Slow Neutron Velocity Spectrometer Studies. II. Au, In, Ta, W, Pt, Zr*

W. W. HAVENS, JR., C. S. WU, L. J. RAINWATER, AND C. L. MEAKER
Columbia University, New York, New York

(Received November 4, 1946)

The slow neutron velocity spectrum of Au, In, Ta, W, Pt, and Zr have been investigated. The results for Au and In check the values previously obtained using the "old" system. The results for the gold level at (4.8±0.1)ev with $\sigma_0\Gamma^2=600$, and for the main indium level at (1.44±0.02) ev with $\sigma_0\Gamma^2=210$ agree with the earlier results. Additional indium levels were found at (3.8±0.2) ev with $\sigma_0\Gamma\sim 120$ and at (8.6±0.4) ev with $\sigma_0\Gamma\sim 300$. The cross-section curve for Ta below 1 ev is well matched by $\sigma=[(7.2\pm 0.4)+(3.0\pm 0.1)E^{-\frac{1}{2}}]$. Tantalum has levels at (4.1±0.1) ev with $\sigma_0\Gamma^2\sim 44$, at (10.0±0.3) ev with $\sigma_0\Gamma^2\sim 25$, at (13±0.5) ev with $\sigma_0\Gamma^2\sim 3$, at (22±2) ev with $\sigma_0\Gamma^2\sim 18$, at (37±3) ev with $\sigma_0\Gamma^2\sim 400$, and other dips probably indicating multiple strong levels near 100 ev, 300 ev, and at higher energies. The cross section curve for W below 1 ev is well matched by $\sigma=[(5.7\pm 0.2)+(2.72\pm 0.05)E^{-\frac{1}{2}}]$. There are levels at (4.0±0.1) ev with $\sigma_0\Gamma^2\sim 13$, at (7.4±0.2) ev with $\sigma_0\Gamma^2\sim 5$, at (18.0±0.5) ev with $\sigma_0\Gamma^2\sim 3000$ (perhaps multiple), at (45±2) ev with $\sigma_0\Gamma^2\sim 400$ (perhaps multiple), at (180±20) ev with $\sigma_0\Gamma^2\sim 10{,}000$ if single (probably multiple), and a dip at 1100 ev which is probably multiple. The results for Pt show pronounced crystal interference effects in the thermal region. The $1/v$ line is probably $\sigma=[(12.0\pm 0.3)+(1.03\pm 0.06)E^{-\frac{1}{2}}]$. There are levels at (11.5±0.4) ev with $\sigma_0\Gamma^2\sim 55$, at (18.2±1) ev with $\sigma_0\Gamma^2\sim 30$, and broad dips near 100 ev and near 1000 ev indicating the presence of several strong unresolved levels. The results for Zr below 0.6 ev are well matched by $\sigma=[(6.8\pm 0.3)+(0.74\pm 0.10)E^{-\frac{1}{2}}]$. There are weak levels at (1.09±0.03) ev with $\sigma_0\Gamma\sim 5$ and at (2.30±0.07) ev with $\sigma_0\Gamma\sim 8$. A complex dip near 7 ev probably consists of two levels at $E_0=(5.7\pm 0.5)$ ev with $\sigma_0\Gamma\sim 10$ and at (7.6±0.4) ev with $\sigma_0\Gamma^2\sim 40$.

INTRODUCTION

THIS is the second of a series of papers in which the results of measurements using the new Columbia University Slow Neutron Velocity Spectrometer are presented. A description of the first system and a detailed analysis of operational factors is given in two previous papers.[1,2] The description of the new system and the results for Cd, Ag, Sb, Mn, and Ir are given in the first paper of this series.[3]

For convenience in interpreting these results a few of the factors involved in the operation of the apparatus and in the analyses applied to the data are listed below. A complete discussion of these factors is given in the three previous papers.

OPERATION

1. A burst of neutrons is produced at the source between $t=0$ and $t=\tau$, and these neutrons are detected 6.2 meters from the source between $t=t$, and $t=t+\tau$ to define the neutron energy in terms of its time of flight t, over the measured path length.

2. Sixteen adjacent timing intervals are measured simultaneously for each of two independent detectors, thus 32 measurements are made simultaneously.

3. The detection intervals are spaced in time an amount τ equal to the width of the individual intervals. The resolution function of the instrument may be considered as triangular in shape with a base of approximate width 2τ or twice the spacing between adjacent points. Actually the width of the resolution triangle includes other factors such as a term due to the counter length, and, below 0.3 ev, a term due to the diffusion time of the thermal neutrons leaving the source. In almost all cases, the resolution width may be taken as 2 to 3 times the spacing between adjacent points.

4. The results of the measurements are presented as plots of the slow neutron transmission

* This document is based on work performed under Contract W-7405-Eng-50 with the Manhattan Project and Columbia University. It will also be published in the Manhattan Project Technical Series, Division III, as part of the contribution of the Physics Department, Columbia University. Publication assisted by the Ernest Kempton Adams Fund for Physical Research of Columbia University.

