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Resonance-Region Neutron Spectrometer Measurements on Silver and Tungsten

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A high speed rotating-shutter spectrometer has been built for making slow neutron measurements in the resonance region, using a neutron "pile" as a source. One of the principal advantages of the new apparatus is that comparatively small samples are required—typically less than one gram. Thus measurements can be made on many comparatively rare materials, such as certain separated isotopes.

Measurements are reported here on silver and tungsten. These measurements were made with an effective resolution in reciprocal velocity somewhat better than 1.0 microsecond/meter at high energies. In silver, the measurements show clearly resolved resonances at 5, 16, 30, 41, and 53 ev, and numerous unresolved resonances at higher energies. The constants of the 5-ev resonance are $E_r=5.17\pm0.08$ ev, $\sigma_0=12{,}000\pm1500$ barns (10,000 barns for metallic silver at room temperature), $\Gamma=0.17\pm0.02$ ev, $\Gamma_n\approx0.011$ ev. The tungsten work includes measurements on separated-isotope samples of the four major isotopes. The resonance-level spacings observed in these isotopes are: 10 to 30 ev in 182, about 20 ev in 183, perhaps 100 ev in 184, and several hundred ev in 186.

1. INTRODUCTION

IN the past few years, measurements in the slow neutron resonance region have been made principally by the time-of-flight method, with a pulsed cyclotron as a source.[1] Recently, a resonance region time-of-flight spectrometer for use with a neutron "pile" has been built and put into operation. One of the principal advantages of this instrument is that comparatively small samples are required, so that measurements can be made on many comparatively rare materials, such as certain separated isotopes. The first measurements made with this apparatus are reported here.

2. APPARATUS

The rotating-shutter spectrometer is described in detail elsewhere; only a brief description will be given here.

In the time-of-flight method, a short burst of neutrons of various energies is released at a "source" point at a known time. A detector at a known distance then delivers signals representing neutrons of various energies according to the time elapsed since the burst. In the modulated-cyclotron method the burst is obtained by pulsing the particle source of the cyclotron; for time-of-flight work with a pile, the continuous neutron beam from the pile is pulsed mechanically by a shutter. This shutter, in the present instrument, consists of a steel cylinder (Fig. 1), rotated at high speed, and containing six slits like the one shown. The fixed collimating system contains similar slits, and as the rotor turns the beam passes through in a short burst at the instant that the slits are in line with each other. The slits are about 2 cm high and 0.025 cm wide, the width being chosen to give the desired resolution. The shutter is long enough to make the background counting rate small; in the measurements reported here, the background due to leakage through the shutter was generally less than 2 percent of the timed-neutron rate. (Additional background from the pile gave a total background rate of about 5 percent.)

The electronic circuitry used with the shutter consists essentially of a number of "channels," each recording a separate energy interval. The detector is a BF_3 pulse ion chamber, 30 cm long, operated at a pressure of two atmospheres, and located 10 meters from the shutter. Neutron counts from the detector, which operates continuously, are "sorted" into the appropriate

* Now at Harvard University, Cambridge, Massachusetts.

[1] C. P. Baker and R. F. Bacher, Phys. Rev. **59**, 332 (1941) and further references there; L. J. Rainwater and W. W. Havens, Phys. Rev. **70**, 136 (1946); W. W. Havens and L. J. Rainwater, Phys. Rev. **70**, 154 (1946); Rainwater, Havens, Wu, and Dunning, Phys. Rev. **71**, 65 (1947); Havens, Wu, Rainwater, and Meaker, Phys. Rev. **71**, 165 (1947); Wu, Rainwater, and Havens, Phys. Rev. **71**, 174 (1947).

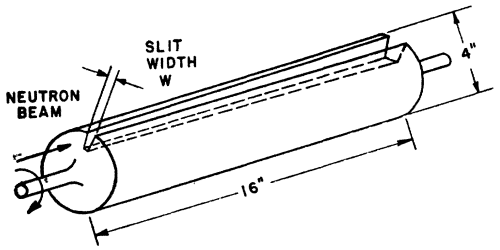

FIG. 1. Basic features of the rotating shutter.

channels at the proper time by means of a coincidence cirtuit in each channel. After each burst from the shutter, and after a further delay if desired, the channels are made sensitive consecutively, one at a time, for equal time intervals (a few microseconds in the present work). The entire timing operation is synchronized with the burst time by a photocell system. The measurements described here were made using 56 channels.

3. RESOLUTION

The resolution function is determined by the time shape of the burst, by the effect of detector length, and by the channel on-time. The burst was closely triangular in shape, with a base width which for most of the measurements reported here was 8 μsec. The detector was 30 cm long and thus contributed a 3 percent uncertainty to the 10 meter flight path. At "high" energies (short time-of-flight) this 3 percent is small compared to the resolution width of the burst time and channel on-time. At low energies, the detector effect becomes appreciable, and in fact makes the resolution function slightly asymmetric because the detection efficiency is high enough to make the intensity decrease along the length of the detector.

