Neutron Cross-Section Measurements of Antimony, Gallium, Cadmium, and Mercury*

R. RONALD PALMER† AND LOWELL M. BOLLINGER
Argonne National Laboratory, Lemont, Illinois
(Received September 7, 1955)

The results of neutron transmission measurements on antimony, gallium, cadmium, and mercury, and on their separated isotopes are presented. Several methods are described for finding resonance parameters from neutron transmission measurements. Level parameters are reported for six resonances of Sb^{121}; four of Sb^{123}; three for Ga^{69}; four for Ga^{71}; and one each for Cd^{110} and Cd^{111}. Isotopic assignments are made for three resonances in mercury.

I. INTRODUCTION

THIS paper is No. II of a series of papers reporting results of neutron cross section measurements using the Argonne Fast Chopper. Paper No. I[1] described the apparatus and operating characteristics of the chopper system, and presented results of transmission measurements on bismuth, selenium, and manganese.

Briefly, the chopper system, as used in the present measurements, consists of a mechanical device for releasing short bursts of neutrons from the Argonne Heavy Water Pile (*CP*-3′), a counter for detecting these neutrons, and a 100-channel flight time analyzer. The latter records the number of neutrons which have traveled a given distance from the chopper as a function of the time required. Flight paths of 10, 20, and 40 meters length were used. Runs of several hours duration taken with and without a sample material interposed in the beam enable one to calculate the transmission of the sample and, from this, its nuclear cross section. The results of such measurements on antimony, cadmium, gallium, and mercury, and on their partially separated isotopes, are presented in this paper, together with a determination of the resonance parameters for the prominent resonances observed.

II. ANALYSIS OF DATA

When the neutron transmission of a particular element is plotted as a function of neutron energy occasional dips may be observed at certain critical energies. For the present data, each dip is due to a selective process of scattering or radiative absorption of the neutron (or both) and, in many cases, the parameters associated with the resonance process may be found by applying the Breit-Wigner one-level formulas. These formulas

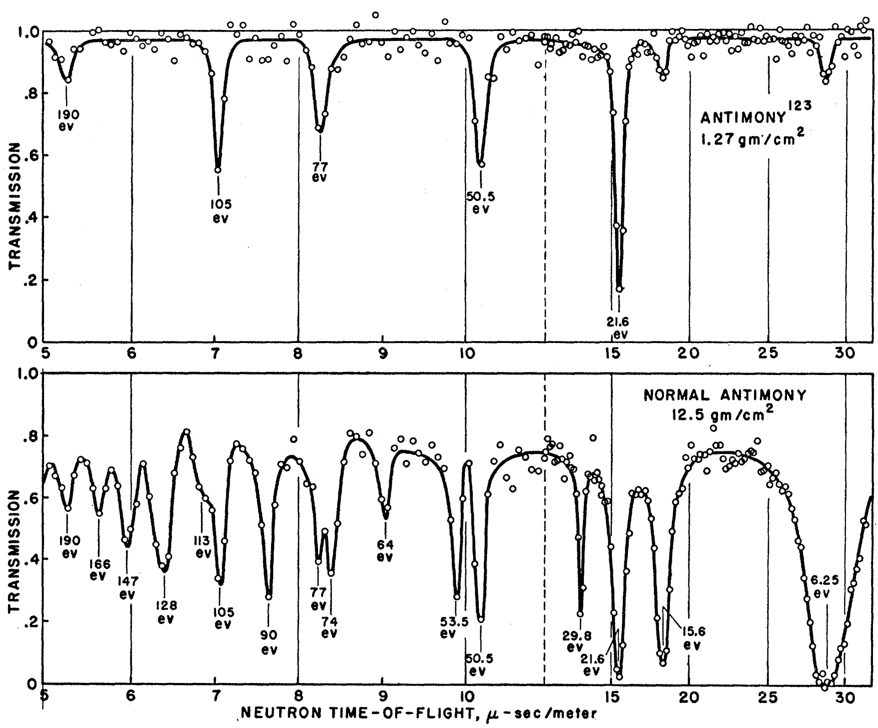

FIG. 1. The neutron transmission of normal antimony and Sb^{123}. The data were obtained with a resolution of 0.12 μsec/m for energies greater than 35 ev and about 0.35 μsec/m at the lower energies.

* Work performed under the auspices of the U. S. Atomic Energy Commission.
† When on leave from Beloit College, Beloit, Wisconsin.
[1] Bollinger, Dahlberg, Palmer, and Thomas, Phys. Rev. 100, 126 (1955).

TABLE I. Resonance parameters for Sb^{121}. Parameters are determined for assumed values of Γ_γ of 0.06 and 0.10 ev except in the case of the 6.25 ev resonance where the most probable value of Γ_γ is 0.06 ± 0.02 ev.

E_0 (ev)	Γ_γ (ev)	σ_0 (barns)	Γ (ev)	$\sigma_0\Gamma^2$ (b-(ev)^2)	Γ_n (ev)	$\Gamma_n/\sqrt{E_0}$ (ev$^{\frac{1}{2}}$)	Samples used for analysis (g/cm^2)
6.25	0.06 ±0.02	10 800 ±4000	0.062 ±0.02	41.5 ±1.5	0.0032 ±0.0003	0.0013	1.8, 0.17, and 12.5
15.6	0.06 0.10	11 900 5800	0.070 0.107	58 66	0.0100 0.0074	0.0025 0.0019	1.8 and 0.17
29.8	0.06 0.10	5200 2600	0.068 0.106	25 29	0.0082 0.0063	0.0015 0.0012	1.8
53.5	0.06 0.10	1400 630	0.064 0.103	5.8 6.6	0.0037 0.0027	0.0005 0.0004	12.5
64.0	0.06 0.10	360 200	0.061 0.101	1.3 2.0	0.0011 0.0010	0.00013 0.00012	12.5
74.0	0.06 0.10	2900 1300	0.072 0.108	15 16	0.0119 0.0083	0.0014 0.0010	12.5
90	0.06 0.10	5800 3500	0.102 0.132	60 61	0.041 0.032	0.0043 0.0033	12.5