[1] L. J. Rainwater and W. W. Havens, Jr., Phys. Rev. **70**, 136 (1946).
[2] W. W. Havens, Jr. and L. J. Rainwater, Phys. Rev. **70**, 154 (1946).
[3] L. J. Rainwater, W. W. Havens, Jr., C. S. Wu and J. R. Dunning, Phys. Rev. **71**, 65 (1947).

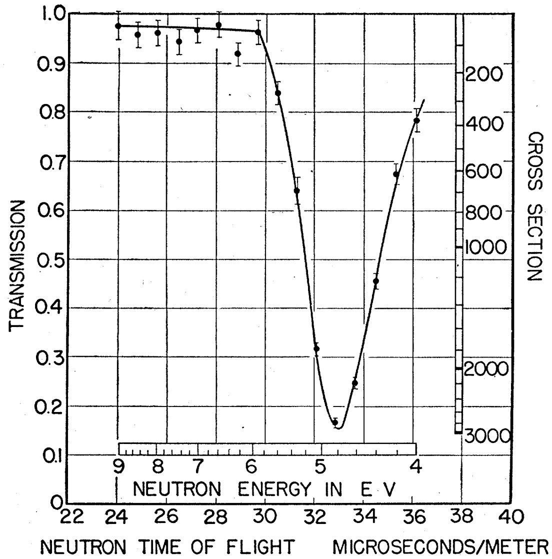

FIG. 1. The slow neutron transmission of 0.210 g/cm^2 of gold. This curve shows the resonance dip in transmission at 4.8 ev.

of the sample *vs.* the slow neutron time of flight in μsec./meter. Scales of energy are provided for convenience. The relation $E=(72.3/t)^2$ ev gives the neutron energy for a timing t μsec./meter.

5. The cross section, σ, is related to the transmission, T, by the relation $T=e^{-n\sigma}$ where n = atoms/cm^2 of the element studied (if only the element is present). From this equation a cross section scale indicated on each curve is computed, and if σ is a slowly varying function of t, the measured value of σ will correspond to the true value within the accuracy of each measurement. Near a resonance the effect of the resolution width will affect the measured cross section appreciably, and for resonances above 1 ev, the value of σ calculated from the transmission curve is usually very much smaller than the true value of σ. In particular the true value of σ_0 at exact resonance may be from 2 to 1000 times larger than the directly measured value σ max., from the transmission dip.

The quantity $\sigma_0\Gamma^2$ can usually be determined to within a factor of two by a method previously described.[2,3] This value is usually given in addition to the position (energy) of the resonance level. In some cases where the condition $n\sigma_0 \gg 1$ is not satisfied, a rough value of $\sigma_0\Gamma$ may be given. Although these values are only roughly quantitative, any information concerning the "strength" of the levels, was thought to be of value.

6. For many elements the cross section curve for energies lower than the first resonance may be closely matched by the sum of a $1/v$ term and a constant term. The equation for the cross section in this form is given where possible.

7. The units of energy E, cross section σ and the $\sigma_0\Gamma$ and $\sigma_0\Gamma^2$ values will usually not be stated specifically. It is to be understood that energy is expressed in units of electron volts, ev, and cross sections in units of $\times 10^{-24}$ cm^2/atoms. Γ is the full level width (in ev) at half-maximum in the Breit-Wigner formula.

Unless otherwise specified all cross sections are averages for the natural element and are not assigned to particular isotopes.

GOLD

The resonance in gold near 4.8 ev has previously been studied with the first Columbia Neutron Spectrometer.[2] The earlier measurements in gold have been checked with the new system. In Fig. 1, the transmission curve is shown for a 0.210 g/cm^2 gold foil. The position of the resonance at (4.8 ± 0.1) ev is in agreement with the previous measurement. The earlier value $\sigma_0\Gamma^2 = 600$ is also in good agreement with Fig. 1.

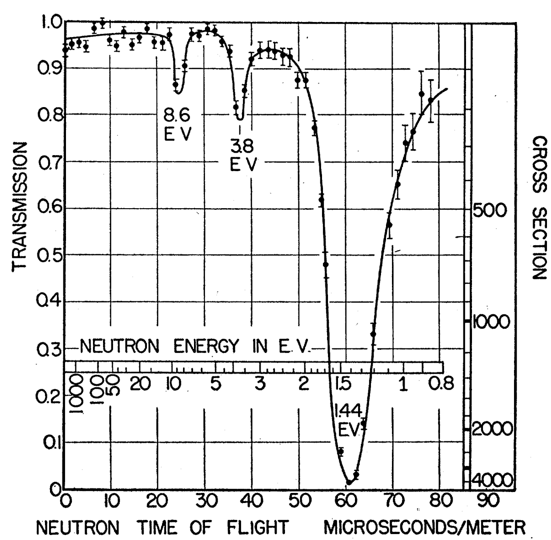

FIG. 2. The slow neutron transmission of 0.193 g/cm^2 of indium. This curve illustrates the three resonances at 8.6 ev, 3.8 ev, and 1.44 ev.

