covered in these experiments with an energy spread of ~0.5 kev to 1.0 kev. These measurements indicate the presence of some 127 resonances in the interval from ~1 kev to 500 kev. This is more than ten times the number which was observed previously. In view of these results, it is obvious that many interfering levels must be included in any meaningful fitting of the present data with resonance parameters.

PHYSICAL REVIEW VOLUME 118, NUMBER 2 APRIL 15, 1960

Photoneutron Cross Sections of Li, N, and A†

R. W. Fast, P. A. Flournoy, R. S. Tickle, and W. D. Whitehead
University of Virginia, Charlottesville, Virginia
(Received November 13, 1959)

Using a Halpern-type photoneutron detection system, the photoneutron yields from Li, N^{14}, and A^{40} have been measured as a function of the maximum bremsstrahlung energy from threshold to approximately 50 Mev. The method of Penfold and Leiss was used to extract from the yield curves the total neutron cross section; $\sigma_T=\sigma(\gamma,n)+\sigma(\gamma,pn)+2\sigma(\gamma,2n)+\cdots$. The results are compared with previous findings of other laboratories. No gross structure was detected in the lithium cross section in the giant resonance region. The data indicate that lithium has a high-energy tail on the cross section of considerable magnitude.

INTRODUCTION

THE preponderance of accumulated data on the systematics of (γ,n) cross sections is, in general, confined to the giant resonance region. The principal tool for investigation of these cross sections has been the betatron, many of which are limited to a peak energy near 25 Mev. In many cases, existing cross sections in the giant resonance region for the partial reactions $\sigma(\gamma,n)$, $\sigma(\gamma,p)$, $\sigma(\gamma,np)$, etc.; fail to exhaust the dipole sum rule when compounded together to give the total absorption cross section.

With this in mind, three elements have been selected for study in the energy region from threshold to approximately 50 Mev. Using a Halpern-type neutron detection system, excitation curves for the total photoneutron cross section have been obtained experimentally for Li, N^{14}, and A^{40}.

The giant resonance shape of the lithium photoneutron cross section has recently been a subject of considerable disagreement. Several laboratories[1,2] have reported the existence of gross structure in the resonance, while other laboratories[3] have searched for structure, but have found none. For this reason, the giant resonance of lithium has been carefully examined in an effort to locate any gross structure which might exist.

The two gases, N^{14} and A^{40}, were examined particularly as to the width of their giant resonances; the previously reported width of N^{14} being anomalously small.[4]

† Supported by Air Force Office of Scientific Research.
[1] T. A. Romanowski and V. H. Voelker, Phys. Rev. **113**, 886–890 (1959).
[2] F. Heinrich and R. Rubin, Helv. Phys. Acta **28**, 185–192 (1955).
[3] T. W. Rykba and L. Katz, Phys. Rev. **110**, 1123–1126 (1958).
[4] G. A. Ferguson, J. Halpern, R. Nathans, and P. Yergin, Phys. Rev. **95**, 776–780 (1954).

EXPERIMENTAL PROCEDURE

Bremsstrahlung from the University of Virginia electron synchrotron was used to disintegrate the target nuclei. The electron energy can be continuously varied from 6 to 70 Mev by changing the length of the radio-frequency envelope. After acceleration to the desired energy, the electrons are allowed to impinge on a 0.030-inch tungsten target mounted on the inner wall of the vacuum tube.

The electron energy is monitored by integrating the magnetic flux passing through a turn around the magnet polepiece. The integrator circuit is similar to one used by the National Bureau of Standards Betatron Section and has proved extremely stable during two years of continuous operation. Energy calibration for the circuit was accomplished by observing the $C^{12}(\gamma,n)C^{11}$ threshold at 18.7 Mev. The energy calibration is good to about 1%.

