Figure 2 is a self-absorption curve for the positron activity of C^{11}. Filter paper was used as a source of carbon for the points corresponding to small thickness (solid squares). The neglect of the bending-over of the curve would have led to an error of 20 percent in determining the activity at zero sample thickness. Similar, though larger, corrections were required for copper.

In Fig. 3 is shown the cross-section curve obtained from the activity curve by the method of analysis previously reported.[2] The cross-section curve has a peak value of 11.6 millibarns at 22.4 ± 0.5 Mev. The width at half-maximum is 4.25 Mev, and the integrated cross section is 0.047 Mev-barn. The ratio of the integrated cross sections of $Cu^{63}(\gamma, n)Cu^{62}$ [2,6] and $C^{12}(\gamma, n)C^{11}$ is $0.63/0.047 = 13.4$. This is in satisfactory agreement with ratios of the yields of these reactions produced by betatron x-rays of maximum energy 50 and 100 Mev (15.2, 14.4, respectively),[7] and also with the ratio 14 given by Helmholz and Strauch[8] for 335-Mev x-rays. This would be expected if the cross sections for these reactions were negligible above 50 Mev. Our value of 0.047 Mev-barn for the integrated cross section is considerably lower than that obtained by Lawson and Perlman,[9] who, however, assumed a sharp resonance occurring at approximately 30 Mev.[1]

The average energy for the x-rays producing the $C^{12}(\gamma, n)C^{11}$ reaction, as obtained from absorption coefficient measurements, is given as 22.1 ± 1.5 Mev by Koch, McElhinney, and Cunningham[10] and 25.3 ± 1.5 Mev by Marshall.[11] Although the peak of our cross-section curve lies at 22.4 Mev, the median ordinate lies at 23.5 Mev, and this probably corresponds more closely to the "average" photon energy obtained by the above authors.

The dotted curve of Fig. 3 shows the shape of the cross-section curve for the (γ, p) reaction in the same nuclide, as determined by Mann and Halpern.[12] It has been normalized to their minimum peak value of 1×10^{-26} cm². It is interesting to note that the maxima of the two curves occur at nearly the same energy.

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[1] G. C. Baldwin and G. S. Klaiber, Phys. Rev. **73**, 1156 (1948).
[2] Johns, Katz, Douglas, and Haslam, Phys. Rev. **80**, 1062 (1950).
[3] Katz, McNamara, Forsyth, Haslam, and Johns, Can. J. Research **A28**, 113 (1950).
[4] McElhinney, Hanson, Becker, Duffield, and Diven, Phys. Rev. **75**, 542 (1949).
[5] G. A. Price and D. W. Kerst, Phys. Rev. **77**, 806 (1950).
[6] B. C. Diven and G. M. Almy, Phys. Rev. **80**, 407 (1950).
[7] M. L. Perlman and G. Friedlander, Phys. Rev. **74**, 442 (1948).
[8] A. C. Helmholz and K. Strauch, Phys. Rev. **78**, 86 (A) (1950).
[9] J. L. Lawson and M. L. Perlman, Phys. Rev. **74**, 1190 (1948).
[10] Koch, McElhinney, and Cunningham, Phys. Rev. **81**, 318 (A) (1951).
[11] L. Marshall, Phys. Rev. **82**, 300 (1951).
[12] A. K. Mann and J. Halpern, Phys. Rev. **80**, 470 (1950).

Photoneutron Cross Sections of Fe^{54}, Ni^{58}, and Zn^{64}

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The photoneutron cross sections of Fe^{54}, Ni^{58}, and Zn^{64} have been investigated in this laboratory with the method outlined by the authors in an earlier paper.[1] The cross section *versus* energy curves are shown in Fig. 1, and the pertinent results are summarized in Table I. The threshold for the reaction in iron was also checked and was found to be in good agreement with values previously reported. Corrections to the observed activity for *K* capture amounted to 7 percent in the case of Zn^{64},[2] 100 percent in the case of Ni^{58},[3] and 3 percent in the case of Fe^{54}. The last correction was estimated from the theoretical curves of Feenberg and Trigg,[4] assuming the transition to be allowed.