Figure 2 shows the calculated resolution function at high energies for the timing used in most of these measurements. This function is compounded from a triangular burst 8 μsec wide at the base and a channel on-time of 4 μsec. Although the curve extends 12 μsec, 90 percent of the area is included in the central 6.6 μsec, 95 percent in the central 7.8 μsec. Thus one could reasonably call the resolution width 7 or 8 μsec. However, in modulated-cyclotron systems, where both the burst and channel on-times are rectangular and the resulting resolution function triangular, it has been customary in the past to give the resolution width as the base width of the triangle. A triangular pattern, having about the same "90 percent-width" and "95 percent-width" as Fig. 2, would have a base width very nearly 10 μsec. Hence, for comparison with modulated-cyclotron work, the "resolution width" may be taken as 10 μsec, or 1.0 μsec/meter.

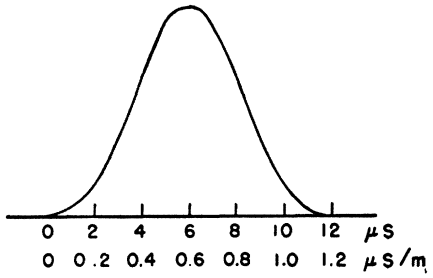

FIG. 2. Resolution function, not including detector-length effect, for 4 μsec channel time and 8 μsec triangular burst.

At low energies the detector effect on the resolution becomes appreciable, and the 1.0 μsec/m value is no longer an overestimate of the true "effective" width. For example, the detector effect amounts to 0.3 μsec/m at 50 ev. At still lower energies the detector effect is even larger and even makes the total resolution function slightly asymmetric, as noted above. No attempt has been made to correct the experimental transmission data for resolution, although in the analysis of the 5-ev resonance data for Ag the resolution was taken into account in a simple way. This is discussed further, below.

There is negligible resolution broadening introduced by detector pulse width. The amplified signals from the ion chamber have a rise time less than one microsecond; the rising edge of these signals is used to generate a very short pulse, which is then sorted into the various channels. The length of this short pulse (a few tenths of a microsecond) is set so that each signal from the detector is recorded in only one channel. Thus the only resolution broadening introduced by detector pulse width is due to the finite rise time of the ion-chamber signals. This time is short compared to the shortest channel time and burst time used.

4. ABSOLUTE ENERGY CALIBRATION

The midpoint of the 30-cm-long detector is set 1000 cm from the point where the beam enters the rotor. At low energies most of the beam is detected in the "front" part of the detector; accordingly, a correction to the flight path is made. This correction is only about 1 cm at 4 ev.

The timing pulses which switch the channels on and off in a "chain" sequence are obtained from a 1-*MC* oscillator and a series of dividers. The oscillator is quite stable, and its frequency is checked occasionally. Each time the shutter opens, a synchronized photocell pulse turns on the oscillator and, after an adjustable delay, starts the chain of channels. (The oscillator is adjusted to shut off shortly before each burst, to be resynchronized.) The photocell pulse is purposely set to occur shortly before the shutter opens so that a check can be kept on the delay between the two events. This delay is a function of the rotor speed and can be determined absolutely by changing the rotor speed and observing the resultant change in delay of "zero" time-of-flight neutrons, or of a resonance of low time-of-flight. Thus the time-of-flight scale is established on an absolute basis, when corrected for the small and measurable effect of all time lags in the electronic circuits.

5. MATERIAL MEASURED

Silver and tungsten were chosen for the first extensive measurements with this apparatus, for the following reasons: (1) They had been measured before,[1] with lower resolution than could now be used. (2) Separated-isotope samples of both elements were available at Argonne, and these could be used to investigate the isotopic distribution of the resonances. (3) Silver has a strong resonance at 5 ev, whose peak cross section σ_0 and width Γ were known only approximately. Measurements at 5 ev could now be made with sufficient resolution to determine σ_0 and Γ to within about 10 percent.

6. MEASUREMENTS ON SILVER

Measurements with Thick Sample

The measurements on normal silver were made with one thick sample and four thin ones. From the pure silver samples available at Argonne, one was chosen of approximately the same thickness as the thick sample

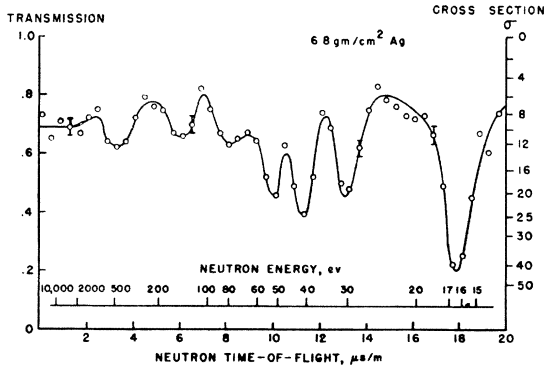

FIG. 3. Transmission of silver. Resolution ~1.0 μsec/m.

measured by Rainwater *et al.*[1] Thus it would be possible to get a fairly close comparison with their work, which will be referred to as "the earlier work."

