mony and gold, are also shown in Table III. Values of the separate L-fluorescence yields are shown in the last column of Table III. From these values and the values of n in the last column of Table I, we compute a weighted mean fluorescence yield for xenon, $\bar{\omega}_L = 0.03$.

Fluorescence yields calculated in this manner by Kinsey for high Z are in general somewhat lower than values found experimentally. For xenon the value is considerably lower and is inconsistent with the present experiment.

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Photoneutron Cross Sections in Mg^{24}, Mg^{25}, Zr^{90}, Zr^{91}†

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The variation of $\sigma(\gamma,n)$ with E_γ from threshold to 24 Mev has been measured by detecting neutrons produced from betatron bremsstrahlung irradiation of separated isotope samples in oxide form. Despite the large threshold differences (9.3 Mev for the Mg isotopes and 5.0 Mev for the Zr isotopes) the peaks of the giant dipole resonances are very close for each pair of adjacent isotopes: Mg^{24}, 19.5 Mev; Mg^{25}, 20.3 Mev; Zr^{90}, 16.4 Mev; Zr^{91}, 16.3 Mev. The half-widths of the Zr resonances are unusually small, 4.1 and 5.4 Mev, compared to 8 Mev for nearby nuclei observed previously. This is apparently a "magic number" effect.

INTRODUCTION

PREVIOUS measurements in this laboratory[1] have indicated that the giant dipole resonances in (γ,n) processes occur at a photon energy which depends only on the mass number of the nuclide. The energy (E_m) at which the maximum cross section occurs varies slowly from about 13.5 Mev for $A=200$ to about 22.5 Mev for $A\leq 20$. Measurements elsewhere[2] have generally been in accord with this observation, but deviations from the smooth variation have been reported. It has been suggested[3] that the apparent smooth variation of E_m with A is accidental and that E_m is instead closely related to the (γ,n) threshold energy, E_{th}, so that $E_m - E_{th}$ is approximately constant. Since E_{th} does in general decrease slowly with increasing A, this is not in absolute contradiction to our observations.

A second interesting feature of the giant resonances which was observed here previously[1] is that the width of the resonance varies slowly from about 7 Mev for $A=238$ to 10 Mev for $A=31$. (Below $A=31$ the widths for the 5 elements we have measured so far are much smaller, 3 to 7 Mev.) However, the nuclides with 28, 52, 82, and 126 neutrons have widths from 2 to 4 Mev less than the smooth variation noted for other nuclides. Except for $N=52$ these are "magic" neutron number nuclides, and $N=52$ is only two units away from the magic number 50.

In making a careful study of the variation of E_m with A or with E_{th}, the neutron detection method is to be preferred over the method of residual activity because the apparatus is identical for all target materials, and problems of half-lives, decay schemes, and decay energies differing for the various nuclides used do not enter. (It is also necessary to use only data from a single laboratory in making a critical evaluation, because of the known difficulties in comparing photonuclear cross sections measured in different laboratories.[4]) There is however the limitation that one is restricted to measurements on isotopes of not much less than 100 percent abundance. It is thus possible that observed variations of E_m with A might be of a special nature, related to the properties of the relatively small number of nuclides which can be studied in their naturally occurring abundances. This limitation can be overcome by using separated isotopes, which are now rather extensively available from the Oak Ridge National Laboratory.

A critical test of the dependence of E_m on E_{th} or on A can be made by measuring the (γ,n) cross section *vs* energy curve for two adjacent isotopes which have very different E_{th} values. On the hypothesis that the mass number is the determining factor, E_m will be the same for the two isotopes. On the hypothesis that E_{th} is the determining factor, the difference in the E_m values for the two isotopes should be comparable to the difference in the E_{th} values.

One of the most extreme cases available for examination is the isotopic pair Mg^{24}-Mg^{25}. The natural abun-

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

[2] See Montalbetti, Katz, and Goldemberg, Phys. Rev. 91, 659 (1953) for a summary of much data on this and other features of (γ,n) cross sections.

[3] L. Katz and A. S. Penfold, Phys. Rev. 81, 815 (1951); Katz, Baker, Haslam, and Douglas, Phys. Rev. 82, 271 (1951).

