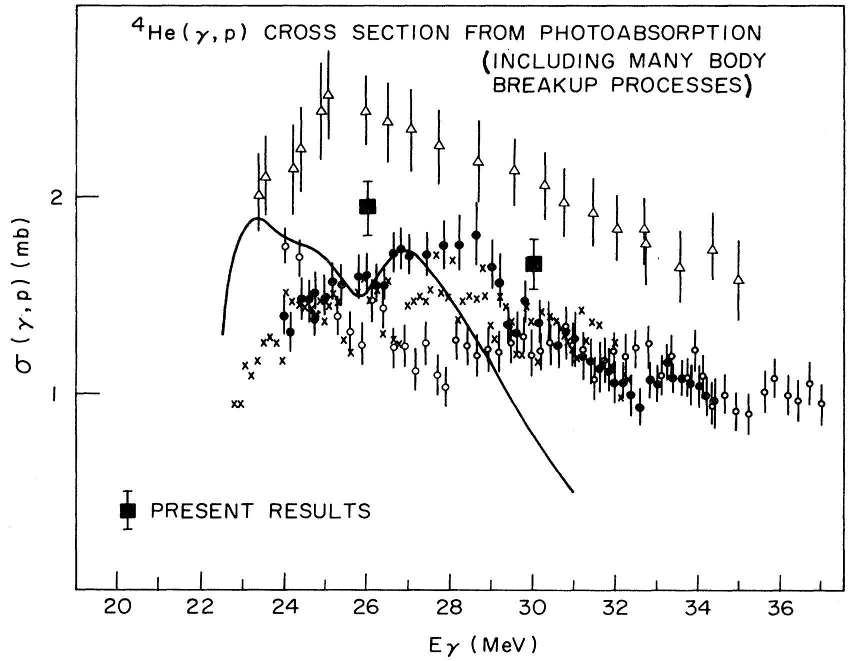

FIG. 4. Comparison of the present results (shown by solid squares) with those from photoabsorption measurements where only a single proton was detected. The data shown are the following: solid line, Sanada *et al.* (Ref. 34); solid circles, Clerc *et al.* (Ref. 25); open triangles, Wait *et al.* (Ref. 21); open circles, Denisov and Kul'chitskii (Ref. 23); ×'s, Mundhenke *et al.* (Ref. 33).

ments, converted by detailed balance to the time reversed reaction $^4He(\gamma,p)^3H$, are compared in Figs. 2–4 with all the other measurements on this reaction. In converting the 90° differential measurements to total cross section, the angular distributions measured by King[16] were used.

III. DISCUSSION AND COMPARISON OF RESULTS

Figure 2 displays the results of other measurements of the $^4He(\gamma,p)^3H$ cross section obtained from proton capture on tritium. The earliest measurements by Perry and Bame[10] used a tritium gas cell for a target and depended upon absolute measurements of gas pressure, beam current, photon detector efficiency, and solid angle in order to obtain an absolute cross section. In these measurements the largest uncertainty is in the knowledge of the detector efficiency, owing to the small size of the NaI crystal used (approximately 3.8 cm×3.8 cm) and the resulting uncertainty in the γ-ray response function. The authors pointed out that a significant increase in accuracy could be obtained by using a larger crystal with proper collimation. Their overall accuracy, shown in Fig. 2 by the shaded area, as reproduced from Fig. 11 of their paper is about 10%.

