satisfying other low-energy scattering data, Cheston obtains for the polarization the experimental sign, though only about a third of the experimental magnitude. He suggests[13] that the inclusion of the spin-spin and tensor interactions would enhance the predicted polarization.

[13] W. B. Cheston (private communication).

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Cross Sections for Photoneutron Emission Induced by the Lithium Gamma Rays*

W. H. Hartley,† W. E. Stephens, and E. J. Winhold
Physics Department, University of Pennsylvania, Philadelphia, Pennsylvania
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Cross sections for emission of photoneutrons produced by $Li^7(p,\gamma)$ gamma rays in thirteen middle-weight and heavy nuclei have been measured. Neutrons were detected by BF_3 counters embedded in paraffin, and the gamma-ray intensity was measured with a NaI scintillation detector. Measurements made with two groups of neutron counters whose efficiencies depended differently on neutron energy indicated that the energy distributions of the emitted neutrons are evaporation-like in shape. The present cross section values are about 20% higher than previous measurements of McDaniel, Walker, and Stearns, but the difference is within the combined errors. The measurements provide an independent check on the accuracy of the cross-section curves obtained with bremsstrahlung beams; agreement is obtained with University of Pennsylvania betatron data but not with some other betatron results.

INTRODUCTION

A LARGE number of measurements of photonuclear reaction cross sections have been made in the last few years, especially in the region of the giant absorption resonance near 15 Mev, with a view to obtaining a better understanding of the photon absorption process.[1] Most of these measurements have been made with bremsstrahlung beams from electron accelerators. The magnitudes and shapes of cross-section curves obtained in this way are subject to several uncertainties. Because of the continuous nature of the photon spectrum, the observed excitation curves must be analyzed by a "photon difference" method[2] to obtain the cross section as a function of photon energy. This procedure exaggerates considerably any errors present in the original data. In addition, the results are rendered somewhat uncertain by a lack of exact knowledge of the bremsstrahlung spectrum shape, and by the x-ray intensity monitoring methods commonly used.

Measurements of photonuclear cross sections using monoenergetic gamma rays, while restricted to a few energies, avoid the above difficulties and provide an important check on the accuracy of the cross section data obtained with x-rays. This paper presents measurements of cross sections for photoneutron emission by the $Li^7(p,\gamma)$ gamma rays for thirteen middle-weight and heavy nuclei. Direct neutron detection is employed. These measurements represent an extension, with some improvements, of the work of McDaniel *et al.*[3] Those authors obtained cross-section values somewhat lower than the betatron data, and it was thus of interest to obtain independent values for these numbers.

One interest in accurate measurements is to make a comparison of experimental values for the integrated cross section for photon absorption by nuclei with the theoretical predictions of the sum rules.[4,5] In the case of heavy nuclei, the absorption of gamma rays results predominantly in the ejection of neutrons, and consequently these photoneutron cross sections are a good measure of the cross section for absorption.

EXPERIMENT

The lithium proton-capture gamma rays consist of a narrow line at 17.6 Mev and a broad line at 14.8 Mev. In the present experiment these gamma rays were produced by bombarding a thick lithium metal target with a magnetically analyzed beam of 480-kev protons from the Pennsylvania electrostatic generator. Under these conditions nearly all the gamma rays are associated

* Supported in part by a grant from the National Science Foundation.
† Now at Westinghouse Atomic Power Division, Pittsburgh, Pennsylvania.
[1] For reviews of this field see K. Strauch, *Annual Review of Nuclear Science* (Annual Reviews, Inc., Stanford, 1953), Vol. 2, p. 105; J. S. Levinger, *Annual Review of Nuclear Science* (Annual Reviews, Inc., Stanford, 1954), Vol. 4, p. 13.
[2] See, for example, L. Katz and A. G. W. Cameron, Can. J. Phys. **29**, 518 (1951).
[3] McDaniel, Walker, and Stearns, Phys. Rev. **80**, 807 (1950).
[4] J. S. Levinger and H. A. Bethe, Phys. Rev. **78**, 115 (1950).
[5] Gell-Mann, Goldberger, and Thirring, Phys. Rev. **95**, 1612 (1954).