[4] J. Goldemberg and L. Katz, Can. J. Phys. 32, 49 (1954), discuss the degree of agreement among various laboratories engaged in this work.

dances and (γ,n) thresholds are given in Table I. The difference in the E_{th} values is 9.3 Mev. Katz *et al.*[5] have reported measurement of the $Mg(\gamma,n)$ cross section, of the natural element, by neutron detection, and of the $Mg^{24}(\gamma,n)Mg^{23}$ cross section by residual activity. They have used these results to estimate the $Mg^{25}(\gamma,n)$ and $Mg^{26}(\gamma,n)$ cross sections, but a direct measurement is necessary if the results are to be used for a quantitative check of the hypotheses.

It is also desirable to investigate a case with a larger value of A, since the parameters of the giant resonance are believed to behave more regularly for A values above 40. A favorable case for study is the isotopic pair Zr^{90}-Zr^{91}, the natural abundances and (γ,n) thresholds of which are given in Table I. The difference in the E_{th} values is 5 Mev. These isotopes are also favorable for studying the "magic number" effect on the widths of the giant resonances, since Zr^{90} has 50 neutrons.

EXPERIMENT

The neutron detector consisted of four BF_3 counters embedded in a large (2 ft×2 ft×3 ft) paraffin block, with shielding from external neutrons. This is the same apparatus used in previous measurements, and has been described in detail.[6] The only modification for the present work was in the sample holder. This consisted of an aluminum tube 0.645 in. in diameter and $1\frac{7}{16}$ in. long with 0.011 in. thick walls, supported in the center of the hole through the paraffin house by a light aluminum ring. The samples, which were powdered oxides, were held in the tube by polyethylene end caps 0.0015 in. thick. These end caps, being flexible, bowed out somewhat in the middle, and for Zr^{91} it was necessary to take a check point on the yield curve using flat aluminum end caps, in order to determine the mass of the sample in the beam during the main run. The correction in this case was about 15 percent. For the other samples it was negligible. The Mg^{25} sample was compressed into a solid pill $\frac{5}{16}$ in. in diameter and was held by the taut polyethylene end caps so that it was entirely in the gamma-ray beam from the betatron, which had a diameter of 0.95 cm at the sample.

TABLE I. (γ,n) thresholds and natural abundances of isotopes investigated.

Nuclide	Natural abundance (percent)	$E_{th}(\gamma,n)$ (Mev)
Mg^{24}	78.60	16.6
Mg^{25}	10.11	7.3
Zr^{90}	51.46	12.2
Zr^{91}	11.23	7.2

The isotopic compositions of the samples are shown in Table II. The contribution of the oxygen content of the samples was subtracted from the measured yields using the oxygen yield measured here previously.[7] The contribution of the Mg^{24} in the Mg^{25} sample was subtracted, using the present Mg^{24} measurements. Similarly the Zr^{90} contribution to the Zr^{91} sample was subtracted. In addition, the contribution of a 1.1 percent Hf impurity in the Zr^{91} sample was subtracted on the assumption that the (unknown) Hf yield is the same as that measured for Ta.[1] The conversion of the net yield curves into cross-section curves was done by the usual "total spectrum" method, using the Schiff thin-target bremsstrahlung spectrum modified by the absorbing materials in the beam.

TABLE II. Isotopic compositions (atomic percent) of the 4 samples used. The mass numbers refer to the magnesium and zirconium isotopes.

Mass No.	Abundance	Abundance
	A	*B*
24	99.59	5.87
25	0.30	92.33
26	0.11	1.80
	C	*D*
90	98.66	12.3
91	0.77	75.1
92	0.34	10.5
94	0.18	1.9
96	0.04	0.2

The total number of counts recorded for each sample is shown in Table III. The background varied from about 15 percent in Mg^{25} to about 1.5 percent in Zr^{90}, and about 20 000 counts were recorded each of the three times the background was measured, once for the zirconium isotopes and once each for the magnesium isotopes. The oxygen contribution varied from 25 percent of the total yield at maximum energy in Mg^{24} to 1.8 percent in Zr^{91}.

