Photoneutron Cross Sections With Monoenergetic Neutron-Capture Gamma Rays*†

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Monoenergetic gamma rays produced by thermal neutron capture have been used to study photoneutron cross sections of the isotopes Ta^{181}, Li^7, Li^6, C^{13}, and B^{10} for γ-ray energies between threshold and 10.8 MeV. Some cross sections were obtained with uncertainties as low as 10%. Wherever possible, these cross sections are compared with those obtained by other methods. The threshold for the $Ta^{181}(\gamma,n)$ reaction has been determined to be 7.64±0.04 MeV. Information about the radiative widths of the 7.47-MeV level in Li^7 and the 8.89-MeV level in B^{10} is presented.

I. INTRODUCTION

IN the experiments described in this paper, monoenergetic γ rays produced by thermal neutron capture in various substances have been used to measure the cross sections for photoneutron production in tantalum and in several light elements. In the past, most photonuclear studies have used bremsstrahlung from electron accelerators, and the interpretation of such experiments has been complicated and subject to some uncertainties. The work described here was done to provide some accurate cross sections with which previous measurements could be compared. In addition, it was expected that some structure would be observed which was missed in the averaging process used to analyze the bremsstrahlung data. For those cases in which a capture γ ray nearly coincides in energy with an isolated level in the target nucleus, the photoneutron cross section should yield some information concerning the ground-state radiative width of that level.

Recently two new techniques have been developed for studying photonuclear reactions,[1,2] and the measurements with capture γ rays should provide a good check for these new methods.

II. EXPERIMENTAL PROCEDURE

A schematic drawing of the experimental arrangement is shown in Fig. 1. The source of neutrons was a 200 kW, pool-type reactor. Adjacent to the reactor was a 4-in.-thick bismuth plug, and next to this bismuth was the material in which the capture γ rays were produced. The purpose of the bismuth was to reduce the background in the experimental area which results from γ rays produced in the reactor core. The γ-ray sources contained from one to a few kilograms of the appropriate material.

The capture γ rays passed through a 4-ft. air tube, approximately 4 ft. of water and paraffin, and copper collimators, so that a beam with a diameter of about 2 in. was incident on the target whose (γ,n) cross section was to be measured. The purpose of the air tube was to limit the angle through which a γ ray could be Compton scattered by electrons in the filter and still reach the target. The water and paraffin filter was used to remove from the beam neutrons produced in the reactor. This filter reduced the intensity of γ rays incident upon the target by about a factor of twenty, but reduced the fast-neutron flux by about a factor of 10^7.

Except for the C^{13} sample, which was 1.5 in. in diam, the various targets all had 1-in. diam. These targets were positioned in the beam at the center of a neutron counter similar to the system described by Nathans and Halpern.[3] This counter consisted of four $B^{10}F_3$ detectors imbedded in a paraffin cylinder with their axes parallel to the direction of the γ-ray beam, as shown in Fig. 1. The amount of paraffin between the beam and the axes of the detectors was adjusted so that the efficiency of the system was approximately constant for neutrons with energies from 200 keV to 5 MeV. The efficiency of the counter was measured to be 2.75% with an Am-Be source, for which the neutron-emission rate was known to within 3%.

The neutron yield from photonuclear reactions was obtained by subtracting from the measured counting rates corrections for room background and for scattering into the counter of neutrons in the beam. No correction was necessary for γ rays scattered from the beam into the counter. For (γ,n) cross sections of less than 1 mb, the corrections for scattered neutrons were often quite large, and in a few instances, several times as large as the net signal of photoneutrons. However, in most cases, a sufficient amount of data was collected so that statistical uncertainties in neutron yields were considerably smaller than uncertainties in γ-ray intensities.

