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^{3}H(p,γ) ^{4}He reaction and the $(\gamma,p)/(\gamma,n)$ ratio in ^{4}He

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The absolute differential cross section for the $^3\mathrm{H}(p,\gamma)^4\mathrm{He}$ reaction has been measured at $\theta_\gamma = 90°$ for $E_p = 2.0$–15.0 MeV, corresponding to photon energies $E_\gamma = 21.3$–31.1 MeV. The present results are 35% lower than previously measured (p,γ) cross sections and are in excellent agreement with recent (γ,p) data obtained with monoenergetic photons. Comparing our results to current photoneutron cross sections gives a ratio $\sigma(\gamma,p)/\sigma(\gamma,n) = 1.09 \pm 0.17$ for $E_\gamma = 24$–31 MeV. This ratio is consistent with conventional theoretical predictions, indicating that no charge-symmetry violation in ^{4}He is required.

Charge symmetry is believed to be a fundamental property of the nuclear force. This implies that, in the absence of isospin mixing, the p-p and n-n nuclear interactions are expected to be equal. This hypothesis can be tested by comparing mirror reactions on self-conjugate nuclei. The use of the photonuclear reactions (γ,p) and (γ,n) for this purpose was first suggested by Barker and Mann, who examined the photonucleon cross section ratio in ^{12}C in the energy region of the giant dipole resonance.[1] In the limit of pure isospin, this ratio is expected to be unity.

The simplest and most well-understood self-conjugate nucleus is ^{4}He. It is therefore quite surprising to note that photonuclear work on this system establishes a cross section ratio $R_\gamma \equiv \sigma(\gamma,p)/\sigma(\gamma,n)$ rather different from unity; in fact, $R_\gamma \approx 1.7$–1.2 for $E_\gamma = 25$–35 MeV.[2] Various theoretical approaches[3–9] have attempted to account for this result. Most efforts which explicitly include charge-symmetry-breaking effects in the nuclear interaction have failed to reproduce the large R_γ value. Exceptions are Gibson,[8] who incorrectly allowed different channel spins to mix coherently in the cross section, and Barker,[9] who arbitrarily introduced a hypothetical (and unobserved) $S=0$, $T=0$, $J^\pi = 1^-$ state of a higher configuration than $1s^3 1p$. Asymmetries due to Coulomb effects in the energy range of interest (i.e., more than 2–3 MeV above the $^3\mathrm{H}+p$ threshold at 19.8 MeV) have been shown to increase R_γ above 1.0 by only $\sim$10%.[3–7]

Much attention has been focused on verifying the validity of the experimental data. Significant discrepancies in the $^4\mathrm{He}(\gamma,n)^3\mathrm{He}$ data raised serious questions about uncertainties in the absolute cross section. These questions were largely laid to rest by a new measurement of this reaction using monoenergetic photons by Berman *et al.*,[10] the result of which was subsequently confirmed by the $^3\mathrm{He}(n,\gamma)^4\mathrm{He}$ work of Ward *et al.*[11] The photoproton data reported by different groups did not display such severe fluctuations. Furthermore, the inverse (p,γ) capture data[12–17] appeared to corroborate the magnitude and energy dependence of the $^4\mathrm{He}(\gamma,p)^3\mathrm{H}$ cross section. A careful review of the existing photonuclear (and capture) data on ^{4}He was presented by Calarco, Berman, and Donnelly,[2] leading to the conclusion that R_γ differs appreciably from unity for $E_\gamma = 25$–35 MeV.

A puzzling aspect of this problem relates to the experiments which determined the ratio R_γ by simultaneous measurement of the (γ,p) and (γ,n) cross sections, thereby reducing the sensitivity to systematic uncertainties.[18,19] In both cases, the extracted value of R_γ was consistent with unity for E_γ=30–40 MeV. A new simultaneous measurement of $(e,e'p)$ and $(e,e'n)$ cross sections for E_x=22–36 MeV in ^{4}He was also entirely consistent with a calculation employing a charge-symmetric nuclear interaction, giving a ratio $R_e \approx 1.1$–1.3.[20] Furthermore, a completely different technique of examining isospin mixing in ^{4}He by inelastic scattering of π^+ and π^- gave $R_\pi = 1.05 \pm 0.08$ below 30 MeV.[21] It is difficult to reconcile these simultaneous ratio measurements with the ratio obtained from separate experiments. The failure of most reasonable theoretical calculations to get $R_\gamma > 1.1$ must be considered as well.