RESULTS

The parameters of the "giant resonance" cross section curves are given in Table IV for the four isotopes we have measured. There is a discussion of the sources and magnitudes of the errors in these quantities in reference 1, which is applicable to the present work. It

TABLE III. The total number of counts recorded in measuring the yield curves of the four samples, the mass of the samples within the γ-ray beam, and the area densities of the sample in the direction of the γ-ray beam.

	Sample	Counts	Sample in γ-ray beam Grams	Grams/cm²
A	$Mg^{24}O$	280 000	2.610	2.394
B	$Mg^{25}O$	186 000	0.870	1.759
C	$Zr^{90}O_2$	687 000	1.606	2.253
D	$Zr^{91}O_2$	309 000	0.446	0.626

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[5] Katz, Haslam, Goldemberg, and Taylor, Can. J. Phys. **32**, 580 (1954).

[6] Halpern, Mann, and Nathans, Rev. Sci. Instr. **23**, 678 (1952).

[7] Ferguson, Halpern, Nathans, and Yergin, Phys. Rev. **95**, 776 (1954).

TABLE IV. Parameters of the (γ,n) cross-section curves measured. E_m is the energy at which the maximum cross section, σ_m, occurs. Γ is the full width of the curve between the two points at $\frac{1}{2}\sigma_m$. Column 6 gives the value predicted for E_m from an empirical relationship (see reference 1).

1 Nuclide	2 E_m (Mev)	3 Γ (Mev)	4 σ_m (mb)	5 $\int_0^{24}\sigma dE$ (Mev-b)	6 $38.5A^{-0.19}$
Mg^{24}	19.5	7–8	8.4	0.055	21.1
Mg^{25}	20.3	5.0	16.5	0.096	20.9
Zr^{90}	16.0	4.1	185	0.89	16.4
Zr^{91}	16.2	5.4	200	1.27	16.3
Errors	±1.0	±1.0	±15%	±15%	

should be noted, however, that the errors quoted in Table IV are estimates of the absolute errors in the quantities, and the *relative* magnitudes for two isotopes of the same element are probably much better known. For example, the quoted errors on the half-widths would permit the possibility that the two zirconium isotopes have the same widths. The data actually show unambiguously that the Zr^{90} curve is narrower than that of Zr^{91}. Individual comments for each of the isotopes follow.

Magnesium-24

The (γ,n) cross section measured for Mg^{24} is shown in Fig. 1. The agreement with the result of Katz *et al.*[8] for $Mg^{24}(\gamma,n)Mg^{23}$ by residual activity is as good as is to be expected.

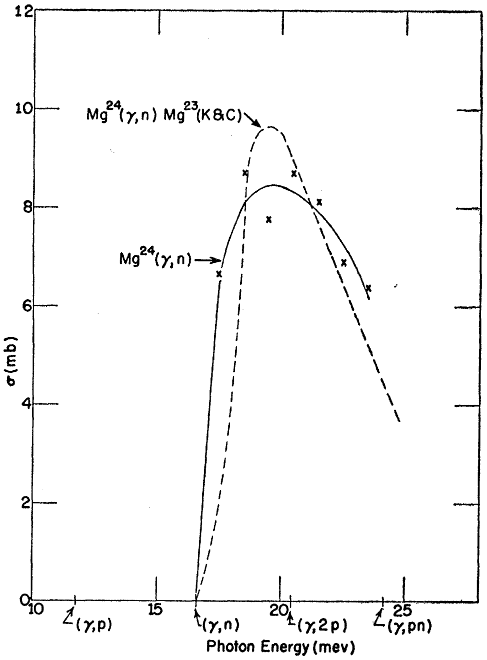

FIG. 1. (γ,n) cross section for Mg^{24}. The ordinate scale is in millibarns (10^{-27} cm²). The locations of the thresholds for various reactions are indicated by arrows. The crosses are the points calculated from the yield data. The solid curve is drawn to fit the points. The dashed curve represents results previously reported by others for $Mg^{24}(\gamma,n)Mg^{23}$ by the residual activity method (see reference 8).

