Neutron-Capture Cross Sections by Capture-Gamma Counting

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A method is described for determining neutron capture cross sections and locating capture resonances by capture gamma counting. Breit-Wigner parameters for the strong resonance in cadmium are determined to be $E_0=0.177$ ev, $\sigma_{c0}=7600$ barns, $\Gamma=0.110$ ev. Resonances have been found in cadmium at 19 and 28 ev with evidence of unresolved resonances at about 100 ev and above; $\sigma_{c0}\Gamma\cong 3$ barn-ev for the 19-ev level, and $\sigma_{c0}\Gamma^2\cong 9$ barn(ev)^2 for the 28-ev level. Comparison transmission measurements on cadmium show the capture-gamma method to be quicker and more sensitive under some circumstances than transmission measurements for locating weak capture levels. Factors affecting the relative sensitivity of the two methods are discussed. A resonance was found in strontium at 3.58 ev; its strength ($\sigma_{c0}\Gamma^2$) is approximately 8 barn-(ev)^2. Resonances were found in barium at energies of 25, 93 and 380 ev, with strengths ($\sigma_{c0}\Gamma^2$) estimated to be 8, 90, and 550 barn(ev)^2, respectively. Measurements on a thick silver sample show that the method can be used to measure σ_c/σ_t through a resonance over a fairly large range of values of transmission and cross sections. The strength of the 5.13-ev resonance in silver is determined to be $\sigma_{c0}\Gamma^2=345\pm 30$ barn(ev)^2.

INTRODUCTION

THE analysis of nuclear structure by studying nuclear energy levels requires both detailed information about individual levels and also extensive information about the position and spacing of levels. Such information has been derived from a variety of sources, including transmission[1] and scattering[2] measurements with slow neutrons. The present paper describes a technique for measuring as a function of neutron energy the relative number of gamma rays emitted when a neutron is captured by a nucleus. This technique is applicable to detailed study of neutron capture cross sections in the neighborhood of a resonance, thus providing an independent analysis of the Breit-Wigner resonance shape for comparison with the results of transmission and scattering measurements; it also provides a quick sensitive method of detecting weak capture resonances.

DESCRIPTION OF APPARATUS AND EXPERIMENTAL PROCEDURE

The Columbia University pulsed cyclotron and slow neutron velocity selector which has been adequately described previously[1] were used with a modified sample and detector arrangement. A 2-in.×3-in. rectangular sample was placed in the pulsed neutron beam at a measured distance (about 6 meters) from the neutron source. Above and below the sample were placed stilbene scintillation counters shielded by a special lead-lithium collimating system as shown in Fig. 1. Neutrons captured in the sample produce immediate capture gammas which are detected by the scintillation counters; amplified pulses from these counters are fed into the detection circuits of the velocity-selector; thus, the over-all apparatus records as a function of neutron time-of-flight the relative number of capture-gammas produced in the sample.

For each sample investigated, sample-in and sample-out runs were made. In addition, two standard samples were used: a cadmium standard was used to compare counting rates from one run to the next to take account of possible slight variations in geometry and neutron beam intensity; a Co^{60} source (made in the shape of the samples) was used to calibrate and monitor the operations of the detectors, amplifiers, and pulse-recording system. The following second-order effects have been investigated and found to be negligible in the apparatus used: scattering by the sample of background gammas, capture in detector or structural material of neutrons scattered by sample, and production of capture gammas in aluminum sample-holders.

ANALYSIS OF DATA

After correction for background effects, the experimental data consist of capture-gamma counts as a function of neutron energy. The capture-gamma count for a single detection channel can be represented as the product of a number of factors as in Eq. (1),

$$R=\phi M\tau_d AC\epsilon_\gamma, \tag{1}$$

where R=capture gamma counts in one detection interval, ϕ=neutron flux [neutrons at sample cm^{-2}(monitor count)$^{-1}$(μsec/meter)$^{-1}$], M=cyclotron monitor counts, τ_d=width of velocity selector detection channel (μsec/meter), A=area of neutron beam striking sample, C=fraction of neutrons captured in sample, $\epsilon_\gamma=N_\gamma T_\gamma\Omega$=gamma counts per neutron captured, N_γ=gamma multiplicity factor (includes the combined effect of the number of gammas emitted per neutron captured and the effective detector efficiency for the capture-gamma spectrum, aside from the solid angle factor), T_γ=average transmission of sample for capture-gammas produced in the sample,

[1] W. W. Havens, Jr., and L. J. Rainwater, Phys. Rev. 83, 1123 (1951) (contains references to previous work by the same and other authors). For extensive references, see "Nuclear Data," Natl. Bur. Standards Circ. No. 499 (Government Printing Office, Washington, D. C., 1950).

[2] Jay Tittman and Charles Sheer, Phys. Rev. 83, 746 (1951) (contains further references).

and Ω=effective solid angle between sample and detectors.

The data are analyzed by comparing the counting rate for a given sample with that for a standard; ϕ in Eq. (1) is a function of source and collimator characteristics and can be made equal for the sample and standard; M is directly measured; A is always the same; T_γ is nearly unity in most cases which require accurate analysis and can therefore be estimated theoretically with sufficient accuracy; Ω is the same for samples of equal thickness, and corrections for difference in thickness between sample and standard can be made on the basis of experimental tests using a standard gamma-ray source.

