Confirmation of the photoneutron cross section for ^{4}He below 33 MeV

L. Ward and D. R. Tilley
North Carolina State University, Raleigh, North Carolina 27607
and Triangle Universities Nuclear Laboratory, Duke Station, Durham, North Carolina 27706

D. M. Skopik
University of Saskatchewan, Saskatoon, Saskatchewan S7N0W0, Canada

N. R. Roberson and H. R. Weller
Duke University, Durham, North Carolina 27706
and Triangle Universities Nuclear Laboratory, Duke Station, Durham, North Carolina 27706
(Received 17 February 1981)

A recently reported measurement of the photoneutron cross section for ^{4}He indicates a value of about 1.0 mb for E_x of ~23 to ~33 MeV. This result, when combined with the previously reported (γ,p) cross section in this energy region, implies a (γ,p)-to-(γ,n) cross section ratio of 1.6 to 1.9 in the 26 to 29 MeV region of ^{4}He. We have used the inverse reaction ^{3}He$(n,\gamma)^4$He to measure the photoneutron cross section for ^{4}He. Our detailed balanced results confirm the recently reported measurements.

[NUCLEAR REACTIONS ^{3}He$(n,\gamma)^4$He; measured $\sigma(E;\theta)$, $E=6.0$ to 17.0 MeV. Results confirm the most recent ^{4}He$(\gamma,n)^3$He measurements.]

The experimental ratio of the photoproton and photoneutron cross sections for ^{4}He has been plagued with discrepancies for over 10 years, especially in the energy region below about 30 MeV in ^{4}He.[1-3] In the recent work of Berman *et al.*[1] a new measurement of the ^{4}He$(\gamma,n)^3$He cross section was made with monoenergetic photons and a gas sample. The results agreed with earlier monoenergetic-photon results obtained with a liquid helium sample and with some of the time-of-flight results at the lower energies. (Reference 1 should be consulted for a recent discussion of these experiments.) When the literature values of the ^{4}He$(\gamma,p)^3$H cross section are used, this result implies a (γ,p)-to-(γ,n) cross section ratio of between 1.6 and 1.9 for energies between 26 and 29 MeV in ^{4}He. This ratio has not been predicted by conventional nuclear structure calculations.[4-7] It has, however, been used to infer the existence of a large charge-asymmetric component of the nuclear force in the four-nucleon system near 27 MeV.[2,3]

In order to make an independent check of this result we have measured the ^{3}He$(n,\gamma)^4$He cross section at 90° for $E_n(E_x)$ between 6.0 (25.1) and 17.0 (33.3) MeV. In addition, a seven-angle angular distribution was measured at 9.0 MeV. This measurement verified the essential validity of the relationship $\sigma_T=(8\pi/3)\sigma(90°)$. This relationship and the principle of detailed balance[8] allow us to compare our results with those of Ref. 1.

The neutron flux for this experiment was produced by using the ^{2}H$(d,n)^3$He reaction. The large and rather well known cross section and the strong forward peaking of the outgoing neutrons make this an especially attractive neutron source.[9] The deuterium target was in the form of a gas cell 2.5 cm in length with a 6.4 μm Havar entrance foil. The gas pressure was set at 90 psi (absolute). This arrangement yielded a neutron energy spread which ranged from 800 keV at $E_n=6.0$ MeV to 500 keV at $E_n=17.0$ MeV.

The ^{3}He target consisted of a 1.6 mm thick stainless steel cell filled to a pressure of 140 atm. The cell was a 3.4 cm diameter, 3 cm high cylinder with a hemispherical dome. The volume of the cell was 40 cm^3. The ^{3}He gas was obtained from Mound Laboratories[10] and had a quoted purity of 99.9%. The target thickness was determined from the pressure obtained with a mechanical gauge. The relation $PV/nRT=Z$, where Z is the compressibility (equal to 1.068 at 294 K and 1.379×10^4 kPa for ^{4}He), was used to find the number of target nuclei.[11] This result was checked by weighing the gas cell before and after filling and computing the number of target nuclei from the difference in these weights. The two results agreed to within 4%. We estimate the uncertainty in the target thickness as 4% which is due mainly to inaccuracies in the weighing procedure.

