$^{12}C(n,\gamma_0)^{13}C$ cross section in the 8–11 MeV region

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To resolve the discrepancy between two sets of $^{12}C(n,\gamma_0)^{13}C$ cross-section data, the reaction has been reinvestigated in the neutron energy region between 8 and 11 MeV. The present and previous data sets are compared with each other and with existing data on the $^{13}C(\gamma,n_0)^{12}C$ cross section using the principle of detailed balance. The present data are in agreement with one of the previous data sets, which has an energy dependence in good agreement with that of the (γ,n_0) data. These (n,γ_0) cross-section data are, however, approximately a factor of 2 smaller than the (γ,n_0) cross sections over the entire neutron energy range of the comparison (from 7 to 20 MeV).

I. INTRODUCTION

The principle of detailed balance is commonly accepted because of strong theoretical and experimental support. Therefore, it is a serious problem when data obtained in a nucleon induced reaction experiment do not agree with the corresponding results from the inverse photonuclear reaction. This has turned out to be the case in studies of the (n,γ) and (γ,n) reactions in some light nuclei. For example, in a previous experiment,[1] performed at Los Alamos (LANL) and Uppsala (TSL), we found that the $^{12}C(n,\gamma_0)^{13}C$ cross section is approximately a factor of 2 lower than the corresponding quantity deduced from a measurement of the $^{13}C(\gamma,n_0)^{12}C$ reaction.[2,3] A similar situation exists to a lesser extent in the case of $^{14}N(n,\gamma_0)^{15}N$ and its inverse reaction,[4,5] where the photonuclear data is approximately 12% larger than the neutron capture results.

In the case of the $^{12}C(n,\gamma_0)^{13}C$ reaction there is not only discrepancies between the photonuclear and the nucleon capture data but also poor agreement within the results of the nucleon capture experiments. In a recent publication August, Weller, and Tilley[6] reported an experimental study of the $^{12}C(n,\gamma_0)^{13}C$ reaction performed at the Triangle Universities Nuclear Laboratory (TUNL). They found cross sections approximately a factor of 2 larger than the TSL-LANL results[1] in the neutron energy range from 6 to 12 MeV, while smaller discrepancies were obtained in the 15–20 MeV region. It is particularly important to have accurate cross section measurements in this reaction because differences between the $^{12}C(n,\gamma_0)^{13}C$ and the $^{12}C(p,\gamma_0)^{13}N$ cross sections[7] might indicate a possible violation of isospin invariance. August, Weller, and Tilley[6] concluded that the larger cross sections measured around 12 MeV excitation energy by TUNL are consistent with isospin invariance.

The disagreement in the neutron capture data is surprising because radiative neutron capture cross sections for calcium measured over a large energy range by the two groups are in agreement.[8,9] In order to resolve inconsistencies between the different measurements, we have remeasured the 90° differential cross section of the $^{12}C(n,\gamma_0)$ reaction at 7.8, 9.3, and 10.8 MeV using substantially different conditions compared to the previous experiment.[1]

The present experiment was performed using a new detector system[10] with superior energy resolution compared to the old one. To eliminate any concerns raised by August, Weller, and Tilley[6] regarding the large corrections for sample size effects in our previous experiment,[1] we used a considerably smaller (approximately 10 times by weight) sample in the new measurement. To further reduce systematic uncertainties we chose to measure the $^{12}C(n,\gamma_0)^{13}C$ cross section relative to the $^{40}Ca(n,\gamma_0)^{41}Ca$ reaction, for which the results of the two groups are in agreement. The $^{40}Ca(n,\gamma_0)$ cross section has in fact been used as a "standard" in fast neutron radiative capture.

II. EXPERIMENTAL TECHNIQUES

The experiment was performed at The Svedberg Laboratory, Uppsala, Sweden. The entire setup has been described in detail recently[10] and only a brief description will be given here.