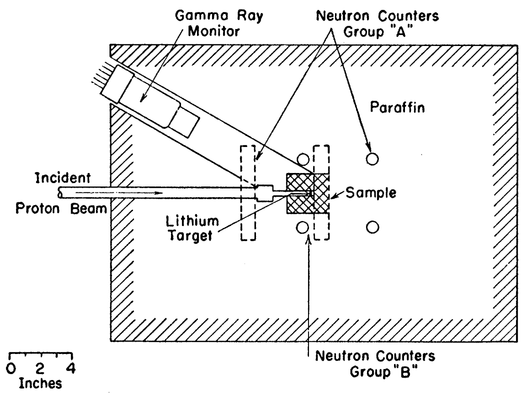

FIG. 1. The experimental arrangement.

with the 441-kev resonance; the relative intensity of the 17.6- and 14.8-Mev components is about 1.7:1.[6]

The experimental arrangement is shown in Fig. 1. High-purity powder samples of thirteen elements (of atomic numbers ranging from 26 to 83) were irradiated in thin aluminum cylindrical containers which fit over the proton beam tube and thus subtend almost the total solid angle at the lithium target. Several sizes of containers were used so that the gamma-ray attenuation in the different samples ($\sim\frac{1}{3}$) would be roughly similar. The target was situated at the center of a large moderating paraffin cylinder in which were embedded eight enriched boron trifluoride counters (1-in. diameter by $4\frac{1}{2}$-in. active length). One group of four counters (Group *A*) consisted of two counters above and two below the sample. The other four (Group *B*) formed a square array about the sample at 90° to the proton beam. The counters in Group *B* were positioned considerably closer to the source than those in Group *A*. As discussed below, this resulted in a detection efficiency which was higher but which depended more strongly on neutron energy. Output pulses from the two counter groups were separately amplified, discriminated, and counted.

A 1.5-in. by 1.5-in. cylindrical NaI(Tl) crystal was used to monitor the gamma ray intensity. The crystal was sealed in an aluminum container with magnesium oxide reflector and mounted on a DuMont 6292 photomultiplier tube. The energy response of the detector was calibrated with the Cs^{137} and Co^{60} photopeaks as well as with the $F^{19}(p,\alpha\gamma)$ and $Li^7(p,\gamma)$ gamma rays. The pulse discrimination level was set at 8 Mev during the experiment.

Before and after the irradiation of each sample, a run was made with an identical empty aluminum container to give a measure of the background as well as to check the gamma-ray attenuation in the sample. Each set of runs was repeated several times.

[6] M. B. Stearns and B. D. McDaniel, Phys. Rev. **82**, 450 (1951).

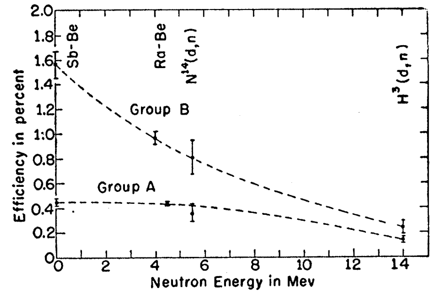

FIG. 2. Efficiency calibration for the two groups of neutron counters.

NEUTRON COUNTER EFFICIENCY

The absolute efficiency of the neutron counters was measured for neutrons of several different energies. Sources of Ra-Be neutrons (heterogenous energies with a mean ~4 Mev) and Sb-Be neutrons (25 kev), and neutrons from the $N^{14}(d,n)$ reaction (5 Mev) and from the $H^3(d,n)$ reaction (14 Mev) were used for this calibration. The Ra-Be source was calibrated by the National Bureau of Standards and its absolute strength was known to 5%. Source strengths for each of the other three neutron sources used were determined by measuring the counting rate of a flat response long counter[7] at a distance of 220 cm from all four sources. The efficiency of the long counter for these sources was obtained by using its measured efficiency for the neutrons from the calibrated Ra-Be source together with the published data[7–9] on the dependence of long-counter efficiency on neutron energy. The data thus obtained with a large empty sample container in position are shown in Fig. 2. It was found that the Group *A* efficiency was very nearly independent of container size and of the particular sample present, but that the efficiency for Group *B* depended somewhat on these factors. The Group *A* efficiency also seems to be essentially energy independent over the expected range of photoneutron energies. Therefore we believe the data obtained with this group to be more reliable than that obtained with Group *B*.