Subsequent measurements on the capture reaction were also made with tritium gas targets. Gemmell and Jones[17] used an uncollimated 12.7 cm×10.2 cm NaI detector without anticoincidence shield, which again exhibited a poor line shape. Gardner and Anderson[18] used a shielded and collimated 12.7 cm×15.2 cm NaI detector which gave an improved line shape, but they still attributed most of their uncertainty of 15% to possible errors in the extrapolation of the line shape. Gemmell and Jones[17] obtained results in agreement with those of Perry and Bame,[10] while Gardner and Anderson[18] obtained somewhat larger cross sections which were, however, within the quoted systematic uncertainties. The excitation function of Perry and Bame[10] was extended to higher energies by Meyerhof *et al.*[9] using a tritiated solid target. More recent measurements by McBroom *et al.*[19] have extended the results to even higher energy and they overlap well with those of Meyerhof *et al.*[9]

Our new results confirm all the previous measurements[9,10,17,18] within their quoted uncertainties. Furthermore, the absolute uncertainty in the present measurements is decreased by a factor of about 2 over the best previous measurement and the new measurements are not subject to possible uncertainties owing to density changes in a gas cell or in current integration and less subject to difficulties in the γ line shape extrapolation. We therefore consider the new result to be significantly more reliable than those published previously for the H(p,γ)He reaction.

Figure 3 shows a comparison of the present results with those from photoabsorption by ^{4}He that result in an experimentally determined two-body final state. Of the photodisintegration measurements only that of Gorbunov[20] agrees with the time reversed capture results in the region below 30 MeV, all other results being 12–20% lower. Above 30 MeV there is reasonable agreement among the results of Gorbunov,[20] Wait *et al.*,[21] Arkatov *et al.*,[22] Dodge and Murphy,[11] Denisov and Kul'chitskii[23] and the capture results in the regions of overlap. The results of Balestra *et al.*[24] appear to be lower than almost all other results above 30 MeV, but are in reasonable agreement with those of Arkatov *et al.* below 30 MeV. The results of Clerc *et al.*[25] appear to be in reasonable agreement with the others above about 34 MeV, but are significantly lower between 30 and 34 MeV.

The cross section measurements that do not extend below 30 MeV were obtained by detecting only the triton and are possibly subject to problems associated with detecting low energy tritons in the region just above 30 MeV. This difficulty may explain the deviation of the cross section of Clerc *et al.* in the region of 30–34 MeV. Wait *et al.* and Dodge and Murphy used magnetic spectrometers, while Clerc *et al.* used quadrupole focusing followed by a counter telescope and Denisov and Kul'chitskii used a counter telescope.

Another source of discrepancies in these results is the way in which the cross sections were normalized to obtain absolute values. Most of the photodisintegration results were normalized to the reaction $D(\gamma,p)n$ for which the cross section was taken either from theory[26,27] or from experiment.[28–32] However, a discrepancy of about 15% exists among the various measurements on the $D(\gamma,p)n$ reaction in the range of $E_\gamma=20-30$ MeV and between some of the measurements and the theory in the same region. However, the measurements of Dodge and Murphy[11] and Wait *et al.*[21] which agree with the capture measurements at high energy were carried out with virtual photons rather than real photons, i.e., they were electrodisintegration measurements. Thus they are subject to the limitations and approximations involved in correcting virtual photon data to real photon cross sections. In these electrodisintegration experiments the absolute cross sections were obtained by direct integration of the electron beam current and measurement of the ^{4}He pressure in the gas cell. This agreement of the electrodisintegration results with one another, with the capture measurements, and with Gorbunov's photodisintegration results[20] certainly suggests that the disagreement of the results of Arkatov *et al.*[22] and Balestra *et al.*[24] may be due to their methods of normalization, which are not explicitly given in their papers.

Figure 4 shows a comparison of the present results with photoabsorption measurements in which only a single proton is detected.[21,23,25,33,34] Although all these references claim that corrections were made for possible three- and four-body cross sections, the great disparity in the measurements clearly suggests that these corrections are not trustworthy. It is interesting in this connection that Gorbunov finds the (γ,pn) and $(\gamma,2p2n)$ cross sections to be about one-tenth and one-twentieth, respectively, of the (γ,p) cross section in the energy region of interest.