The counting rate depends on the neutron capture and scattering cross section of the sample through the factor C, the fractional capture. In many cases of practical interest, this relation can be accurately approximated by

$$C \cong 1-e^{-N\sigma_c}, \qquad (2)$$

where N=atoms per cm^2 of sample, and σ_c=capture cross section (cm^2).

In other cases (relatively large scattering cross section and transmission considerably less than 1) a more complicated expression is needed, which takes account of multiple scattering in the sample. In these cases an independent transmission measurement is required to determine the capture cross section uniquely.

The factor N_γ of Eq. (1) represents the number of capture gammas emitted per neutron captured multiplied by the efficiency of the detector averaged over the energy spectrum of the emitted gammas. Since the gamma multiplicity and energy spectrum depend on the level structure of the excited compound nucleus, it is not possible to assume that N_γ is the same for sample and standard or even for two different resonances in the same sample. The perfect standard is a slab of the same material as the sample being investigated which is thick enough to be "black" (absorb all incident neutrons, i.e., $C=1$) over the entire energy range of interest and which is physically thin enough to make self-absorption of capture gammas small. In this case, N_γ is the same for standard and sample because they are made of the same material and are being compared at the same neutron energy. In this ideal case, then, the fractional capture of the sample is just equal to the ratio of counting rates for sample and standard (after corrections for M, T_γ, and Ω have been made). In most cases, a slab of the sample material cannot be obtained which absorbs all incident neutrons over the entire energy range of interest. It is often possible, however, to obtain a sample which is essentially "black" at some particular energy—either at the peak of a strong resonance or at the low-energy end of the thermal region; relative cross sections can then be obtained at other energies from the counting rates at those energies if the variation of incident neutron flux with energy is known. If no "black" region can be found or if it is necessary to make comparison from one resonance to another, N_γ must either be measured directly[3] or estimated from "reasonable" theoretical considerations.[4] Such theoretical estimates are not reliable for exact cross section measurements but are adequate for order-of-magnitude estimates of resonance strengths.

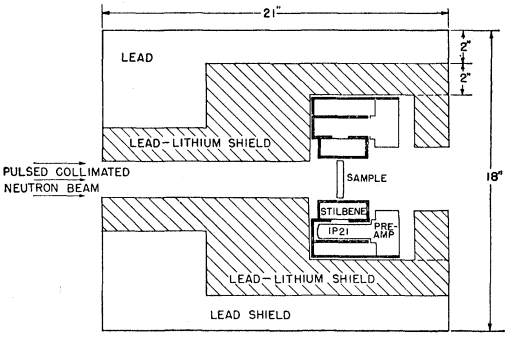

FIG. 1. Capture-gamma apparatus for neutron cross-section measurement.

RESULTS

A. Shape of 0.176-ev Cadmium Resonance

A run was made on cadmium in the region of the well-known resonance at 0.176 ev[5] in order to check the Breit-Wigner formula[6] by direct measurements of the (n,γ) cross section. The sample used was a piece of uniform 1-mil cadmium foil of 0.0195 g/cm^2(=0.0001045 atom/barn). A thicker slab of 0.522 g/cm^2(=0.00280 atom/barn) of cadmium was used as a standard. (This is an example of the ideal standard discussed above.) Figure 2 shows the experimental values for σ_c plotted against time of flight. The theoretical Breit-Wigner curve is shown for the resonance parameters E_0=0.177 ev, Γ=0.110 ev, and σ_{c0}=7600 barns. The solid curve is corrected for instrument resolution while the dashed curve is uncorrected. Background varied from about 7 percent to about 4 percent of the counting rate due to the sample at the peak. The uncertainties in the above parameters may be taken as the amount by which they must be changed to cause a significant difference between the theoretical curve and the experimental results. These are $\pm$0.005 ev in E_0 and Γ, and $\pm$300 barns in σ_{c0}. Within the estimated

[3] C. O. Muehlhause, Phys. Rev. **79**, 277 (1950); B. Hamermesh, Phys. Rev. **81**, 487 (1951); Kinsey, Bartholomew, and Walker, Phys. Rev. **77**, 723 (1950); Phys. Rev. **78**, 77 (1950); Phys. Rev. **78**, 481 (1950).

[4] For example, J. M. Blatt and V. F. Weisskopf, *Theoretical Nuclear Physics* (John Wiley and Sons, Inc., New York, 1952), Chap. XII, Sec. 7D. Shell structure considerations will in many cases be important in such estimates.

[5] Rainwater, Havens, Wu, Dunning, Phys. Rev. **71**, 65 (1947); W. H. Zinn, Phys. Rev. **81**, 752 (1947); Sawyer, Wollan, Bernstein, and Peterson, Phys. Rev. **72**, 109 (1947); B. N. Brockhouse, Can. J. Phys. **31**, 432 (1953).

[6] G. Breit and E. Wigner, Phys. Rev. **49**, 519 (1936).