Gamma rays produced by thermal-neutron capture have been studied in detail, and two compilations of the results of such investigations are available.[4,5] The γ-ray energies quoted in these references have been

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[1] R. L. Bramblett, J. T. Caldwell, G. F. Auchampaugh, and S. C. Fultz, Phys. Rev. **129**, 2723 (1963).
[2] B. Kowalski, W. Bertozzi, P. T. Demos, C. P. Sargent, and W. E. Turchinetz, Bull. Am. Phys. Soc. **6**, 236 (1961).
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[4] G. A. Bartholomew and L. A. Higgs, Atomic Energy of Canada Ltd., Report No. 669 (unpublished).
[5] L. V. Groshev, V. N. Lutsenko, A. M. Demidov, and V. I. Pelekhov, *Atlas of Gamma Ray Spectra from Radiative Capture of Thermal Neutrons* (Pergamon Press, Inc., New York, 1959).

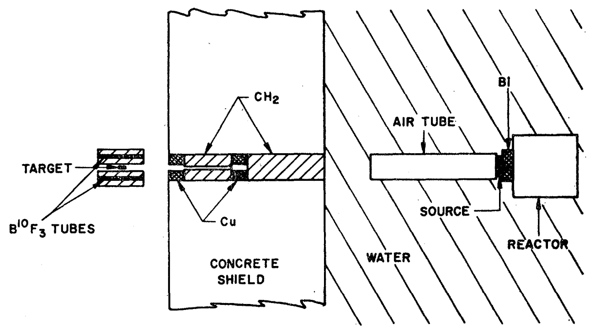

FIG. 1. Neutron counter and source arrangement.

used in this work. To measure the γ-ray intensity in the beam, the neutron counter shown in Fig. 1 was replaced by a 4-in.-diam by 6-in.-long NaI(Tl) crystal. A lead collimator in front of this crystal insured that it sampled just that part of the beam which was incident upon the targets used in the photoneutron yield measurements. The intensities of the γ rays were too high for direct measurement at 200 kW. Instead several measurements were made at reduced power levels for each of the sources, and the results extrapolated linearly to 200 kW.

Data from the NaI(Tl) crystal were stored in a 128-channel pulse-height analyzer. Gamma-ray intensities were deduced from measured areas of the full energy peaks of the various γ rays, together with the values of crystal efficiencies and the ratios of the area under the full-energy peak to the area under the entire response function obtained by Miller and Snow[6] from Monte Carlo calculations. These calculations are extensions of the work described in Ref. 7 to the energy range and geometry used in these experiments. The quoted uncertainties in the intensities result from uncertainties in the measured areas under the total absorption peaks, and in the extrapolated reactor power levels. The error resulting from uncertainties in the calculated efficiencies and response functions was neglected. As mentioned above, for most of the measurements presented here, the percent errors in intensities are larger than those of the neutron yields, and are the main source of uncertainties in the (γ,n) cross sections.

Most of the γ-ray sources used in this work emitted neutron-capture γ rays of more than one energy. The intensities of only two or three of the strongest γ rays could be measured with the NaI(Tl) spectrometer. Results of all γ-ray intensity measurements are shown in Table I. These intensities are for the particular geometry and reactor power used in these experiments. However the relative intensities of different γ rays from a particular source can be compared with those quoted in Refs. 4 and 5. When intensities of weak γ rays were needed to obtain (γ,n) cross sections, averages were used of the relative intensities of these γ rays obtained with high-resolution instruments.[4,5] These γ rays were so weak that uncertainties in their intensities did not contribute significantly to the uncertainties in the (γ,n) cross sections.

TABLE I. Measured gamma-ray intensities.