The γ rays were detected with the TUNL NaI spectrometer. This system has been described in detail elsewhere.[12] The detector consists of a 25.4×25.4 cm NaI crystal surrounded by a plastic (NE110) anticoincidence shield. The entire detector is surrounded by lead, paraffin doped with lithium carbonate, and cadmium sheet to shield against background. In addition a tungsten shadow bar was employed to shield the detector from the direct neutron flux generated in the deuterium gas cell. The experimental arrangement is shown in Fig. 1. The incident deuteron beam was pulsed to allow the use of time-of-flight techniques to discriminate against neutron-induced background. Only events which corresponded to γ-ray events were accepted. The time resolution of our system was about 3 nsec. Our measurement of the absolute efficiency of this detection system is based on the $^{12}C(p,\gamma)^{13}N$ reaction at $E_p = 14.24$ MeV.[13] A thick target yield curve measured at 125° in the region of $E_P = 14.2$ to 14.4 MeV determines the efficiency for 15.07 MeV γ rays since the number of γ's per proton is known for this resonance. In order to determine the efficiency at other energies it is necessary to know the energy dependence of the γ-ray attenuation factor of the shielding material in front of the NaI detector, the energy dependence of the accept/reject ratio of the spectrometer system, and the energy dependence of the line shape.[14] These were measured using the $^3H(p,\gamma)$ and the $^{13}C(p,\gamma)$ reactions. This procedure resulted in efficiency values for E_γ over the range of this experiment with, for example, a value of $(26 \pm 2)\%$ at $E_\gamma = 25$ MeV.[14]

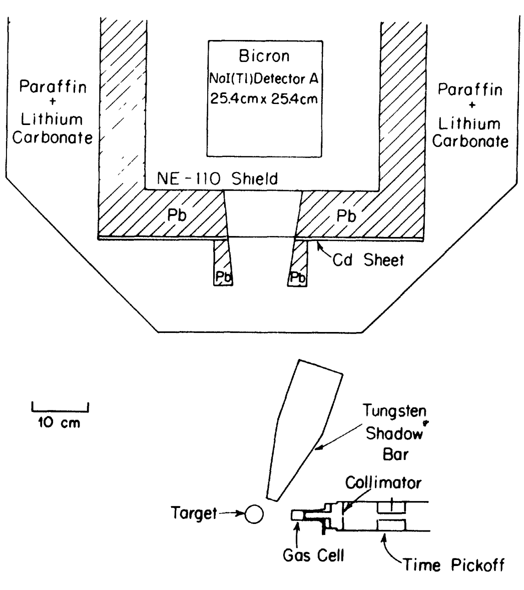

FIG. 1. Experimental setup showing the geometrical arrangement of the deuterium gas cell, ^{3}He target, and detector.

A computer code was written to calculate the corrections which must be applied to the data as a result of the finite geometry effects. The numerical integrations over the source, target, and detector were performed with Monte Carlo techniques. This procedure is similar to that used in neutron scattering studies. The effects of neutron and γ-ray attenuation in the target were also included in the calculations. The resulting differential cross section at 90° for the $^3He(n,\gamma)^4He$ reaction as a function of E_n is shown in Fig. 2. The previously reported $^3H(p,\gamma)^4He$ differential cross section data at 90° are also shown here.