express the cross section for scattering σ_s, and for neutron capture σ_γ as a function of energy as follows[2]:

$$\sigma_s=\sigma_0\frac{\Gamma_n}{\Gamma}\frac{1+\dfrac{4R}{\lambda_0\Gamma_n}(E-E_0)}{1+[(E-E_0)/\frac{1}{2}\Gamma]^2}+\sigma_p, \tag{1}$$

$$\sigma_\gamma=\sigma_0\frac{\Gamma_\gamma}{\Gamma}\left(\frac{E_0}{E}\right)^{\frac{1}{2}}\frac{1}{1+[(E-E_0)/\frac{1}{2}\Gamma]^2}, \tag{2}$$

$$\sigma_0=4\pi\lambda_0^2 g\Gamma_n/\Gamma, \tag{3}$$

where

$$g=\tfrac{1}{2}\left(1\pm\frac{1}{2i+1}\right),\quad\text{and}\quad \Gamma=\Gamma_\gamma+\Gamma_n.$$

Here E is the energy of the incident neutron and E_0 is the energy at exact resonance; σ_0 is the cross section at resonance; σ_p is the potential cross section—that cross section which presumably would prevail in the absence of the resonance; i is the spin of the target nucleus; $2\pi\lambda_0$ is the wavelength of the neutron at resonance; R is the "hard core" radius of the target nucleus; Γ is the width of the resonance at half-maximum; and Γ_n/Γ and Γ_γ/Γ give the fraction of σ_0 due to neutron scattering and neutron capture, respectively.

Because of finite instrumental resolution and because of the temperature motion of target nuclei, one cannot, in general, obtain resonance parameters directly from an experimentally determined transmission dip. The methods used by the Columbia Velocity Selector Group and by the Brookhaven Fast Chopper Group for determining resonance parameters have been described in detail in recent papers.[3,4] The methods used in this paper are quite similar; modifications will be described as required.

[2] H. A. Bethe, Revs. Modern Phys. **9**, 115 (1937).

[3] Melkonian, Havens, and Rainwater, Phys. Rev. **92**, 702 (1953).

[4] Seidl, Hughes, Palevsky, Levin, Kato, and Sjostrand, Phys. Rev. **95**, 476 (1954).

III. RESULTS

Antimony

The cross section of antimony had earlier been measured by the Columbia Velocity Selector Group.[5] However, since the Argonne Fast Chopper had a higher resolution, and since an enriched sample of Sb^{123} was available, it seemed desirable to repeat the measurements over the resonance energy region. It is of course possible to make a detailed determination of resonance parameters only if isotopic assignment is known.

Three different normal antimony samples were used, with thicknesses 0.170, 1.786, and 12.52 g/cm^2. The thickness of the Sb^{123} sample was 1.27 g/cm^2. The measured transmission of the thick antimony sample and also that for the Sb^{123} sample are shown in Fig. 1, plotted as a function of time-of-flight in μsec/meter. The energy corresponding to each resonance is indicated in electron volts. Though the transmission curves for the other antimony samples are not reproduced here they were all used in making the analyses reported below. Cross sections calculated from our data appear in the literature.[6]

By comparing the two curves of Fig. 1, each of the major resonances can be assigned to one of the two isotopes of antimony. Those resonances which have been assigned to Sb^{121} and for which resonance parameters have also been determined, are listed in Table I. Likewise, Table II lists those assigned to Sb^{123}.

[5] Rainwater, Havens, Wu, and Dunning, Phys. Rev. **71**, 65 (1947).

[6] *Neutron Cross Sections*, and 3 supplements, U. S. Atomic Energy Commission Report AECU-2040 (Office of Technical Services, Department of Commerce, Washington, D. C., 1952). Also, D. J. Hughes and J. A. Harvey, "Neutron Cross Sections," BNL 325, July 1, 1955, Brookhaven National Laboratory (U. S. Government Printing Office.)

TABLE II. Resonance parameters for Sb^{123}. Parameters are determined for assumed values of Γ_γ of 0.06 and 0.10 ev.

E_0 (ev)	Γ_γ (ev)	σ_0 (barns)	Γ (ev)	$\sigma_0\Gamma^2$ (b-ev)	Γ_n (ev)	$\Gamma_n/\sqrt{E_0}$ (ev$^{\frac{1}{2}}$)	Samples used for analysis (g/cm²)
21.6	0.06	21 000	0.092	177	0.032	0.0069	1.8 and 0.17
	0.10	11 700	0.124	180	0.024	0.0052	and Sb^{123}
50.5	0.06	2480	0.066	11	0.0065	0.0009	12.5 and Sb^{123}
	0.10	1250	0.105	14	0.0050	0.0007	
76.5	0.06	4350	0.080	28	0.020	0.0023	12.5 and Sb^{123}
	0.10	2400	0.116	32	0.016	0.0018	
105	0.06	6700	0.131	115	0.071	0.0069	12.5 and Sb^{123}
	0.10	4600	0.161	119	0.061	0.0060	

Inasmuch as these resonances are primarily capture resonances and are therefore expected to be somewhat symmetrical in shape, the parameters reported in Tables I and II were determined by a modification of the by now standard area analysis method which includes the effect of Doppler broadening.[3,7] A curve fitting procedure was also applied to the wings of the prominent 6.25-ev resonance to yield an independent determination of $\sigma_0\Gamma^2$ for that level.