Recently, a new measurement of the (γ,p) cross section was reported, yielding a $(\gamma,p)/(\gamma,n)$ ratio (based on comparison with the photoneutron data evaluation in Ref. 2) of 1.01 ± 0.06 for E_γ=28.6–42.4 MeV.[22] This was the first photoproton work to use monoenergetic photons and a nearly 4π proton detector, similar to the method employed by Berman *et al.* in the (γ,n) case.[10] These results contrast with the earlier evaluation of (γ,p) results by Calarco, Berman, and Donnelly.[2] We have, therefore, remeasured the ^{3}H$(p,\gamma)^4$He absolute cross section in an effort to provide an independent confirmation.

We have measured γ rays at θ_γ(lab) = 90° from the radiative capture reaction ^{3}H$(p,\gamma)^4$He at 19 proton energies in the range E_p=2.0–15.0 MeV, corresponding to E_γ=21.3–31.1 MeV. Elastically scattered protons were measured simultaneously using a solid-state detector. By comparing the yields from ^{3}H$(p,p)^3$H elastic scattering to precision cross sections in the literature, we were able to determine absolute (p,γ) cross sections independent of direct knowledge of both the tritium target thickness and the absolute integrated beam current.

Proton beams were obtained from the FN tandem Van de Graaff accelerator at the Triangle Universities Nuclear Laboratory (TUNL). Capture γ rays were detected in two anticoincidence-shielded 25.4 cm×25.4 cm NaI(Tl) spectrometers[23] located 80.6 cm from the target. Each detector was surrounded by 10 cm of passive Pb shielding, as well as 20 cm of lithium-carbonated paraffin to moderate neutrons. Cadmium or boron sheets in front of the detectors also absorbed thermal neutrons. A tapered collimator in the front Pb shield defined the detector solid angle to be 45 msr.

The absolute γ-ray detection efficiency was determined at E_γ=15.1 MeV by comparing the thick-target resonance yield at θ_γ=125° for the ^{12}C$(p,\gamma)^{13}$N reaction at E_p=14.23 MeV to the absolute yield given by Marrs *et al.*[24] The energy dependence of the efficiency is well known for this system at these γ-ray energies (E_γ=15–35 MeV), based on previous TUNL work.[16,23] The absolute efficiency was based on a summing region corresponding to lower/upper window limits of 90%/110% of the peak energy. This range was used to obtain all γ-ray yields presented below.

The detector efficiency was checked independently at E_γ=26 MeV using the full line shape response obtained from the ^{3}H$(p,\gamma)^4$He reaction at E_p=8.34 MeV. By summing the total NaI response (accepted+rejected) down to zero energy for a run with no paraffin shielding in front of the NaI detector, we obtained the total number of γ rays reaching the detector. After correcting this value for the known attenuation[25] in the front plastic shield, the ratio of this corrected value to the sum in our standard 90%/110% window in the accepted spectrum for a run with full paraffin shielding gave the γ-ray detection efficiency at this energy. Accounting for the previously determined energy dependence of the efficiency,[16,23] we found that the efficiency extrapolated to E_γ=15.1 MeV using this method agreed with that measured in the ^{12}C$(p,\gamma)^{13}$N reaction to within 5%.

The target consisted of a self-supporting tritiated titanium foil, ~5 μm thick. At E_p=6.5, 8.34, and 13.6 MeV, where proton scattering data[26,27] exist, direct knowledge of the tritium target thickness or the absolute integrated beam current was unnecessary. The yield of scattered protons, which were detected simultaneously with the γ rays, provided a direct measure of the number of beam-target interactions. Protons were detected in a 500 μm Si surface-barrier detector, calibrated using a standard ^{241}Am α-particle source and a precision pulser. Several collimators were used in various runs, giving effective solid angles of 0.28–0.59 msr. At these three proton energies, several laboratory angles (θ_p=40°–70°) were checked to verify consistency of the results with the angular distributions given in Refs. 26 and 27. For other proton energies, a tritium target thickness of 240 ± 20 μg/cm^2 was used, based on the results above. The tritium thickness was also rechecked in a separate beamline with a different geometry ($d\Omega$=0.11 msr), which confirmed the previous results.