Source	Energy[a] (MeV)	Intensity $\times 10^{-4}$ (γ rays/cm²-sec)
Aluminum	7.72	8.1 ±0.7
Copper	7.91	14.0 ±1.4
	7.63	6.4 ±0.6
Chlorine	8.56	2.3 ±0.3
	7.77	6.0 ±0.7
	7.42	6.9 ±0.8
Nitrogen	10.83	0.49±0.03
	8.31	0.10±0.03
Nickel	9.00	19.8 ±2.1
	8.53	9.1 ±0.9
Chromium	9.72	2.5 ±0.4
	8.88	6.2 ±0.9
Iron	7.64	22.0 ±2.8
	9.30	1.9 ±0.2
	6.03+5.92	11.3 ±1.5
Lead	7.38	1.9 ±0.3
Sulphur	5.43	10.2 ±1.4
	8.64	0.6 ±0.1
	7.78	0.8 ±0.2
Titanium	6.75	18.9 ±2.2
	6.41	12.5 ±1.5
	6.61[b]	33.7 ±2.7
Manganese	7.16[c]	19.0 ±1.7
Zinc	7.88	4.5 ±0.5

[a] Energies taken from Refs. 4 and 5.
[b] Weighted average of 6.75-, 6.55-, and 6.41-MeV γ rays.
[c] Weighted average of 7.26-, 7.15-, and 7.05-MeV γ rays.

In addition to the monoenergetic neutron-capture γ rays, the beam also contained some γ rays whose energy had been degraded by small-angle scattering in the filter. However, the geometry of the collimators was such that the ratio of the number of scattered to unscattered photons at the target was small, and the contribution of scattered photons to the total neutron production in the target was negligible.

III. RESULTS AND DISCUSSION

Before individual results are presented, one important correction to the neutron-yield data must be considered. The necessity for this correction results from the fact that, in addition to the primary γ rays which are of interest, most γ-ray sources emit other γ rays with energies greater than the threshold for neutron production of most of the targets used. As an example of the type of correction required, we will describe the measurement of the (γ,n) cross section of tantalum at 9.00 MeV, using γ rays from a nickel source. Nickel emits three γ rays with energies above the (γ,n) threshold in tantalum; these are at 7.82, 8.53, and 9.00 MeV. To obtain the cross section at 9.00 MeV, the following sequence was used. First, the (γ,n) cross section was measured using an aluminum γ-ray source. This source emits only 7.72-MeV γ rays with energies greater than the (γ,n) thresh-

[6] W. J. Snow (private communication).
[7] W. F. Muller, J. Reynolds, and W. J. Snow, Rev. Sci. Instr. 28, 717 (1957); W. F. Muller and W. J. Snow, ANL-6318, 1961 (unpublished).

TABLE II. Summary of measured cross sections (millibarns).

Source	Energy[a] (MeV)	Ta^{181}	Li^7	Targets Li^6	C^{13}	B^{10}
Aluminum	7.72	4.1± 0.4	0.06 ±0.01	1.13±0.12	1.7 ±0.2	...
Copper	7.91	10.8±1.0	0.07 ±0.01	1.1 ±0.2	0.97±0.13	...
Chlorine	8.56	29 ± 6	0.17 ±0.12	...	...	...
Nickel	9.00	44 ± 6	0.16 ±0.06	1.6 ±0.3	0.6 ±0.1	0.11±0.01
Nitrogen	10.83	121 ±12	1.07 ±0.25	...	4 ±2	0.9 ±0.2
Chromium	9.72	84 ±25	0.55 ±0.25	...	...	0.23±0.05
Iron	7.64	0.0± 0.9	0.079±0.014	1.3 ±0.2	0.23±0.05	...
Iron	9.30	...	...	...	...	0.09±0.03
Lead	7.38	...	0.068±0.035	1.2 ±0.2	0.3 ±0.3	...
Sulphur	5.43	...	...	0.42±0.07		
Sodium	6.41	...	...	0.6 ±0.1		
Titanium	6.75	...	...	1.3 ±0.2	...	...
Titanium	6.61[b]	...	...	...	0.32±0.04	...
Manganese	7.16[c]	...	...	0.9 ±0.1	0.4 ±0.1	
Zinc	7.88	...	...	1.0 ±0.2	1.2 ±0.2	

[a] Energies taken from Refs. 4 and 5.
[b] Weighted average of 6.75-, 6.55-, and 6.41-MeV γ rays.
[c] Weighted average of 7.26-, 7.15-, and 7.05-MeV γ rays.

old of tantalum. Next, a chlorine source was used. This source emits γ rays with energies of 7.77 and 8.56 MeV. Using the previously determined cross section at 7.72 MeV, a correction was made for the contribution of the 7.77-MeV γ rays, and the cross section at 8.56 MeV determined. Finally, using the measured cross sections at 7.72 and 8.56 MeV, corrections were made to the data obtained with the nickel source, yielding the cross section at 9.00 MeV.