Magnesium-25

The (γ,n) cross section measured for Mg^{25} is shown in Fig. 2. It is apparent that the peak of the cross section curve occurs at about the same place as that of Mg^{24}, despite the enormous (9.3-Mev) threshold difference. This is in disagreement with the estimate by Katz *et al.*[5] of the $Mg^{25}(\gamma,n)$ cross section. It would seem that the error in that estimate arose from the assumption that the entire giant resonance in the natural element is due to Mg^{24}, when in fact our results show that Mg^{25} contributes in this region twice as much as its abundance would suggest, relative to Mg^{24}; and also from the assumption that the Mg^{24} and Mg^{25} yields are the same far above the thresholds, while our measurements give a 22-Mev yield for Mg^{25} which is almost three times that of Mg^{24}. For comparison with our results the $Mg^{25}(\gamma,p)$ cross sections measured by others[5,9,10] are shown in Fig. 2. As has been generally

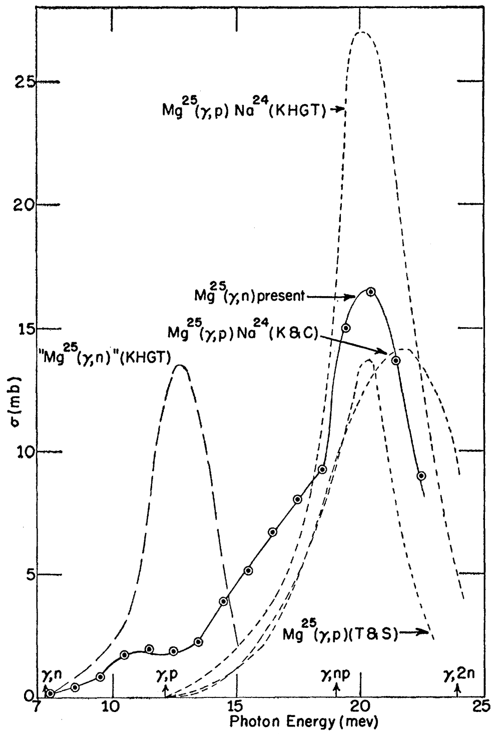

FIG. 2. (γ,n) cross section for Mg^{25}. The ordinate scale is in millibarns (10^{-27} cm²). The locations of the thresholds for various reactions are indicated by arrows. The circles are the points calculated from the yield data. The solid curve is drawn to fit the points. The three dotted curves are the previously reported $Mg^{25}(\gamma,p)Na^{24}$ cross sections (see references 5, 9, and 10). The dashed curve is the estimate of the $Mg^{25}(\gamma,n)$ cross section made previously by subtracting the $Mg^{24}(\gamma,n)$ of reference 8 from the measured cross section for natural Mg (see reference 5).

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[8] Katz, Baker, and Montalbetti, Can. J. Phys. **31**, 250 (1953).

[9] L. Katz and A. G. W. Cameron, Phys. Rev. **84**, 1115 (1951).

[10] E. Toms and W. E. Stephens, Phys. Rev. **82**, 709 (1951).

observed, the (γ,n) and (γ,p) curves are quite similar in shape and location. Our $\mathrm{Mg}^{25}(\gamma,n)$ results are for a net sample of 98.1 percent Mg^{25} and 1.9 percent Mg^{26}.

Zirconium-90

The $\mathrm{Zr}^{90}(\gamma,n)$ cross section is shown in Fig. 3. For comparison the measurement of Katz *et al.*[8] for $\mathrm{Zr}^{90}(\gamma,n)\mathrm{Zr}^{89*}$ is also shown. Making allowance for the usual failure of agreement on shape among different laboratories, it is observed that the peak cross sections agree fairly well, indicating that most of the (γ,n) events in Zr^{90} lead to the isomeric state of Zr^{89}, and few if any to the ground state. For energies near threshold this has been observed previously.[11]

Zirconium-91

The $\mathrm{Zr}^{91}(\gamma,n)$ cross section is shown in Fig. 3. Its resemblance to that of Zr^{90} is remarkable. The location and height of the peak are in excellent agreement. However, the width is definitely greater. The low energy "shelf" is typical of what has been seen in the light elements like N, O, and F which have narrow resonances well above their thresholds. This shelf is not observed when the resonance is broad or close to the threshold. The results represent a sample of 85.6 percent Zr^{91}, 12.0 percent Zr^{92}, 2.2 percent Z^{94} and 0.2 percent Zr^{96}.