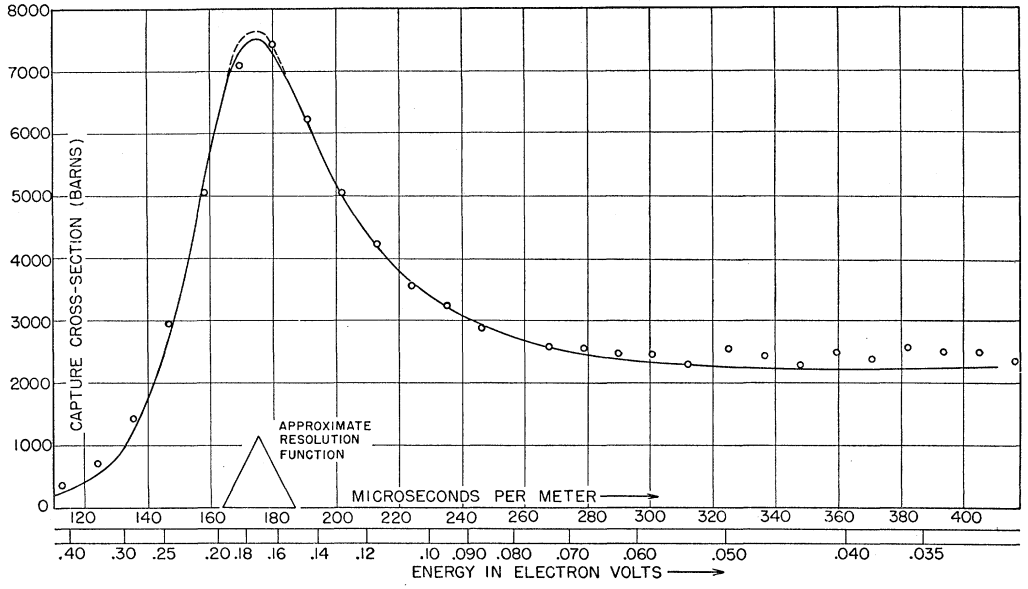

FIG. 2. Capture cross section of cadmium. The points show experimental values of capture cross section calculated from capture-gamma measurements. The full line is a theoretical Breit-Wigner curve (corrected for instrument resolution) calculated using the parameters $E_0=0.177$ ev, $\Gamma=0.110$ ev, and $\sigma_{c0}=7600$ barns.

limits of accuracy these values are consistent with previous measurements.[5]

B. Cadmium: Location of Higher Resonances

Runs were made on a thick sample (0.0622 atom/barn) of cadmium in the resonance region both to look for higher resonances and to compare the sensitivity of this method with that of the transmission measurement method. Figure 3 shows the results obtained. The solid and dashed lines show fractional capture and transmission, respectively. The data for these two curves were taken using the same sample thickness, resolution, and cyclotron running time. The capture curve shows resonances at 19 and 28 electron-volts, with evidence of several unresolved levels in the region of 100 electron-volts and above; dips in the transmission curve occur at essentially the same energies.[7] The scales for the transmission and fractional capture curves of Fig. 3 are chosen so as to make the statistical error bars the same size for the two curves at the 28-ev resonance. The background was about 15 percent of the sample counting rate at the strong peaks, and about 60 percent at the 19-ev peak.

The strengths of the two levels at 19 ev and 28 ev have been estimated by using a second cadmium sample whose thickness was 0.0261 atom/barn (results not shown). The areas under the 28-ev peak for the two samples are approximately proportional to $\sqrt{N}$, where N=atoms/barn; therefore, the "thick" sample approximation is used, and the strength is estimated to be $\sigma_{c0}\Gamma^2=9$ barn(ev)^2. The areas under the 19-ev peak are too small to estimate with any great accuracy, especially that for the thinner sample; the areas appear, however, to be proportional to N instead of $\sqrt{N}$, so the "thin" sample approximation is used to give $\sigma_{c0}\Gamma\cong 3$ barn ev. These values are based on the assumption that the gamma-multiplicity factor for these resonances is the same as that for cadmium in the thermal region.

It is estimated that resonances in the region investigated could have been undetected in the runs on cadmium if their strengths were $(\sigma_{c0}\Gamma)_{\min}\lesssim 0.05E_0$ barn ev if N_γ is the same at the resonances as for the thermal region.

C. Comparison of Sensitivity of Capture-Gamma Measurements and Ordinary Transmission Measurements for Locating Resonances

The obvious difference in the peak-to-hollow ratio for the two curves of Fig. 3 indicates that the capture-gamma method may be more sensitive than the transmission method for locating capture resonances. A quantitative comparison of the sensitivities can be obtained by estimating the minimum resonance strength detectable by the two methods. This comparison is made below by assuming

(1) equal cyclotron intensity and running time, i.e., equal number of cyclotron monitor counts,

(2) optimum sample thickness for the transmission method and a reasonably practical sample thickness for the capture gamma method,

(3) very little time is spent in either method on

[7] Higher-resolution transmission measurements by Bollinger *et al.* at Argonne National Laboratory show resonances at 18.0, 27.2, 66.6, 88.2, and 122 ev. See U. S. Atomic Energy Commission Report AECU-2040 (Technical Information Service, Department of Commerce, Washington, D. C., 1952).

open-beam, background, or standard sample runs. This assumption is a fair one if the purpose is merely to detect weak resonances quickly. If a quantitative measurement of resonance strength is then to be made, some time must be spent on calibration and background runs, and the conclusions obtained below would have to be modified accordingly.