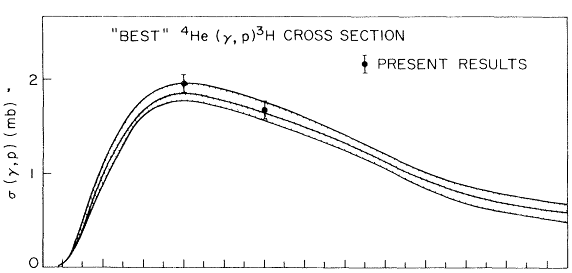

FIG. 5. The consensus or "best" cross section for ^{4}He$(\gamma,p)^3$H derived from the present measurements and all the observations surveyed in this work. The shaded band represents the error based principally on the present work.

Nevertheless, we conclude that measurements of the ^{4}He$(\gamma,p)^3$H cross section in which the triton is *not* observed cannot as yet be trusted to give reliable results.

Because of the agreement between the capture results and the photodisintegration results of Gorbunov[20] below 30 MeV and of Dodge and Murphy,[11] Wait *et al.*,[21] and Arkatov *et al.*[22] above 30 MeV, we conclude that the cross sections quoted by Balestra *et al.*[24] are low over the entire region of 24–44 MeV. Because the data of Arkatov *et al.* are low below 30 MeV and in agreement above 30 MeV, they clearly exhibit a different energy dependence than observed in the other references. We are thus lead to the conclusion that the photodisintegration results of Gorbunov represent the best overall measurement of the energy dependence of the cross section. The capture results, particularly those obtained in the present work, reduce the uncertainties in the region below 30 MeV and thus provide a better absolute normalization for the entire cross section. In Fig. 5 we show what we believe to be the best cross section curve for ^{4}He$(\gamma,p)^3$H based on the present measurements and evaluation of all the data.

From this critique of the measurements we conclude that the average cross section for the reaction ^{4}He$(\gamma,p)^3$H in the region $E_\gamma=26-30$ MeV is 1.8 ± 0.12 mb (where the error is attributed to the uncertainties in the present work). By comparing this value to the ^{4}He(γ,n) cross section in the same energy range we may obtain information on isospin mixing if a suitable theory is available. However, there are large discrepancies in the values reported for the (γ,n) cross section below 30 MeV (see Ref. 12). Cross sections in the region $E_\gamma=26-30$ MeV have been reported ranging from 1.0 mb (Ref. 35) to 2.0 mb (Ref. 36). Despite these discrepancies, the various measurements of the (γ,n) cross section agree quite well above 30 MeV (see Ref. 5) and agree with the $(\gamma,n)/(\gamma,p)$ ratio measurements (≈ 1.0) (Refs. 11 and 12) discussed in the Introduction. The latest measurement of the (γ,n) cross section[5] supports the lower value, 1.0 mb, in the region $E_\gamma=26-30$ MeV. This gives a ratio of cross sections

$$\sigma(\gamma,n)/\sigma(\gamma,p)\simeq 0.6$$

in this region.

This cross section ratio of 0.6 is inconsistent with all the theoretical work on these reactions. Since Coulomb effects are negligible at these energies, the expected ratio of cross sections is expected to be near unity, except within 5 MeV of threshold. The effects of $E2$ and $M2$ radiation have been considered but do not account for the observed discrepancy. It is tempting to assign the remaining discrepancy to isospin mixing between $T=0$ and 1 components of the dipole states. However, if the ground state of ^{4}He is taken to be a closed $1s^4$ configuration, then the only allowed $J=1$ excitation with $T=0$ must have $S=1$, but such a configuration would mix only with $S=1$, $T=1$ states and polarization measurements[16] have shown this contribution to account for less than 2% of the cross section. Isospin mixing with such a small component therefore cannot account for the discrepancy.[37] Because of the serious theoretical implications of this result, it is clear that a definitive result for the $\sigma(\gamma,n)/\sigma(\gamma,p)$ ratio is still badly needed below 30 MeV.

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