$^2H(\gamma,n)$ absolute cross section at 2754 keV

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The absolute cross section of the photodisintegration of deuterium was measured at 2754 keV using an absorptive method by passing the photons through 2-m-long absorbers of H_2O and D_2O. The measured value is 1456±45 μb. The result is compared with calculations that include contributions from meson-exchange currents and isobar configurations.

I. INTRODUCTION

In a recent paper,[1] accurate absolute cross sections of the $^1H(\gamma,n)$ reaction were measured at seven photon energies between 6 and 11.4 MeV using an absorption method. In this method, the photons were obtained from thermal neutron capture and were passed through 2-m-long absorbers of H_2O and D_2O. The photodisintegration cross section was then obtained from a comparison of the transmitted intensities through the two absorbers.[2] Here, a similar method was employed for measuring the absolute $^1H(\gamma,n)$ cross section at a lower energy, namely 2754 keV, using photons emitted by a radioactive ^{24}Na source. An accurate knowledge of the cross section at this low energy is of importance because of the relatively large $M1$ contribution to the transition amplitude near the photodisintegration threshold (2223 keV). This work was also motivated by the fact that previous results at this energy differed from each other by about 10% and were carried out during the 1950's.[3–4] In addition, a recent angular distribution measurement[5] of the photoneutrons from the $^1H(\gamma,n)$ reaction at 2754 keV revealed an asymmetry appreciably different from theoretical predictions. However, the results concerning the $M1/E1$ cross section ratio were found to be consistent with theoretical calculations which include contributions from meson-exchange currents and isobar configurations. The data on the $^1H(\gamma,n)$ reaction were compiled at the National Bureau of Standards,[6] and a critical review of the data in the 10–120-MeV range was reported in Ref. 7.

II. EXPERIMENTAL PROCEDURE

A. γ source

The γ source was obtained from the decay of ^{24}Na generated by the $^{23}Na(n,\gamma)$ reaction. Source intensities of approximately 70 Ci were obtained by irradiating 46 g of NaF encapsuled in thin-walled aluminum containers. The samples were irradiated inside the core of the McMaster Nuclear Reactor in a flux of 2×10^{13} n/cm^{2}s for about 24 h each. The ^{24}Na source (15.03 h half-life) was moved from the reactor core to a position facing a 1-cm diameter through a hole in the 2-m-thick reactor wall. Transferral of the ^{24}Na source was performed under water in the swimming pool of the reactor thus avoiding the shielding problems involved in exposing such an intense source to the surrounding area. In this manner a collimated γ beam was generated and passed through a 2-m-long absorber containing either light water (H_2O) or heavy water (D_2O).

Two ^{24}Na sources were employed and interchanged in an alternate fashion every 24 h. One source was used for the absorption measurement while the other was prepared by n irradiation in the reactor core.

The experimental system is illustrated in Fig. 1. The ^{24}Na source emitted two lines at 1369 and 2754 keV and a very weak line at 3867 keV (0.06%). The transmitted intensities were detected using a (7.6×7.6)-cm^2 NaI crystal which was heavily shielded by lead and especially by borated paraffin to avoid the effect of the relatively high fast-neutron background on the detector and the surrounding shielding. The counting rate obtained in the photopeak of the 2754-keV line was around 150 counts/s, yielding a total of around 2×10^6 counts/d for each absorber. A net total running time of 30 d was used in this measurement. The "background" effect of the very weak line at 3867 keV on the 2754-keV energy region was negligible. The rate of the 1369-keV line was drastically reduced because of the larger attenuation coefficient of water at this energy. In addition, this line was practically overwhelmed by the background line at 1294 keV emitted by ^{41}Ar which is present in the reactor hall. The background was measured by using as a blank an unirradiated NaF sample placed in the position of the irradiated target (Fig. 1). The ratio of signal to background was typically 50, averaged over the 24-h counting period.

B. Temperature effect

The water absorbers (Table I) were contained in stainless steel tubes of equal internal dimensions (4.2 cm) and different lengths: 199.3 cm (filled with H_2O) and 199.967 cm (filled with D_2O); these are the same containers which were used in Ref. 1. This choice of absorber lengths achieved an almost entire cancellation of the atomic

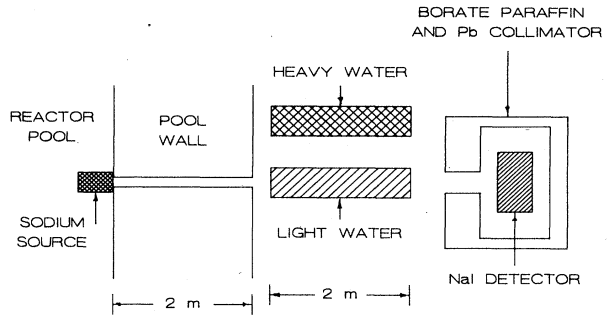

FIG. 1. Schematic diagram (not to scale) of the experimental system showing the position of the γ source, collimation, water absorbers, shielding, and the NaI detector.