Several additional checks have been made in an attempt to verify our measurement of the absolute cross section. A proton recoil counter was used to measure the zero-degree neutron flux obtained with the $^2H(d,n)^3He$ reaction. The result agreed with that calculated from the previously reported cross sections[9] under our operating conditions to within the overall uncertainty of 5%. We also analyzed the ^{3}He target gas with a mass spectrograph to verify the absence of ^{4}He.[15] An additional check of the $^3He(n,\gamma)^4He$ cross section was obtained by normalization to the $^{40}Ca(n,\gamma)^{41}Ca$ cross section. This latter cross section has been previously measured in our laboratory and elsewhere with an accuracy of 20%.[16,17] Since the target geometries were identical, the flux illuminating both samples was the same. The normalization involved the relative yields and the relative

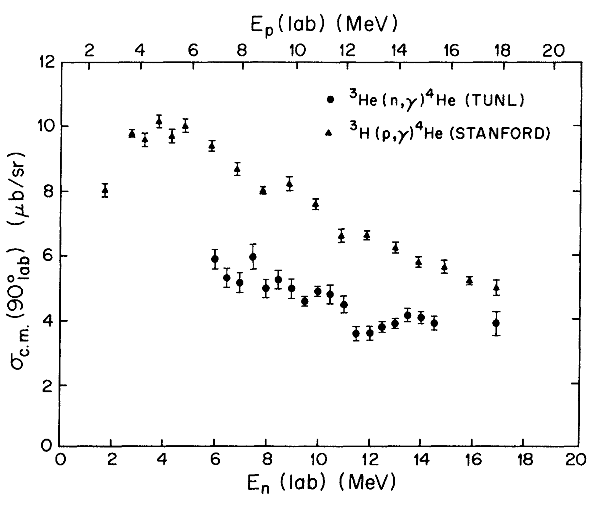

FIG. 2. Differential cross section for the $^3He(n,\gamma)^4He$ reaction at 90° (TUNL). The previously reported $^3H(p,\gamma)$-^4He cross section data at 90° are also shown (Stanford—Ref. 18). The two energy scales are aligned so that the data sets correspond to the same excitation energy in ^{4}He. The error bars are only the statistical errors associated with the data points.

number of target nuclei in the ^{3}He and ^{40}Ca samples. Corrections for attenuation, multiple scattering, and finite geometry effects were applied to both cases. The cross section obtained for the $^3\mathrm{He}(n,\gamma)^4\mathrm{He}$ reaction from this procedure agreed within error with that obtained above. We estimate the overall error associated with our absolute cross section due to uncertainties in target thickness, detector efficiency, neutron flux, correction factors, and counting statistics to be $\pm 15\%$.

In order to obtain the integrated cross section from the 90° differential cross section, it is necessary to know the angular distribution of the reaction. Previous measurements using the (γ,n) reaction at these and higher energies[2,19] have indicated that, at a level of accuracy of a few percent, one can assume a predominantly dipole angular distribution with a dipole-quadrupole interference term: $\sigma(\theta) \propto \sin^2\theta \times (1+\beta\cos\theta)$. This form gives $\sigma_T = (8\pi/3)\sigma(90°)$. In order to verify this factor we have measured an angular distribution at $E_n = 9.0$ MeV. Our data, along with the results of a fit to an expansion in Legendre polynomials through order three which was used to integrate the angular distribution, are shown in Fig. 3. This fit [which gives the normalized coefficient of $P_2(\cos\theta)$ to be $a_2 = -0.94 \pm 0.05$] indicates that $\sigma_T = (8\pi/3)\sigma(90°)$ to within the accuracy of the measurement ($\pm 5\%$).