In the capture-gamma method a resonance is detectable if it produces a peak in the sample-in curve of gamma counts *vs* time-of-flight which is significant compared with peaks due to statistical fluctuations in the gamma background; in the transmission method a resonance is detectable if it produces a dip in the sample-in curve of neutron counts *vs* time-of-flight, which is significant compared with dips due to statistical fluctuations in the counting rate on either side of the resonance energy where the cross section is approximately constant. The following analysis assumes a "thin" sample case throughout. The results would be changed in a fairly obvious way for the thick sample case, but would not be changed qualitatively. The strength $(\sigma_{c0}\Gamma)$ of a resonance can be determined in terms of the area of capture-gamma peak by integrating Eq. (1) over the resonance by using Eq. (2) for C and the Breit-Wigner formula for σ_c. The minimum detectable resonance can then be determined by setting this integral equal to a statistical fluctuation area proportional to the square root of background counts. A similar expression can be derived for the minimum resonance strength detectable by the transmission method. The ratio of these two minimum strengths defines the relative sensitivity S of the capture-gamma detection method. The expression for S is

$$S=\frac{(\sigma_0\Gamma)_{T\ \min}}{(\sigma_0\Gamma)_{\gamma\ \min}}=\frac{\sigma_{c0}}{\sigma_0}\frac{N}{N_T(T_K)^{\frac{1}{2}}}\frac{\epsilon_\gamma A}{(\epsilon A_T)^{\frac{1}{2}}}\left(\frac{\phi_t\tau_d}{R_B}\right)^{\frac{1}{2}}. \quad (3)$$

Thus the ratio of the sensitivities of the capture gamma method to the transmission method is proportional to the square root of the ratio of $\phi_t\tau_d$ (the average flux of neutrons cm^{-2} sec^{-1} per detection channel) to R_B (the average gamma counter background rate per second per channel). It is proportional to the sample area A times the detection efficiency ϵ_γ for the capture gamma method, but inversely proportional only to the square root of the product of the neutron counter area A_T and the counter efficiency ϵ in the transmission method. It is proportional to the capture gamma sample thickness N (except as ϵ_γ decreases for very thick samples), and is inversely proportional as the product of the sample thickness N_T times $(T_K)^{\frac{1}{2}}$ in the transmission method. (T_K is the sample transmission away from resonance.) $N_T(T_K)^{\frac{1}{2}}$ is a maximum when $\ln T_K=-2$, or $T_K=0.135$. The ratio (σ_{c0}/σ_0) of the capture to total cross sections at resonance appears since only that part of σ_0 due to capture contributes to the capture gamma method (for thin samples). Actually, the factor (σ_{c0}/σ_0) is too small for a thick sample since multiple scattering increases the chance of capture.

To examine the consequences of this equation in more detail, we must consider the practical factors related to the selection of the adjustable parameters. For a given sample area A, increasing ϵ_γ by increasing the amount of scintillation detector material tends to increase R_B roughly in proportion. Similarly, increasing A tends to be counteracted by a decrease in ϵ_γ through the solid angle factor Ω, or an increase in R_B if ϵ_γ is kept fixed. Considering all of these effects together, S increases roughly as $A^{\frac{1}{2}}$.

If BF_3 counters are used in the transmission method, S increases as the neutron energy increases because ϵ varies as $E^{-\frac{1}{2}}$. Although ϵ_γ fluctuates in an irregular way through the factor N_γ, it is certainly constant within an order of magnitude and has no systematic trend as E increases.

The factor $(N/N_T\sqrt{T_K})$ multiplied by the factor T_γ (in ϵ_γ) is usually of the order of unity. The optimum thickness for capture-gamma measurements is not easily determined because the dependence of T_γ and Ω (in ϵ_γ) on thickness cannot be simply expressed. With the apparatus used in the present experiments, however, the sample thickness was generally limited to the width (5 cm) of the scintillation crystals, since Ω decreased rapidly for greater thicknesses. For very dense materials, the optimum thickness would be less than 5 cm because of the decrease in T_γ with increasing thickness. The cadmium sample used for the measurements of Fig. 3 was 1.35 cm thick, and $NT_\gamma/N_T\sqrt{T_K}\approx 1$. If $\sigma_K=5$ barns for Cd, (where σ_K is the constant part of the cross section) the optimum sample thicknesses in this case would be about 5 cm and 10 cm, respectively,

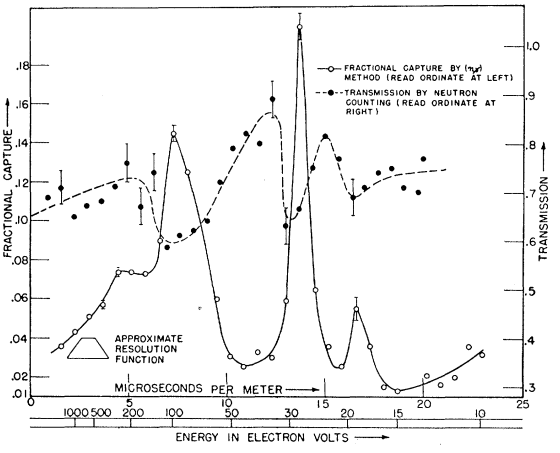

FIG. 3. Cadmium resonances. Open circle points and full line show experimental values of fractional capture (ordinate scale at left) measured by the capture-gamma method; capture resonances occur at 19 and 28 ev, with evidence of several unresolved resonances near 100 ev and above. Solid circle points and dashed line show experimental values of transmission (ordinate scale at right). Same resolution and running time. Vertical scales chosen to make statistical error bars same size at peak of 28-ev resonance.

for the capture gamma and transmission methods giving $NT_\gamma/N_T\sqrt{T_K}\cong 0.5$. If σ_K is 10 barns, the optimum thickness for both transmission and capture-gamma methods is 5 cm and $NT_\gamma/N_T\sqrt{T_K}\cong 1$.