The sample was first measured in the high energy region with a resolution (Fig. 2) about twice that used in the earlier work. The results are shown in Fig. 3. The statistical accuracy of the points is indicated for a few representative points. With 4 μsec channel time, the 56 channels used gave the transmission simultaneously in the region from very high energies (zero time-of-flight) to about 12 ev.

When compared with Fig. 7 of the earlier work, Fig. 3 shows the resolution of the broad 45-ev dip into three resonances, at 30, 41, and 53 ev. It appeared that with broader resolution the latter two might merge, but the 30-ev resonance seemed more sharply resolved than was expected from the earlier work. It was decided to run the sample again, this time with about the same resolution as in the earlier work. The results are shown in Fig. 4; the 30-ev resonance is still clearly resolved, and the two higher ones are no longer resolved. (The

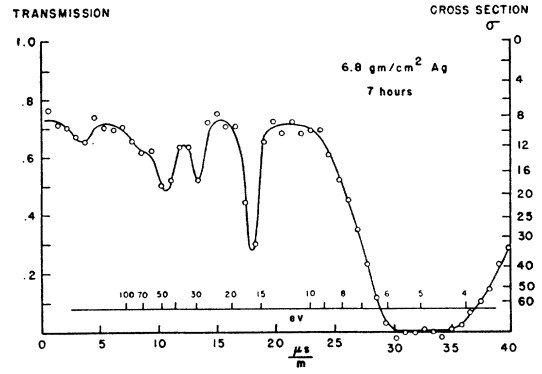

FIG. 4. Transmission of silver. Resolution ~1.6 μsec/m.

resolution used in a measurement is usually two to three times the interval between adjacent points.) The discrepancy with the earlier work has since been explained:[2] the effective resolution in that work was less than the nominal figure given, because of a "tail" on the cyclotron arc-current pulse.

Measurements with Separated Isotopes

Less than 100 mg of each separated silver isotope was available. This meant that only one slit could be used (four were used for the measurements with the thick sample) and that even then the sample would not be very thick. Hence, measurements with these samples took a very long time. Unfortunately, after many tens of hours of measurement, the samples appeared to be indistinguishable. Since they had been at the laboratory for several years and may have become mixed and since the quantities available were so small, the isotopic identification of silver's resonances has been put aside until better samples are available.

Measurements with Thin Samples

Four thin samples of normal silver were measured in the vicinity of the 5-ev resonance with high resolution (same timing as in Fig. 2). The results for a 0.0005-in. sample are shown in Fig. 5, on which a scale of apparent

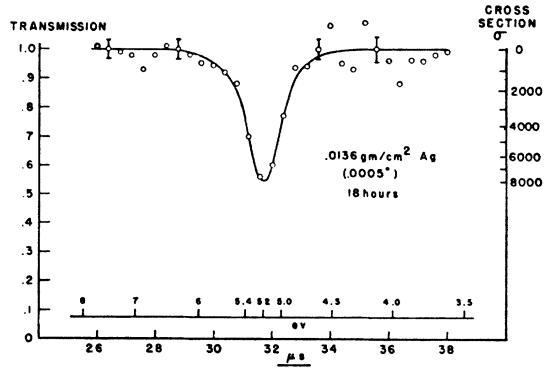

FIG. 5. Transmission of thin silver. Resolution ~1.0 μsec/m.

[2] W. W. Havens, private communication.

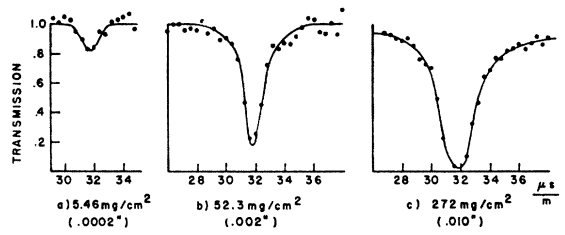

FIG. 6. Transmission of three silver samples.

cross section is also given. The results for three other thicknesses are shown in Fig. 6. About two weeks of two-shift operation was required to get the data for these four curves. (The running time given is only the "sample-in" time. Additional time is required, in the course of a measurement, to take open-beam runs in alternation with the sample-in runs, and to check the equipment occasionally.)

7. ANALYSIS OF THE 5-EV RESONANCE DATA

Since the measured cross section values, in Figs. 5 and 6, vary rapidly within a resolution width, it is clear that some correction must be made to obtain the true cross-section values. One method of analysis, which has been used in the past,[3] consists of a trial-and-error procedure. Various values of Breit-Wigner resonance parameters are assumed, and the corresponding "true" cross section curves and true transmission curves are calculated, corrected for doppler effect. The (calculated) resolution function is then numerically integrated over the true transmission curve. The final "calculated transmission" curves are compared with the experimental data, and the resonance parameters adjusted for best fit. This procedure can be expected to yield fairly accurate values only when the resolution width is smaller than the true width; in the present case this did not appear to be true. Moreover, the trial-and-error procedure involves an assumed resolution function; and, finally, the procedure is rather tedious. Consequently, a different method of analysis was used.