effects of the two water absorbers. This is fulfilled by the following relation, which is caused by the difference in molar volumes between H_2O and D_2O:

$$l_H/V_H = l_D/V_D \ . \tag{1}$$

In Eq. (1), l and V represent the lengths and molar volumes of the absorbers while the subscript H and D refer to H_2O and D_2O, respectively. With this choice, the deviation of the ratio of the transmitted intensities from unity is due mainly to the contribution of the $^1H(\gamma,n)$ cross section. However, the molar volumes of the two absorbers are very sensitive to temperature changes and Eq. (1) can be fulfilled, in practice, only at $T \sim 24\,^\circ$C which is close to the operational temperature of Ref. 1. Since the absorber temperatures in the present work were around 19 °C, it was necessary to measure the extent of matching the atomic attenuation of the photons by the absorbers at this temperature. This was done by passing a beam of 2223-keV γ rays [which is just below the $^1H(\gamma,n)$ threshold] obtained from the $^1H(n,\gamma)$ reaction and measuring the transmitted intensities in a similar fashion to that used for the 2754-keV line. It was found that at $T = 19\,^\circ$C the equality of Eq. (1) was achieved only to within three parts in 10^3. The transmitted intensities were thus corrected for this difference by using the following attenuation coefficients at 2223 and 2754 keV (deduced by interpolation from Ref. 10): 1.3986 b/mol and 1.2445 b/mol respectively, with a relative error of less than 1%.

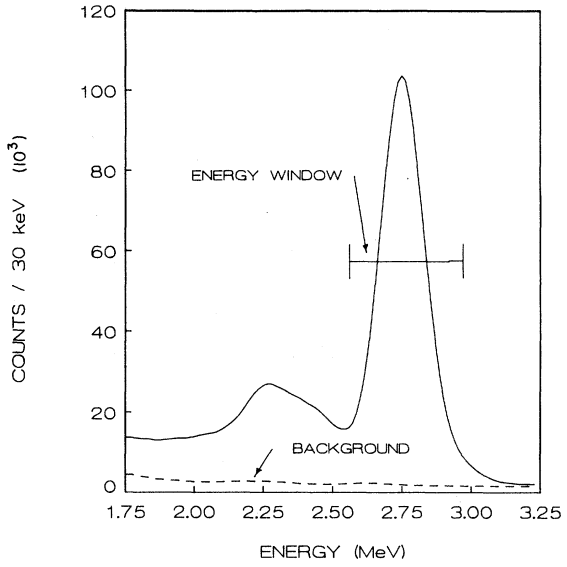

FIG. 2. Transmitted γ spectrum of the ^{24}Na as measured by the (7.6×7.6)-cm^2 NaI detector (solid line). The dashed line represents the "background" spectrum obtained using a blank sample of NaF.

Temperature variations were found to have a crucial effect on the transmitted intensities. This is because the densities of H_2O and D_2O vary with temperature in entirely different fashions. Thus, a temperature change of $\pm 2\,^\circ$C was found to effect the measured attenuation ascribed to $^1H(\gamma,n)$ reaction by about 20%. It was thus necessary to monitor the absorber temperature every hour and correct the transmitted intensity for the density variation[9] at each separate run. The absorbers were mounted on the same sliding table used in Ref. 1 and were positioned parallel to each other, and were aligned coaxially with the collimators and the photon beam. In addition, care was taken not to allow any scattered radiation from the walls of the stainless steel tubes to reach the NaI detector. The effect of multiple scattering in the water absorbers was calculated and found to be negligible because of the very small angular aperture subtended by the detector ($\theta = 0.6°$).

The signals from the detector were fed to a multichan-

TABLE I. Characteristics of the two absorbers and the containers. The values of H_2O are those of pure natural water. Numbers in parentheses indicate uncertainty in the last digit.

	H_2O	D_2O
Length	199.300(2)	199.967(2) cm
Density ($T = 19\,^\circ$C)	0.99841	1.10549 (g/cm^3)[a]
Molar volume ($T = 19\,^\circ$C)	18.04401	18.11647(130) (cm^3/mol)[a]
^2D in absorbers (%)	0.0148	99.73(6)[b]
^{18}O in absorbers (%)	0.204	0.47(3)[b]
^{17}O in absorbers (%)	0.038	0.57(7)[b]

[a]Reference 8.
[b]This measured value agrees with that of Ref. 9.

