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On the Absorption of Slow Neutrons by Rhodium

ROBERT R. MEIJER*
Cornell University, Ithaca, New York
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The absorption of neutrons in rhodium as a function of their time of flight was studied with the Cornell slow neutron velocity spectrometer in the energy range of 0.0044 to 330 ev. A resonance was observed at an energy of 1.21 ± 0.02 ev. No other resonances were observed. Values of the Breit-Wigner parameters, which best seem to fit the experimental results for a resonance energy of 1.21 ev, are 2750 ± 200 barns for the cross section at resonance (σ_r) and 0.21 ± 0.01 ev for the level width (Γ). The Breit-Wigner formula fits the experimental data in the low energy region. The coefficient of the $1/v$ term is 0.295 ± 0.005 barn/μsec./m and the constant term (taken as the scattering cross section) is 6 ± 2 barns. Values for the strength of the resonance ($\sigma_r\Gamma^2$) were computed from the minimum cross section on the low energy side of the resonance, from the $1/v$ slope, from an activity plot, and from the chosen Breit-Wigner parameters. The average of these values of $\sigma_r\Gamma^2$ is 117 ± 8 barn-ev^2. Self-absorption measurements were made to check the results of the time-of-flight measurements. The resonance cross section obtained from the self-absorption measurements is 3120 ± 50 barns, which is in closer agreement with the results of the spectrometer measurements than with those of previous investigators.

I. INTRODUCTION

THE absorption of slow neutrons by rhodium has been investigated by a number of workers. Experimental results were first obtained by various workers using indirect methods for determining neutron energies. These have been summarized by Bethe.[1] Values for the resonance cross section and the width of the resonance have been obtained from mutual and self-absorption measurements.[2–4] Baker and Bacher[5] measured the resonance energy by time-of-flight measurements. A recent investigation of slow neutron absorption in rhodium was undertaken with a crystal spectrometer by Sturm.[6]

This investigation of neutron absorption in rhodium with a slow neutron velocity spectrometer was conducted for two reasons. First, there were indications that rhodium has only one resonance in the energy range so far investigated and that the resonance level is wide so that the Doppler width is small compared to the resonance width. Hence the investigation of neutron absorption in rhodium should be extremely useful in determining the validity of the Breit-Wigner theory.[7] Second, the values of the resonance energy, the cross section at resonance, and the width of the resonance were in doubt since previous investigators were unable to obtain consistent results.

As a check on the results obtained from the experiments with the spectrometer, the cross section at resonance was also determined by self-absorption experiments similar to those of Hornbostel *et al.*[3]

II. APPARATUS AND EXPERIMENTAL PROCEDURE

In this investigation the transmission of neutrons by various rhodium absorbers was measured as a function of the time of flight of the neutrons. The neutron velocity spectrometer used in these time-of-flight measurements is similar to that used by McDaniel[8] and has been described in detail by Jones.[9] The timing apparatus records the number of neutrons arriving at a detector as a function of the time of flight of the neutrons from the source to the detector. In many respects, the procedure for measuring the transmission of neutrons by rhodium was similar to that described previously.[5, 8–10]

* Now at The George Washington University, Washington, D. C.

[1] H. A. Bethe, Rev. Mod. Phys. **9**, 113 (1937).

[2] Manley, Goldsmith, and Schwinger, Phys. Rev. **55**, 39 (1939); Manley, Hornbostel, and Goldsmith, Phys. Rev. **55**, 1116 (1939).

[3] Hornbostel, Goldsmith, and Manley, Phys. Rev. **58**, 18 (1940).

[4] Feeney, LaPointe, and Rasetti, Phys. Rev. **61**, 469 (1942).

[5] C. P. Baker and R. F. Bacher, Phys. Rev. **59**, 332 (1941).

[6] William J. Sturm, Phys. Rev. **71**, 757 (1947).

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

[8] Boyce D. McDaniel, Phys. Rev. **70**, 832 (1946).

[9] Wm. B. Jones, Jr., Phys. Rev. **72**, 362 (1947).

[10] Bacher, Baker, and McDaniel, Phys. Rev. **69**, 443 (1946).

The source-detector distance was three meters. A water moderator[8] served as the source of the slow neutrons. The detector was a BF_3 ionization chamber, whose active length was 10 cm. The repetition frequencies used were 200, 250, and 2500 c.p.s. The on-times used were 5, 10, 40, and 100 μsec.

The random background in this experiment was about three total counts per minute and amounted to about one-half percent of the recorded counts for most of the data; occasionally it was as high as two percent. Because of the collimator,[9] the fast neutron background was negligible except at high energies. For example, at energies of 30 ev the fast neutron background was only one percent of the total counting rate, whereas at energies of 100 ev it was about 10 percent.