In applying the above procedure, it is necessary to know that none of the γ rays for which corrections are made coincide in energy with strong resonances in the cross section. For the light elements studied here, energies of resonances have been fairly well established by experiments involving various nuclear reactions,[8] and for tantalum, absorption resonances are so close together that they overlap to form a smooth cross-section curve.

Corrections for extraneous γ rays emitted by a particular source are not always as simple as the case described above, and some of the instances in which they are not so straightforward are discussed below. However, in most cases, the γ rays of interest are the most intense ones emitted by a given source, so that the contribution of other γ rays is small. For example, in the measurements with γ rays from nickel incident upon a tantalum target discussed above, the neutron production from the 7.82- and 8.53-MeV γ rays was only about 25% of that from the 9.00-MeV γ rays.

The results of all of our cross-section measurements are listed in Table II. These measurements are discussed individually below.

A. $Ta^{181}(\gamma,n)Ta^{180}$

The tantalum target consisted of 95.8 g of tantalum metal. Corrections were made for electronic attenuation of the γ-ray beam in the target. The magnitude of this correction was determined by measuring the neutron yield versus target thickness for the nickel γ-ray source. These measurements yielded the correct absorption coefficient to use for calculating the attenuation of 9-MeV γ rays in the tantalum target. Since absorption coefficients vary quite slowly with energy for γ rays from 7.5 to 10.8 MeV, the coefficient obtained for 9-MeV γ rays was used for all of the γ-ray energies employed in the tantalum experiments. We estimate that the percent error in the $Ta(\gamma,n)$ cross sections at energies other than 9 MeV which could have resulted from this procedure is less than 2%. This is small compared to other uncertainties, and was not included in the final calculations of errors.

Cross sections versus γ-ray energies for the $Ta^{181}(\gamma,n)Ta^{180}$ reaction are plotted in Fig. 2. A smooth curve has been drawn through our points. Also shown in the figure are some results for this reaction obtained by Fuller and Weiss,[9] and by Bramblett *et al.*[1] The agreement

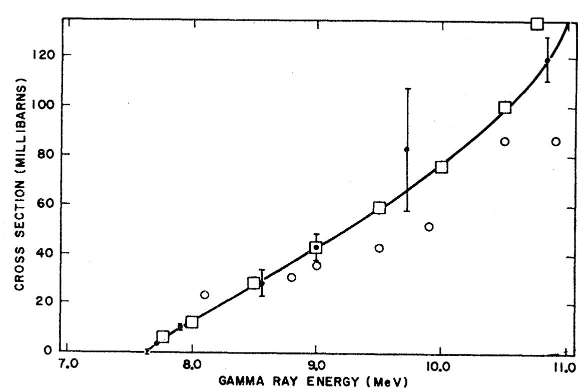

FIG. 2. Energy versus cross section, $Ta^{181}(\gamma,n)$. Boxes are data of Fuller and Weiss (Ref. 8), circles are data of Bramblett *et al.* (Ref. 1). The solid line is a smooth curve through the present cross-section measurements.

[8] F. Ajzenberg-Selove and T. Lauritsen, Nucl. Phys. **11**, 1 (1959).

[9] E. G. Fuller and M. S. Weiss, Phys. Rev. **112**, 560 (1958), and private communication.