The EN tandem Van de Graaff accelerator, which is equipped with a pulsing and klystron bunching system,

delivered pulsed beams of 5.0, 6.5, and 8.0 MeV deuterons at a repetition rate of 2 MHz with a pulse width of approximately 2 ns and an average beam current of 0.5–1 μA. Neutrons of 7.8, 9.3, and 10.8 MeV energy were produced with the $^2H(d,n)^3He$ reaction, using a 2.5 cm long stainless steel gas target cell with a 6 mg/cm^2 thick nickel entrance foil, filled with deuterium gas to a pressure of approximately 1.7 atm.

The cylindrical samples, 3.1 cm in diameter and 3.8 cm in height, were oriented with the symmetry axis perpendicular to the reaction plane and at a distance of 11 cm from the target. The carbon and calcium sample masses were 51.24 g and 46.21 g, respectively, and they were both of natural isotopic composition.

The gamma-ray spectrometer consisted of a NaI(Tl) crystal, 24 cm in diameter and 36 cm long, surrounded by a plastic anticoincidence shield, consisting of an annulus detector and a front detector. Borated paraffin was used to shield the detector from room-scattered neutrons, while a layer of lead served as a shield for background γ rays. A large hevimet ($\approx$90% tungsten) shadow bar, positioned between the neutron production target and the lead collimator, attenuated the direct neutron flux from the gas cell. To reduce the background from scattered neutrons from the sample, a plug of lithium hydride was inserted into the detector collimator.

The signals from the PM-tubes of the NaI detector and the anticoincidence shield were fed to a conventional setup of NIM electronics, which included a time-of-flight branch to facilitate discrimination between neutrons and prompt γ rays. Data were sorted into four spectra: A total pulse-height spectrum (i.e., without the anticoincidence requirement), an accepted pulse-height spectrum (with the anticoincidence requirement), a time-of-flight spectrum, and a spectrum containing pulses from a pulse generator driving a light-emitting diode (LED) mounted on the NaI detector. The LED was used to determine the dead time in the system ($\approx$3%). The measurements at each energy were split into several runs of a few hours duration to monitor possible gain shifts and instabilities during the experimental period. Background runs without sample were performed under identical conditions and at each energy. Normalization of the different runs was accomplished with a plastic neutron detector operating in the time-of-flight mode which viewed the neutron production target at a distance of 4 m and at an angle of 60°.

III. DATA ANALYSIS

Each short run was analyzed off line and energy calibrated separately before adding them together. The γ rays from thermal neutron capture in hydrogen and iodine (2.225 and 6.83 MeV, respectively), from inelastic neutron scattering in carbon (4.439 MeV), and from neutron capture ground-state transitions in carbon and calcium (Q=4.95 and 8.36 MeV, respectively) were used as calibration points. They were fitted with a parabola to take into account the small nonlinearity of the detector system, which has been reported previously.[10]

The time correlated background associated with the neutron production target was removed by subtracting the sample-out spectra from the sample-in spectra, after normalization to the same monitor yield. Because the pulse-height spectra associated with the random background outside the prompt γ-ray peak in the time-of-flight spectra were found to be identical in runs with and without a sample for γ-ray energies above 10 MeV, the time-independent background cancelled out when the sample-in and sample-out runs were subtracted. The yields for the ground-state transitions were extracted by integrating the energy spectra from 1.3 MeV below to 0.3 MeV above the centroid of the ground-state peaks.

A typical time-of-flight spectrum for carbon at a neutron energy of 9.3 MeV is shown in Fig. 1(a). As can be seen, the neutrons and γ rays are very well separated. Figure 1(b) shows the same time-of-flight spectrum after subtracting the sample-out background. It is clear that most of the neutrons have been eliminated and only the γ peak remains. Figure 2 shows γ-ray energy spectra from carbon (a) and calcium (b) at a neutron energy of 9.3