The sum of the various time lags in the timing apparatus is obtained from the fast neutron distribution which we shall call the sensitivity function, *SF*. A typical *SF* for an on-time of 5 μsec. is shown in Fig. 1. The sensitivity function was obtained frequently, and the time delay was found to be 7.5 ± 0.2 μsec.

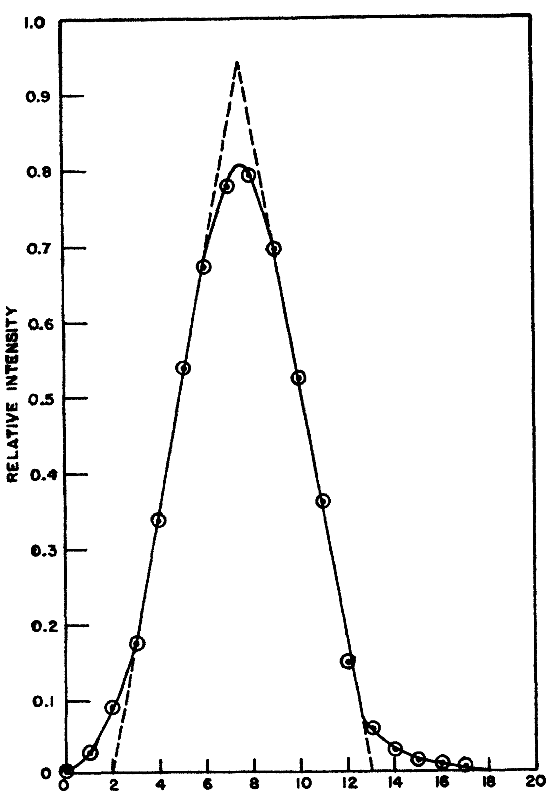

FIG. 1. Sensitivity function (*SF*) for 5-μsec. on-time. The solid curve is the measured fast neutron time distribution, or *SF*. The dashed curve shows the ideal shape of the *SF*.

As was mentioned in Section I, self-absorption measurements were made in order to check the results of the spectrometer measurements. In the self-absorption measurements the arc of the cyclotron was unmodulated and the deuteron beam was about 100 microamperes. A rhodium disk, having a thickness of 15.9 mg/cm², was used as a detector and rhodium disks, having thicknesses of 43.4 and 83.9 mg/cm², were used as absorbers. A 206-mg/cm² rhodium disk was used as a monitor. A more detailed description of the rhodium disks is given in Section III. The detector (or detector and absorber) was placed just above the monitor so that the detector (or detector and absorber) and the monitor were in the same vertical plane. Hence both detector (or detector and absorber) and the monitor received the same neutron flux. Both sides of the combination were covered with 0.9-g/cm² Cd sheet to absorb the thermal neutrons. The entire assembly was placed inside the collimator at a distance of 70 cm from the face of the water tank. The assembly was irradiated for 10 minutes to bring out the 4.2-minute period. The detector and monitor were placed in known and reproducible positions inside lead shields which housed Geiger counters. The output of each Geiger counter was connected to a discriminating amplifier which coupled into a scale-of-64 circuit and thence to mechanical counters. Data taking was started six minutes after the irradiation ended, so that the 44-second period activity was practically negligible. Counts were taken for 2 minutes for both the detector and the monitor. To guard against changes in sensitivity of the counters or the amplifiers, each foil was placed in the other shield and counts again taken for two minutes. This cycle was repeated until the background counts became as high as 1–10 percent of the total counts in a two-minute period. The background was about the same for each Geiger counter and was 0.35 scaled count/minute. A minimum of one hour elapsed between successive irradiations of the detector; hence, no correction for earlier irradiations was required.

TABLE I. Values of experimental parameters.

Condition number	On-time μsec.	Repetition frequency c/sec.	Absorber thickness g/cm²	Time of flight μsec./m	Energy ev	Moderator	Filter
1	10	2500	1.99	4–61	1.4–330	Water	0.9 g/cm² Cd
2	10	2500	1.58	24–61 70–107	1.4–9.1 0.46–1.06	Water	0.9 g/cm² Cd
3	5	2500	0.496	47–66	1.2–2.3	Water	0.9 g/cm² Cd
4	5	2500	0.0434	57–75	0.92–1.6	Water	0.9 g/cm² Cd
5	5	2500	0.206	57–75	0.92–1.6	Water	0.9 g/cm² Cd
6	10	2500	0.496	70–107	0.46–1.06	Water	0.9 g/cm² Cd
7	100	200	1.58	64–750	0.0092–1.3	Water and tray	none
8	40	250	1.58	103–245	0.087–0.49	Water and tray	none
9	100	200	0.412	720–1090	0.0044–0.010	Water and tray	none

Three runs were taken with each absorber. The entire procedure was, of course, standardized to obtain reproducible results. The consistency of the results of the three runs attests to the effectiveness of the standardization.