Since the Group *B* efficiency varies significantly with neutron energy, the energy distribution of the observed photoneutrons must be known in order to obtain the number of emitted photoneutrons from the Group *B* data. Available information,[10–13] although quite incomplete, indicates that at these excitation energies the photoneutron spectra are evaporation-like in shape,

[7] A. O. Hanson and J. L. McKibben, Phys. Rev. **72**, 673 (1947).
[8] Nobles, Day, Henkel, Jarvis, Kutarnia, McKibben, Perry, and Smith, Rev. Sci. Instr. **25**, 334 (1954).
[9] Barschall, Rosen, Taschek, and Williams, Revs. Modern Phys. **24**, 1 (1952).
[10] P. R. Byerly, Jr., and W. E. Stephens, Phys. Rev. **83**, 54 (1951).
[11] G. A. Price, Phys. Rev. **93**, 1279 (1954).
[12] W. E. Stephens (unpublished data).
[13] W. R. Dixon, Can. J. Phys. **33**, 785 (1955).

peaking in the vicinity of 1 Mev. Calculated evaporation neutron spectra[14] with a 10% high-energy tail added to conform to experimental indications were therefore used in obtaining average efficiencies for each element. Since the Group B data are sensitive to this assumption about the photoneutron energy spectrum while the Group A data are not, the ratio of the cross-section values as obtained from the A and B groups for a given element in principle yields information on the magnitude of the deviation of the actual energy distribution from the assumed one.

GAMMA-RAY MONITOR EFFICIENCY

The efficiency of the NaI crystal for the detection of the 14.8- and 17.6-Mev gamma rays was determined in several ways. The most direct method involved calculation of the total number of electron-producing events in the crystal per gamma ray emitted from the target, using the calculated total absorption coefficient in sodium iodide for these gamma rays.[15] This number should correspond to the number of counts at zero discriminator bias, provided that the effect of scattered photons, photons from inelastic neutron scattering, etc., is negligible. The relation between the number of counts as actually obtained at the 8-Mev bias level and the number at zero bias was found experimentally with the large paraffin cylinder removed. A slight correction had to be made because the pulse-height distributions with and without the paraffin cylinder present were slightly different even above 8 Mev. The sensitivity as obtained in this way was $(3.8\pm0.5)\times10^{-4}$ gamma-ray counts with the 8-Mev bias per photon emitted from the target.

As a check on this result, an attempt was made to actually calculate the number of events in the crystal giving pulses over 8 Mev. An exact calculation is difficult to perform because of the sizeable effects on the pulse-height distribution due to escape from the crystal of electrons and secondary photons.[16] The result obtained was $(4.2\pm0.6)\times10^{-4}$ gamma counts per photon. Both of the above values include a small correction for the slight angular anisotropy of the lithium gamma rays.[17]

A third method of calibration involved measuring the integrated proton current incident on the lithium target. Use of the published values of the thick target yield of the lithium gamma rays[18] gives a value of $(4.2\pm0.5)\times10^{-4}$ gamma counts per photon for the sensitivity.

These three values all agree within their errors. Their weighted average is $(4.1\pm0.3)\times10^{-4}$ gamma counts per photon.

BACKGROUND

The neutron counter background was measured by running with each sample replaced by an empty aluminum container. For several of the lighter elements the counting rate with the empty container was as much as 40% of the counting rate with sample in. In these cases it is important to know the origin of the background. The size of any gamma-ray associated background is decreased significantly by insertion of the sample, while that due to neutrons produced in the lithium target is much less dependent on the sample presence. We estimate that about 35% of the observed background is due to photoneutrons produced in the walls of the neutron counters themselves. This estimate is based on measurements of counter efficiency for various neutron source positions on the walls of the same and adjacent counters, as well as on background measurements using alternately brass and aluminum wall counters. The only other appreciable contribution to the background appears to be from neutrons produced in the lithium target by the reaction $Li^7(p,\alpha)$ followed by $Li^7(\alpha,n)$. An estimate of the magnitude of this effect indicates that it is of the correct order of magnitude to account for the rest of the background. We have therefore corrected only 35% of the observed background for gamma-ray attenuation in the sample.