This level must be assigned to the Au^{197} for gold has only one isotope. The half-life of Au^{198} resulting from the capture of a neutron by Au^{197} is 2.7 days.[4,5] If $\Gamma \sim 0.1$ ev, then $\sigma_0 \sim 60,000$, which is 20 times larger than the measured σ max.

INDIUM

The indium resonance was also investigated with the previous system.[2] The main level was located at 1.44 ev with $\sigma_0\Gamma^2 = 210$. The same sample has been remeasured over a wider range with better resolution using the new system with the results shown in Fig. 2. Two additional resonances at 3.8 ev and 8.6 ev have been located with $\sigma_0\Gamma \sim 120$ for the 3.8 ev level and $\sigma_0\Gamma \sim 300$ for the 8.6 ev level. For $\Gamma \sim 0.1$ ev this corresponds to $\sigma_0 \sim 1200$ and 3000 respectively. There is no indication of other strong levels. (Since the sample is thin, only strong levels would be observed.)

The results $E_0 = 1.44$ ev and $\sigma_0\Gamma^2 = 210$, for the main level, agree with the results of Fig. 2. The 1.44 ev level was also studied using a 38.65 mg/cm^2 sample with the results shown in Fig.3, where the resonance is more nearly resolved since σ max. $= 11,000$. If $\Gamma = 0.09$ ev, then $\sigma_0 = 26,000$ which is within a factor of $2\frac{1}{2}$ of the measured value of σ max.

Indium has two isotopes In^{113} (4.5 percent) and In^{115} (95.5 percent). In^{114} results from the capture of a neutron by In^{113}, which has a half-life of 48 days.[6] The 13-sec. and 54-min. In^{116} are isomers.[4,7] The level strengths for the responsible isotopes must be correspondingly corrected. The final results may be expressed:

1. The first resonance has $E_0 = (1.44 \pm 0.02)$ ev $\sigma_0\Gamma^2 \sim 210$. (If $\Gamma = 0.09$ ev, then $\sigma_0 \sim 26,000$.) Value $\sigma_{max} = 11,000$ was obtained.
2. The second resonance has $E_0 = (3.8 \pm 0.2)$ ev $\sigma_0\Gamma \sim 120$. (If $\Gamma \sim 0.1$ ev, then $\sigma_0 \sim 1200$.)
3. The third resonance has $E_0 = (8.6 \pm 0.4)$ ev with $\sigma_0\Gamma \sim 300$. (If $\Gamma \sim 0.1$ ev, then $\sigma_0 \sim 3000$.)

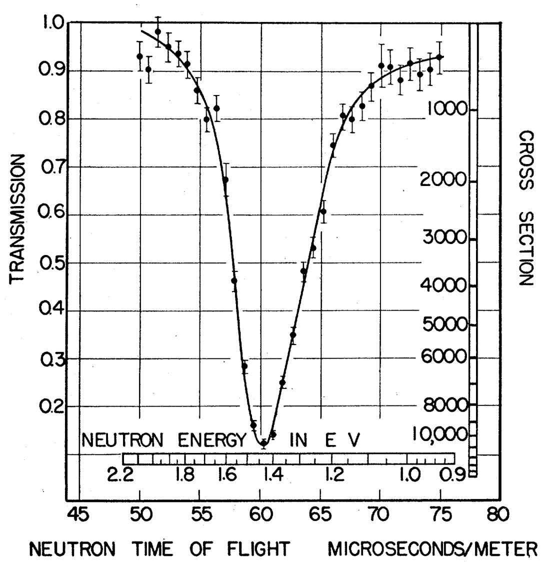

FIG. 3. The slow neutron transmission of 0.03865 g/cm^2 of indium near the 1.44 ev resonance. The solid line is a theoretical Breit-Wigner curve with $E_0 = 1.44$ ev, $\sigma_0\Gamma^2 = 210$, and $\Gamma = 0.09$ ev, corrected for the resolution width of the apparatus.

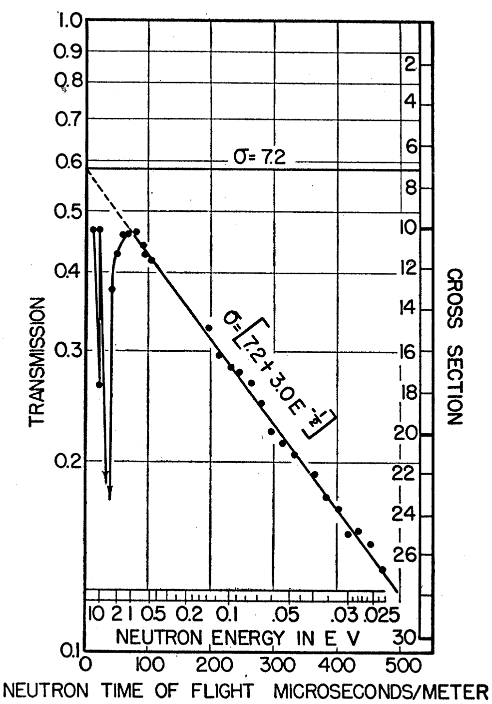

FIG. 4. The slow neutron transmission of 22.4 g/cm^2 of tantalum. This curve illustrates the $1/v$ type cross section in the thermal region with ($\sigma = 7.2 + 3.0E^{-\frac{1}{2}}$) and also shows the resonance levels at the higher energies.