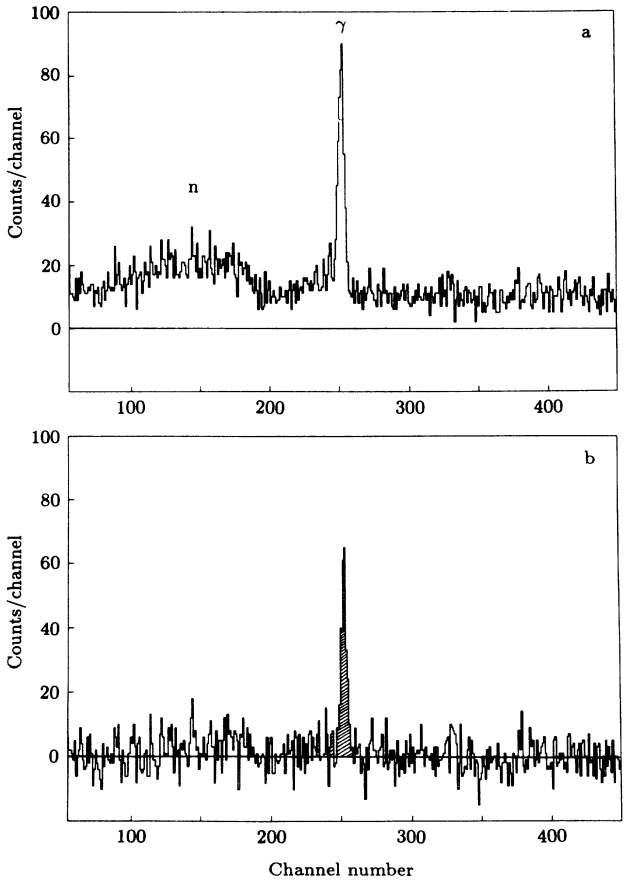

FIG. 1. (a) Time-of-flight spectrum obtained for the carbon sample at a neutron energy of 9.3 MeV; (b) the same spectrum as in (a) after subtraction of a normalized sample-out background spectrum. The setting of the time-of-flight software gate is indicated by the hatched area.

MeV. These spectra were obtained after subtraction of normalized sample-out spectra, and with a software gate placed around the γ peak in the corresponding time-of-flight spectra, as is indicated by the hatched area in Fig. 1(b). The hatched areas in Figs. 2(a) and 2(b) represent the 1.6-MeV interval used to extract the ground-state yields.

The carbon cross sections were obtained by comparing the yield in the carbon spectra with the corresponding yield in the calcium spectra, using the calcium cross section and normalizing with respect to the neutron yield and the number of sample atoms. The γ-ray yields were also corrected for attenuation of γ rays and neutrons in the samples and for the energy dependence of the detector efficiency. This energy dependence was calculated with the computer code CYLTRAN (Ref. 11) using the geometry for the entire system. The neutron attenuation corrections were calculated both with the Monte Carlo code MULTSCAT4 (Ref. 12) and by means of a finite-element method. The neutron and γ-ray attenuation corrections were of the order of 10% for both samples.