Figure 1 is a schematic diagram of the synchrotron area. The x-ray beam is collimated to a diameter of approximately one inch at the center of the neutron house by a half-inch aperture in the lead collimator located 80 cm from the x-ray target. A thick-walled parallel plate ionization chamber is used to monitor the photon flux.

The photoneutrons are thermalized and detected by BF_3 counters in a geometry based on the setup described by Halpern.[5] Nine BF_3 counters (N. Wood Counter Laboratory, 96% B^{10}, 12-in. effective length, 1-in. diameter) are held in thin-walled aluminum tubes spaced symmetrically on a circle of 13.5-cm radius within a two foot paraffin cube. A Lucite tube with a $1\frac{1}{2}$ in. inside diameter runs through the center of the

[5] J. Halpern, A. Mann, and R. Nathans, Rev. Sci. Instr. **23**, 678–680 (1952).

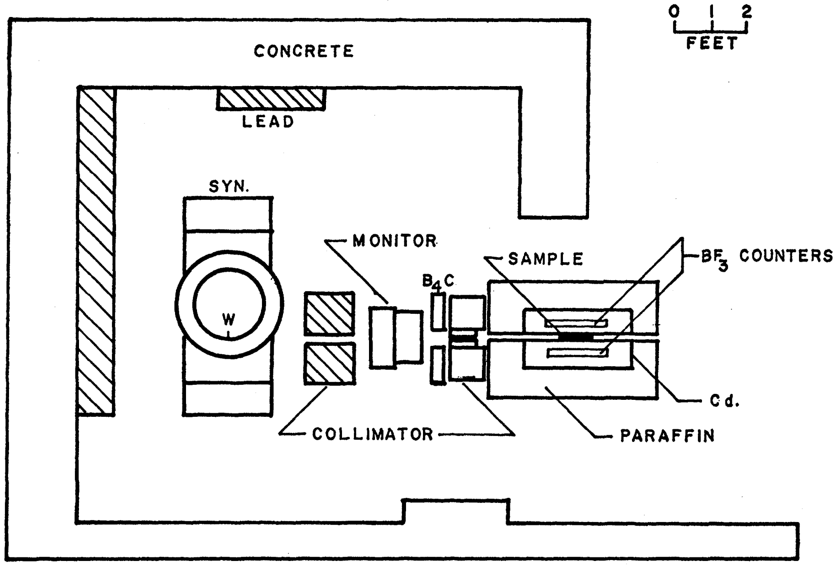

FIG. 1. Experimental arrangement.

matrix allowing the x-ray beam to pass through undisturbed.

To lower the counting efficiency for neutrons originating outside the sample position, extreme care was taken in shielding the counting matrix. The cube is covered with a 0.09-inch layer of cadmium sheet and a one-inch layer of paraffin impregnated with boron carbide pellets. An additional eight inches of paraffin is used on all sides except the one facing the beam where twelve inches of paraffin is used. To complete the shielding a $1\times2\times2$ foot tank of boric acid solution is used on the side facing the accelerator.

The nine counters are connected in parallel to a single cathode follower. The pulses are then fed into a nonoverload amplifier, discriminator, and gating circuit, respectively. For this experiment, the gate was set to open 20 microseconds after the x-ray burst and to remain open for seven hundred microseconds. In this way counts due to pileup of gamma-ray pulses are avoided.

An absolute counting efficiency of 2.9% was obtained for the detector by counting neutrons from a 10 mC Ra-α-Be neutron source. The neutron flux from the Ra-Be source was calibrated by the National Bureau of Standards on July 30, 1959, and found to be $1.48\times10^5\pm3\%$ neutrons per second.

The variation in efficiency with position along the Lucite tube is shown in Fig. 2. The variation of efficiency is believed to be independent of energy for neutron energies found in the giant resonance region.[5] The efficiency for high-energy neutrons should decrease with increasing neutron energy. No correction was made for this change in efficiency and the results reported here accordingly indicate a lower limit to the true situation.