The method used is basically independent of both the resolution and the doppler effect and assumes only that the one-level Breit-Wigner formula gives the correct variation of cross section near an isolated resonance.[4,5] The procedure gives the peak cross section, σ_0, and the natural width, Γ, both uncorrected for doppler effect. The method consists of determining (1) $\sigma_0\Gamma$ from the "absorption integral" of a thin sample, and (2) $\sigma_0\Gamma^2$ from the cross section "far" from resonance (i.e., several half-widths away from exact resonance). In both of these determinations the doppler effect does not enter.[6] The resolution has no effect on (1); the resolution also has no effect on (2) if (a) the determination is made where the transmission varies approximately linearly with time-of-flight, and (b) the resolution is symmetrical on a time-of-flight scale. Even if (a) and (b) are not true, the resolution still has a negligible effect on (2) if the measured cross section does not vary rapidly within a resolution width. In any event, if the same value of $\sigma_0\Gamma^2$ fits a large energy region, reasonable confidence can be felt in this value.

The data of Fig. 4, in the vicinity of the 5 ev resonance, were fitted to an expression of the form $\sigma=b+(E_r/E)^{\frac{1}{2}}\sigma_0\Gamma^2/4(E-E_r)^2$ and the values of b and $\sigma_0\Gamma^2$ adjusted to give the best fit. The resonance energy E_r was determined, from the thin-sample data, as 5.17 $\pm$0.08 ev. The quantity b represents the "constant" part of the cross section in the vicinity of 5 ev. Strictly, b is not really constant; it includes effects from interference terms due to other resonances of the same J (spin of the compound nucleus) and from the asymmetric interference term involving the "potential scattering." It also includes effects from resonances of different J, and from the cross-section curve of the isotope not responsible for this resonance. Nevertheless, over the energy region in which the above expression was fitted, between $6\frac{1}{2}$ and $7\frac{1}{2}$ ev, the approximation can be expected to be fairly good, and did indeed provide a good fit. In this region the "resonant" part of the cross section varies by a factor of 3. The best fit was obtained for $b\approx 9$ barns (1 barn$=10^{-24}$ cm^2) and $\sigma_0\Gamma^2=365\pm30$ barn (ev)^2. The probable error is estimated, from the quality of the fit and from a rough estimate of the magnitude of the complicating effects.

$\sigma_0\Gamma$ was determined from the data of Figs. 5 and 6. The area under the transmission curve, defined as the "absorption integral," A, can easily be shown to be related to $\sigma_0\Gamma$, in the case of a thin sample, by $A\equiv\int(1-T)dt\approx\pi n\sigma_0\Gamma t_r/4E_r$ where T is the transmission, t is time-of-flight, t_r and E_r are the values of t and the energy at exact resonance, and n is the number of atoms/cm^2 in the sample. This result is not affected by resolution or doppler effect. For thicker samples, A no longer increases as fast as n. In Fig. 7, A is plotted against n. From the slope at the origin, $\sigma_0\Gamma$ is calculated as 2100$\pm$200 barn ev. The probable error given is again an estimated one.

From the values given for $\sigma_0\Gamma^2$ and $\sigma_0\Gamma$, one obtains $\sigma_0=12{,}000\pm2500$ barns, and $\Gamma=0.17\pm0.02$ ev. The principal contribution to the uncertainty in σ_0 comes from the probable error in $\sigma_0\Gamma$. It can be noted that σ_0 has approximately twice the relative error of $\sigma_0\Gamma$; this results from the dependence of σ_0 on the square of $\sigma_0\Gamma$, in the analysis used.

The probable error in σ_0 can be narrowed down by making an approximate calculation of the effect of the resolution, a calculation similar to that described at the

[3] B. D. McDaniel, Phys. Rev. **70**, 832 (1946).

[4] This assumption is adequately supported by experimental data. See, e.g., Goldsmith, Ibser, and Feld, Revs. Modern Phys. **19**, 259 (1947), and further references there.

[5] There is much literature on the resonance formula. See, e.g., E. P. Wigner, Phys. Rev. **70**, 15, 606 (1946), and further references there.

[6] H. Bethe, Revs. Modern Phys. **9**, 140 (1937).

start of this section. First, the doppler effect must be calculated. The doppler width for this resonance is calculated to be 0.074 ev.[7] (The effective temperature of the silver atoms is taken as 12 percent higher than the room temperature of 300°K. This is on the basis of calculations by Lamb.[7]) As a result of the Doppler effect, the peak cross section is lowered to 80 percent of its "natural" value.

Using the calculated resolution, a rough calculation was then made of the apparent peak cross section which would be measured for a thin sample. This gave about 8000 barns, which is in excellent agreement with the experimentally measured 8000±1000 barns (Fig. 5). Therefore, it seems reasonable to place limits of about 1500 barns on the probable error of σ_0, instead of the 2500 barns given above.