The integrated $^4\mathrm{He}(\gamma,n)^3\mathrm{He}$ cross section was determined using this factor and the principle of detailed balance following the prescription of Ref. 8. The resulting (γ,n) cross section is shown as a function of E_x in Fig. 4 where we have included the (γ,p) results of Refs. 18 and 19 and the (γ,n) cross section of Berman *et al.*[1] (Note that the absolute cross section in Ref. 18 was obtained from Ref. 20.) It can be seen that there is excellent agreement in the absolute $^4\mathrm{He}(\gamma,n)^3\mathrm{He}$ cross section obtained by the authors of Ref. 1 and in the present work. Although the structure near 29 MeV appears in both data sets, we have not reproduced it as yet, and feel that fur-

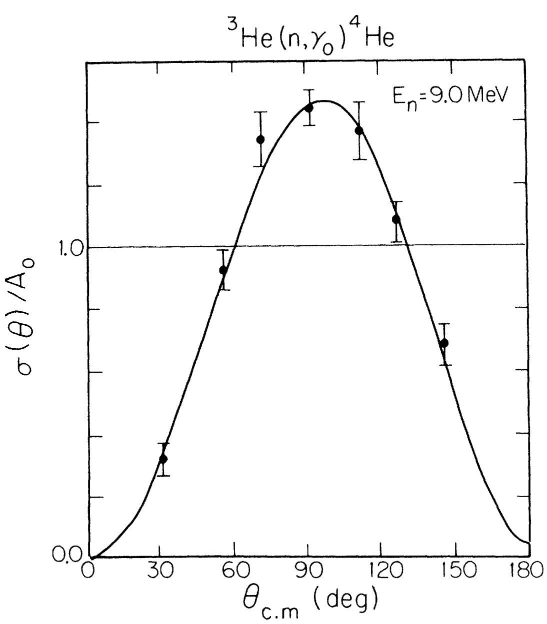

FIG. 3. The measured angular distribution at $E_n = 9.0$ MeV. The error bars represent statistical errors associated with the data points. The solid curve is the result of a fit to Legendre polynomials and was used to obtain the ratio of $\sigma(90°)$ to σ_T.

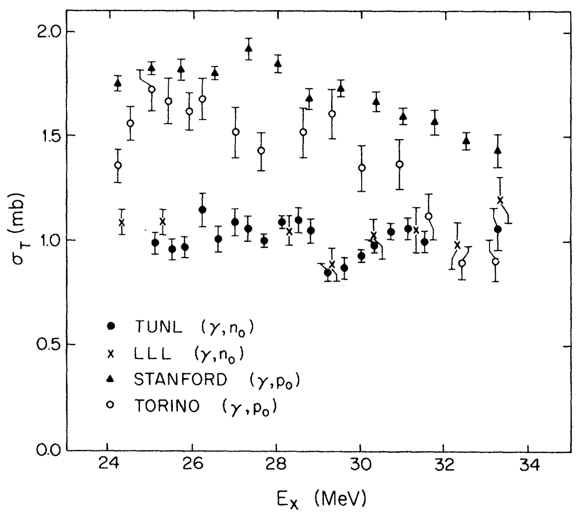

FIG. 4. The angle integrated $^4\mathrm{He}(\gamma,n)^3\mathrm{He}$ data obtained via detailed balance (TUNL) are shown along with the ^{4}He (γ,n) ^{3}He data of Ref. 1 (LLL). The $^4\mathrm{He}(\gamma,p)^3\mathrm{H}$ results of Ref. 19 (Torino) and those obtained from the data of Ref. 18 (Stanford) are also shown. All error bars are statistical.

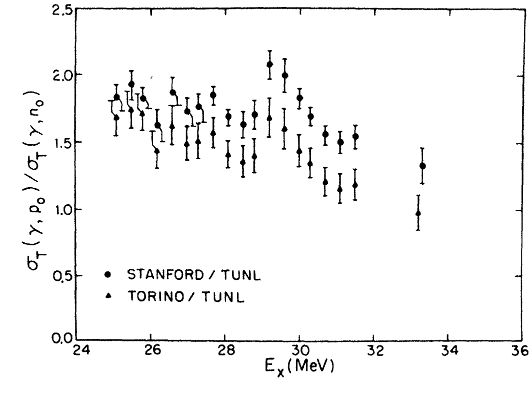

FIG. 5. The (γ,p)-to-(γ,n) ratio using the present (γ,n) data (TUNL) and the (γ,p) data sets obtained from Refs. 18 and 19. The error bars represent the statistical errors only.

ther study is required here.