(a) *6.25-ev Resonance*

Figure 2 gives the result of applying the area analysis technique to the 6.25-ev transmission dip for two sample thicknesses. The two heavy intersecting lines give pairs of values of σ_0 and Γ which satisfy the area-Doppler criterion for the respective sample thicknesses. The point of intersection of the two heavy lines gives preliminary estimates of σ_0 and Γ. The dashed line in Fig. 2 is an independent determination of the combination of parameters $\sigma_0\Gamma^2$ by making use of the shape of the experimental curve in the wings of the resonance as follows: Since the 6.25-ev resonance is primarily a capture resonance (i.e., $\Gamma_\gamma \approx \Gamma$), the total cross section in the wings, where $|E-E_0| \gg \Gamma$, is given to a good approximation by

$$\sigma_t - \frac{\sigma_0 \Gamma R}{\lambda\!\!\!^{-}_0 (E-E_0)} = \frac{\sigma_0\Gamma^2}{4(E-E_0)^2}\left(\frac{E_0}{E}\right)^{\frac{1}{2}} + \sigma_p.$$

It turns out that the second term on the left is small compared to the term in $(E-E_0)^{-2}$; therefore appreciable uncertainties in the values of $\sigma_0\Gamma$ and R have but a small effect on the value of the equation. Furthermore, one may use experimentally measured cross sections for σ_t in this equation, for neither instrumental resolution nor Doppler broadening appreciably affects the measurement of cross section in the wings of the resonance. Using approximate values for $\sigma_0\Gamma$ and for R, the quantity $Z=\sigma_t-\sigma_0\Gamma R/[\lambda\!\!\!^{-}_0(E-E_0)]$ may be plotted as a function of $(E_0-E)^{-2}(E_0/E)^{\frac{1}{2}}$. This should yield a straight line with its Z intercept equal to σ_p and a slope equal to $\sigma_0\Gamma^2/4$. Since $\sigma_p=4\pi R^2$, R may be calculated. If the derived parameters are appreciably different from the values initially used in the calculation, the process is repeated for new parameters. Only one or two repetitions are required before satisfactory agreement is reached.

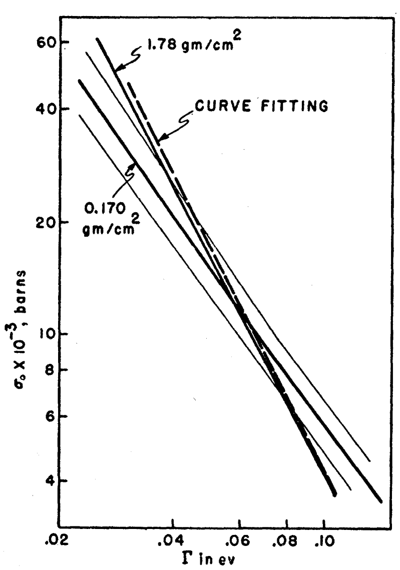

FIG. 2. Analysis of the 6.25-ev resonance in Sb^{121}. The heavy solid lines were obtained from area data and the heavy dashed line was calculated from the value of $\sigma_0\Gamma^2$ obtained by curve fitting. The fine solid lines indicate the magnitude of the errors associated with the 0.170 g/cm² data.

Figure 3 shows the result of applying this procedure to the 6.25-ev resonance of antimony using the thick 12.5 g/cm² data for σ_t. The slope of the line gives us $\sigma_0\Gamma^2 = 24.6$ b-(ev)² referred to normal antimony or 43 b-(ev)² referred to the proper isotope, Sb^{121} (since normal antimony is 57.2% Sb^{121}). When $\sigma_0\Gamma^2=43$ is plotted in Fig. 2, it quite accurately parallels the line obtained by the area analysis method applied to the 1.8-g/cm² data. Evidently a 1.8-g/cm² sample of antimony is a "thick" sample. The parameters obtained for the 6.25-ev resonance by combining the results of the area and curve fitting techniques of analysis are listed in Table I.

The Z-intercept of the straight line of Fig. 3 yields a potential cross section of $\sigma_p=4\pi R^2=4.4\times10^{-24}$ cm², or $R=0.59\times10^{-12}$ cm. This is 20% less than the radius

[7] G. von Dardel and R. Persson, Nature **170**, 1117 (1952).

calculated from the frequently used relation $R=1.45\times10^{-13}A^{\frac{1}{3}}$.

The above method of determining $\sigma_0\Gamma^2$ is somewhat similar to that used by Kato *et al.*[8] to give $g\Gamma_n$ for resonances which have a scattering shape, knowing beforehand the approximate value of $\sigma_0\Gamma^2$.

(*b*) *Resonance at Higher Energies*

An area analysis of two sets of data obtained for the 15.6-ev resonance yields the intersecting straight lines in Fig. 4. The errors associated with the thin sample data are so large, however, that reliable independent values of σ_0 and Γ cannot be deduced from the area data alone. Additional information can be obtained by making use of Eq. (3), which for our purpose may be written $\sigma_0=2.6\times10^6 gE_0^{-1}(1-\Gamma_\gamma/\Gamma)$. A plot of this equation may be superposed on the graph of σ_0 *vs* Γ obtained from the area analysis, using assumed values for the radiation width Γ_γ and the statistical factor g. Such curves have been drawn in Fig. 4 for two assumed values of Γ_γ, namely 0.06 ev and 0.10 ev; 0.06 ev was selected as the value obtained for the 6.25-ev resonance and 0.10 ev was the value suggested by the widths of neighboring isotopes, as quoted by Hughes and Harvey[9] and Heidmann and Bethe.[10] It is seen that, for a given Γ_γ the two possible values of g, 5/12 and 7/12 in the case of antimony, give nearly the same curve in the region of interest—an effect caused by the small magnitude of Γ_n/Γ. On the other hand, when $\Gamma_n/\Gamma\ll1$, the value assumed for Γ_γ has a strong influence on the values derived for σ_0 and Γ. The present technique can nevertheless give meaningful results because other useful parameters, such as Γ_n, are not sensitively dependent on the value assumed for Γ_γ.