RESULTS AND DISCUSSION

The cross section for photoneutron production is given by

$$\sigma = Y\epsilon_\gamma/(N\bar{t}\epsilon_n),$$

where Y is the observed number of neutron counts per gamma-ray count corrected for background and effect of gamma-ray attenuation in the sample on the gamma monitor counting rate, and ϵ_γ and ϵ_n are the sensitivities of the gamma-ray monitor and neutron counters, respectively. N is the number of nuclei per unit volume and $\bar{t}$ is an effective sample thickness given by

$$\bar{t}=\frac{1}{4\pi\mu}\int_{4\pi}(1-e^{-\mu t})d\Omega,$$

where μ is the linear photon absorption coefficient for the lithium gamma rays in the sample.

The cross-section values obtained from the data are given in Table I. These values represent averages over the energies of the two lithium gamma rays. We estimate the uncertainty in absolute value of each cross section obtained with the Group A neutron counters to be 15%, determined chiefly by the uncertainties in the neutron and photon detector efficiencies. Because the detector efficiencies are effectively the same from sample

[14] Feld, Feshbach, Goldberger, Goldstein, and Weisskopf, Atomic Energy Commission Report NYO-636, 1951 (unpublished).

[15] G. R. White, National Bureau of Standards Report 1003, 1952 (unpublished).

[16] See, for example, J. G. Campbell and A. J. F. Boyle, Australian J. Phys. **6**, 171 (1953).

[17] S. Devons and M. G. N. Hine, Proc. Roy. Soc. (London) **A199**, 56 (1949).

[18] W. A. Fowler and C. C. Lauritsen, Phys. Rev. **76**, 314 (1949).

TABLE I. Cross sections for photoneutron emission induced by the lithium gamma rays. The results are compared with previous data.

Element	Present cross-section data: Counter Group *A*	Present cross-section data: Counter Group *B*	Data of McDaniel *et al.*[a]	Betatron data, Pennsylvania: σ_{Av}[b]	Betatron data, Pennsylvania: $\sigma_{14.8}/\sigma_{17.6}$	Betatron data, Saskatchewan: σ_{Av}[b]	Betatron data, Saskatchewan: $\sigma_{14.8}/\sigma_{17.6}$	$\sigma_{14.8}$[h]	$\sigma_{17.6}$[h]
$_{26}$Fe	38 mb	33 mb	37 mb			60[f] mb	0.5	23 mb	47 mb
$_{27}$Co	49	49	47	60[c] mb	0.5	95[f]	0.5	30	60
$_{28}$Ni	28	25	23			40[g]	0.7	22	32
$_{29}$Cu	64	61	55±12			95[f]	0.6	45	75
$_{30}$Zn	48	45	48			90[f]	0.7	38	54
$_{47}$Ag	175	170	135			240[f]	1.0	175	175
$_{50}$Sn	200	190	180						
$_{73}$Ta	355	360	260	350[d]	1.3	420[g]	2.3	420[i] 550[j]	320[i] 240[j]
$_{74}$W	365	355	325						
$_{79}$Au	330	295		315[e]	1.7	480[f]	1.9	460	255
$_{80}$Hg	365	340	290						
$_{82}$Pb	310	295	250	320[e]	1.6	440[f]	2.5	400[i] 500[j]	250[i] 200[j]
$_{83}$Bi	305	280	250	270[d]	2.6	550[f]	2.4	490	195

[a] See reference 3.
[b] Average of 14.8- and 17.6-Mev cross sections weighted with relative intensities of the lithium gamma-ray lines.
[c] See reference 24.
[d] R. Nathans, Ph.D. thesis, University of Pennsylvania, 1954 (unpublished).
[e] J. Halpern (private communication).
[f] See reference 23.
[g] See reference 32.
[h] Separate cross sections at 14.8 and 17.6 Mev as obtained from Group *A* data and 14.8/17.6 betatron cross-section ratios.
[i] Obtained using 14.8/17.6 cross-section ratio from Pennsylvania betatron data.
[j] Obtained using 14.8/17.6 cross-section ratio from Saskatchewan betatron data.

to sample, the relative cross-section values for the different elements are known to better than 10%.