The factor $(\phi_t\tau_d/R_B)^{\frac{1}{2}}$ shows the dependence of S on neutron intensity and gamma background. If the gamma background is directly proportional to neutron intensity, this factor is a constant. There is, however, a gamma background counting rate which is independent of neutron intensity; this adds a term to R_B which is proportional to cyclotron running time instead of monitor counts. This means that S decreases if the cyclotron intensity falls too low. (It has been assumed that there is no analogous background counting rate in the neutron counters used in transmission measurements.) If cyclotron intensity is high, then S will decrease (or increase) with intensity depending on whether gamma background varies more rapidly (or less rapidly) than neutron intensity.

Values for the various parameters and the relative sensitivity at three different energies are given in Table I for the data on cadmium (Fig. 3).

It can be seen that in this particular example the sensitivity of the capture-gamma method is perhaps an order of magnitude greater than the transmission method. The relative sensitivity increases with energy for two main reasons: the decrease in neutron counter sensitivity, and the increase in incident neutron flux relative to gamma background.

In summary it can be stated that since the transmission method measures the total cross-section (scattering plus capture), the relatively constant potential scattering integrated over the whole resolution width may be large enough in some cases to obscure a narrow capture resonance if the resolution of the instrument is poor. Scattering is of minor importance in the capture-gamma method, and therefore the method is most useful as a means of locating weak capture levels at relatively high energies, where resolution is poor. The sensitivity of the capture-gamma method is limited by the gamma background. A level will be undetected when it is so weak that the actual capture-gamma counting rate from the sample integrated over the whole level is not large compared with the uncertainty in the background counting-rate integrated over the detection channel width. Experience in the present investigations has shown that it is difficult to improve the signal-to-background ratio (and hence the sensitivity) beyond a certain point without at the same time cutting the absolute counting rate too much. This is, however, an instrument limitation, not a fundamental limitation of the method.

D. Strontium

Measurements were made using a sample of strontium fluoride, of thickness 0.0317 molecule of SrF_2 per barn, in the region from about 0.025 ev to about 500 ev. A single resonance at about 3.6 ev was found. The survey measurements were made at a sensitivity such that resonances would have been undetected if their strengths were $(\sigma_{c0}\Gamma)_{\min}\lesssim 0.2E_0$. The black circles in Fig. 4 give the experimental values of fractional capture assuming N_γ for the cadmium is 1.7 times that for strontium. The factor 1.7 represents the maximum possible value since larger values would give fractional captures larger than unity. The dashed line in Fig. 4 shows fractional capture (corrected for resolution), with the Breit-Wigner parameters $E_0=3.58$ ev, $\sigma_{c0}=840$ barns, $\Gamma=0.1$ ev. If 1.7 is the correct gamma-multiplicity ratio, the sample is "thick" and the experimental data can be used to obtain a value of $\sigma_{c0}\Gamma^2[=8.4$ barn $(\text{ev})^2]$ but not to separate values of σ_{c0} and Γ.[8] (The curve for $\Gamma=0.2$ and $\sigma_{c0}=210$ falls nearly on the dashed curve of Fig. 4 in the wings of the resonance but falls slightly below it at the peak.) Background was about 10 percent of the counting rate due to the sample at the peak.

It is probable that the factor N_γ is less for strontium[4] than for cadmium because (a) its mass number is smaller and (b) if the resonance is due to capture in Sr^{87}, the compound nucleus is even-even and has a closed shell of 50 neutrons. If it is assumed that N_γ for strontium equals that for cadmium, the fractional capture is as shown by the open circle points in Fig. 4. The solid line on the graph is a theoretical Breit-Wigner curve (corrected for instrument resolution but not Doppler broadening) calculated using the parameters $E_0=3.58$ ev, $\sigma_{c0}=35$ barns, and $\Gamma=0.4$ ev. This gives $\sigma_{c0}\Gamma^2=5.6$ barn$(\text{ev})^2$. The values of 5.6 barn$(\text{ev})^2$

TABLE I. Calculated values of the various factors in the relative sensitivity formula [Eq. (3)] for three different energies, obtained from the data used for the graphs in Fig. 3.

E_0 (ev)	t_0 μsec/meter	$\frac{N}{N_T\sqrt{T_K}}$	$\frac{A}{\sqrt{AT}}$ cm²/cm	ϵ_γ	ϵ	$\frac{\epsilon_\gamma A}{(\epsilon AT)^{\frac{1}{2}}}$	$\frac{\phi_t\tau_d}{\text{neutrons/channel}}$ cm² sec	$\frac{R_B}{\text{background counts}}$ sec channel	$\left(\frac{\phi_t\tau_d}{R_B}\right)^{\frac{1}{2}}$	$\frac{\sigma_0 S}{\sigma_{c0}}$
12.6	20.2	1.16	8.11	0.073	0.027	3.6	0.20	0.027	2.7	11
49.3	10.2	1.16	8.11	0.073	0.014	5.1	0.47	0.035	3.7	22
214	5.2	1.16	8.11	0.073	0.0067	7.2	1.02	0.053	4.4	36

[8] A detailed discussion of the relation between capture-gamma counting rate and resonance parameters is given in the Columbia University PhD thesis on which this paper is based. In many cases the area method will give $\sigma_{c0}\Gamma^2$ to a good approximation with thick samples.