[4] Amaldi, D'Agostino, Fermi, Ponticorvo, Rasetti, and Segrè, Proc. Roy. Soc. London **A149**, 522 (1935).

[5] McMillan, Kaman, and Ruben, Phys. Rev. **52**, 375 (1937); Pool, Cork, and Thornton, Phys. Rev. **52**, 239 (1937); Dzelepow and Constantinov, Comptes Rendus U.S.S.R. **30**, 701 (1941).

[6] Lawson and Cork, Phys. Rev. **52**, 531 (1937); Mitchell, Phys. Rev. **53**, 269 (1938).

[7] Lawson and Cork, Phys. Rev. **52**, 531 (1937); Mitchell and Langer, Phys. Rev. **53**, 505 (1938).

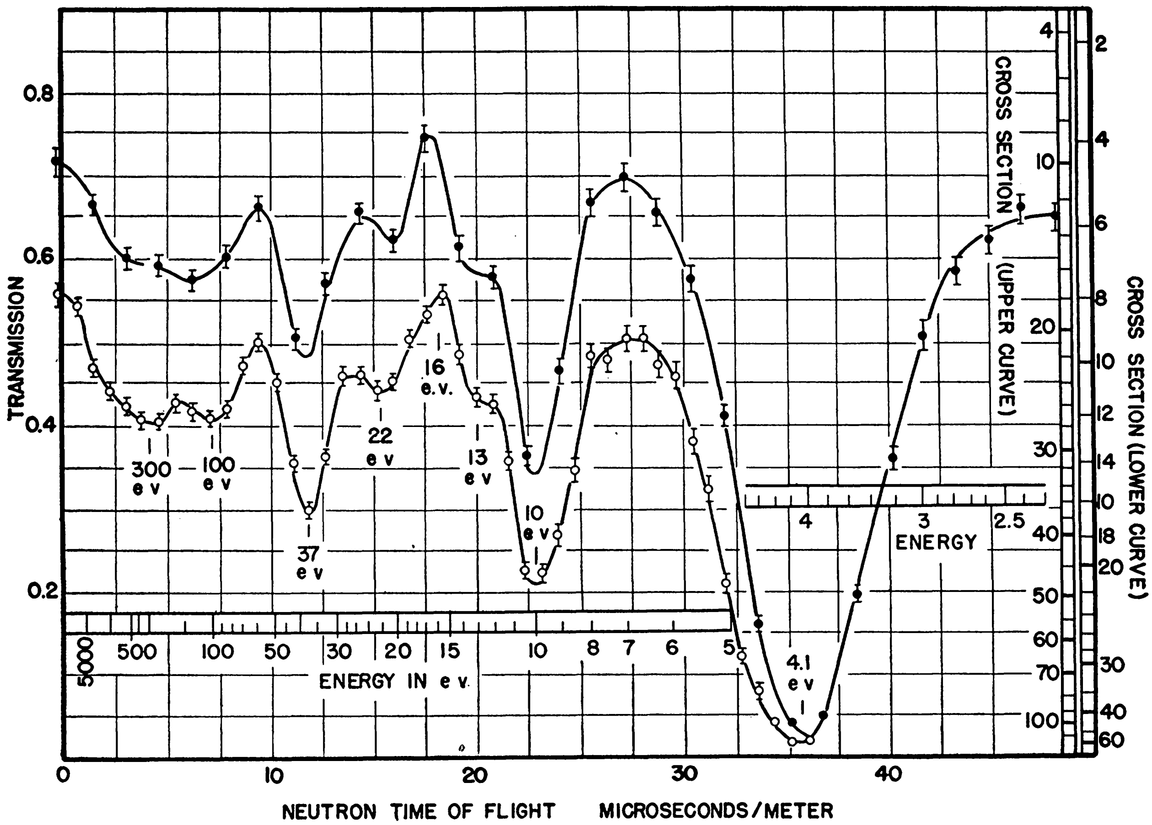

FIG. 5. The slow neutron transmission of tantalum. The upper curve shows the transmission for a 9.98 g/cm^2 sample with a resolution width of 3.6 μsec./meter. The lower curve shows the transmission for a 22.44 g/cm^2 sample with a resolution width of 1.8 μsec./meter. The use of the thicker sample with higher resolution increases the detail that can be obtained.