The following procedure was used to compute the transmission. The background counts are subtracted from the total counts. The ratio, A, of the detector-with-absorber counts to the monitor counts is obtained. The ratio, W, of detector-without-absorber counts to the monitor counts is obtained. The ratio, A/W, is the transmission. The possibility of difference between counters was taken into account by computing the transmission for each orientation and obtaining an average, weighted according to the total number of counts obtained in each orientation.

III. RESULTS

The transmission of neutrons by various thicknesses of rhodium absorbers was measured in the time-of-flight interval from 4.0 to 1090 μsec./m, corresponding to an energy range of 0.0044 to 330 ev. A resonance was found at an energy of 1.21 ev, or at a time of flight of 65.8 μsec./m. No resonances were found at higher energies. However, the resolution became progressively poorer with an increase in energy, and, hence, weak resonances probably would not be detectable at the highest energies measured.

The values of pertinent experimental param-

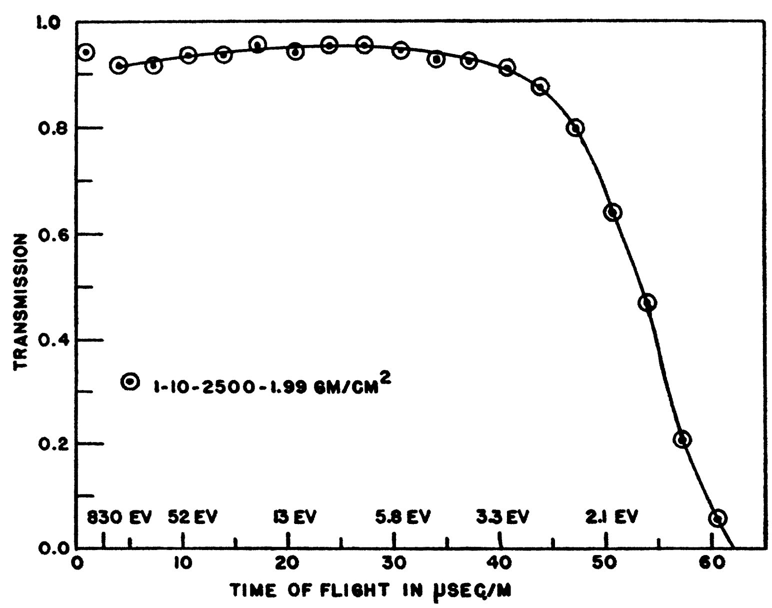

FIG. 2. Measured transmission of Rh in the energy region 1–300 ev.

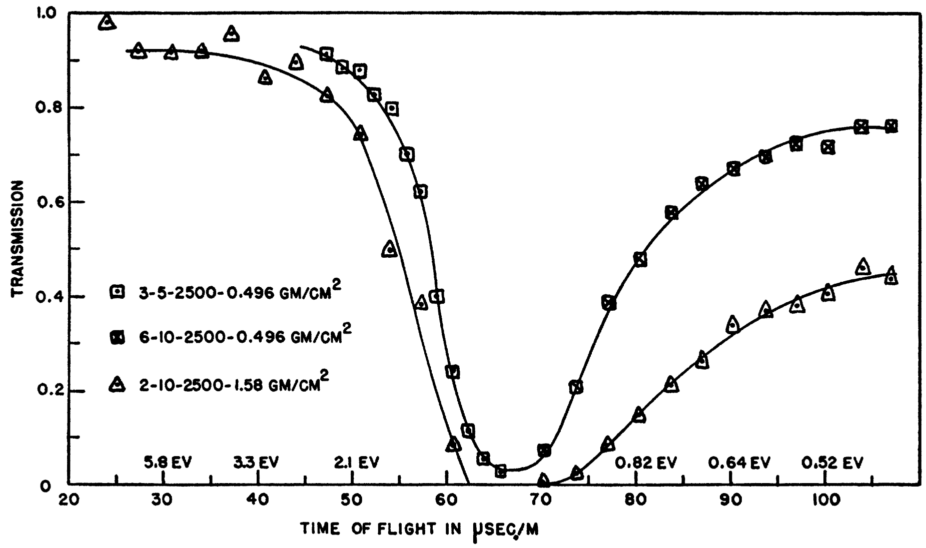

FIG. 3. Measured transmission of Rh in the energy region 0.5–10 ev.

eters used are listed in Table I. The different experimental conditions are each assigned numbers for identification purposes. A legend accompanies each graph showing experimental data. The legend indicates the condition number, the on-time, the repetition frequency, and the absorber thickness in that order. The rhodium absorbers used were uniform disks, $2\frac{1}{4}$ inches in diameter, cut from rolled sheet. The absorbers were obtained from Baker and Company, who stated that an analysis of the rhodium showed it to have a minimum purity of 99.85 percent, most of the impurities being other noble metals.