At very forward solid-state detector angles (θ_p=30°–40°), triton recoils were also detected, thus giving another consistency check with back-angle points in the proton angular distributions. Extraction of the triton yields was more difficult than the elastic proton yields due to more significant backgrounds, but the recoil analysis agreed with the elastic proton scattering results to within 10%. To test for the possible presence of ^{3}He in our target due to decay of tritium, a 6.35 μm Havar foil was placed in front of the solid-state detector to stop ^{3}He recoils; a repetition of the recoil analysis indicated that our target contained no interstitial ^{3}He residue.

The current (p,γ) cross section supersedes an earlier TUNL measurement[16] on the same reaction. Unfortunately, it is not possible to determine with certainty a specific flaw in the previous work. Target nonuniformities and the tight geometry of the solid-state detectors in the capture target chamber seem to be the most likely sources of error. In the present case, greater care was taken in verifying the tritium target thickness, as outlined above.

A particle spectrum and a γ-ray spectrum for E_p=6.5 MeV are shown in Fig. 1. Clear separation between the elastic scattering peak from ^{3}H and peaks due to scattering to low-lying states of ^{48}Ti (E_x=0.00, 0.98 MeV) is evident in the proton spectrum. A flat background was subtracted from the ^{3}H elastic peak to obtain the yield, and all yields were corrected for dead time. In the γ-ray spectrum, the summing region shown in the figure corresponds to 90%–110% of the γ-ray energy. The spectrum

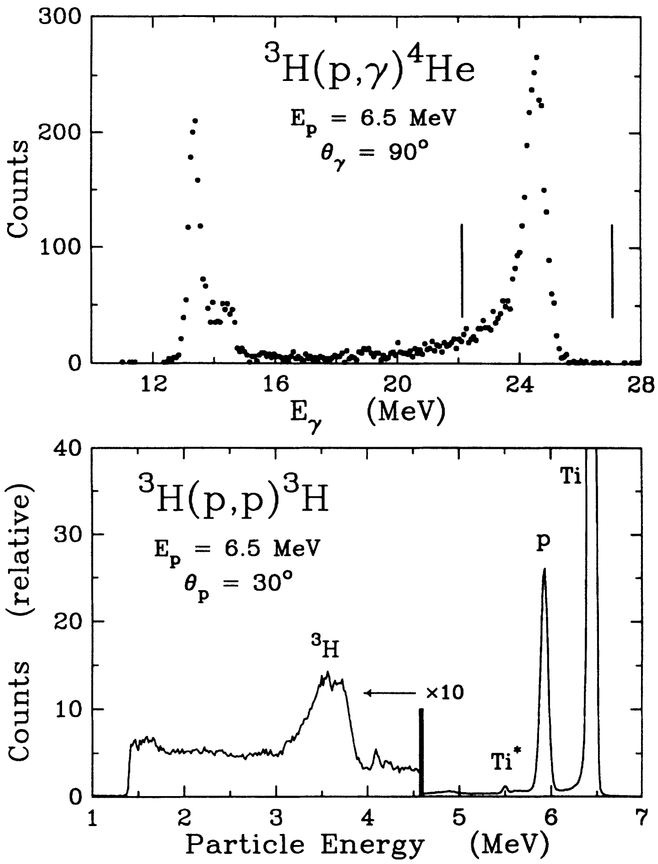

FIG. 1. Upper panel: Measured γ-ray spectrum for $^3H(p,\gamma)^4He$ at $E_p = 6.5$ MeV ($\theta_\gamma = 90°$). The summing region corresponds to 90%–110% of the γ-ray energy. Lower panel: Spectrum of scattered particles for protons incident on the tritiated titanium target at $E_p = 6.5$ MeV ($\theta_p = 30°$). The elastic scattering peak from ^3H is clearly resolved from the elastic and first inelastic peaks from ^{48}Ti ($E_x = 0.00$, 0.98 MeV). The scale of the lower-energy portion of the spectrum has been multiplied by a factor of 10 to show the triton recoil peak.