TANTALUM

The slow neutron transmission of tantalum was investigated using plates of tantalum metal obtained from the University of Chicago Metallurgical Laboratories. A spectrographic analysis of the samples showed less than 5 percent Cb; less than 0.05 percent Zr and Al; less than 0.005 percent Ti, Mo, Fe, Co, Os, Ag, Zn, Cd, Sn, Pb, Sb and traces of Cr, Ni, Ru, Rh, Pd, Pt, and Hg. For all other metals the prominent lines were not apparent, therefore the impurity was probably less than 0.05 percent for arc insensitive materials and less than 10^{-5} percent for arc sensitive materials. Samples of 9.98 g/cm^2 and 22.44 g/cm^2 thickness were studied. The results of these measurements are shown in Figs. 4 and 5.

The general features of the curve over a wide energy range are shown in Fig. 4. The results for $E<1$ ev are well matched by the relation $\sigma=(7.2+3.0E^{-\frac{1}{2}})$ and several levels are shown at higher energies. The high energy region was first investigated using a 9.98 g/cm^2 sample with about 3.2 μsec./meter resolution width. The results shown in the upper curve of Fig. 5 show the presence of strong levels at 4.1 ev, 10 ev, and 37 ev with indication of several other levels near 13 ev, 22 ev, and above 100 ev.

In view of the complex structure revealed, the portion of the curve above 4 ev was remeasured using a 22.44 g/cm^2 sample with twice the resolution. The results are shown in the lower curve of Fig. 5. All of the structure in the upper curve is repeated with better resolution in the lower curve, thus conclusively demonstrating the reality of the effects obtained.

An analysis of Fig. 5 can be made by using the position of the $1/v$ line and the constant term for the thick sample as determined in Fig. 4. If the curve is assumed to consist of a series of resonance dips there are strong levels at 4.1 ev, 10 ev, and 37 ev, weaker levels at 13 ev, 22 ev, and probably multiple levels near 100 ev and 300 ev, and in the higher energy region. Even though the levels below 100 ev may be multiple, an analysis to determine $\sigma_0\Gamma^2$ has been made assuming them to be single. The curve cannot be divided into a series of separate dips with any degree of accuracy near 13 ev and 22 ev. Therefore, the values of $\sigma_0\Gamma^2$ for these levels may be uncertain by more than the customary factor of 2.

The results for tantalum are of particular importance since all of the levels must be ascribed to the single Ta^{181} isotope. This is the first time in the knowledge of the authors that so many closely spaced levels have been experimentally demonstrated to belong to a single nucleus, although such effects are expected from the theory of level spacing.[8] The strength of the levels makes it unlikely that slight sample impurities can be responsible for any of the levels observed. The activity induced in tantalum by the (n, γ) reaction has a half-life of 97 days.[9]

The results for tantalum may be summarized:

1. Below 1 ev the data are well matched by the $1/v$ relation
   $\sigma = [(7.2\pm 0.4)+(3.0\pm 0.1)E^{-\frac{1}{2}}]$.
2. The first and main level occurs at $E_0 = (4.1 \pm 0.1)$ ev
   $\sigma_0\Gamma^2 \sim 44$.
   (If the $1/v$ slope were entirely attributed to a level at 4.1 ev then $\sigma_0\Gamma^2 = 96$ is required.)
3. The second strong level is at $E_0 = (10.0 \pm 0.3)$ ev
   $\sigma_0\Gamma^2 \sim 25$.
4. The third level is at $E_0 = (13\pm 0.5)$ ev
   $\sigma_0\Gamma^2 \sim 3$.
5. The fourth level is at $E_0 = (22\pm 2)$ ev
   $\sigma_0\Gamma^2 \sim 18$.
6. The fifth level is at $E_0 = (37\pm 3)$ ev
   $\sigma_0\Gamma^2 \sim 400$.
7. There are indications of probably more than one strong level near 100 ev, near 300 ev and at higher energies.

[8] H. A. Bethe, Phys. Rev. **50**, 332 (1936).

[9] Oldenberg, Phys. Rev. **53**, 35 (1938); Fomin and Houtermans, Physik. Zeits. Sowjetunion **9**, 273 (1936); Houtermans, Naturwiss. **28**, 578 (1940).

TUNGSTEN

The slow neutron transmission of tungsten was studied using rolled tungsten plates supplied by the General Electric Company, Cleveland Wire Works. Six plates were used for the 29.2 g/cm² sample (Fig. 6) and single plates of 5.06 and 4.90 g/cm² for the high energy region (Figs. 7 and 8). A spectrographic analysis of the sample showed less than 1 percent As; 0.5 percent Bi; 0.05 percent Zr, V, Zn, Cd, and Si; 0.005 percent Be, Fe, Pd, Au, Ge; traces of La, Ru, Rh, Cu, Hg, Al, Tl, Sn, Pb. For all other metals the prominent lines were not apparent.

The entire region was first investigated with low resolution using the thick sample as shown in Fig. 6. Below 1 ev the data are well matched by the relation $\sigma = (5.7+2.72E^{-\frac{1}{2}})$, and a dip is obtained showing the presence of one or more levels above 3 ev.