The measured transmissions of the various thicknesses of absorber are shown in Figs. 2–5. All the data have been corrected for backgrounds and time lags. The statistical error of the points is indicated by the lengths of the vertical lines

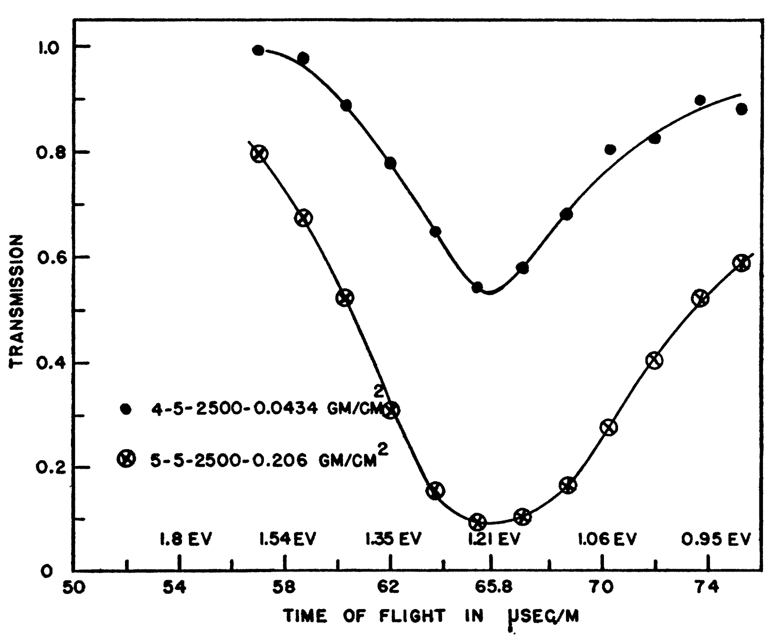

FIG. 4. Measured transmission of Rh in the energy region 0.8–1.8 ev.

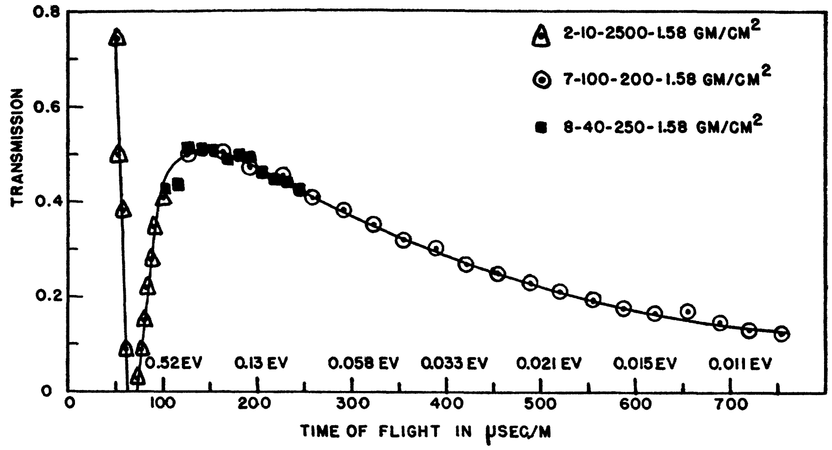

FIG. 5. Measured transmission of Rh in the energy region 0.01–1 ev.

through the points. In cases where the statistical error is less than the diameter of the plotted points, no vertical line is drawn.

The variation of the total cross section with time of flight in the low energy region is shown in Fig. 6. The cross section is obtained from the measured transmission by the relation

$$T=\exp(-\sigma n),$$

where T = transmission, σ = cross section, and n = absorber thickness. The equation of the solid curve drawn through the experimental points is

$$\sigma=(0.295\pm 0.005)t(1+8650t^{-2})+(6\pm 2),$$

where σ is the total cross section in barns (10^{-24} cm^2/atom), t is the time of flight in μsec./m and 6 is a constant term taken to be the scattering cross section. This equation is discussed in Section IV. There are variations in the transmission at the lowest measured energies which are outside the statistical error and which may be due to the crystaline structure of rhodium. The lattice constant of rhodium metal is 3.8A. Neutrons of this wave-length have an energy of 0.0057 ev or a time of flight of 960 μsec./m.