Since the results for Group *B* depend on the assumptions made about the photoneutron energy spectra, we believe the Group *A* values to be more accurate than those obtained with Group *B*. The results for the two groups agree, however, to better than 10% in nearly every case. This approximate agreement can thus be construed as evidence that the assumed energy spectra are roughly correct and that the photoneutron spectra are indeed all evaporation-like in shape. The results are however rather insensitive to the detailed shapes of the assumed spectra. For instance, if the effective temperature were increased by $\frac{1}{2}$ Mev the cross-section data for Group *B* would be increased by about 10%; if the high-energy tail were increased by 10% of the total, the *B* results would be increased by about 5%. Any fluctuation of the energy spectrum shape from element to element should result in a variation in the ratio of the *A* to *B* cross-section values. There are however no strong fluctuations of this ratio. The tantalum ratio is somewhat lower than those for the other heavy elements, implying perhaps lower energy neutrons from tantalum.

Also tabulated in Table I are the results of McDaniel *et al.* for the elements we investigated and the weighted average of the results at 14.8 and 17.6 Mev of the Pennsylvania and Saskatchewan betatron groups as taken from their cross-section curves.‡ Our results are, on the average, about 20% higher than those of McDaniel *et al.*, but the differences, except perhaps for silver and tantalum, are within the errors. We also agree with the Pennsylvania betatron data to better than 10%. Such agreement can be regarded as an indication that no sizeable errors are present in the betatron work. Further, in the heavy elements 17.6 Mev is on the high-energy side of the giant resonance and this is the region of the cross-section curve most open to doubt in the betatron work. Thus the present data provide some assurance as to the approximate correctness of the cross-section shapes above the resonance maximum.

The agreement with the Saskatchewan data is less good, their results being, on the average, about 50% higher than ours. The shapes of their curves are approximately similar to those of the Pennsylvania group for the cases measured by both, implying that the difficulty here is primarily one of absolute magnitudes. The Saskatchewan data are all normalized to the $Cu^{63}(\gamma,n)$ cross-section curve, for which they obtained (by activity counting) an integrated cross section to 22 Mev of 650 Mev mb.[19] Recent work on the $Cu^{63}(\gamma,n)$ reaction using extracted electron beams[20,21] indicates that the integrated cross section to 22 Mev has a value of the order of only 470 Mev mb, implying that the Saskatchewan results are all high by perhaps as much as

‡ *Note added in proof.*—A similar set of bremsstrahlung measurements was recently reported at Amsterdam [B. I. Gavrilov and L. E. Lazareva, *Proceedings of the International Conference on Nuclear Reactions*, Amsterdam, 1956 (to be published)]. The weighted averages of their results at 14.8 and 17.6 Mev are 100, 65, 350, 390, and 300 mb for Cu, Zn, Ta, Au, and Bi, respectively. Except for copper, these values are in reasonable agreement with the present results.

[19] L. Katz and A. G. W. Cameron, Can. J. Phys. **29**, 518 (1951).
[20] A. I. Berman and K. L. Brown, Phys. Rev. **96**, 83 (1954).
[21] Scott, Hanson, and Kerst, Phys. Rev. **100**, 209 (1955).

40%. This would account for the major part of the discrepancy with the present measurements.§

In Table I are listed the ratios of the cross sections at 14.8 and 17.6 Mev as obtained from the betatron data. We have used these ratios to obtain separate cross-section values at 14.8 and 17.6 Mev from our Group A data. These values are tabulated in the last two columns of Table I.

The general increase of photoneutron cross sections with increasing atomic weight, as indicated by the data, has been noted by many workers. The interruption to this trend at nickel is probably due to increased (γ,p) competition in this case.[22] The apparent slow decrease in the cross section values with increasing atomic weight for the heavy elements is likely due at least in part to the fact that the giant absorption resonance is below 15 Mev for these elements and is shifting to lower photon energies with increasing atomic weight.[23,24]

Recent measurements[25,26] indicate structure in the giant resonance in light elements. Even though the 17.6-Mev line is only about 12 kev wide,[18] any such structure in the elements investigated here would be expected to have a spacing smaller than this, and the measured cross sections should then be averages over any such possible structure.