The foregoing procedure has been followed for each of the resonances of antimony. The values of parameters that were obtained are reported in Tables I and II. In each case the parameters selected are the coordinates of the point on the theoretical curve, obtained for each Γ_γ, which is midway between the two straight lines obtained by the area analysis method outlined previously. The principle source of error in the parameters of all resonances except that at 6.25 ev is the uncertainty in the value of Γ_γ. A qualitative measure of the magnitude of the resulting uncertainties in the derived parameters is given by the differences between the values obtained for $\Gamma_\gamma=0.06$ and $\Gamma_\gamma=0.10$.

(*c*) *Determination of* Γ_γ *from Resonance Scattering Integral*

In principle, it is possible to make a determination of a weighted average value of Γ_γ for an element for which $\Gamma_\gamma\ll1$ by making use of measured values of its resonance scattering integral. Such measurements have been reported by Muehlhause and co-workers,[11] who give values of the quantity $\frac{1}{2}\pi\sum_r(S(E_0)\sigma_0\Gamma_n/E_0)_r$, where $S(E_0)$ is the sensitivity of the detection system used and the summation is over all resonances r. An average radiation width may be obtained by finding the Γ_γ giving resonance parameters which, when substituted in the above summation, result in a "resonance integral" equal in value to that reported by Muehlhause; the value of the sum varies rapidly with Γ_γ since the $\sigma_0\Gamma_n$ obtained for each resonance depends sensitively on the assumed Γ_γ. A comparison of this kind can only be accomplished in those cases where the parameters σ_0 and Γ_n are known for a sufficient number of resonances so that the contribution of the higher energy resonances to the summation can be satisfactorily approximated.

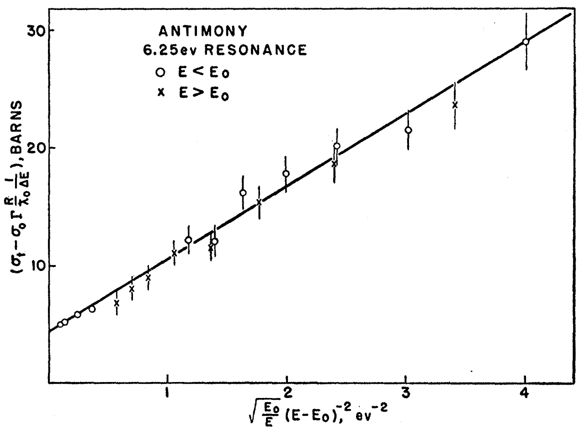

FIG. 3. Wing analysis of the 6.25-ev resonance in Sb^{121}. The slope of the straight line gives $\sigma\Gamma_0^2=24.6$ b-ev^2 for normal antimony or 43 b-ev^2 referred to Sb^{121}. The Z-intercept gives $R=0.59\times10^{-12}$ cm.

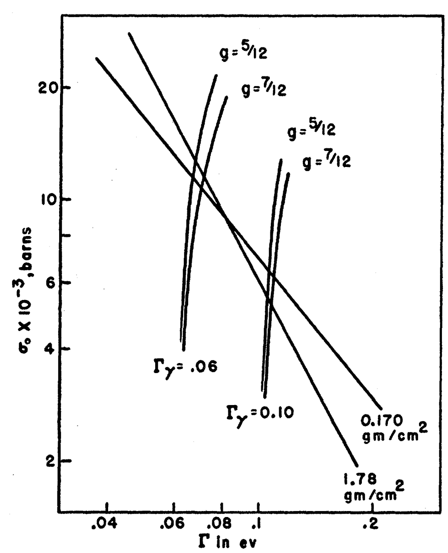

FIG. 4. Analysis of the 15.6-ev resonance in Sb^{121}, illustrating a convenient technique of obtaining resonance parameters from area data for assumed values of Γ_γ.

[8] Kato, Hughes, and Levin, Phys. Rev. 93, 931 (1954).
[9] D. J. Hughes and J. A. Harvey, Nature 173, 942 (1954).
[10] J. Heidmann and H. A. Bethe, Phys. Rev. 84, 274 (1951).
[11] Harris, Muehlhause, and Thomas, Phys. Rev. 79, 11 (1950).

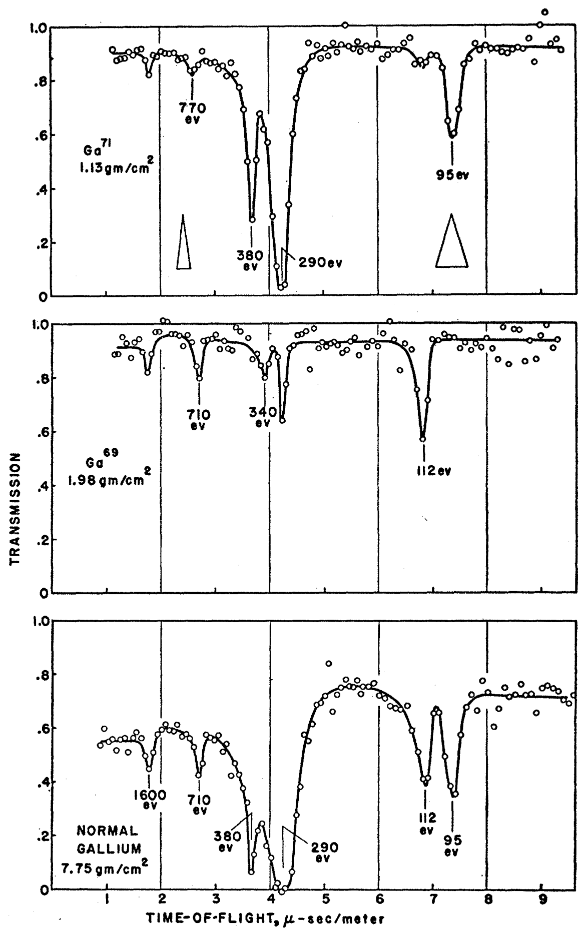

FIG. 5. Neutron transmission of normal gallium and its isotopes as obtained with a resolution of 0.14 μsec/m.