The (γ,p)-to-(γ,n) cross section ratios obtained by using the present (γ,n) data and the (γ,p) data of Refs. 18 and 19 are shown as a function of E_x in Fig. 5. This figure supports the claim of Ref. 1 that this ratio is between 1.6 and 1.9 in the energy region $E_x = 26-29$ MeV. It also appears that the ratio approaches 1.0 in the vicinity of 33 MeV, a result which is in agreement with previous measurements[2,21] at energies at and above 33 MeV. A detailed theoretical explanation of the (γ,p)-to-(γ,n) cross section ratio remains to be developed.

We gratefully acknowledge the assistance of M. Jensen, S. Manglos, S. A. Wender, C. Fitzpatrick, M. Wright, S. King, and G. Mitev in obtaining these data. This work was partially supported by the U. S. Department of Energy.

---

[1]B. L. Berman, D. D. Faul, P. Meyer, and D. L. Olson, Phys. Rev. C 22, 2273 (1980).
[2]B. L. Berman, S. C. Fultz, and M. A. Kelly, Phys. Rev. Lett. 25, 938 (1970); Phys. Rev. C 4, 723 (1971); T. W. Phillips *et al.*, *ibid.* 19, 2091 (1979).
[3]B. L. Berman, F. W. K. Firk, and C. P. Wu, Nucl. Phys. A179, 791 (1972).
[4]J. T. Londergan and C. M. Shakin, Phys. Rev. Lett. 28, 1729 (1972).
[5]A. H. Chung, R. G. Johnson, and T. W. Donnelly, Nucl. Phys. A235, 1 (1974).
[6]P. P. Delsanto, A. Pompei, and P. Quarati, J. Phys. G 3, 1133 (1977).
[7]Dean Halderson and R. J. Philpott, Phys. Rev. Lett. 42, 36 (1979); 44, 56 (1980).
[8]See, for example, Evans Hayward, in *Nuclear Structure and Electromagnetic Interactions*, edited by N. McDonald (Plenum, New York, 1965), p. 141.
[9]M. Drosg, Report No. LA-UR 77-2097 (unpublished); Nucl. Sci. Eng. 67, 190 (1978).
[10]Monsanto Research Corp., Miamisburg, Ohio 45342.
[11]W. Braker and A. L. Mossman, *Matheson Gas Data Book,* 5th ed. (Matheson Gas Products, East Rutherford, N.J., 1971), p. 278.
[12]H. R. Weller *et al.*, Phys. Rev. C 13, 922 (1976).
[13]R. E. Marrs *et al.*, Phys. Rev. Lett. 35, 202 (1975).
[14]H. R. Weller and N. R. Roberson, in *Proceedings of the Conference on the Application of Accelerators in Research and Industry, Denton, Texas, 1980* in *Transactions on Nuclear Science* (IEEE, New York, 1981), Vol. NS 28, p. 2.
[15]M. L. Miles, Dept. of Chemistry, North Carolina State University (private communication).
[16]S. A. Wender, N. R. Roberson, M. Potokar, H. R. Weller, and D. R. Tilley, Phys. Rev. Lett. 41, 1217 (1978).
[17]I. Bergqvist, D. M. Drake, and D. K. McDaniels, Nucl. Phys. A231, 29 (1974).
[18]W. E. Meyerhof, M. Suffert, and W. Feldman, Nucl. Phys. A148, 211 (1970).
[19]F. Balestra *et al.*, Nuovo Cimento A 38, 145 (1977).
[20]J. E. Perry and S. J. Bame, Phys. Rev. 90, 316 (1953).
[21]W. R. Dodge and J. J. Murphy, II, Phys. Rev. Lett. 28, 839 (1972).