DISCUSSION

E_m

The lack of dependence of the location of the giant resonance peak on the (γ,n) threshold is clearly shown by the Zr^{90}-Zr^{91} results, and also by the Mg^{24}-Mg^{25} results. The Zr isotopes are presumably more typical of the intermediate and heavy nuclides, and so verify the A-dependence of the peak location for this region. The second and sixth columns of Table IV compare the observed peak locations with those calculated from the empirical formula, $E_m=38.5A^{-0.19}$, derived from previous observations.[1] The agreement is excellent. One expects marked deviations from the systematic behavior for light elements, and the shapes of the Mg^{24} and Mg^{25} curves are accordingly radically different. Despite this the peaks are within 1 Mev of each other. This, as well as the closeness with which all the E_m values we have so far observed fall on a smooth curve suggest that the location of the peak of the resonance is almost completely independent of anything except the mass number A. It has been pointed out that on rather fundamental grounds there ought to be a close connection between the location of the peak and the mean kinetic energy of nucleons in the nucleus. This latter quantity is presumably determined mostly by the mass number, via the nuclear radius.

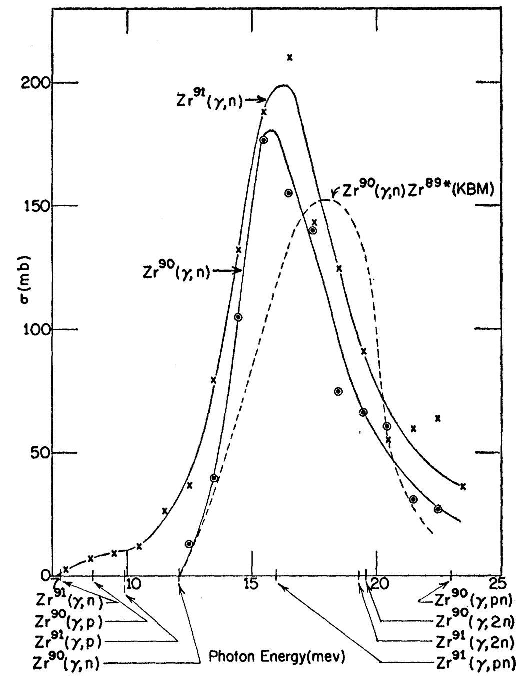

FIG. 3. (γ,n) cross sections for Zr^{90} and Zr^{91}. The ordinate scale is in millibarns (10^{-27} cm^2). The points shown are those calculated from the yield data. The solid curves are drawn to fit the points. The dashed curve is the cross section reported (see reference 8) for the production of the isomeric state of Zr^{89} by photon bombardment of natural Zr. The locations of the thresholds for various reactions in the two isotopes are indicated by the arrows.

Half-Widths

The half-widths of the cross-section curves for the Zr isotopes are substantially less than for most other medium and heavy elements.[1] The Zr^{90} curve is the narrowest of the 16 elements above a mass number of 30 that we have so far measured. The isotopes Zr^{90}, Zr^{91}, and Nb^{93} form a progression of neutron numbers, 50, 51, and 52. The corresponding half-widths are 4.1, 5.4, and 6.8 Mev. This strongly suggests a sharp "dip" in the half-widths at magic neutron numbers.

The estimate of Katz *et al.* regarding the $\mathrm{Mg}^{25}(\gamma,n)$ cross section being incorrect, there is now no indication that the inversion of the usual order of the thresholds for (γ,p) and (γ,n) in this isotope produces any anomaly in the location of the corresponding resonance peaks. The agreement of the locations and shapes of the $\mathrm{Mg}^{25}(\gamma,n)$ and $\mathrm{Mg}^{25}(\gamma,p)$ peaks is excellent.

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[11] P. Axel and J. D. Fox, Phys. Rev. **95**, 613(A) (1954).