The foregoing summation has been calculated for antimony using both sets of parameters listed in Tables I and II, i.e., those for $\Gamma_\gamma = 0.06$ ev and also for 0.10 ev. The measured scattering integral for antimony reported by Harris *et al.*[11] falls approximately midway between these two calculated summations. On estimating the possible range of errors in the reported value

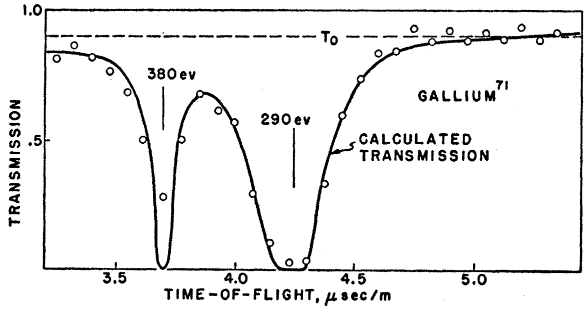

FIG. 6. Comparison of the calculated transmission, using the parameters given in Table III, and the experimentally measured transmission in the vicinity of the 290- and 380-ev resonances of Ga^{71}.

of the measured scattering integral and also in the values of the parameters used in the summation, this method leads to $\Gamma_\gamma = 0.07 \pm 0.02$ ev for the capture width of antimony. This value is a weighted average value which is strongly influenced by the width of the 21.6-ev resonance. It is noteworthy that the two values obtained for Γ_γ, namely, 0.07 ± 0.02 and 0.06 ± 0.02, are in good agreement.

Gallium

The neutron cross section of gallium had previously been measured at Harwell[12] and at Columbia[3] but with poorer instrumental resolution than available with the Argonne Fast Chopper. Our results for the potential cross section are in essential agreement with these earlier measurements, but because of better resolution, we observe a finer structure in the resonance region. Furthermore, since separated isotopes of gallium were available for transmission measurements, we were able to make isotopic assignment for several of the prominent resonances, and thus to determine their resonance parameters.

(*a*) *Resonance Parameters*

Two different samples of normal gallium were used, one of thickness 7.75 g/cm² and the other, 5.95 g/cm². The latter was used only for normalization purposes at low resolution. The Ga^{69} and Ga^{71} samples were oxides of thickness 1.98 g/cm² and 1.126 g/cm², respectively; they were 98.4% and 98.1% isotopically pure, respectively.

The measured transmission for normal gallium and for its isotopes is plotted in Fig. 5. The Columbia Velocity Selector Group[3] reported broad resonances at about 100 and 300 ev; it will be noted from Fig. 5 that each of these is in reality two separate resonances. No additional resonances have been observed at lower energy in runs taken down to about 3 ev. A comparison of the three transmission curves of Fig. 5 enables one to make isotopic assignment for several of the major resonances. These assignments are listed in Table III. One cannot be certain from the present data whether the 340-ev transmission dip observed with the Ga^{69} sample is caused by Ga^{69} or by a Mn impurity in the sample. A later run with improved resolution[13] shows, however, that it should certainly be attributed to Ga^{69}.

The parameters which have been assigned the gallium resonances are also recorded in Table III. The parameters for several of these resonances were obtained by the area analysis method outlined in the foregoing; for the 290-ev, the 380-ev, and the 710-ev resonances the modified procedure to be described below was employed. In each case the value of Γ_γ was taken to be 0.30 ev as suggested by Fig. 1 in reference 10. The value of g was taken to be $\frac{1}{2}$, the two possible values being either $\frac{3}{8}$ or $\frac{5}{8}$ for both gallium isotopes.

[12] A. W. Merrison and E. R. Wiblin, Proc. Roy. Soc. (London) A65, 992 (1952).
[13] Bollinger, Cote', and LeBlanc (private communication).

Since the 290-ev and the 380-ev resonances in Ga^{71} are predominantly scattering resonances, the assumption of resonance symmetry, which governs the validity of the method of area analysis used with the antimony data, is not justified. However, it is always true that the experimental transmission area must be equal to the calculated area if the correct resonance shape and parameters are used. For the case of a resonance having a scattering shape, in particular, the width Γ may be obtained by finding the value of Γ for which the area above the calculated transmission dip is equal to that above the experimental dip for assumed values of Γ_γ, R, and g; the appropriate Γ must be found by a method of successive approximation. This procedure is especially suitable for the wide resonances in gallium since Doppler broadening may be neglected and since $\Gamma_n/\Gamma \approx 1$, making the final Γ insensitive to the assumed value of Γ_γ.

In applying the above technique to the 290 ev and 380 ev transmission dips in the Ga^{71} data of Fig. 5, the combined effects of the two resonances were calculated. For both resonances, Γ_γ was assumed to be 0.30, a value of $\frac{1}{2}$ was used for g, and R was obtained from the relationship $R=1.5\times10^{-13}\,A^{\frac{1}{3}}$ cm; it was found, moreover, that the measured shape of the transmission dip could be explained only by assuming the two resonances to be of differing J-values. The final values of the widths Γ that were arrived at in this manner are recorded in Table III, and were used to draw the transmission curve shown in Fig. 6. Data points for the experimentally measured transmission also appear in the figure. As is to be expected, primarily because of instrumental resolution, a curve through the experimental data would yield transmission dips both broader and less deep than those of the theoretical curve. However, because of the satisfactory area agreement, it is believed that the parameters selected are reasonably good.

TABLE III. Resonance parameters of gallium for the assumed values $\Gamma_\gamma=0.3$ and $g=\frac{1}{2}$. The errors quoted do not include those caused by the uncertainty in the correct values of g.