The region above 2 ev was next investigated using the 4.90 g/cm² sample and about 3.2 μsec./meter resolution width as shown in Fig. 7. This shows the presence of a strong level at 18 ev, a strong level at 4.0 ev, and weaker levels near 7.4 ev, 45 ev, 180 ev, and 1100 ev. Since the curve was so complex, it was considered of interest to investigate the region above 4 ev with higher resolution. A 5.1-g/cm² sample was

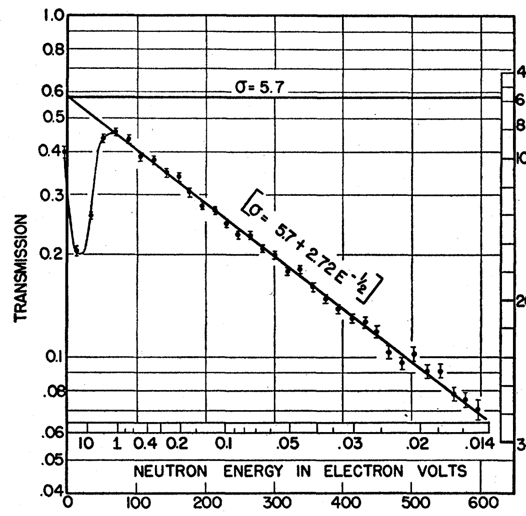

FIG. 6. The slow neutron transmission of 29.2 g/cm² of tungsten. This curve shows the $1/v$ type cross section for tungsten in the thermal region with $\sigma = (5.7+2.72E^{-\frac{1}{2}})$ and also illustrates the effect of resonances in the high energy region when broad resolution is used.

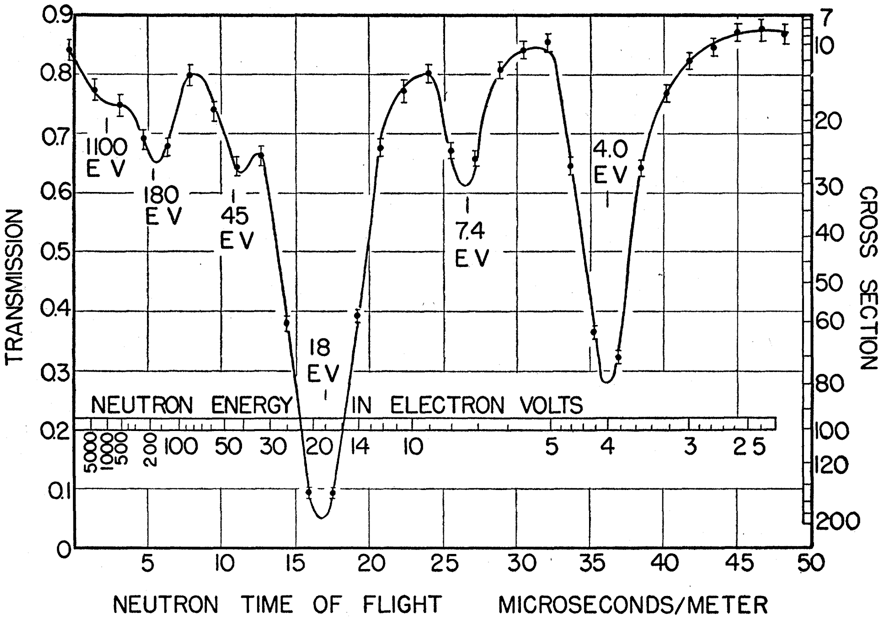

FIG. 7. The slow neutron transmission of 4.90 g/cm² of tungsten. This curve illustrates the complex neutron spectrum of tungsten showing transmission dips at 4.0 ev, 7.4 ev, 18 ev, 180 ev, and possible dips at 45 ev and 1100 ev.

used for this purpose with the results shown in Fig. 8. As in the case of tantalum all of the effects observed with the thicker sample and higher resolution are repeated with greater detail thus giving an excellent check on the measurements. The level at 7.4 ev appears again as a sharp dip, a more definite dip is now obtained at 45 ev; the level (or levels) near 180 ev is more pronounced; and the dip near 1100 ev is more definite. The shape of the curve near 10 ev may suggest the presence of a weak level, but the magnitude of the effect is so small that the presence of the level here is questionable.

Tungsten has 5 stable isotopes of which 4 have (within a factor of 2) approximately equal abundances. The single odd isotope W^{183} of 17.3 percent abundance should be responsible for the strong levels.[8] There are two well-established activities with half-lives of 77-d and 24.1-hr. induced in tungsten by (n, γ) reactions.[4,10]

The possibility has been suggested that the 4.0 ev level in Fig. 7 is caused by a small tantalum impurity and represents the 4.1 ev tantalum level. A comparison of Figs. 5 and 7, however, indicates a small but definite difference in level position. In addition a calculation of the strength $\sigma_0\Gamma^2\sim 13$ for the level would require that the sample be about 30 percent tantalum by weight.