A curve giving the total cross section as a function of the energy on logarithmic scales is shown in Fig. 7. Only those data are plotted which best represent the cross section in the regions where data are obtained with several thicknesses of absorber. The maximum measured cross section is about 2400 barns. At an energy of 0.025 ev the total cross section is about 150 barns. The minimum cross section on the low energy side of the resonance is about 73 barns and occurs at an energy of 0.25 ev, or at a time of flight of 145 μsec./m.

In the self-absorption experiments, the following transmissions were obtained: 0.710 ± 0.008 for the 43.4-mg/cm^2 absorber and 0.504 ± 0.012 for the 83.9-mg/cm^2 absorber. The errors are the r.m.s. deviations of the three separate runs with each absorber. For both absorbers the r.m.s. deviation is greater than the probable statistical error in the number of counts obtained.

IV. DISCUSSION

We are now concerned with the problem of obtaining the actual transmission (or cross section) from the measured transmission in order that the values of the parameters in the Breit-Wigner one-level formula may be obtained. The

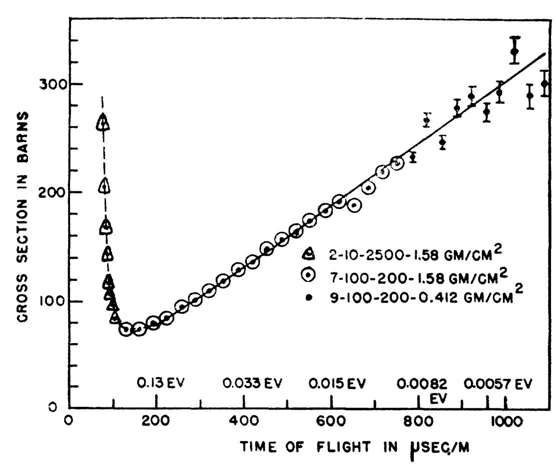

FIG. 6. Total cross section of Rh in the energy region 0.004–1 ev.

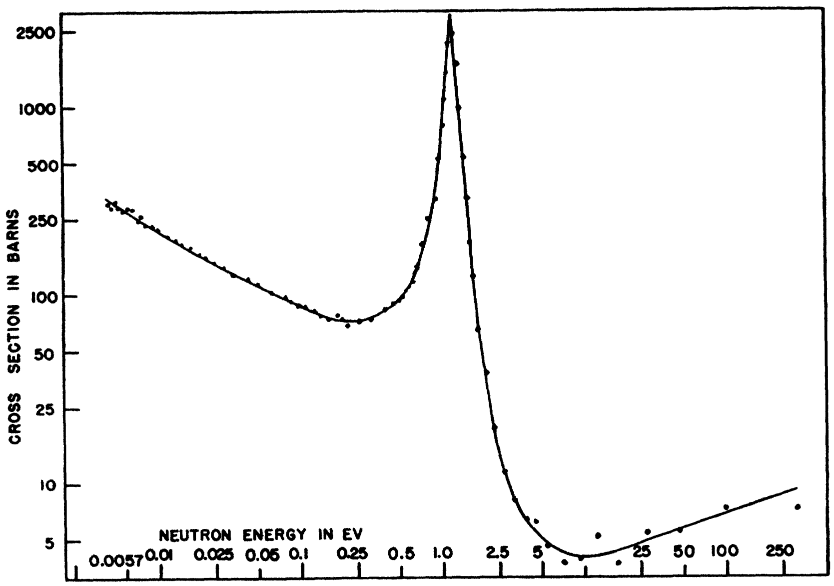

FIG. 7. Total cross section of Rh in the energy region investigated, namely, 0.004–300 ev. No correction has been made for apparatus resolution or Doppler effect. Both cross section and neutron energy are on logarithmic scales.