E_0 (ev)	$\sigma_0\Gamma^2$ (b-ev²)	σ_0 (barns)	Γ (ev)	Γ_n (ev)	$\Gamma_n/\sqrt{E_0}$ (ev$^{\frac{1}{2}}$)	Thermal capture contribution (barns)
			Ga^{69} Resonance			
112	233	1800±400	0.36±0.02	0.06	0.005	0.30
340	360±150	1500	0.49	0.19	0.010	0.05
710	3840	1500±200	1.6 ±0.2	1.3	0.047	0.06
					Total	0.41
			(Measured thermal σ_c = 2.0 b)			
			Ga^{71} Resonances			
95	370	2700±1000	0.37±0.04	0.07	0.007	0.57
290	25 500	4300±100	7.7 ±0.5	7.4	0.43	3.00
380	4000	3100±100	3.6 ±0.5	3.3	0.19	0.74
770	194	710±200	0.52±0.10	0.22	0.008	0.01
					Total	4.32
			(Measured thermal σ_c = 4.9 b)			

(b) *Thermal Capture Cross Section*

It is possible to calculate the contribution which each of the gallium resonances makes to the thermal capture cross section by using the parameters assigned each resonance. This contribution also appears in Table III. The sum of the contributions due to the three resonances of Ga^{71} is seen to be 4.3 barns whereas the measured value of its thermal capture cross section[6] is 4.9 barns. This difference represents a reasonable contribution for the remaining resonances at higher energies and those at negative energies. This suggests that the value 0.30 ev used for Γ_γ in our analysis (and which is used in this

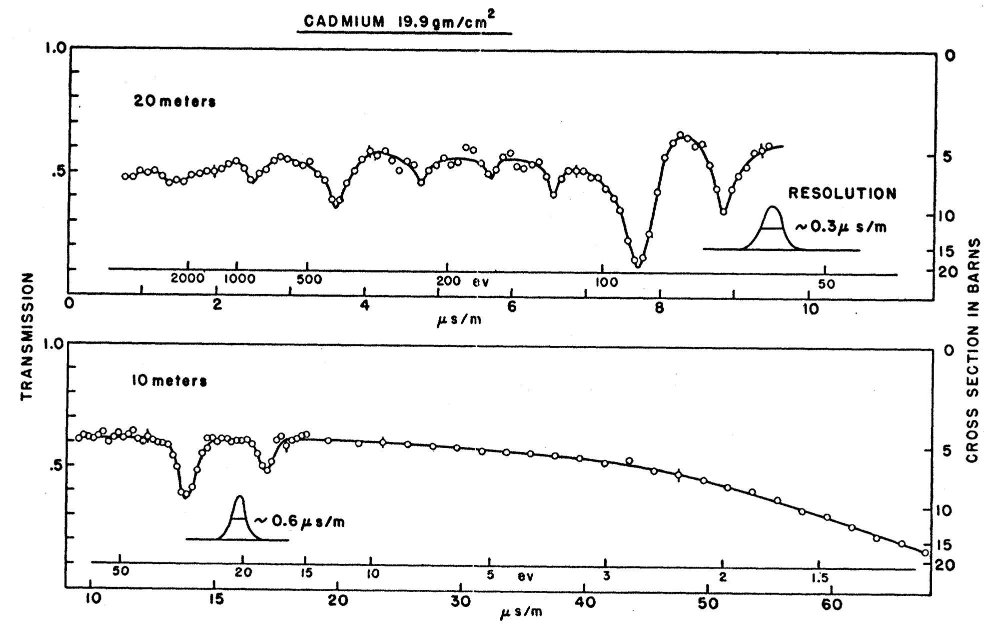

FIG. 7. Neutron transmission of cadmium as a function of time of flight.

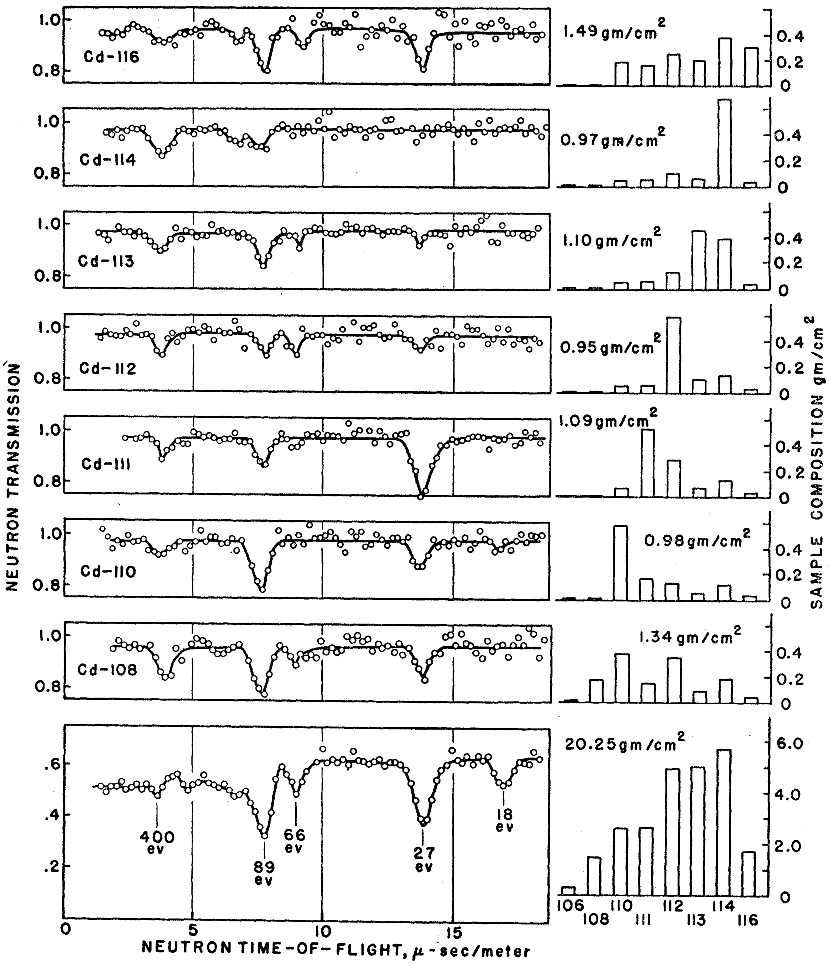

FIG. 8. Neutron transmission of the separated isotopes of cadmium and the transmission of normal cadmium.

calculation) is approximately correct, though if there are any significant resonances in Ga^{71} at small negative energies its value would have to be reduced somewhat. In the case of Ga^{69}, the four resonances analyzed contribute only 0.41 barn to the thermal capture cross section, whereas the measured value is 2.0 barns.[6] Since it does not appear that higher energy resonances could account for this difference, it may well be that there is a fairly prominent resonance in Ga^{69} at a small negative energy.