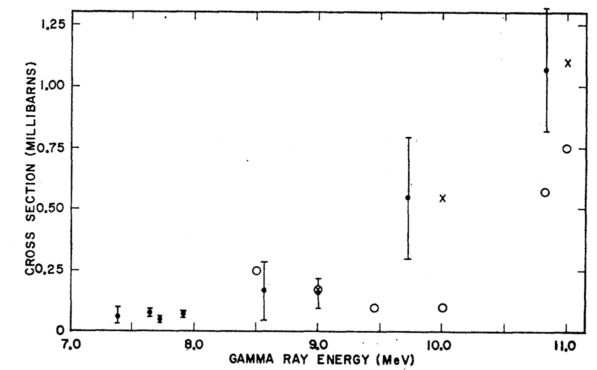

FIG. 3. Energy versus cross section, $Li^7(\gamma,n)$. Crosses are data of Goldemberg and Katz (Ref. 3), circles are data of Romanowski and Voelker (Ref. 12).

between our results and those of Fuller and Weiss is very good. From an expanded plot of the first five points in Fig. 2, an estimate of the threshold for this reaction can be made. The result obtained, $E_{\text{th}}=7.64\pm0.04$ MeV, is in good agreement with two of the previous measurements,[10,11] but considerably lower than a third one.[12]

B. $Li^7(\gamma,n)Li^6$

The Li^7 target consisted of 13.7 g of lithium metal enriched to 99.99% in Li^7. Because of its low density, the attenuation of γ rays in this target was less than 2%. Similarly small attenuations occurred in the Li^6 and C^{13} targets used in the measurements described below. No corrections for γ-ray attenuations were made for any of these three targets. Cross sections as a function of energy are plotted in Fig. 3. Some results of Romanowski and Voelker[13] and Goldemberg and Katz[14] are also shown in the figure. As can be seen from this figure, our uncertainties are quite large, and for this target they result primarily from statistical uncertainties in neutron counting rates.

A careful inspection of our data shows that the points at 7.38 and 7.64 MeV are probably influenced by the well-known ($\frac{5}{2}-$) level in Li^7 at 7.47 MeV. If values of 110 and 165 keV are used for the neutron width and total width of this level,[8,15] from our data it is possible to obtain a value for the ground-state radiative width of this level, $\Gamma_\gamma{}^0=0.9\pm0.4$ eV. This is about one-tenth of the Weisskopf estimate for an $M1$ transition, in agreement with the findings of Wilkinson,[16] who concludes that $M1$ radiative widths are of the order of one-seventh of the Weisskopf estimates.

C. $Li^6(\gamma,n)$

The Li^6 target consisted of 12.0 g of lithium metal enriched to 95.6% in Li^6. No corrections were necessary for γ-ray attenuation in this target. The three reactions which produce neutrons when photons are incident on Li^6 and their thresholds, are $Li^6(\gamma,np)He^4$(3.7 MeV), $Li^6(\gamma,p)He^5\rightarrow He^4+n$(4.7 MeV), and $Li^6(\gamma,n)Li^5$(5.4 MeV). Titterton and Brinkley[17] have shown that in the energy range of interest here, the cross section of the first of these reactions is of the order of, or less than, 5×10^{-30} cm^2, and therefore could not be detected in these experiments. Even so, the threshold for the second reaction is sufficiently low so that there are no neutron-capture γ-ray sources which emit only a single γ ray with an energy greater than the threshold for neutron production. Therefore, to obtain neutron-production cross sections from our data it was necessary in a few instances to use the previous cross-section measurements of Romanowski and Voelker[13] to correct for the effect of low-energy γ rays from the source. For example, to obtain a cross section at 7.72 MeV using an aluminum γ-ray source, corrections for contributions to the neutron yields of γ rays with energies between 4.7 and 7.7 MeV were made using their cross sections and relative γ-ray intensities from Refs. 4 and 5. The correction so made was about 20% of the neutron yield produced by the aluminum source, so that even large errors in the correction would not radically influence the value of the cross section at 7.72 MeV. For only three γ-ray sources was it necessary to use the cross sections of Romanowski and Voelker to make corrections to our data which were greater than 10%, and in each of these, the correction was less than 20%.