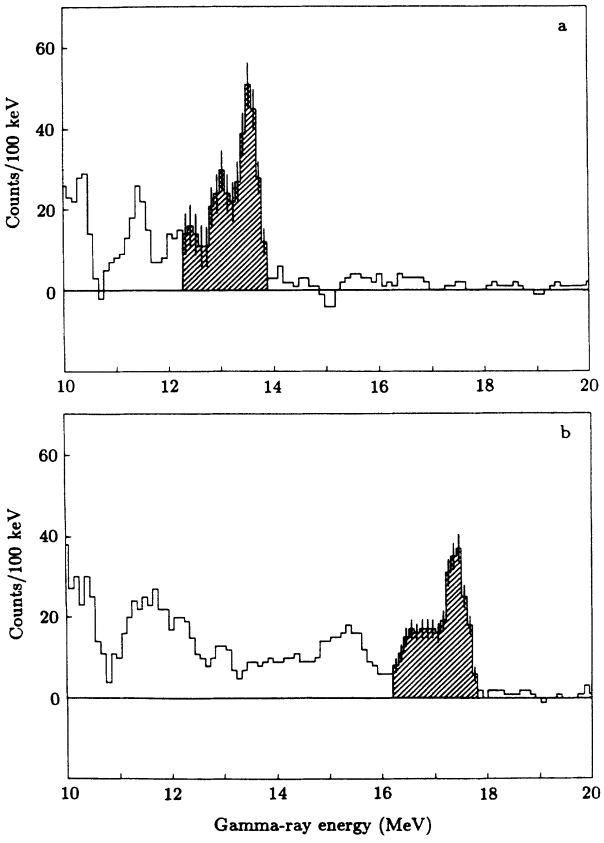

FIG. 2. Gamma-ray spectra from carbon (a) and calcium (b) at a neutron energy of 9.3 MeV. These spectra were obtained with a software gate over the γ-ray peak in the time-of-flight spectrum [see Fig. 1(b)] and after subtraction of the sample-out background. The 1.6-MeV regions defining the ground-state transition yields are indicated by the hatched areas. To smooth the statistical fluctuations the spectra shown are running averages over three consecutive energy intervals.

TABLE I. Experimentally determined 90° radiative neutron capture cross sections for the ground-state transition in carbon and the corresponding cross sections for calcium used for normalization of the absolute scale. The errors quoted are only the statistical ones. In addition, there is a systematic uncertainty of about ±20%.

	Cross section (μb/sr)	
E_n (MeV)	Carbon	Calcium
7.8	2.95±0.51	7.89±0.21
9.3	3.14±0.36	12.68±0.23
10.8	3.22±0.37	15.65±0.28

IV. RESULTS AND DISCUSSION

The 90° differential cross sections for the $^{12}C(n,\gamma_0)^{13}C$ reaction obtained in this experiment are listed together with the statistical uncertainties in Table I. Also given in Table I are the cross sections for the $^{40}Ca(n,\gamma_0)^{41}Ca$ reaction, which were used to determine the absolute cross section. These values were obtained from a polynomial fit to all the data given in Refs. 8 and 9, and the uncertainties were obtained from the statistical errors of the data points and from the fitting procedure. With the comparative method used in this work the dominating uncertainty ($\approx$±20%) in the carbon cross sections is the calcium cross section data, for which very good agreement between the two groups has been established.[8,9]

The results of the present work are shown as solid circles in Fig. 3. Also shown in Fig. 3 are the previous data from the TSL-LANL collaboration[1] and from TUNL

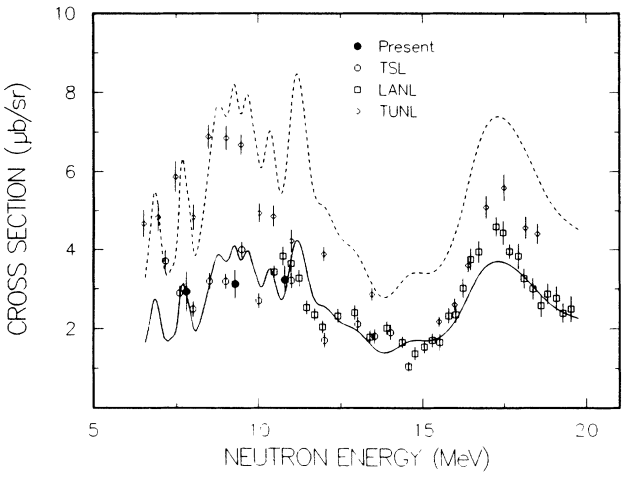

FIG. 3. Differential 90° cross sections for the capture reaction $^{12}C(n,\gamma_0)^{13}C$ from the present experiment (solid circles). Plotted are also previous data from TSL (open circles) and LANL (open squares) (Ref. 1), and some recent results from TUNL (diamonds) (Ref. 6). Only the statistical uncertainties are shown; in addition there is a systematic uncertainty of about ±20%. The dashed line represents the results from the $^{13}C(\gamma,n_0)^{12}C$ reaction (Ref. 3) after applying the principle of detailed balance. The same photonuclear data multiplied by 0.5 are shown as a solid line.