The x-ray flux was monitored by integrating the current from a thick-walled duraluminum ionization chamber. The chamber was constructed from drawings supplied by the Betatron section of National Bureau of Standards. Leiss et al., have used a crystal spectrometer to calibrate an identical chamber.[6] Their results have been used in the analysis reported here.

EXPERIMENTAL DATA AND ITS ANALYSIS

In this laboratory, a modified Penfold-Leiss method is used to extract the cross section as a function of energy from the measured yield. The Penfold-Leiss matrix[7] itself yields values for the cross section which exhibit considerable fluctuation. In order to obtain a meaningful cross section, Penfold and Leiss suggest[8] adding the individual cross-section values to obtain the integrated cross section as a function of energy. A smooth curve is then constructed through these points

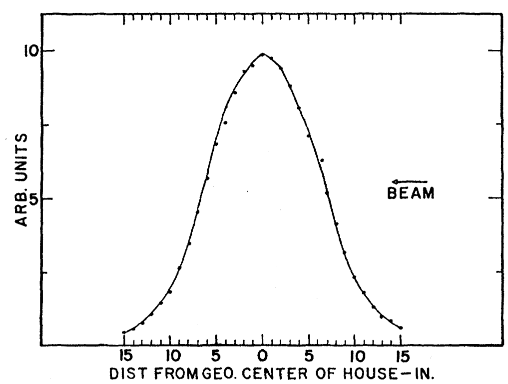

FIG. 2. Efficiency of neutron house as a function of axial position.

[6] J. Leiss, J. Pruitt, and R. Schrack, National Bureau of Standards Report 6149, September, 1958 (unpublished).

[7] A. S. Penfold and J. E. Leiss, Phys. Rev. 114, 1332–1337 (1959).

[8] A. S. Penfold and J. E. Leiss, Physics Research Laboratory, University of Illinois, Champaign, Illinois, 1958 (unpublished).

and first differences taken to yield final cross-section values. To avoid this indirect method, the Penfold-Leiss B numbers were used by us to construct a Cook type matrix[9] which, when applied to the reduced yield points, gives values of the integrated reduced cross section. The reduced cross section is defined as:

$$\Omega(E)=n_s f_s(E)[\sigma(E)/E],$$

where: n_s = number of nuclei per cm^2 of sample, and $f_s(E)$ = photon transmission function for all material between synchrotron target and the sample. A curve is drawn by eye through these points, the slope of which is used to obtain the value of the cross section as a function of energy from the above equation. The cross-section values are added to compute a running integral of the cross section.

In each of these experiments the total yield data were taken at the half-integer energies of maximum bremsstrahlung at one Mev intervals, no extrapolation being therefore necessary to use the matrix. Subtraction

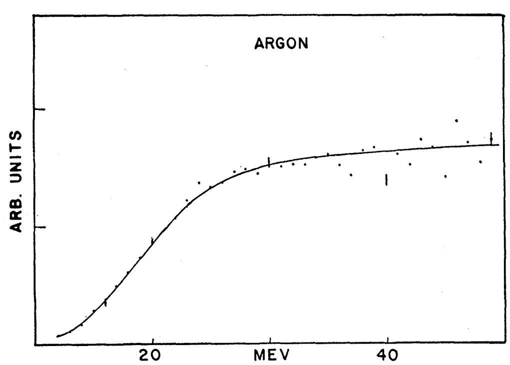

FIG. 3. Integrated reduced cross section for the reaction $A^{40}(\gamma,xn)$ as a function of maximum bremsstrahlung.

of the normalized background from the normalized yield produced the reduced yield as a function of energy. Normalization was accomplished through the use of the monitor response provided by the National Bureau of Standards for the ion chamber used. No method of smoothing was applied to the reduced yield points; the measured points themselves were fed into the matrix. The data were corrected for absorption in the donut walls and ionization chamber.