In Fig. 4, cross sections for $Li^6(\gamma,n)$ reactions are plotted versus γ-ray energies. The point at 7.16 MeV was obtained with a maganese γ-ray source. This source emits intense γ rays with energies of 7.26, 7.15, and

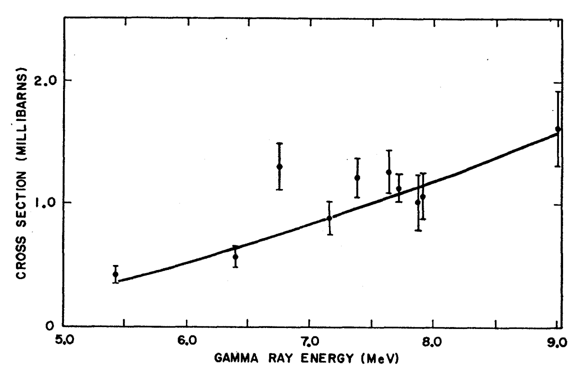

FIG. 4. Energy versus cross section, $Li^6(\gamma,n)$. Smooth curve from the data of Romanowski and Voelker (Ref. 13).

[10] R. E. Welsh and D. J. Donahue, Phys. Rev. **121**, 880 (1961).
[11] B. D. Chidley, L. Katz, and S. Kowalski, Can. J. Phys. **36**, 407 (1958).
[12] K. N. Geller, J. Halpern, and E. G. Muirhead, Phys. Rev. **118**, 1302 (1960).
[13] T. A. Romanowski and V. H. Voelker, Phys. Rev. **113**, 886 (1959).
[14] J. Goldemberg and L. Katz, Can. J. Phys. **32**, 49 (1954).
[15] F. Gabbard, R. H. Davis, and T. W. Bonner, Phys. Rev. **114**, 201 (1959).
[16] D. H. Wilkinson, in *Nuclear Spectroscopy*, edited by F. Ajzenberg-Selove (Academic Press Inc., New York, 1960).
[17] E. W. Titterton and T. A. Brinkley, Proc. Phys. Soc. (London) **A65**, 1052 (1952).

7.05 MeV. The cross section was plotted at an energy which is a weighted average of the three groups. Such a procedure is valid if the cross section from 7.05 to 7.26 MeV is reasonably smooth and slowly varying. Also shown in Fig. 4 is a solid curve, as drawn by Romanowski and Voelker[13] to represent their results for this reaction. They indicate that errors in their measurements are approximately 30%. In general there is agreement between the two types of measurements. However, there is some indication of structure in our results. In particular, the high cross section at 6.75 MeV may result from the contribution of a known level in Li^6 at 6.63 MeV.[8]

D. $C^{13}(\gamma,n)C^{12}$

The C^{13} target consisted of 14 g of graphite, which contained 7.69 g of C^{13}.[18] Our cross sections are shown in Fig. 5. The point at 6.61 MeV was obtained with a titanium source which emits intense γ rays with energies of 6.75, 6.55, and 6.41 MeV. It is plotted at an energy which is the average of these three γ rays weighted by their intensities. As was the case with the Li^6 targets, because of the low threshold for the $C^{13}(\gamma,n)C^{12}$ reaction (4.95 MeV) it was necessary to use previously measured cross sections to correct our results for the effects of extraneous γ rays from some of the sources. These corrections were made using cross sections measured at MIT.[18] In the worst case, the cross section at 7.63 MeV obtained with γ rays from an iron source, this correction was 30% of the total neutron yield. For all other sources, corrections requiring the use of previously measured cross sections were less than 10% of the neutron yield produced by these sources. The data of the MIT group were used mainly to insure that no strong resonance coincided in energy with any of the extraneous γ rays. From an inspection of Fig. 5 the existence of a reasonance at about 7.7 MeV is evident. However, the peculiar shape of this resonance indicates that it does not result from a single level in C^{13}, so an analysis of its properties from the (γ,n) measurements is not possible.