The results for tungsten may be summarized as follows:

1. Below 1 ev the data are well matched by the $1/v$ relation.
   $\sigma=[(5.7\pm 0.2)+(2.72\pm 0.05)E^{-\frac{1}{2}}]$.
2. The first strong level is at $E_0=(4.0\pm 0.1)$ ev $\sigma_0\Gamma^2\sim 13$.

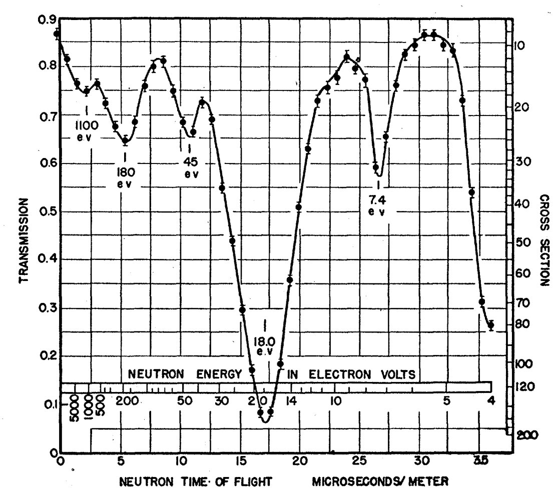

FIG. 8. The slow neutron transmission of 5.06 g/cm² of tungsten. The resolution used in this curve is twice as high as that used for Fig. 7 and confirms dips at 45 ev and 1100 ev. This data also gives greater detail for the levels at 7.4 ev and 180 ev.

[10] Minakawa, Phys. Rev. **57**, 1189 (1940); Fajans and Sullivan, Phys. Rev. **58**, 276 (1940); McLennan, Grimmet, and Read, Nature **135**, 147 (1935).

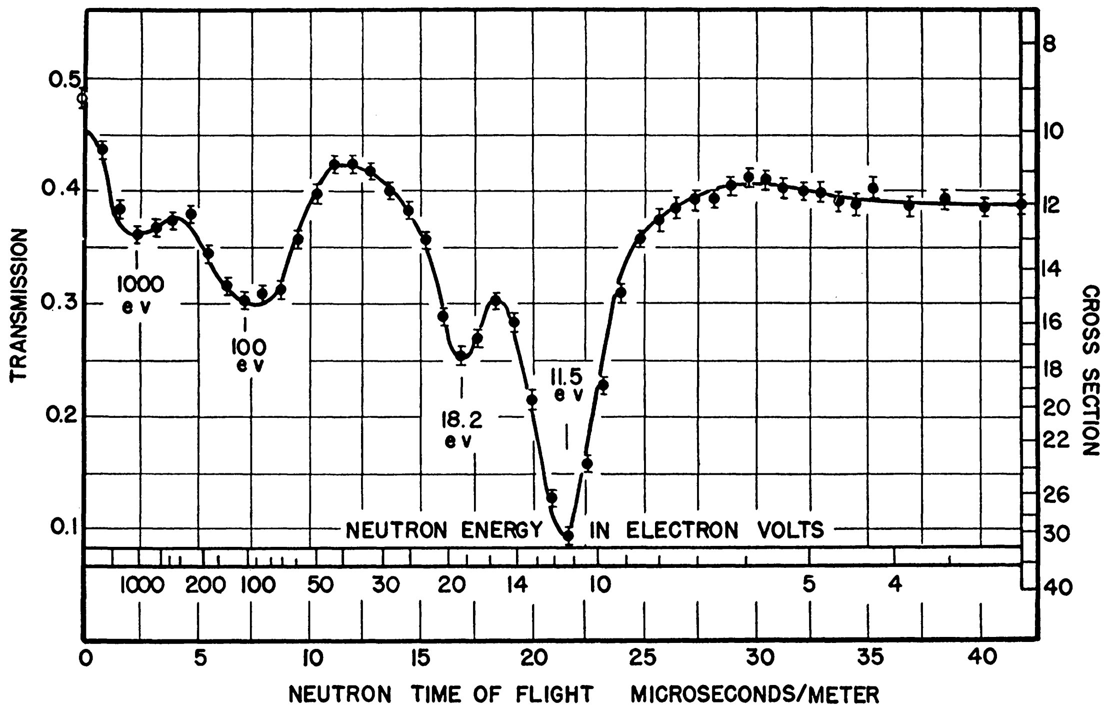

FIG. 9. The slow neutron transmission of 25.8 g/cm² of platinum above 2.2 ev. This curve shows transmission dips for platinum at 11.5 ev, 18.2 ev, 100 ev, and 1000 ev with the upper transmission dips not completely resolved.

If the W^{183} isotope is responsible, then $\sigma_0\Gamma^2 \sim 75$ for this isotope.

3. The second (weaker) level is at $E_0 = (7.4 \pm 0.2)$ ev
   $\sigma_0\Gamma^2 \sim 5$.
4. The third and strongest level is at $E_0 = (18.0 \pm 0.5)$ ev
   $\sigma_0\Gamma^2 \sim 3000$.
   This may be multiple as the curve in Fig. 8 recovers more slowly on the high energy side of the resonance than would be expected for a single level.