(Ref. 6). As can be seen, the present data confirm, within their errors, the previous measurements from TSL-LANL.

Included also in Fig. 3 are the 90° differential cross sections obtained from the $^{13}C(\gamma,n_0)^{12}C$ results of Woodworth *et al.*[3] These results were obtained by calculating the 90° differential (γ,n_0) cross section from the given angle-integrated cross sections and the angular distribution coefficients. These cross sections were then converted to (n,γ_0) cross sections by applying the principle of detailed balance (dashed line). It is obvious that the data from Woodworth *et al.*[3] agree with the data from TUNL in the energy region from 6.5 to 9 MeV, while they are considerably greater than all the data (TUNL and TSL-LANL) above 10 MeV. If the photonuclear cross sections are multiplied by 0.5 (solid line), they agree, except for the peak cross section at 17 MeV, with the TSL-LANL data set over the entire neutron energy range of comparison from 7.5 to 20 MeV. At 17 MeV, the normalized photonuclear data fall below the TSL-LANL data by approximately 20%. It should be noted that at this energy the resolution of the photonuclear data is approximately 1.2 MeV which would tend to reduce the measured cross section at the peak. Moreover, most of the structure in the photonuclear data is reproduced in the TSL-LANL data.

In conclusion, we find that our new measurements, performed with a new detector system and using small samples which reduce corrections, confirm the previous data from this laboratory and from LANL (Ref. 1), while they disagree with the data from TUNL (Ref. 6). According to the arguments presented in Ref. 6 the TSL-LANL cross sections might imply violation of isospin invariance when compared with the corresponding (p,γ) data. We also find that the shape of the cross section curve of the inverse reaction agrees excellently with the TSL-LANL results. However, the serious discrepancy of a factor of 2 between the (n,γ) and (γ,n) cross sections is still present.

[1]I. Bergqvist, D. M. Drake, D. K. McDaniels, S. A. Wender, A. Lindholm, L. Nilsson, N. Olsson, R. Zorro, and F. S. Dietrich, Nucl. Phys. **A456**, 426 (1986).

[2]J. G. Woodworth, K. G. McNeill, J. W. Jury, P. D. Georgopulos, and R. G. Johnson, Can. J. Phys. **55**, 1704 (1977).

[3]J. G. Woodworth, K. G. McNeill, J. W. Jury, P. D. Georgopulos, and R. G. Johnson, Nucl. Phys. **A327**, 53 (1979).

[4]S. A. Wender, H. R. Weller, N. R. Roberson, D. R. Tilley, and R. G. Seyler, Phys. Rev. C **25**, 89 (1982).

[5]J. D. Watson, J. W. Jury, P. C.-K. Kuo, W. F. Davidson, N. K. Sherman, and K. G. McNeill, Phys. Rev. C **27**, 506 (1983).

[6]R. A. August, H. R. Weller, and D. R. Tilley, Phys. Rev. C **35**, 393 (1987).

[7]D. Berghofer, M. D. Hasinoff, R. Helmer, D. F. Measday, and K. Ebisawa, Nucl. Phys. **A263**, 109 (1976).

[8]I. Bergqvist, R. Zorro, A. Håkansson, A. Lindholm, L. Nilsson, N. Olsson, and A. Likar, Nucl. Phys. **A419**, 509 (1984).

[9]S. A. Wender, N. R. Roberson, M. Potokar, H. R. Weller, and D. R. Tilley, Phys. Rev. Lett. **41**, 1217 (1978).

[10]A. Håkansson, J. Blomgren, S. Crona, A. Likar, A. Lindholm, L. Nilsson, N. Olsson, and R. Zorro, Nucl. Instrum. Methods **A273**, 211 (1988).

[11]J. A. Halbleib and T. A. Mehlhorn, Sandia National Laboratory Report No. SAND 84-0573 (1984).

[12]B. Holmqvist, B. Gustavsson, and T. Wiedling, Ark. Fys. **34**, 481 (1967).