TABLE IV. Resonance parameters for cadmium for an assumed value $\Gamma_\gamma = 0.12$.

Isotope	E_0 (ev)	g	σ_0 (barns)	Γ (ev)	Γ_n (ev)	$\sigma_0\Gamma^2$ (b-ev²)
Cd^{111}	27.2	$\frac{1}{4}$	2400	0.130	0.010	41
		$\frac{3}{4}$	2600	0.123	0.003	39
Cd^{110}	88	1	19 000	0.34	0.23	2300
		1	22 000	0.46	0.34	4.600

Cadmium

The unique cross section of cadmium has made it a significantly useful metal in neutron physics research. Because of its strong resonance near thermal neutron energies, a relatively thin sheet of cadmium can be used to filter out the slow neutrons from a beam of broad distribution in velocity. Furthermore, since earlier cross-section measurements of the Columbia Velocity Selector Group[5] showed no significant resonances at higher energies, neutrons passed by such a filter have been assumed to be fairly uniformly attenuated. Our results show that this is not the case.

The measured transmission of a normal cadmium sample about one inch thick (19.9 g/cm²) is plotted as a function of time of flight in Fig. 7. Prominent resonances are observed at 18.0, 27.2, 66.6, and 88.2 ev, and others less prominent at higher energies.

The transmission of seven samples of the separated isotopes of cadmium was also measured. These samples were in the form of oxides of cadmium, most of them somewhat less than 1.0 g/cm² in thickness. Figure 8 shows the measured transmission for these samples

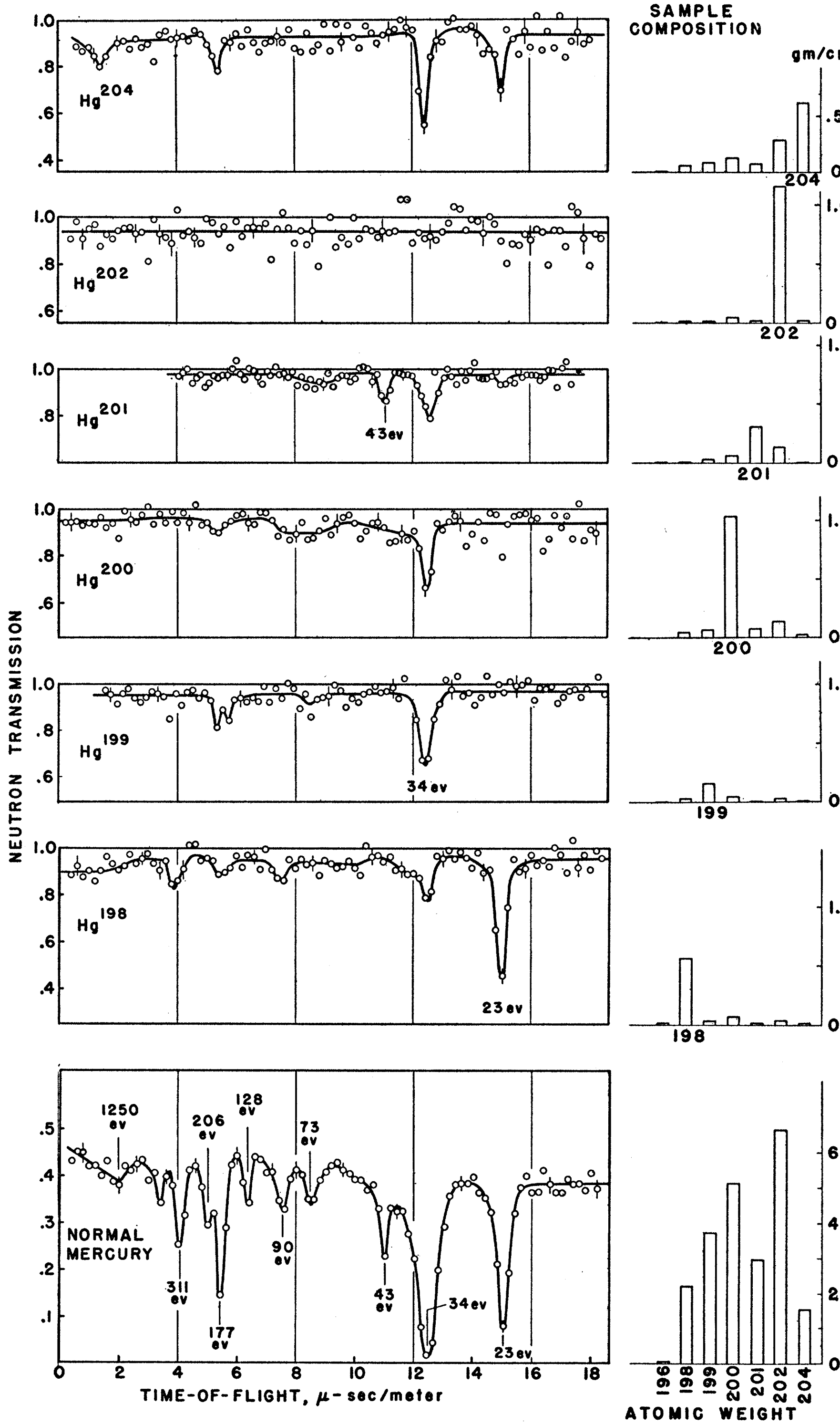

FIG. 9. Neutron transmission of separated isotopes of mercury and the transmission of normal mercury. The resolution used was about 0.3 μsec/m.

together with that of normal cadmium plotted over the energy region of interest. The isotopic constitution for each sample is displayed at the right of each curve. A comparison of these curves, taking into consideration isotopic constitution, enables one to assign the 27.2-ev resonance to Cd^{111} and the 88-ev resonance to Cd^{110}.