Breit-Wigner one-level formula is given[11] by

$$\sigma_a(E) = [E_r/E]^{\frac{1}{2}}[\sigma_r/(1+(4/\Gamma^2)(E-E_r)^2)],$$

where $\sigma_a(E)$ is the absorption cross section for neutrons of energy E, σ_r is the cross section at exact resonance, E_r is the resonance energy, and Γ is the width of the resonance level. The measured transmission can be taken as the actual transmission in regions where the transmission varies slowly with energy (e.g., in the $1/v$ region). However, in the region of a resonance, it may be necessary to make large corrections in order to obtain the actual transmission. The procedure used in the analysis of the data is similar in many respects to that used by McDaniel.[8]

Values for the parameters, σ_r and Γ in the Breit-Wigner formula, are chosen such that the experimental data in the resonance region are

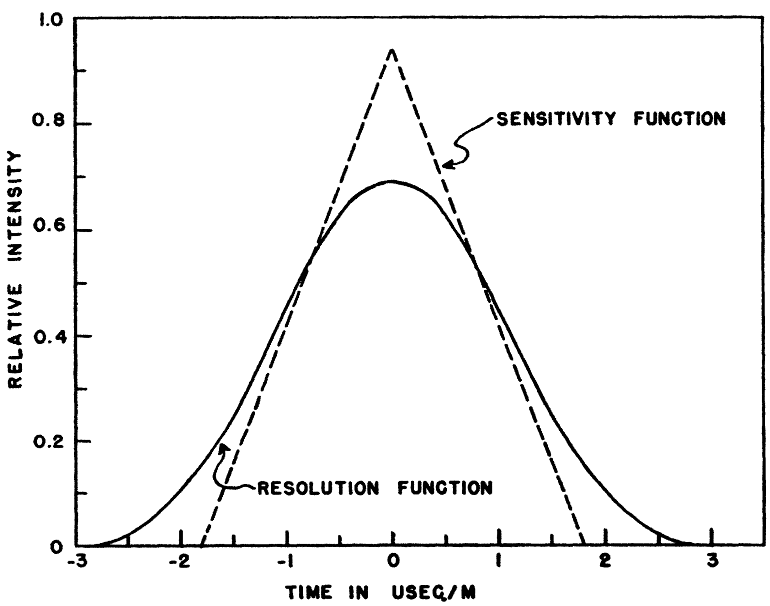

FIG. 8. Resolution function for 5.5-μsec. on-time and 1.2-ev neutrons. The solid curve is the resolution function. It is derived from the sensitivity function shown by the dashed line (and also in Fig. 5).

[11] H. A. Bethe, Rev. Mod. Phys. 9, 140 (1937).

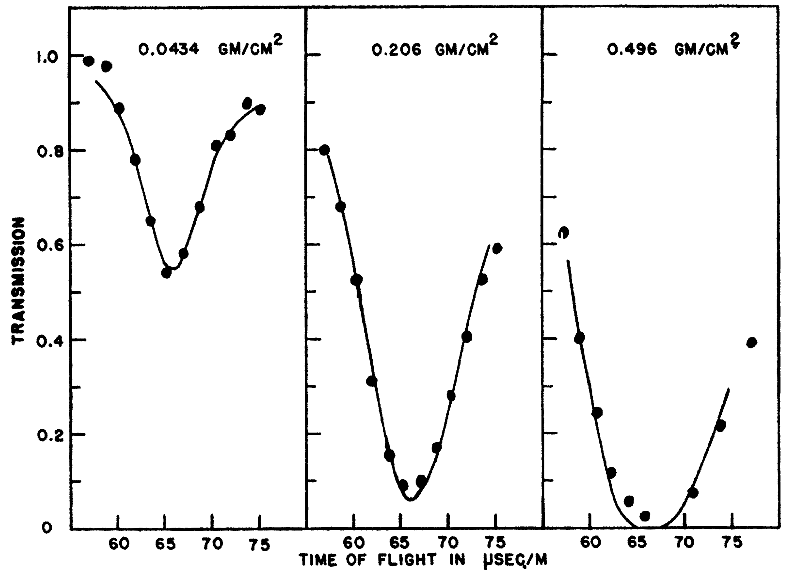

FIG. 9. Comparison of the transmissions expected from the Breit-Wigner formula with the measured transmissions. The solid curves are the expected transmissions obtained from the Breit-Wigner formula for the chosen parameters and the dots are the measured transmissions for each of three Rh absorbers.

reasonably well fitted by the formula. Since it is the total cross section that is measured, one has to subtract from it the scattering cross section to get the absorption cross section.

To obtain the scattering cross section, the procedure suggested by McDaniel *et al.*[12] was used. In the low energy region ($E^2/E_r^2 \ll 1$), the Breit-Wigner formula can be written in the approximate form $\sigma_a(E)=k(E_r/E)^{\frac{1}{2}}(1+2E/E_r)$, where $k=\sigma_r\Gamma^2/4E_r^2$, provided that $4E_r^2/\Gamma^2 \gg 1$. Hence, the total cross section in the low energy region is $\sigma(t)=kt/t_r(1+2t_r^2/t^2)+\sigma_s$, where t is the time of flight, t_r is the time of flight corresponding to the resonance energy, E_r, and σ_s is the scattering cross section. The constants, k and σ_s, were chosen so that the resultant curve, $\sigma(t)$ *vs.* t, fits the experimental points in Fig. 6. The values chosen are $k=19.4\pm0.3$ barns and $\sigma_s=6\pm2$ barns.