The cross sections reported here are for photoneutron emission. In the middle-weight elements the (γ,n) reaction is the predominant neutron-emitting process at 14.8 and 17.6 Mev. For the heavy elements, however, the $(\gamma,2n)$ and (γ,pn) reactions are energetically possible at 17.6 Mev. The (γ,pn) process will be much less important than the $(\gamma,2n)$ since proton emission is strongly inhibited in the heavy elements by the large Coulomb barrier.[27] Since two neutrons are emitted in each $(\gamma,2n)$ process, the measured photoneutron cross sections in these cases are effectively the sum of the (γ,n) and twice the $(\gamma,2n)$ cross sections. Most of the $(\gamma,2n)$ thresholds for the heavy elements investigated are in the range between $13\frac{1}{2}$ and $15\frac{1}{2}$ Mev[28,29]; the magnitude of the $(\gamma,2n)$ cross section at 17.6 Mev should depend rather strongly on this threshold energy. For tantalum, whose $(\gamma,2n)$ threshold is near 14 Mev, the $(\gamma,2n)$ cross section has been shown to be somewhat larger than that for (γ,n) at 17.6 Mev.[30–32] Lacking detailed information on the other elements, we cannot break up the measured photoneutron emission cross sections into their (γ,n) and $(\gamma,2n)$ components.

In heavy elements the cross section for neutron emission should be the major part of the absorption cross section, and experiments indeed suggest that in these cases the integrated cross section for emission of photoneutrons is roughly comparable to the integrated absorption cross section predicted by the sum rules.[23,24] The sum rule given by Gell-Mann *et al.*[5] relates to absorption of all multipolarities over the range of energies up to the meson production threshold. Even though the present data provide an independent check of the experimental cross-section curves, detailed comparison with this sum rule is still not warranted. The neutron emission experiments in heavy elements overestimate the integrated cross section by perhaps 10 to 25% because they weight the $(\gamma,2n)$ reaction by a factor of two with respect to the (γ,n) process; at the same time the absorption cross section is underestimated since the (γ,γ') process[33] and the high-energy tail above the giant resonance are neglected. Rather little is known about the tails, although there are indications that their contribution may be very sizeable. According to Jones and Terwilliger,[34] who made neutron emission measurements in this energy region, the tail contributes of the order of 30% of the total integrated absorption cross section up to the meson threshold in the heavy elements. However there are large uncertainties both in their experimental measurements and their neutron multiplicity estimates. There also exists an assortment of radioactivity yield data[35] on various multiple-particle photoreactions in middle-weight elements. These data indicate that the tails are indeed nonzero but do not yet give quantitative information on their actual size and shape.

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§ *Note added in proof.*—Professor L. Katz has pointed out to us that the Saskatchewan cross-section values should be reduced by 10% because of calibration corrections.

[22] J. Heidmann and H. Bethe, Phys. Rev. **84**, 274 (1951).
[23] Montalbetti, Katz, and Goldemberg, Phys. Rev. **91**, 659 (1953).
[24] R. Nathans and J. Halpern, Phys. Rev. **93**, 437 (1954).
[25] Katz, Haslam, Horsley, Cameron, and Montalbetti, Phys. Rev. **95**, 464 (1954).
[26] A. S. Penfold and B. M. Spicer, Phys. Rev. **100**, 1377 (1955).
[27] E. V. Weinstock and J. Halpern, Phys. Rev. **94**, 1651 (1954).
[28] A. H. Wapstra, Physica **21**, 385 (1955).
[29] J. R. Huizenga, Physica **21**, 410 (1955).
[30] E. A. Whalin and A. O. Hanson, Phys. Rev. **89**, 324 (1953).
[31] Carver, Edge, and Wilkinson, Phil. Mag. **44**, 404 (1953).
[32] J. Goldemberg and L. Katz, Can. J. Phys. **32**, 49 (1954).
[33] Burkhardt, Winhold, and Dupree, Phys. Rev. **100**, 199 (1955), and references therein.
[34] L. W. Jones and K. M. Terwilliger, Phys. Rev. **91**, 699 (1953).
[35] T. T. Sugihara and I. Halpern, Phys. Rev. **101**, 1768 (1956) and references therein.