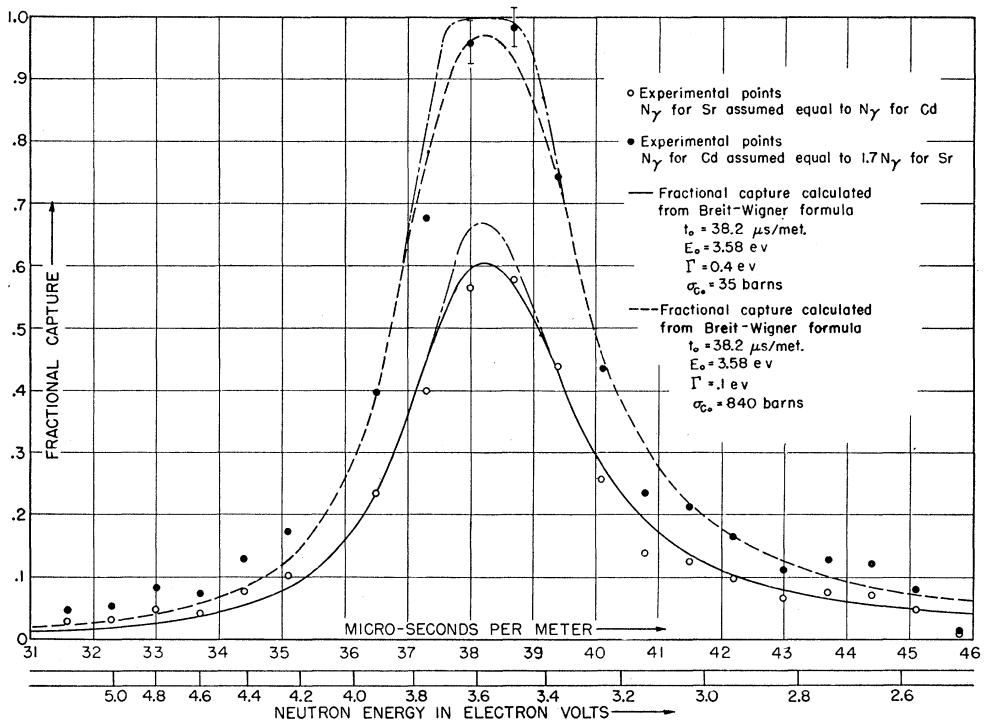

FIG. 4. Neutron capture resonance in strontium (for 0.0317 atom/barn). O = experimental values of fractional capture (capture-gamma multiplicity N_γ of strontium assumed equal to that of cadmium), ● = experimental fractional capture (N_γ for Cd assumed equal to 1.7 times N_γ for Sr). Theoretical Breit-Wigner curve (corrected for resolution) with parameters

———— $E_0=3.58$ ev, $\Gamma=0.4$ ev, $\sigma_{c0}=35$ barns.
- - - - - - - $E_0=3.58$ ev, $\Gamma=0.1$ ev, $\sigma_{c0}=840$ barns.
— - — - — = theoretical curves uncorrected for resolution.

and 8.4 barn(ev)^2 for $\sigma_{c0}\Gamma^2$ represent minimum and maximum values corresponding, respectively, to maximum and minimum values of the gamma-multiplicity factor of strontium relative to that for cadmium.

If the radiation width Γ_γ is assumed to be 0.1 ev, a statistical theory of level spacing[9] predicts spacings of 95, 5.4, 15, and 0.6 ev if the observed level is assigned to strontium isotopes of mass number $A=84$, 86, 87, and 88, respectively. If the reduced width ($\Gamma_N E_0^{-\frac{1}{2}}$) is assumed constant for levels of the same isotope and spin state, then the experimental sensitivity and the Breit-Wigner formula require minimum level spacings of about 50, 80, 75, and 80 for $A=84$, 86, 87, and 88, respectively. Otherwise levels at lower energies would have been seen with the sensitivity used. Although the theory is statistical and not accurate for detailed predictions, the two sets of predicted spacings indicate that the resonance is most probably in Sr^{84} and then, in order of decreasing probability, Sr^{87}, Sr^{86}, and Sr^{88}.

E. Location of Resonances—Barium

A sample of barium fluoride of thickness = 0.0252 molecule/barn was investigated in the energy range from 12 to about 500 ev. Resonances were found at 25, 93, and 380 ev. Figure 5 shows the fractional capture as a function of time of flight calculated from the capture-gamma counting rate with the assumption that the gamma-multiplicity-factor is the same for the barium resonances as for cadmium in the thermal region. The strengths of these resonances have been estimated from the area under the curves to be the following:

for the 25-volt level

If $\Gamma=0.4$ ev, $\sigma_{c0}\Gamma\cong 30$, $\sigma_{c0}\Gamma^2\cong 12$ barn(ev)^2,
$\Gamma<0.4$ ev, $12\gtrsim\sigma_{c0}\Gamma^2\gtrsim 8$ barn(ev)^2,
$\Gamma>0.4$ ev, $30\gtrsim\sigma_{c0}\Gamma\gtrsim 20$ barn ev;