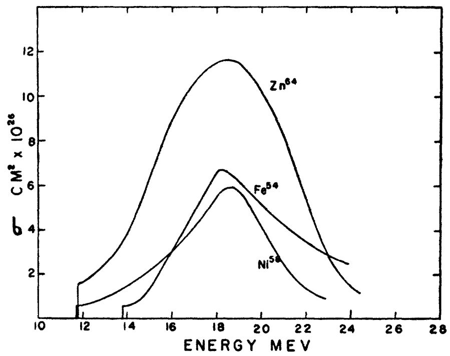

FIG. 1. Cross sections of Fe^{54}, Ni^{58}, Zn^{64} for (γ, n) reactions as a function of energy.

An examination of all published (γ, n), (γ, p), and (γ, d) cross sections would seem to indicate considerable similarity among them. For example, they all have half-widths of about 6 Mev, and their maximum cross sections, as previously pointed out by Katz and Penfold,[5] occur about 6 Mev above the threshold (see also Table II). Fluctuations from this value are generally less than 1.5 Mev. Cameron[6] analyzes the published neutron yield data on the basis of this similarity to obtain some interesting results. In addition, we would like to draw attention to the shape of the $Fe^{54}(\gamma, n)Fe^{53}$ and $C^{12}(\gamma, n)C^{11}$ curves. (See Haslam *et al.*[7] for the latter curve.) These cross sections rise more steeply than the other curves; and after passing through a maximum value, they drop off relatively slowly, resulting in a long tail. We might infer from the behavior of these two isotopes that the relative position of the cross-section maximum and the threshold are not necessarily

TABLE I. Photoneutron cross-section data.

Parent isotope	Threshold Mev	Energy at peak cross section Mev	Maximum cross section barn	Half-width Mev	Integrated cross section Mev-barn
Fe^{54}	13.7 ± 0.2	18.3	0.067 ± 0.006	5.7	0.42
Ni^{58}		18.5	0.060 ± 0.006	4.6	0.33
Zn^{64}		18.5	0.12 ± 0.01	7.1	0.83

TABLE II. Summary of photoneutron cross-section data.

Isotope and reaction	Threshold Mev	Energy at peak cross section Mev	Energy of peak cross section above threshold Mev	Reference
$C^{12}(\gamma, n)C^{11}$	18.7	22.4	3.7	a
$C^{12}(\gamma, p)B^{11}$	16	22.2	6.2	b
$Al^{27}(\gamma, n)Al^{26}$	14	19.6	5.6	c
$P^{31}(\gamma, n)P^{30}$	12.4	19	6.6	d
$S^{32}(\gamma, np)P^{30}$	19.1	25.8	6.4	d
$Fe^{54}(\gamma, n)Fe^{53}$	13.8	18.3	4.5	
$Ni^{58}(\gamma, n)Ni^{57}$	12.0	18.5	6.5	
$Cu^{63}(\gamma, n)Cu^{62}$	10.9	17.5	6.6	e
$Cu^{65}(\gamma, n)Cu^{64}$	10.7	19.0	8.5	e
$Zn^{64}(\gamma, n)Zn^{63}$	11.6	18.5	6.9	
$Ag^{109}(\gamma, n)Ag^{108}$	9.3	16.0	6.7	f
$Ag^{109}(\gamma, p)Pd^{108}$	6.1		6.5	f
$Sb^{121}(\gamma, n)Sb^{120}$	9.3	14.5	5.2	e
$Sb^{123}(\gamma, n)Sb^{122}$	9.3	14.5	5.2	e
$Ta^{181}(\gamma, n)Ta^{180}$	8.0	13.5	5.5	e
			Average 6.0	

[a] Reference 7.
[b] A. K. Mann and J. Halpern, Phys. Rev. **80**, 470 (1950).
[c] To be published.
[d] Reference 5.
[e] Reference 1.
[f] B. C. Diven and G. M. Almy, Phys. Rev. **80**, 407 (1950).

related; though as indicated, they generally fall about 6 Mev apart.