Next the Doppler effect must be taken into

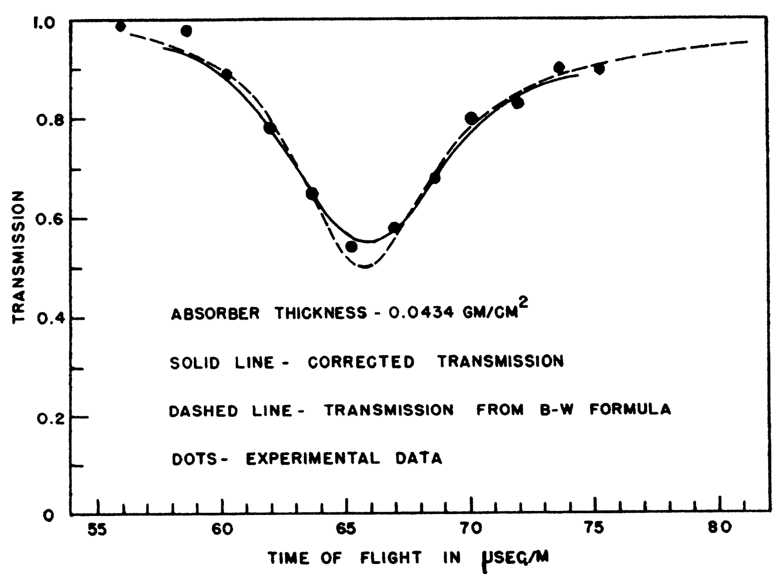

FIG. 10. Comparison of measured transmission with the transmission obtained from the Breit-Wigner formula with and without corrections. The dots are the measured transmissions. The dashed curve is the transmission obtained from the Breit-Wigner formula without any corrections. The solid curve is the (expected) transmission obtained from the Breit-Wigner formula after corrections have been made for the Doppler effect and apparatus resolution.

[12] McDaniel, Sutton, Lavatelli, and Anderson, Phys. Rev. 72, 729 (1947).

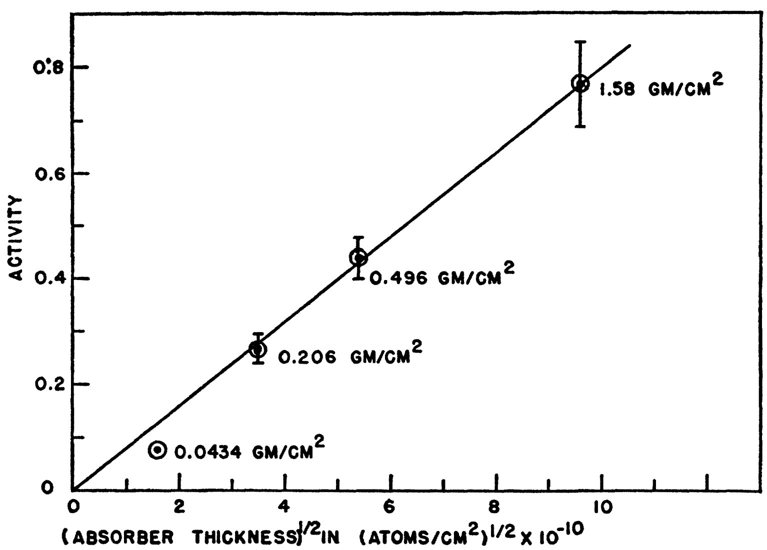

FIG. 11. Activity plot.

account. Since the Debye temperature for rhodium metal is 370°K,[13] the Doppler width, Δ, is found to be 0.038 ev for $E_r=1.21$ ev. For this value of Δ and the chosen values of σ_r and Γ, the effective cross section[11] is computed by numerical integration. The transmission, for each absorber thickness, is then computed as a function of the time of flight. The effect of the apparatus resolution of the transmission must next be considered.

The resolution function is the sensitivity of any one channel of the detector to neutrons of various times of flight. The resolution function for an on-time of 5.5 μsec., a source-detector distance of three meters, and 1.2-ev neutrons is shown in Fig. 8 (the dashed curve shows the sensitivity function).