for the 93-volt level

If $\Gamma\cong 1.3$ ev, $\sigma_{c0}\Gamma\cong 100$, $\sigma_{c0}\Gamma^2\cong 130$ barn(ev)^2,
$\Gamma<1.3$, $130\gtrsim\sigma_{c0}\Gamma^2\gtrsim 90$,
$\Gamma>1.3$, $100\gtrsim\sigma_{c0}\Gamma\gtrsim 70$;

for the 380 volt level

If $\Gamma\cong 3.4$ ev, $\sigma_{c0}\Gamma\cong 250$ barn ev, $\sigma_{c0}\Gamma^2\cong 850$ barn(ev)^2,
$\Gamma<3.4$ ev, $850\lesssim\sigma_{c0}\Gamma^2\gtrsim 550$ barn(ev)^2,
$\Gamma>3.4$ ev, $250\gtrsim\sigma_{c0}\Gamma\gtrsim 170$ barn ev.

[9] Feshbach, Peaslee, and Weisskopf, Phys. Rev. **71**, 145 (1947); Feshbach, Porter, and Weisskopf, Phys. Rev. **90**, 166L (1953).

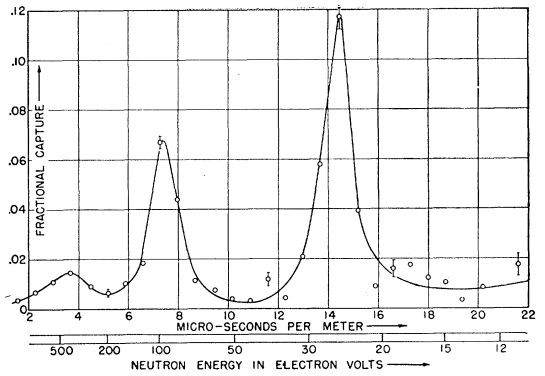

FIG. 5. Capture resonances in barium (as BaF_2). Resonances occur at 25, 93, and 380 ev. Since resolution is very poor, numerical values of fractional capture represent the fraction captured of all incident neutrons in the energy band covered by the resolution width. Gamma multiplicity is assumed equal to that of cadmium in thermal region.

It is estimated that in this barium run, the precision was such that levels in the region investigated might not have been detected if $\sigma_{c0}\Gamma \lesssim 0.1E_0$ for "thin" samples, assuming that the gamma-multiplicity factor is the same for barium as for cadmium. Background was $\frac{1}{3}$ to 1 times the counting rate of sample at the peaks.

Barium has isotopes of mass numbers 130, 132, 134, 135, 136, 137, and 138 with spin-abundance weighting factors of 0.001, 0.001, 0.024, 0.041 or 0.025, 0.078, 0.071 or 0.042, and 0.717. Arguments similar to those applied to strontium yield only a little information about which isotopes are responsible for the resonances. It can be concluded that the 25-ev level is not assignable to Ba^{138}; the 93-ev level is not assignable to Ba^{130} or Ba^{132}; the 380-ev level is probably due to Ba^{138}, but Ba^{136} and Ba^{137} are not excluded. These conclusions are meaningless if the level actually consists of a number of unresolved levels.

F. Relative Cross Section Measurements—5.13-ev Silver Resonance

A "thick" sample of silver (4.08 g/cm^2=0.0228 atom/barn) was investigated in the region of the 5.13-ev resonance[1] to test the applicability of the method to measurement of relative cross sections for a given material over a fairly wide range of values of transmission and of the ratio of capture to total cross section. Scattering[10] and transmission[1] measurements show that for this sample σ_c/σ_T should vary from 0.5 to 0.9 and the transmission should vary from 0.6 to 0.0 in the region investigated. The results obtained are shown in Fig. 6. The solid lines are values of fractional capture calculated from the Breit-Wigner formula using Sheer's parameters $\Gamma_N/\Gamma=0.110$ and $\sigma_p=6$ barns,[2] where Γ_N=neutron width, Γ=total width,