It is to be noted that $_{26}Fe^{54}$ has the "magic" number of 28 neutrons and $_{28}Ni^{58}$ the "magic" number of 28 protons. The neutron yield per mole per roentgen for the 6 percent Fe^{54} isotope is found to be about 3/5 of that obtained by Price and Kerst[8] (Table III). Nickel, on the other hand, which is "magic" in all isotopes, is found to give the same yield, within experimental error, for the 68 percent isotope Ni^{58} as for the natural element. We find about 20 percent more neutron yield from the 50 percent isotope Zn^{64} than Price and Kerst found for the natural element. This difference may still be within the combined experimental error. These measurements substantiate the neutron yield from nickel found by Price and Kerst, which was about one-half of that from the other elements in this region of the periodic table.

TABLE III. Photoneutron yields.

Isotope	Neutrons/mole/roentgen Present work indicated isotope only	Price and Kerst natural element
Fe^{54}	1.01×10^6	1.64×10^6
Ni^{58}	1.12×10^6	1.04×10^6
Zn^{64}	2.82×10^6	2.35×10^6

The absolute neutron yields are based on a maximum cross section for Cu^{63} of 0.10 barn. This value is 10 percent less than our previously published result[1] and is believed to be more accurate.

[1] Johns, Katz, Douglas, and Haslam, Phys. Rev. 80, 1062 (1950).
[2] Huber, Medicus, Preiswerk, and Steffan, Helv. Phys. Acta 20, 495 (1947).
[3] Friedlander, Perlman, Alburger, and Sunyar, Phys. Rev. 80, 30 (1950).
[4] E. Feenberg and G. Trigg, Revs. Modern Phys. 22, 399 (1950).
[5] L. Katz and A. Penfold, Phys. Rev. 81, 815 (1951).
[6] A. G. W. Cameron, Phys. Rev. 82, 272 (1951).
[7] Haslam, Johns, and Horsley, Phys. Rev. 82, 270 (1951).
[8] G. A. Price and D. W. Kerst, Phys. Rev. 77, 806 (1950).

Interpretation of Photoneutron Yields

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"RESONANCE" cross-section curves for several (γ, n)reactions have recently been determined by activation measurements in this laboratory.[1–3] These resonances are of the type predicted for nuclear dipole transitions by Goldhaber and Teller[4] and by Levinger and Bethe.[5] The curves are so similar in relative shape (except for Fe^{54} and C^{12}, which rise steeply owing to high (γ, n) thresholds) that it is possible to use their average cross-section shape in an analysis of the photoneutron yields obtained for 53 elements by Price and Kerst.[6]

TABLE I. Characteristics of (γ, n) cross-section curves.

Reaction	Energy of maximum Mev	E_m-Q Mev[a]	Maximum σ barn	Half-width Mev	Integrated cross section, Mev-barn
$P^{31}(\gamma, n)P^{30}$	17.0	4.6	0.017	7.6	0.13
$Ni^{58}(\gamma, n)Ni^{57}$	18.5	6.8	0.060	4.5	0.33
$Cu^{63}(\gamma, n)Cu^{62}$	17.5	6.6	0.10[b]	5.8	0.63[b]
$Zn^{64}(\gamma, n)Zn^{63}$	18.5	6.7	0.12	7.2	0.83
$Sb^{121}(\gamma, n)Sb^{120}$	14.5	5.2	>0.21	5.4	>1.2
$Sb^{123}(\gamma, n)Sb^{122}$	14.5	5.2	0.34	5.5	2.0
$Ta^{181}(\gamma, n)Ta^{180}$	13.5	5.5	>0.078	4.5	>0.39
Average	—	6.0	—	5.5[c]	—

[a] Energy of peak maximum above threshold.
[b] A 10 percent correction has been applied to the values of reference 1.
[c] This is not the mean of the above values, because the shape averaging was carried out vertically rather than horizontally.