TABLE II. Measured and calculated values of the photodisintegration cross section of the deuteron at $E=2754$ keV. Values with asterisks include contributions from meson-exchange currents and isobar configurations.

Experiment	Predicted (μb) Arenhovel					Rustgi[a]		
(μb)	Reid[c]	Paris[d]	DRS[e]	WSA[f]	MHE[g]	SSB	Paris	Partovi[b]
	1441	1464	1467	1475	1464			1430
1456±45	1457*	1477*	1479*	1489*	1471*	1583*	1547*	

[a]Reference 12.
[b]Reference 13.
[c]Reference 14.
[d]Reference 17.
[e]Reference 18.
[f]Reference 15.
[g]Reference 16.

nel analyzer and the system was controlled using an on-line computer which moved the absorbers back and forth to face the gamma beam. The gamma spectra were stored in the computer memory, every 10 min. A sum spectrum corresponding to each absorber was then obtained. Corrections were applied for the decay of the ^{24}Na source due to the time lapse between two alternate absorbers and also for the temperature change in the absorbers. In this manner, the effect of drifts in the electronic system were averaged out and could be considered the same for the two absorbers.

III. RESULTS AND DISCUSSION

Figure 2 shows the 2754-keV line of the transmitted γ spectrum as measured using the NaI detector. The "background" spectrum (Fig. 2) obtained by placing a blank sample in the position of the ^{24}Na source was subtracted. Background originated partly from the effect of fast neutrons on the surrounding shielding materials on the detector itself, and partly from the radiation coming from the hole in the reactor wall. In addition, the transmission ratio was also corrected for the mismatching of the two tubes as found in the 2223-keV transmission measurement. The $^1H(\gamma,n)$ cross section obtained was 1456±45 μb to be compared with 1430±110 μb of Ref. 4 and 1590±60 μb of Ref. 3, measured at the same energy.

Table II compares the present results with theoretical calculations of Arenhovel,[11] Rustgi,[12] and Partovi[13] obtained using various potentials. In his calculations, Arenhovel[11] employed five different potentials: (1) The Reid soft-core potential.[14] (2) The nucleon-nucleon (NN) potential of Wiringa *et al.*[15] which contains 14 operator components describing NN channels and another 14 operators with explicit $\Delta(1232)$ degrees of freedom among which are 12 transition operators for $\pi N\Delta$ and $\pi\Delta\Delta$ couplings and 2 operators for $N\Delta$ and $\Delta\Delta$ channels. (3) The Bonn potential[16] which includes 2π exchange contributions in addition to the well-known 1π-exchange and 1ω-exchange contributions. No fictitious terms such as those of the one-boson exchange model were included in this potential. (4) The Paris potential[17] has long-range and intermediate-range parts which are determined from πN and $\pi\pi$ interactions. (5) The NN potential of de Tourreil *et al.*[18] which employs a super-soft core (SSC) and included π-, ρ-, and ω-exchange contributions, while the core and the intermediate range were treated phenomenologically. The results of these calculations were found to differ from each other by at most 2%, while the inclusion of meson exchange currents (MEC) and isobar configurations (IC) increases the absolute cross section, generally less than 1%. Two different potentials were used in the calculations of Rustgi (Table II), the SSC potential version *B* and the Paris potential. In these calculations, the effects of two-body charge density caused by π-exchange and two-body current density caused by π-, ρ-, and ω-meson exchanges were taken into account. In the calculations of Partovi[13] the Hamada-Johnston potential was employed; the contributions of MEC to the electric transitions were introduced implicitly[11] through the use of Seigert's theorem and hypothesis. The calculated cross sections of Rustgi listed in Table II differed from each other by 2.3% but were higher by about 6% than the average of the cross sections predicted by Arenhovel. This large difference persisted even when the Paris potential was used for the two calculations. The reason for this large deviation between the calculations is not yet clear.

The present experimental value (Table II), which has a 3% accuracy, may be seen to be in much better agreement with the results of Arenhovel and Partovi than those of Rustgi. The measured value overlaps all the calculated values of Partovi and Arenhovel within one standard deviation (with and without the explicit inclusion of MEC and IC contributions). Thus a much higher experimental accuracy is necessary to distinguish between the various potentials used by Arenhovel.

It should also be added that this low-energy measurement of the absolute cross section is very important for the determination of the electric polarizability of the deuteron.[19] This is because the polarizability is dependent on the inverse-square energy-weighted photonuclear sum rule. This energy weighting greatly enhances the importance of the data near threshold. It also adds more confidence in the reliability of the value of the electric polarizability of the deuteron because the value of σ_D used in Ref. 19 was practically the same as that measured in the present work.

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