The constants for the 5-ev resonance, as measured in the normal element, may now be summarized as follows:

$$\left.\begin{aligned} E_r &= 5.17\pm0.08 \text{ ev} \\ \Gamma &= 0.17\pm0.02 \text{ ev} \end{aligned}\right\} \text{uncorrected for doppler effect}$$

$$\sigma_0 = \begin{cases} 12{,}000\pm1500 \text{ barns} \\ 10{,}000\pm1300 \text{ barns} \end{cases} \text{doppler-corrected.}$$

With values of this accuracy and with rough values of Γ_n/Γ which have been obtained by other workers, it is easily possible to determine the spin of the compound nucleus, J, and thus the neutron width, Γ_n. The peak isotopic cross section given by the Breit-Wigner formula is $\sigma_0=4\pi\lambda\!\!\!^{-}_r{}^2 g\Gamma_n/\Gamma$ where $\lambda\!\!\!^{-}_r$ is $1/(2\pi)$ times the neutron wavelength at resonance, and g is a spin factor, $\frac{1}{2}(2J+1)/(2I+1)$. The isotope having the 5-ev resonance, Ag^{109}, has an abundance of 49 percent, so that one calculates from σ_0 that $g\Gamma_n/\Gamma=0.048$. The nuclear spin I is $\frac{1}{2}$, so that g is $\frac{1}{4}$ or $\frac{3}{4}$ according to whether J is 0 or 1. From measurements on the resonance integral (essentially $\int\sigma dE/E$) for scattering and for activation (capture) the value of Γ_n/Γ for this resonance has been found[8] to be $\sim$0.04 for Ag^{109}. This establishes J as 1. It follows that $\Gamma_n\approx0.011$ ev.

In conclusion, we compare our results with other measurements on this resonance. In very early measurements, Amaldi and Fermi[9] found an absorption coefficient for self-absorption of 20 cm²/g. This is equivalent to a cross section for self-absorption of 3600 barns. According to whether one assumed the doppler width to be small or not compared to the natural width, this value would then give a peak cross section of 7200 barns or higher. Attempts to determine the natural width Γ from the early data gave badly inaccurate values.[10] This is explained by the fact that the resonance energy was measured by the boron method and gave 3 ev instead of the correct value of 5; consequently, even though the relative effective total width Γ_{eff}/E_r was measured fairly accurately, the calculated value for Γ_{eff} was not larger than that expected from doppler effect alone, and hence the natural width was thought to be very small.

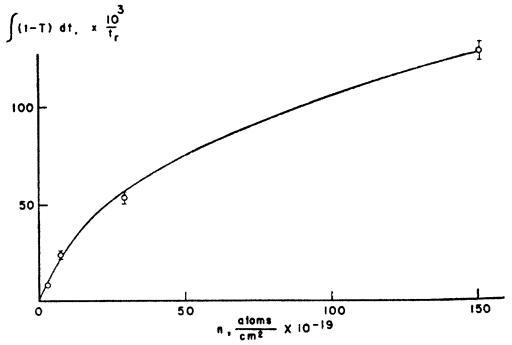

FIG. 7. "Absorption integral" of silver as a function of sample thickness.

Lowry and Goldhaber[11] have recently given values for the width and resonance integral of the 5-ev resonance. They find $\int\sigma_{\text{capture}}dE/E=1080$ barns for all the resonances of Ag^{109} taken together and find[12] that about 75 percent of this is due to the 5-ev resonance. This gives $\sigma_0\Gamma\approx1350$ barn ev for 5-ev capture in the normal element, which is about 30 percent less than the results of the present measurements. Their measurement of σ_0, by self-indication, is about 12,000 barns,[12] the same as that given here for the value without doppler effect, so that they obtain a value of 0.12 ev for Γ, about 30 percent less than that reported here. The differences between their figures and those given here are not very far outside the combined probable errors.

De Vries and his co-workers have obtained, for the width of the 5-ev resonance, a value in good agreement with that of the present work: their result, 0.18 ev, is an "effective" value which includes a contribution from doppler effect.[13]

8. MEASUREMENTS ON TUNGSTEN

Tungsten has four major isotopes of approximately equal abundance and a fifth (W^{180}) of very low abundance (0.14 percent). Separated-isotope samples of several hundred milligrams of each of the major isotopes were available, recently obtained from the AEC Isotopes Division. Measurements on normal tungsten and on the separated-isotope samples are shown in Fig. 8.

[7] W. E. Lamb, Phys. Rev. **55**, 190 (1939).

[8] Harris, Muehlhause, and Thomas, Phys. Rev. **79**, 11 (1950). The measurements reported there give $\Sigma_i(\sigma_0\Gamma_n/E_r)_i$ and $\Sigma_i(\sigma_0\Gamma/E_r)_i$, where Γ_n and Γ are scattering and total widths, and the summations extend over all resonances. Since the 5-ev resonance is very much stronger than the other resonances in silver (see Fig. 4), the ratio of these measurements gives approximately the value of Γ_n/Γ for the 5-ev resonance alone.

[9] E. Amaldi and E. Fermi, Phys. Rev. **50**, 899 (1936).