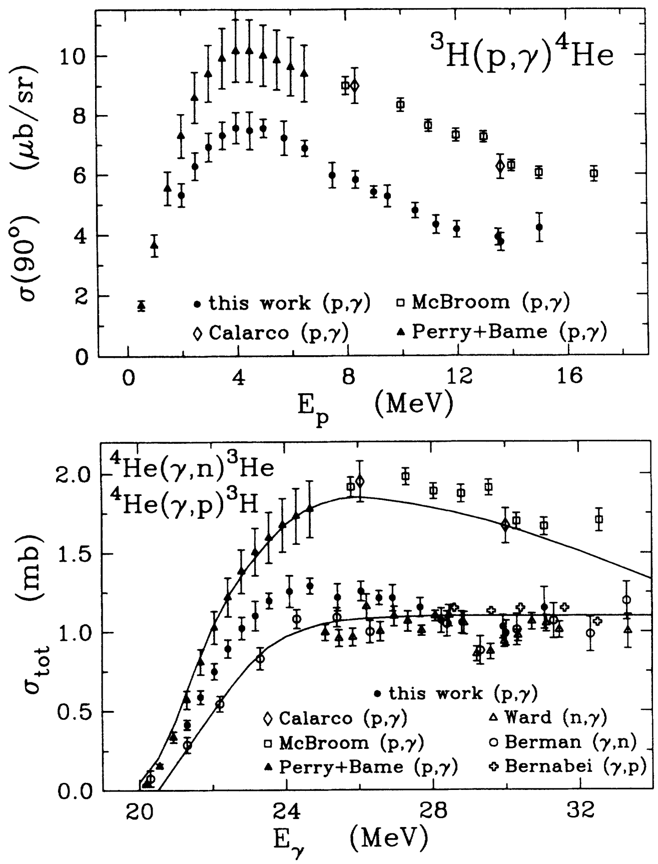

FIG. 2. Upper panel: Differential (p,γ) cross section at $\theta_\gamma = 90°$ for $^3H(p,\gamma)^4He$ as a function of proton energy. Error bars represent relative uncertainties of the present data; an additional overall scale error of $\pm 10\%$ is estimated. Also shown are previous (p,γ) results from Refs. 12, 16, and 17. Lower panel: Total ^4He photonuclear cross sections $\sigma(\gamma,p)$ and $\sigma(\gamma,n)$ as a function of γ-ray energy. Along with the data of the upper panel are the (γ,n) results of Ref. 10 and the (n,γ) results of Ref. 11, as well as the (γ,p) data of Ref. 22. Solid curves are suggested cross section values of Ref. 2.

can be seen to be free of cosmic-ray background or contaminants from the Ti foil. Such backgrounds were studied in previous work[28] on this reaction and were found to be less than $\sim 2\%$ at $\theta_\gamma = 90°$. The extracted γ-ray yields were corrected for accidental rejection by the anticoincidence shield and for dead-time effects.

The present results for the differential $^3H(p,\gamma)^4He$ laboratory cross section at $\theta_\gamma = 90°$ are illustrated in the excitation function in the upper panel of Fig. 2. The error bars represent the relative uncertainties due to counting statistics and target nonuniformities. In addition, we estimate an overall scale error of $\pm 10\%$ due to the uncertainty in the γ-ray detection efficiency. The current data are compared to the previous (p,γ) work of Perry and Bame,[12] McBroom *et al.*,[16] and Calarco *et al.*[17] While the energy dependence of the cross section is similar, the new results are lower by approximately 35%.

In the lower panel of Fig. 2, the (p,γ) cross sections have been converted by detailed balance to inverse (γ,p) values and are plotted with the (γ,n) cross sections of Berman *et al.*[10] and Ward *et al.*,[11] along with the recent (γ,p) cross sections of Bernabei *et al.*[22] The differential cross sections of the present work were converted to total cross sections by assuming that $\sigma_{tot} = (8\pi/3)\sigma(90°)$. The validity of this assumption has been demonstrated by several groups,[28–30] who have shown that $E1$ radiation accounts for $\sim 98\%$ of the total cross section in this energy region (in the γ-ray angular distribution, $|a_4| \leq 0.05$ and $a_k \approx 0$ for $k > 4$). The solid curves in the figure are the suggested values of these cross sections from the review of Ref. 2. Clearly, the present results are much closer in magnitude to the neutron cross sections than to the previous proton results. Furthermore, above $E_\gamma = 28$ MeV, the present measurements are in excellent agreement with the photoproton work of Bernabei *et al.*[22]