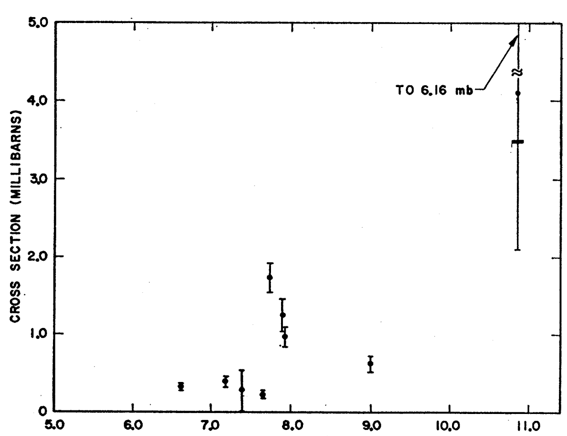

FIG. 5. Energy versus cross section, $C^{13}(\gamma,n)$.

[18] W. E. Turchinetz (private communication).

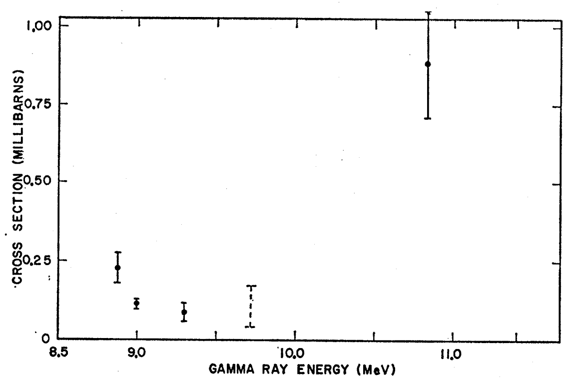

FIG. 6. Energy versus cross section, $B^{10}(\gamma,n)$.

E. $B^{10}(\gamma,n)B^9$

The results of measurements with a sample of 49.9 g of boron, enriched to 93% in B^{10}, are plotted in Fig. 6. Only four points could be measured above the 8.5-MeV threshold for the $B^{10}(\gamma,n)B^9$ reaction. Because of the existence of a resonance in B^{10} at 8.89 MeV,[19] the analysis of results proceeded as follows. With nickel, iron and nitrogen sources, (γ,n) cross sections were measured at 9.00, 9.30, and 10.83 MeV, respectively. From these measurements, limits to the cross section at 9.7 MeV were established. These limits are illustrated by the dashed vertical line in Fig. 6. With these limits and the neutron yield measured with a chromium source ($E_\gamma = 8.88$ and 9.72 MeV), the cross section at 8.88 MeV was determined. It was necessary to make a small (approximately 5%) correction for electronic attenuation of the γ-ray beam in this target.

Using the properties of the 8.89-MeV level in B^{10} obtained by Marion,[19] $E_0 = 8.89 \pm 0.01$ MeV, $\Gamma = 85 \pm 10$ keV, $J = 3^+$, and assuming that the level has a Breit-Wigner shape, we can deduce from the (γ,n) cross sections a value for the quantity $\bar{\Gamma} = \Gamma_\gamma{}^0 \Gamma n / \Gamma = 0.6 \pm 0.3$ eV, so that $\Gamma_\gamma{}^0 \gtrsim 0.6$ eV. Again this is consistent with Wilkinson's estimate[16] for the widths of $M1$ transitions. This agreement is good evidence for the assignment to this level of $T=1$, as suggested by Marion,[19] since $M1$, $\Delta T = 0$ transitions in this nucleus would probably be strongly inhibited.[16]

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[19] J. B. Marion, Phys. Rev. **103**, 713 (1956).