[10] H. Bethe, Revs. Modern Phys. **9**, 69 (1937), Sec. 61B.

[11] L. L. Lowry and M. Goldhaber, Phys. Rev. **76**, 189(A) (1949).

[12] Private communication.

[13] Hl. de Vries, Helv. Phys. Acta **23**, 169 (1950); Coster, Groendijk, and de Vries, Physica **14**, 1 (1948), and further references there.

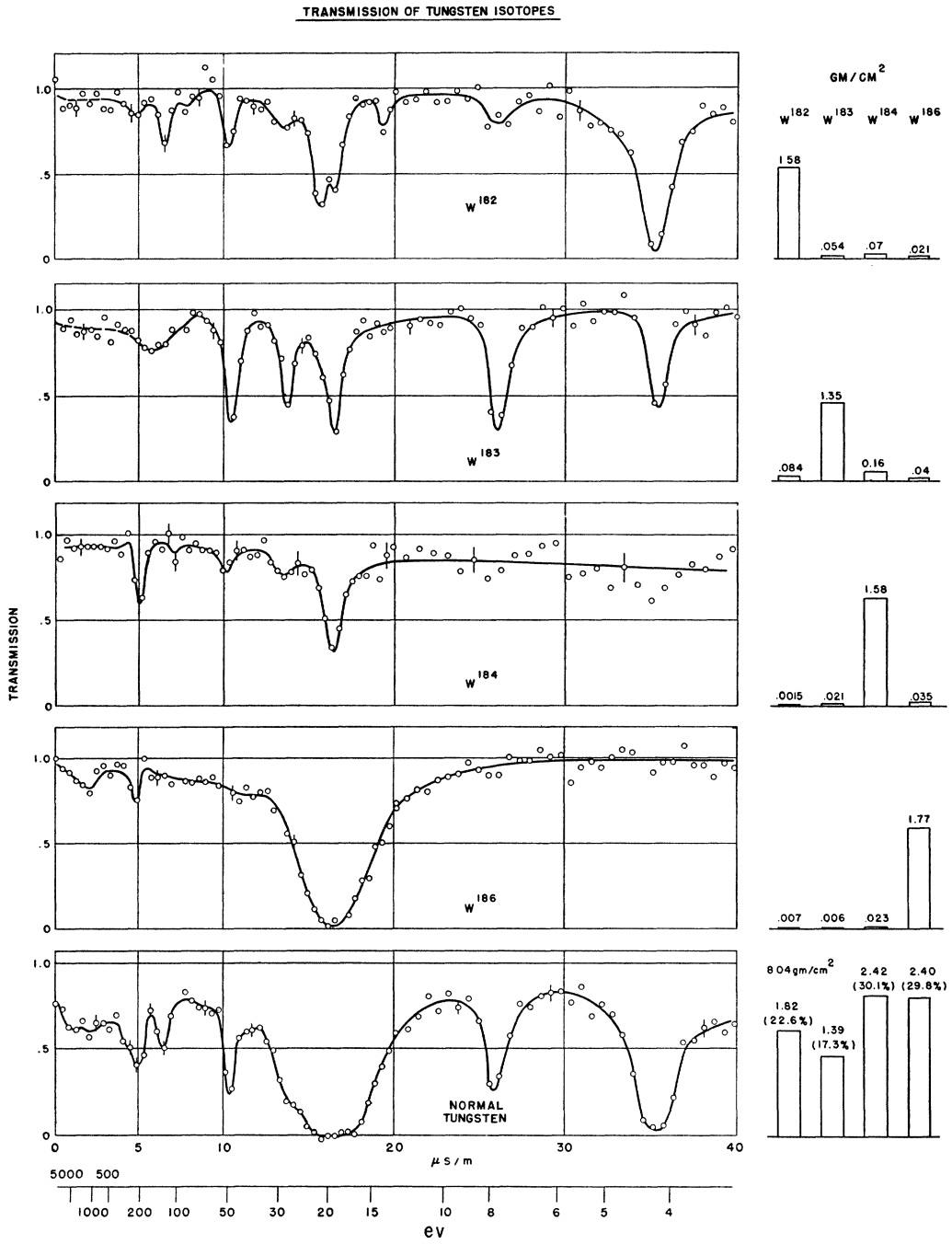

FIG. 8. Transmission of tungsten, in separated-isotope form and in normal isotopic distribution. The composition of each sample is shown at the right.

Samples

The sample thicknesses were chosen, after preliminary measurements, primarily on the basis of investigating the isotopic resonance distribution. Each separated-isotope sample contained approximately the same thickness of one isotope as was in the "normal tungsten" sample.

No cross-section values are shown on Fig. 8. Such values could be calculated from the sample thicknesses given, but they would be rather meaningless for most of the data. The samples were generally too thin to give accurate values for the cross section where σ is low, and too thick where σ is high. To obtain accurate values of σ would require the measurement of samples of various thicknesses.