To compute a ratio R_γ from our data, we have used the suggested (γ,n) cross section from Ref. 2 to obtain the values of $\sigma(\gamma,p)/\sigma(\gamma,n)$ plotted in Fig. 3. The error bars reflect the folding of our relative errors with the error band given in Fig. 1(b) of Ref. 2. The ratio derived in this manner falls within the range $R_\gamma = 1.3$–0.9 above $E_\gamma = 24$ MeV, which is consistent with the current theoretical predictions.[3–7] Also shown in the figure are the continuum shell-model calculations of Halderson and Philpott[3] (with recoil corrections included) and Londergan and Shakin,[5] *both with no charge-symmetry-breaking interaction.* The recent work of Wachter, Mertelmeier, and Hofmann[6,7] using the resonating group model gives results quite similar to those of Halderson and Philpott.[3] The good agreement of the theoretical curves with the experimentally determined points is evident over the entire energy region. By contrast, the ratio obtained from the evaluated cross sections in Ref. 2 is quite distinct from both the calculations and the present experimental results. Above $E_\gamma \approx 30$ MeV, previous experimental results for the ratio R_γ obtained from simultaneous measurements of the (γ,p) and (γ,n) cross sections[18,19] are given for purposes of comparison.

The total (γ,p) cross section integrated up to $E_\gamma = 32$ MeV obtained from the present results is 12.1 ± 0.9 MeV mb, compared to 18.0 ± 1.2 MeV mb as given by Ref. 2. Combining the suggested value[2] of the integrated (γ,n) cross section of 10.2 ± 1.2 MeV mb with our (γ,p) value gives 22.3 ± 2.1 MeV mb for the total integrated photonuclear cross section, which is in excellent agreement with the integrated cross section (up to 32 MeV) of 21 ± 5 MeV mb obtained from inelastic electron scattering.[31] This independent comparison is further evidence that our present measurement establishes a generally more consistent picture of the photodisintegration of ^{4}He.

In conclusion, we have measured the absolute cross section for the $^3H(p,\gamma)^4He$ reaction corresponding to $E_\gamma = 21.3$–31.1 MeV and have confirmed the recent photoproton measurement of Bernabei *et al.*[22] Our present results, and those of Ref. 22, contrast with the earlier evaluation of Calarco, Berman, and Donnelly.[2] Comparing our data to the current consensus photoneutron cross sections leads to a ratio R_γ which, over the entire energy range of the present study, is in accord with current theories employing charge-symmetric nuclear interactions. Above threshold, we obtain an average ratio $\langle R_\gamma \rangle = 1.09 \pm 0.17$ in the energy range $E_\gamma = 24$–31 MeV. This value of R_γ can be easily accounted for by conventional Coulomb effects. Our results indicate that the $\sigma(\gamma,p)/\sigma(\gamma,n)$ ratio in ^{4}He, at the present level of accuracy, can be understood without requiring any charge-symmetry violation in the nuclear force.

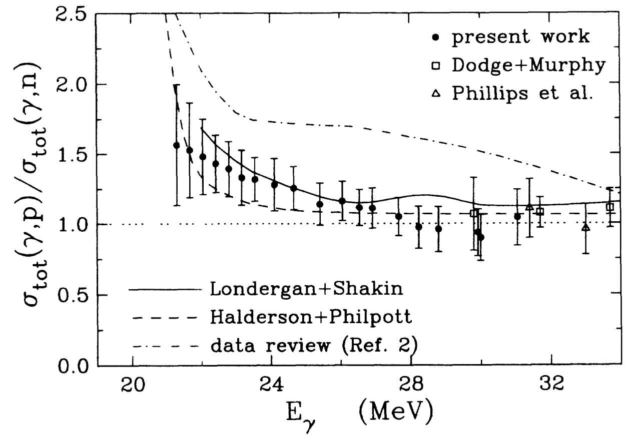

FIG. 3. The ratio $\sigma(\gamma,p)/\sigma(\gamma,n)$ obtained from the present data and the suggested (γ,n) cross section from Ref. 2. Error bars include the relative errors of the present work and the error band of Ref. 2. Also shown are direct ratio measurements from Refs. 18 and 19. The dashed and solid curves are continuum shell-model calculations of Refs. 3 and 5, respectively, with no charge–symmetry-breaking interaction in the nuclear force. The dot-dashed curve is the ratio given directly by the suggested photonuclear cross sections of Ref. 2.

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