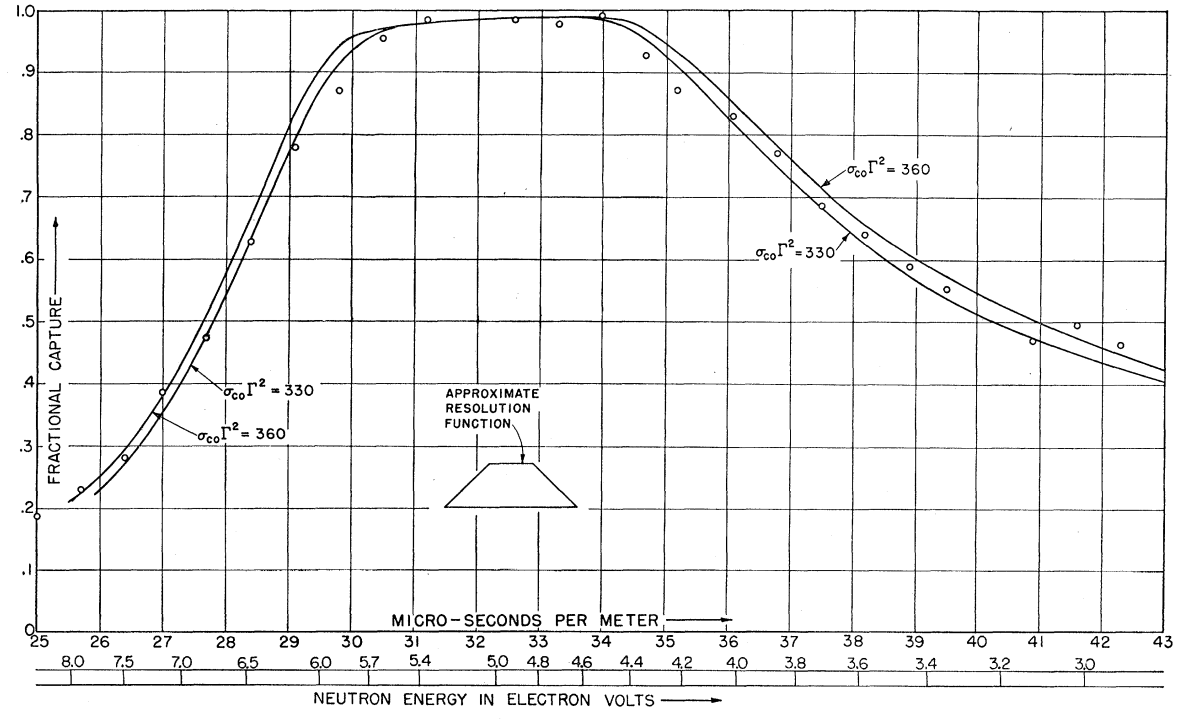

FIG. 6. Fractional capture at 5.13-ev resonance in silver. Thick sample (0.0228 atom/barn). O=experimental values of fractional capture (normalized by assuming $\Gamma_N/\Gamma=0.110$; see text for discussion). Full lines show fractional capture calculated from Breit-Wigner formula for cross sections. Parameters $\Gamma_N/\Gamma=0.110$, $\sigma_p=6$ barns; $\sigma_{c0}\Gamma^2=360$ and 330 barn(ev)^2 for upper and lower curves, respectively.

[10] C. Sheer (private communication).

and σ_p=potential scattering; the upper and lower curves use $\sigma_{c0}\Gamma^2=360$ and 330 barn(ev)^2, respectively. The experimental points on the graph (obtained from the capture-gamma counting rates) have been normalized to the calculated curves at the peak of the resonance ($C=0.98$ at $T=0$ and $\sigma_c/\sigma_T=0.89$). The shape of the calculated curve fits the experimental points well over the whole range of the measurements. Background in these measurements was less than 10 percent of the counting rate due to the sample at its maximum. It is concluded from these data that $\sigma_{c0}\Gamma^2=345\pm30$ barn(ev)^2; this is consistent with values reported in the literature.[11] In Fig. 6, the experimental points are normalized by using independent scattering data to obtain Γ_N/Γ, and the relative values of cross sections from the capture-gamma measurements are then shown to be consistent with scattering and transmission data throughout the range of the measurements. Actually, a good approximation to the true fractional captures can be made in many cases without using independent scattering data. If the sample is thick enough so that the experimental curve has a flat portion at the top, then it can be concluded that the transmission is zero at the top. Figure 7 shows calculated dependence of the fractional capture on σ_s/σ_t for a semi-infinite zero-transmission sample. (Processes involving up to three collisions were considered.) It can be seen that even at high values of σ_s/σ_t the fractional capture is not very different from unity. If, for all "thick" samples it is assumed that $C=0.95$ at the peak, then the error in normalizing the experimental data would not exceed 5 percent for values of $\Gamma_N/\Gamma(=\sigma_s/\sigma_t$ at the resonance peak) from 0 to 0.45; if $C=0.9$ is assumed, Γ_N/Γ can be anything from 0 to 0.7 without causing a normalization error of more than 10 percent. Since for most cases of interest Γ_N/Γ is expected to be fairly small

[11] W. W. Havens, Jr., and J. Rainwater, Phys. Rev. **70**, 154 (1946); W. Selove, Phys. Rev. **84**, 869 (1951).

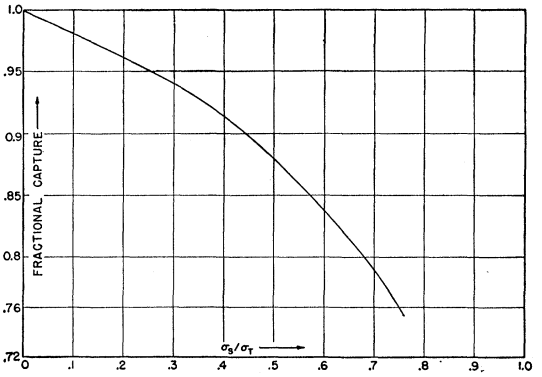

FIG. 7. Calculated value of fractional capture as a function of σ_s/σ_t (ratio of scattering to total cross section) for a "thick" (zero-transmission) sample, taking account of multiple scattering in the sample, neglecting energy change upon scattering.

(<0.5), the peak fractional capture can safely be assumed to be equal to about 0.95. Although such measurements have not been made in this case, a "thick" sample such as this would provide a fairly ideal standard for measurements using a thin sample in the neighborhood of a resonance. The "thick" sample data, of course, can be used to determine only the parameter $\sigma_{c0}\Gamma^2$ since the data are insensitive to Γ_N/Γ and to σ_p.

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