As it happens, a small amount of data for various

thicknesses is included in the data of Fig. 8, because each separated-isotope sample is not absolutely pure. Thus, e.g., the W^{183} sample incidentally contains a "thin sample" of W^{182}, so that an approximate value of $\sigma_0\Gamma$ can be obtained for the 4-ev resonance.

The separated-isotope samples were in the form of WO_3. The curves shown have been corrected for the oxygen (transmission about 94 percent) and for the sample-holders used. The latter had a transmission of about 91 percent, with a possible systematic error of a few percent in this value.

Resolution

Each of the five curves shown in Fig. 8 was taken in two sections: the data from 0 to 20 microseconds/meter were taken at one time, with the same resolution pattern shown in Fig. 2. The data from 20 to 40 μsec/m were taken with slightly larger values for the burst time (10 μsec instead of 8) and channel on-time (6 μsec instead of 4).

Level Spacing

From the data of Fig. 8, one can obtain rough values for the level spacing for the various isotopes. W^{182} has definite levels at 4.15 ev and $21\frac{1}{2}$ ev, possibly faint levels at 14 ev and near 90 ev, a strong level or group at 125 ev, and many more above 200 ev. W^{183} has definite levels at 7.8 ev, 28 ev, and 49 ev, and many more at 100 ev and higher. W^{184} has a level at 100 ev, a stronger one at 205 ev, and probably more levels near 300 ev and above. W^{186} has a very strong level at $19\frac{1}{4}$ ev, another at 225 ev, and many more at 1000 ev and higher. Thus the average spacing is seen to be of the order of 10 to 30 ev in W^{182}, about 20 ev in W^{183}, perhaps 100 ev in W^{184}, and hundreds of ev in W^{186}.

The general trend of these spacings with the atomic weight of the isotopes is in agreement with what one would expect from theory. Namely, level densities should increase rapidly with binding energy,[14] and binding energy should be greater for an odd-N nucleus (i.e., for a nucleus with an odd number of neutrons, which forms an even-N compound nucleus) than for an even-N nucleus. Consequently, the level spacing for W^{183} should be smaller than for the even-N isotopes. Moreover, among the even-N isotopes, one would expect the binding energy, and hence the level density, to decrease with increasing atomic weight; the heavier isotopes, richer in neutrons, should bind an additional neutron less tightly than do the lighter isotopes.

Although these expectations are qualitatively confirmed by the data, however, the level spacing for W^{182} is surprisingly small: 10 to 30 times smaller than for W^{186}, which is an even-N nucleus like W^{182}, and about the same as for W^{183}, which is an odd-N nucleus. What is the possibility that this small spacing for W^{182} is due to an unusually large binding energy[15] for a neutron added to W^{182}? The experimental evidence concerning the neutron binding energies for the various isotopes, although meager, indicates that the binding energy for this case is not unusually large—in particular, it seems to be close to the value expected from the semi-empirical mass formula.[16] If we therefore rule out this possibility, the most likely explanation which has been offered for the small spacing found for W^{182} seems to be that of a statistical fluctuation in the level density.[17,18] One other possibility which may be mentioned is that W^{182} may have a higher spin than W^{184} or W^{186}; according to Bethe's theory of level densities,[14] this would result in a greater level density. This possibility is rather small since all three of these nuclei are even Z—even N; all even Z—even N nuclei measured thus far have zero spin.

All of the above discussion is based on the somewhat rough estimates of level spacing which can be obtained from the rather limited data of Fig. 8. It is, therefore, worth remarking that these estimates of the level spacings are supported by additional evidence from the neutron widths Γ_n of some of the resonances. According to theory,[19] $\Gamma_n = cD(E_r)^{\frac{1}{2}}$, where D is the level spacing, E_r is resonance energy, and c is a universal constant. The value of c should be about 0.00013;[19] for a considerable number of slow neutron resonances in different nuclei, c has been found to have this value on the average, varying within a factor of about 3 in either direc-

[14] See, e.g., H. A. Bethe, Revs. Modern Phys. **9**, 79 ff. (1937); and V. Weisskopf, Phys. Rev. **52**, 295 (1937).

[15] To discuss this possibility we consider how much binding energy difference is required to explain the difference in level spacings—i.e., how rapidly is the level spacing to be expected to change with binding energy—and how much binding energy difference may be expected from the semi-empirical mass formula, allowing for possible effects of nuclear shell structure. The answer to the first of these questions is that the level spacing in the tungsten isotopes should change by a factor of 3 to 6 for a one-Mev change in binding energy [H. Bethe, *Elementary Nuclear Theory* (John Wiley and Sons, Inc., New York, 1947), p. 117]. As for the second question, from the mass formula one would expect the binding energy for a neutron added to W^{182} to be about $\frac{1}{2}$ Mev greater than for W^{186} and about $1\frac{1}{4}$ Mev less than for W^{183}.