ARGON

Argon of natural isotopic abundance, 99.6% A^{40}, was contained under a pressure of 1600 pounds per square inch in a stainless steel tube, 7 feet in length. The target cylinder was positioned in the neutron detector so that the synchrotron beam passed through the tube parallel to its long axis without striking the walls. The length of the target container allowed the end caps to protrude beyond the outside layers of paraffin so that

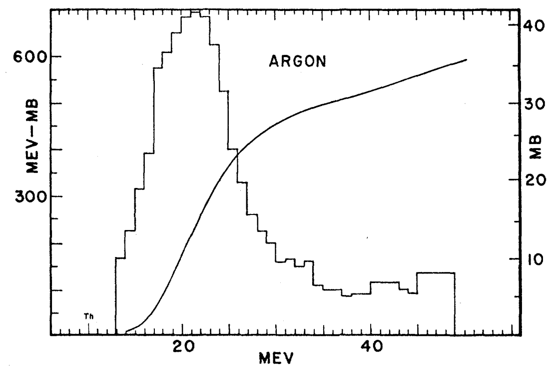

FIG. 4. Cross section and integrated cross section for argon reaction as functions of energy.

the neutrons produced as the beam passed through the end caps were not counted.

The total neutron yield as a function of the maximum bremsstrahlung energy was obtained at 1-Mev intervals from threshold to approximately 50 Mev. The statistical errors on the total number of recorded counts were approximately 1% in the region of the giant resonance and 0.6% at the higher energies. The background runs were made with the sample tube evacuated. Total yield to background ratio was about 8:1.

The integrated reduced cross section extracted from the yield data is shown in Fig. 3. Shown in Fig. 4 are the cross section and its running integral. The cross section has a maximum of 41 mb at 21 Mev and a full width at half maximum of 10 Mev. Statistical errors at the peak are roughly 22%, commensurate with 1% yield data. These values are in agreement with those reported previously by McPherson et al.,[10] who obtained a value of 38 mb for the peak cross section occurring at 20 Mev. Halpern[4] has given a somewhat lower value, 31 mb at an energy of 21 Mev.

At higher energies, the A^{40} cross section exhibits a tail which is 6 mb at 40 Mev. However, with only 0.6%

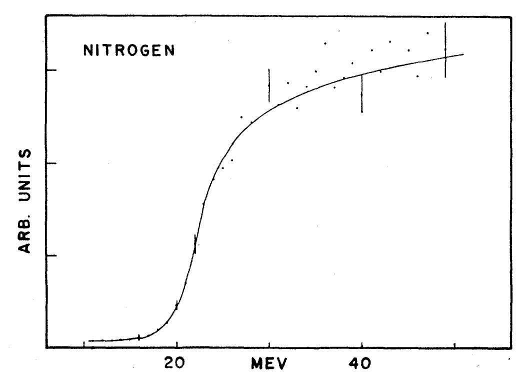

FIG. 5. Integrated reduced cross section for the reaction $N^{14}(\gamma,xn)$ as a function of energy.

[9] B. C. Cook, Phys. Rev. **106**, 300–314 (1957).

[10] D. McPherson, E. Pederson, and L. Katz, Can. J. Phys. **32**, 593–598 (1954).

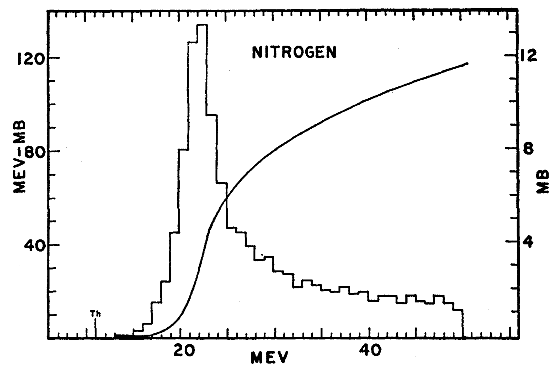

FIG. 6. Cross section and integrated cross section for nitrogen reaction as functions of energy.

yield data in this region, the tail is not statistically significant. The magnitude of the tail could be reduced somewhat if accurate corrections could be made for the neutron multiplicity.