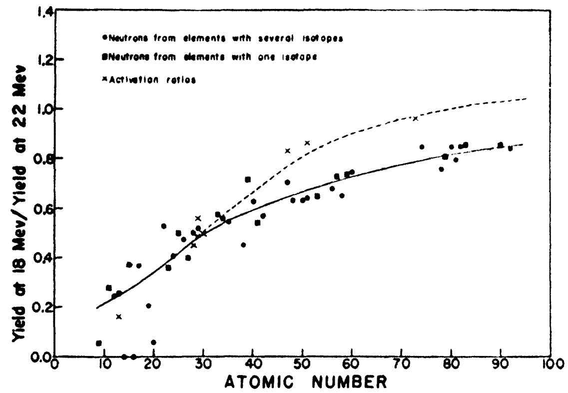

FIG. 1. Ratio of photoneutron yields with 18- and 22-Mev x-rays.

The essential characteristics of the cross-section curves are shown in Table I. An average of the curves was obtained by normalizing them at their peaks in arbitrary cross-section and energy position.

Steinwedel *et al.*[7] predict that the resonance peak energies should vary as $A^{-1/3}$, whereas Goldhaber and Teller predict a variation as $A^{-1/6}$. With the peak position data of Table I and the values for (γ, n) reactions in Cu^{65} (19.0 Mev), Fe^{54} (18.5 Mev),[3] Ag^{109} (16.5 Mev),[8] Al^{27} (19.6 Mev),[9] and C^{12} (22.4 Mev),[10] the best fit to the above type of relationship is

$$E_m = 36A^{-0.18}, \quad (1)$$

where E_m is the peak energy in Mev. This favors the prediction of Goldhaber and Teller. However, the empirical relationship

$$E_m = 21.5\exp(-0.00274A) \quad (2)$$

fits the data much better and has been used in the following considerations.

With the peak energies as calculated from Eq. (2), the average cross-section shape as determined above, and the Schiff x-ray spectrum,[1] the ratio of photoneutron yields for 18 and 22 Mev x-rays was calculated as a function of atomic number. This is plotted as the broken line in Fig. 1. The crosses are the activation ratios which fundamentally determine the curve. The data of Price and Kerst are also plotted in this figure, and the solid curve is the empirical fit to their points. Elements with one or many isotopes are represented, respectively, by solid squares or solid circles. Both types of points fit the empirical curve equally well, indicating that the resonance peak energies for the isotopes in a given element are not appreciably different.

Figure 1 shows that above $Z=30$ there are more neutrons at 22 Mev than can be accounted for from (γ, n) reactions. From threshold considerations these neutrons can only arise from $(\gamma, 2n)$ and (γ, pn) reactions. The ratio of the broken to the solid curve diverges from unity at $Z=30$ and reaches a fairly constant value of 1.22 at $Z=50$. This indicates that the resonance peak energy for $(\gamma, 2n)$ and (γ, pn) reactions falls below 22 Mev at about $Z=40$. Since there are fewer photons at this peak than at the (γ, n) peak, it may be estimated that the sum of the $(\gamma, 2n)$ and (γ, pn) integrated cross sections is of the order of 30 percent of that for (γ, n) reactions (assuming equal contributions from each multiple reaction).

With the above assumptions as to peak shape and energy, the maximum and integrated (γ, n) cross sections were computed directly from the photoneutron yield data. The 22-Mev data were used up to $Z=30$; beyond that, the 18-Mev data were used so as to minimize the contribution from multiple reactions. For the average resonance curve, the integrated cross section (Mev-barns) is related to the peak cross section σ_m (barns) by the expression

$$\int \sigma_{\gamma n} dW = 6.05\sigma_m. \quad (3)$$

These quantities are plotted to relative scales in Fig. 2 as a func-