The experimental information as to the binding energies in question consists of measurements made by J. Halpern (private communication) on the (γ, n) thresholds in unseparated isotopes of tungsten. The smallest threshold observed is 6.0 ± 0.3 Mev, and the next is 7.5 ± 0.3 Mev. These figures correspond within a few tenths of a Mev to values predicted by the mass formula. In particular, the 6.0 figure almost undoubtedly corresponds to the (γ, n) threshold of W^{183}—i.e., to the binding energy of a slow neutron added to W^{182}. If this interpretation is correct, then the binding energy for $W^{182}+n$ is not unusually large by any amount sufficient to explain the high level density found.

[16] H. Bethe, Revs. Modern Phys. **8**, 165–168 (1936); E. Fermi, *Nuclear Physics* (University of Chicago Press, Chicago, 1950), p. 6.

[17] I wish to thank R. J. Sachs for this suggestion.

[18] This possibility might be checked if the level density could be measured over a wider energy range than is possible with present time-of-flight spectrometers. One possible method might be to make measurements of the (n, γ) cross section with broad resolution, in the Mev region; such measurements give the average level spacing—more accurately, the average Γ_γ/D, where D is the level spacing and Γ_γ is the radiation width. See, e.g., Hughes *et al.*, Phys. Rev. **75**, 1781 (1949).

[19] See, e.g., Feshbach, Peaslee, and Weisskopf, Phys. Rev. **71**, 145 (1947), in particular Eq. (26). The value of 0.00013 for c is obtained by taking a value of K corresponding to an energy of $\sim$25 Mev, and by taking $D^* \approx D$.

tion.[20] In the present case, one sees qualitatively that W^{182} has comparatively weak resonances, indicating small Γ_n and thus small D, whereas W^{186} has comparatively strong resonances, indicating large Γ_n and thus large D. Approximate values of Γ_n for the first resonances in W^{182} and W^{186} (estimated by a method given below) indicate level spacings of the order of magnitude of 4 ev and 400 ev, respectively.

Resonance Constants in W^{182} and W^{186}

Approximate values for the resonance parameters σ_0, Γ, and Γ_n can be obtained for the 4-ev resonance in W^{182} and the 19-ev resonance in W^{186}. For the 4-ev resonance, $\sigma_0\Gamma$ is estimated as $\sim$600 barn ev, from the absorption integral for the "thin-sample" data in the W^{183} curve. (See Sec. 7.) $\sigma_0\Gamma^2$ is estimated from the absorption integral for the "thick-sample" data in the W^{182} curve. (For a thick sample the absorption integral, $\int(1-T)dt$, is simply related to $\sigma_0\Gamma^2$. The method used to evaluate $\sigma_0\Gamma^2$ for the 5-ev resonance in silver is not satisfactory for the particular resolution and sample thickness used here.) The result obtained is $\sigma_0\Gamma^2 \sim 45$. Thus $\sigma_0 = 8500 \pm 3000$ barns, $\Gamma = 0.07 \pm 0.02$ ev. Γ_n is obtained by using the Breit-Wigner relation $\sigma_0 = 4\pi\lambda^2 g\Gamma_n/\Gamma$, with the above values of σ_0 and Γ and with a value of 1 for g. This value of g corresponds to the assumption that the spin of the even-even W^{182} nucleus is zero. The result is $\Gamma_n \approx 0.001$ ev.

The 19-ev resonance in W^{186} was analyzed by examining the detailed values of the cross section between 4 and 7 ev away from resonance on both sides, as obtained from Fig. 8. This type of analysis is fruitful here because there are no other resonances nearby. It is necessary to investigate both sides of the resonance because of the strong asymmetry introduced by the interference term due to potential scattering. This term is especially prominent here because this resonance is predominantly a scattering resonance.[21] The interference effects are clearly visible in Fig. 8, which shows that the cross section on the low energy side is very low, only a few barns, whereas on the high energy side it remains rather high for 50 to 100 ev and then goes through a minimum—very likely near zero—near the 225-ev resonance. (Note that the energy scale becomes rapidly compressed at high energies.)

The analysis of the 19-ev resonance gives approximate values for $\sigma_0\Gamma^2$: $14{,}000 \pm 3000$ barn ev^2, and Γ_n/Γ: 0.6 ± 0.3. From these, and, as for the 4-ev resonance, using $\sigma_0 = 4\pi\lambda^2 g\Gamma_n/\Gamma$ and assuming $g=1$, one finds $\Gamma = 0.4 \pm 0.1$ ev, $\Gamma_n = 0.25 \pm 0.1$ ev.

I wish to express my appreciation for the interest that Professor E. Teller has taken in this work. The construction of the equipment was initiated because of suggestions made by him concerning certain interesting problems in slow neutron resonance work. The construction was made possible only by the encouragement and cooperation of D. J. Hughes. Many people contributed greatly to the construction of the equipment, chiefly, N. Hochstetler and A. Denst in the engineering and precision machining of the rotating-shutter unit, C. Zaander in the development of the electronic circuits, and A. Hill in their construction. W. Woolf gave very valuable assistance in putting the equipment into operation and in taking data.

[20] E. P. Wigner, Am. J. Phys. **17**, 99 (1949).

[21] Harris, Muehlhause, and Thomas, Phys. Rev. **79**, 11 (1950).