The integrated cross section to 50 Mev is 0.598 Mev-barn. Correcting for neutron multiplicity, Penfold and Garwin[11] obtain a value of 0.900 Mev-barn for the total integrated cross section, $\sigma_T=\sigma(\gamma,p)+\sigma(\gamma,np)+\sigma(\gamma,n)+\sigma(\gamma,2n)$, up to 40 Mev.

NITROGEN

Nitrogen gas under 2000 pounds per square inch pressure in a 1.25-inch diameter stainless steel tube was used as a target. The end caps were well outside the sensitive region of the house and the beam did not strike the walls of the tube. Background runs were made with the sample tube evacuated. The total count to background ratio was approximately 3 to 1.

The yield points were taken at one Mev intervals from 13.5 to 60.5 Mev. At least four independent runs were made at each energy. The statistical deviation in the yield points above 20 Mev is better than 3%. Below the resonance the deviation is much worse becoming 10% at 13.5 Mev.

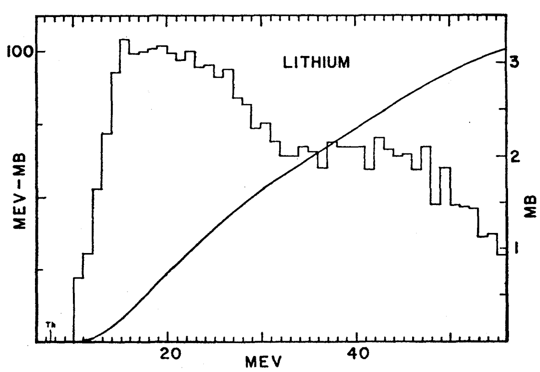

FIG. 7. Cross section and integrated cross section for lithium reaction as functions of energy.

[11] A. S. Penfold and E. L. Garwin, Phys. Rev. 114, 1139–1142 (1959).

The results for nitrogen are presented in Fig. 5. The curve represents the best fit "by eye" to the integrated reduced cross-section points which were determined by operating on the yield data with the Cook matrix. The histogram shown in Fig. 6 represents the first differences taken from the smooth curve.

The cross section exhibits a peak value of 14.5 mb at 22.5 Mev with a width at half maximum of 3.8 Mev. An uncertainty of 30% must be allowed for individual cross-section points when the counting statistics are considered. The integrated cross section to 25 Mev is 0.060 Mev-barn in excellent agreement with Halpern.[4] When the integrated cross section is extended to 50 Mev, a value of 0.116 Mev-barn is obtained.

The nitrogen cross section is interesting because of its narrow half-width, which is less than that obtained for some "magic number" nuclei.[12] Also of interest is the twelve Mev separation between threshold and resonance energies.

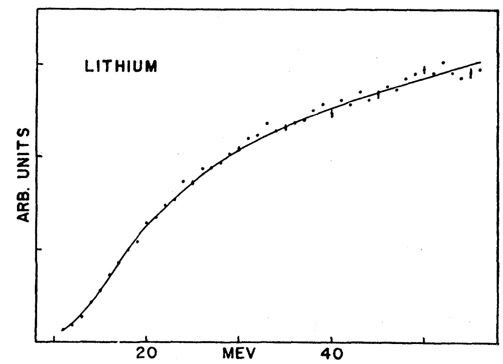

FIG. 8. Integrated reduced cross section for the reaction Li(γ,xn).