These two resonances have been analyzed to determine their resonance parameters, and the results are

TABLE V. Isotopic assignment for the resonances in mercury.

Resonance energy (ev)	Isotope	Resonance energy (ev)	Isotope
23	198	128	...
34	199	177	199
43	201	206	...
73	199[a]	311	198[a]
90	198[a]		

[a] These assignments are in some doubt.

recorded in Table IV. The capture width Γ_γ was taken to be 0.12 ev as suggested by Fig. 1 of reference 10. The spin of Cd^{111} is $\frac{1}{2}$, and hence the value of g may be either $\frac{1}{4}$ or $\frac{3}{4}$. The parameters were determined for both these possible values, using the area analysis procedure for a symmetrical resonance. Since the spin of Cd^{110} is zero, g can have only the value unity. Using this value, the parameters for the 88-ev resonance were approximated by both the standard area analysis method and by the comparison method for asymmetric resonances used for the gallium data.

Mercury

Cross-section measurements of mercury over the resonance region had also been made by the Harwell group.[6] They had observed two prominent resonances at 23 and 35 ev and some unresolved resonances at higher energies. By using better instrumental resolution and by making in addition, transmission measurements on the separated isotopes we are able to resolve a number of other resonances and to make isotopic assignment for several of the prominent resonances. This assignment has been used at Brookhaven in determining the parameters of the first two resonances.[14]

The measured transmission for normal mercury and for six samples of its partially separated isotopes is plotted in Fig. 9. The sample thickness and isotopic constitution of each sample is given adjacent to each curve. By comparing the various curves in this figure it is possible to make the four isotopic assignments listed in Table V. An area analysis of these resonances based on this assignment gives consistent results, thereby confirming the assignment. Three additional possible assignments are also listed in the table.

Reduced Neutron Widths

On the black nucleus model of the nucleus,[15] the ratio $\bar{\Gamma}_n^0/\bar{D}$ of the average reduced neutron width to the average level spacing should be a constant independent of atomic weight. On the more recent "cloudy crystal ball" model,[16] which assumes that the incident neutron interacts with a complex potential well of the form $V=V_0(1+i\zeta)$, the width-to-spacing ratio is not constant but is predicted to have sharp maxima in the neighborhood of atomic weights 11, 55, and 155. The data presented in the present paper are not extensive enough, in themselves, to give much information about the validity of these theories. For convenience in comparing our results with others reported in the literature, however, the average nuclear parameters that may be deduced from the present data $\bar{D}$, $\bar{\Gamma}_n^0$, and $\bar{\Gamma}_n^0/\bar{D}$, are summarized in Table VI. Since there are two possible spin states, $\bar{D}$, which is the average spacing per spin state, was assumed to be twice the average observed spacing $\bar{S}$. The probable errors associated with these parameters were all calculated on the basis of the number of resonances for which data were obtained, assuming that the density distributions of both D and Γ_n^0 are of exponential form and are independent.

TABLE VI. Summary of average resonance parameters.

Nuclide	Number of reso-nances	$\bar{S}$ (ev)	$\overline{\Gamma_n^0}$ (ev$^{\frac{1}{2}}$)	$(\bar{\Gamma}_n^0/\bar{D})$ $\times 10^4$ (ev$^{-\frac{1}{2}}$)	Probable range of $(\bar{\Gamma}_n^0/\bar{D})$ $\times 10^4$ (ev$^{-\frac{1}{2}}$)	Theoretical $(\bar{\Gamma}_n^0/\bar{D})$ $\times 10^4$ (ev$^{-\frac{1}{2}}$)
Ga^{69}	3	236	0.031	0.66	0.36–1.2	0.40
Ga^{71}	4	192	0.160	4.2	2.5 –7.0	0.32
Sb^{121} $\Gamma_\gamma=0.06$	7	13	0.0017	0.65	0.45–0.93	0.29
Sb^{121} $\Gamma_\gamma=0.10$	7	13	0.0013	0.50	0.35–0.72	
Sb^{123} $\Gamma_\gamma=0.06$	4	26	0.0042	0.81	0.48–1.3	0.33
Sb^{123} $\Gamma_\gamma=0.10$	4	26	0.0034	0.65	0.39–1.1	

The abnormally large value of $\bar{\Gamma}_n^0/\bar{D}$ that is obtained for Ga^{71} is probably caused by a statistical fluctuation. If it were a reliable value, it would be expected that other wide resonances, in addition to those at 290 and 370 ev, would be observed at higher energies. The results obtained for the antimony isotopes should be more reliable, however; a greater number of resonances were observed and there is fair agreement in the results obtained for the two isotopes. For these data, values of $\bar{\Gamma}_n^0/\bar{D}$ are listed for the two assumed values of Γ_γ that were used. It is seen that $\bar{\Gamma}_n^0/\bar{D}$ does not depend sensitively on Γ_γ.

The last column in Table VI lists the values of $\bar{\Gamma}_n^0/\bar{D}$ that are predicted by the cloudy crystal ball model for the currently favored constants $V_0=-42$ Mev and $\zeta=0.03$. The experimental results contain uncertainties that are too large to make a quantitative comparison with the theory meaningful. It is seen, however, that the theoretical values of $\bar{\Gamma}_n^0/\bar{D}$ agree, as to order of magnitude, with the results obtained from our data.

[14] J. S. Levin and D. J. Hughes, Phys. Rev. **95**, 645 (1954).
[15] Feshbach, Peaslee, and Weisskopf, Phys. Rev. **71**, 145 (1947).
[16] Feshbach, Porter, and Weisskopf, Phys. Rev. **96**, 448 (1954).