Using this resolution function, an expected transmission curve is obtained. That is, after having chosen the parameters in the Breit-Witner formula, an effective cross section which takes into account the Doppler effect is computed, and the corresponding transmission curves for several thicknesses of absorber are obtained. These transmission curves are multiplied by the resolution function, and the product is integrated numerically to give points on the transmission curves which one would expect to obtain experimentally with the apparatus. The expected transmissions are compared with the measured transmissions and the parameters adjusted until the best fit is found between the expected and the measured transmission curves in the resonance region.

The expected transmission curves, using values for the parameters which yield the best fit to the measured curves, are shown in Fig. 9. The solid curves are the expected transmissions with the dots showing the experimental data. The values of the parameters yielding this correspondence are $E_r=1.21\pm0.02$ ev, $\sigma_r=2750\pm200$ barns and $\Gamma=0.21\pm0.01$ ev. The errors given are estimated and are based on statistical errors and resolution. Figure 10 shows the effect of the corrections. The assumed transmission obtained from the Breit-Wigner formula for the 0.0434-g/cm² absorber with $\Gamma=0.21$ ev and $\sigma_r=2750$ barns is shown by the dashed line. The solid line is the expected transmission and shows how the assumed transmission is modified by the Doppler effect and the finite resolution. The dots are the experimental data. It is interesting to note that the corrections are not very large.

No correction was made for the effect of the apparatus resolution function on the transmission in the low energy region. If the transmission varies linearly with time of flight, the measured transmission is equal to the actual transmission. Hence, a resolution correction is unnecessary, since the variation of the transmission with time of flight is almost linear within a resolution width in the low energy region.

[13] Frederick Seitz, *Modern Theory of Solids* (McGraw-Hill Book Company, Inc., New York, 1940), p. 110.

It has been pointed out by Jones[9] that a study of the behavior of the activity integral for a resonance as a function of the absorber thickness is useful in obtaining information about the values of the Breit-Wigner parameters. The activity, A, for a particular absorber thickness resulting from a resonance is defined by the relation, $A=\int(1-T)dy$, where T is the transmission of the absorber as a function of the time of flight, t, and $dy=dt/t_r$, where t_r is the time of flight corresponding to the resonance energy, E_r. The limits of the integral are taken as the values of t on either side of the resonance where $T\approx 1$. It can be shown that, for thin absorbers (i.e., $\sigma_r n \ll 1$), $A=\pi n\Gamma\sigma_r/4E_r$, and for thick absorbers

$$A=[\pi n\Gamma^2\sigma_r]^{\frac{1}{2}}/2E_r.$$

In this study the Doppler effect and apparatus resolution may be neglected in obtaining expressions for A.

A plot of the activities for the various thicknesses of absorber as a function of the square root of the absorber thickness is shown in Fig. 11. From the slope of this curve the value of $\sigma_r\Gamma^2$ is 120 ± 12 barn-ev^2. Other values of $\sigma_r\Gamma^2$, in barn-ev^2, are: 121 ± 11 computed from the chosen Breit-Wigner parameters, 114 ± 2 computed from the slope of σ_a *vs.* t in the $1/v$ region, and 112 ± 3 computed from the minimum cross section on the low energy side of the resonance.

The self-absorption data were analyzed by the method used by Hornbostel *et al.*[3] For the 43.4-mg/cm^2 absorber, the coefficient of self-indication, K_s, is found to be 9.14 cm^2/g, which gives a value of 3120 ± 50 barns for the cross section at resonance. Hornbostel found K_s to be 11.5 cm^2/g and σ_r 4100 barns. Computations were not made for the 83.9-mg/cm^2 absorber, since the approximations made in the analysis are no longer valid for such a thickness. It is of interest to note that the transmissions obtained in this experiment are higher for both absorber thicknesses than those obtained by Hornbostel.[3] The measurements above give a transmission of 0.71 and 0.50 for the 43.4- and the 83.9-mg/cm^2 absorbers, respectively, whereas the corresponding values of the transmission obtained by Hornbostel are 0.59 and 0.43. The discrepancy may be due to the fact that Hornbostel had to make a large obliquity correction since his source-detector distance was small (more than a factor of ten smaller than the source-detector distance used in this experiment). In the present experiment the maximum apparent thickness is only 1.5 percent greater than the actual thickness of the absorber.

Finally, it should be noted that, for elements in the neighborhood of rhodium, the expected spacing between energy levels is about 10 to 30 ev, for small kinetic energy of the neutron. For example, in indium[8] and in iodine[9] the spacing between levels is in this range. However, the data obtained in this investigation seem to indicate that, for rhodium, the spacing between levels is more than 300 ev.

V. ACKNOWLEDGMENTS

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