LITHIUM

A cylindrical block of metallic lithium in a holder of 0.001-in. Mylar served as the sample. It has a mass of 72 grams, was 99.8% pure and of natural isotopic abundance, 92.6% Li^7, 7.4% Li^6. The total yield was secured from a bremsstrahlung energy of 11.5 Mev, four Mev above the (γ,n) threshold, to 56.5 Mev, in one Mev intervals. The yield points were run until 10^5 counts were recorded at bremsstrahlung energies above 24.5 Mev. The deviation in the measured yields due to counting statistics was 0.5% at bremsstrahlung energies above 20.5 Mev and 1.0% at the lower energies. Background was obtained using an empty Mylar holder identical to the one used to contain the lithium. Background yield was measured to a statistical deviation of 1.5% above 24.5 Mev and 3.0% below. The ratio of total yield to background was at least 10:1 at all energies.

The resulting photoneutron cross section and integrated cross section as functions of the maximum energy of bremsstrahlung are presented in Fig. 7. The

[12] R. Nathans and J. Halpern, Phys. Rev. 93, 437–442 (1954).

TABLE I. Summary of data.

Element	$\int_0^{25} \sigma_n(E)dE$	$\int_0^{50} \sigma_n(E)dE$	$\int \sigma_p(E)dE$	Total	Sum rule limits $x=0$	$x=1$
	Experimental results (Mev·barns)				Mev·barns	
Nitrogen	0.060	0.116	0.045[a]	0.161	0.203	0.365
Argon	0.392	0.598	0.350[b]	0.948	0.594	1.069
Lithium	0.039	0.093	0.060[c]	0.153	0.103	0.185

[a] H. E. Johns, R. J. Horsley, R. N. H. Haslam, and A. Quinton, Phys. Rev. **84**, 856 (1951); and I. F. Wright, D. R. O. Morrison, J. M. Reid, and J. R. Atkinson, Proc. Phys. Soc. (London) **A69**, 77 (1956).
[b] I. P. Iavor, J. Exptl. Theoret. Phys. (U.S.S.R.) **34**, 1420 (1958) [translation: Soviet Phys. JETP **34**(7), 983 (1958)].
[c] R. von Rubin and M. Walter, Helv. Phys. Acta **27**, 163 (1954).

integrated reduced cross section from which they were derived is shown in Fig. 8. No attempt was made to resolve either the Li^6 or Li^7 values from the measured curves. Statistical deviation on the two curves is 1.0% on points of the integral curve above 20 Mev and is 25% at the maximum cross section on the histogram. The cross section has a maximum value of 3.2 ± 0.8 mb occurring at 19 ± 4 Mev. The value of the cross section integrated from 11 to 56 Mev is 0.101 ± 0.001 Mev-barn. The cross section is marked by the high values which it exhibits at energies above the giant resonance. Neutron multiplicity due to $(\gamma,2n)$ and (γ,np) reactions, for which accurate corrections could not be made, constitute part of the observed tail. The marked departure in the shape of the lithium integrated reduced cross section from the nitrogen and argon curves suggests that the tail is more significant than the counting statistics indicate. A decrease in counting efficiency of the neutron house for high-energy neutrons would tend to make the tail more pronounced at high bremsstrahlung energies. The maximum cross section and the energy at which it occurs agree with the results of Rybka and Katz.[3] Narrow, double resonances in the cross section as reported by Romanowski and Voelker[1] and by Heinrich and Rubin[2] are not seen, but the broad nature of the curve may suggest two widely separated, unresolved maxima.

A summary of the values of the integrated cross section is presented in Table I, along with photoproton results of other laboratories. The sum of the photoneutron and photoproton integrated cross sections may be compared with the dipole sum rule of Levinger[13]; $\int \sigma_T(E)dE = 0.06(NZ/A)(1+0.8x)$.

ACKNOWLEDGMENTS

The authors wish to thank A. P. Batson, R. F. Askew, L. B. Aull, and G. C. Reinhardt for their interest in these experiments and their assistance in the taking of the data.

[13] J. S. Levinger, *Annual Review of Nuclear Science* (Annual Reviews, Inc., Palo Alto, 1954), Vol. 4, p. 25.