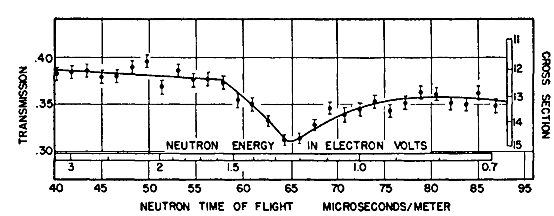

FIG. 10. The slow neutron transmission of 25.8 g/cm² of platinum from 0.7 ev to 3 ev. This curve shows a transmission dip at about 1.25 ev which is probably caused by a rhodium impurity.

5. The fourth level is at $E_0 = (45 \pm 2)$ ev
   $\sigma_0\Gamma^2 \sim 400$. (Perhaps multiple.)
6. The fifth dip is at $E_0 = (180 \pm 20)$ ev
   $\sigma_0\Gamma^2 \sim 10{,}000$ if it is due to a single level.
7. Another dip near 1100 ev is probably multiple.

PLATINUM

A sample containing 25.8 g/cm² of metallic platinum was used for the slow neutron transmission measurements. A spectrographic analysis of the sample showed less than 0.5 percent Ca, Al; 0.05 percent Fe, Rh, Pd, Cu, Au; 0.005 percent Ag and Si; traces of Cr, Ru, and In. For all other metals the prominent lines were not apparent.

The results of the measurements with the highest resolution for energies above 2.2 ev are shown in Fig. 9. This shows that there is a moderately strong level at 11.5 ev, a weaker level at 18.2 ev, a broad dip probably indicating several strong levels from 70 ev to 200 ev, and another broad dip near 1000 ev again suggesting several levels.

The region was extended with somewhat lower resolution as shown in Fig. 10. This shows a shallow dip at about 1.25 ev which is probably because of a slight rhodium impurity.

The results of the measurements with wide resolution from 0.009 ev to 0.4 ev are shown in Fig. 11. A $1/v$ slope $\sigma=(12.0+1.03E^{-\frac{1}{2}})$ is obtained for the first part of the curve while definite crystal interference effects are obtained for lower energies. The main discontinuities correspond to Bragg reflection limits at neutron wave-lengths of 1.6A and 2.4A.

Platinum has 5 stable isotopes of which the isotope Pt^{195} (35.3 percent abundance) is the only odd isotope and, according to theory, should be responsible for the strong levels.[8] There are only three activities of 18-hr. 3.3-d and 31-min. associated with the (n, γ) reactions in platinum.[11]

The results for platinum may be summarized as follows:

1. The $1/v$ slope (0.04 to 0.8 ev) is $\sigma=[(12.0\pm0.3)+(1.03\pm0.06)E^{-\frac{1}{2}}]$.
2. There are definite crystal effects for $E<0.035$ ev with transmission discontinuities for the neutron wave-lengths $\lambda=1.6$A and 2.4A.
3. There is a level at $E_0=(11.5\pm0.4)$ ev $\sigma_0\Gamma^2\sim55$.
4. There is a level at $E_0=(18.2\pm1)$ ev $\sigma_0\Gamma^2\sim30$.
5. There are broad dips at 100 and 1000 ev indicating the presence of strong unresolved levels.

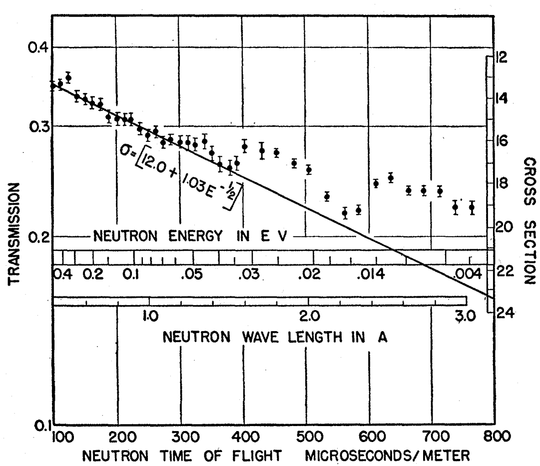

FIG. 11. The slow neutron transmission of 25.8 g/cm² of platinum in the thermal region. This curve illustrates the $1/v$ type curve in the thermal region with $\sigma=(12.0+1.03E^{-\frac{1}{2}})$ and the crystal interference effects observed at the lower energies.

[11] McMillan, Kaman, and Ruben, Phys. Rev. **52**, 375 (1937); Sherr, Bainbridge, and Anderson, Phys. Rev. **60**, 473 (1941); Pool, Cork, and Thornton, Phys. Rev. **52**, 239 (1937); McLennan, Grimmet, and Read, Nature **135**, 147 (1935).

ZIRCONIUM

A sample consisting of 6.45 g/cm² of ZrO_2 was used to investigate the slow neutron transmission of zirconium. A spectrographic analysis of the sample showed less than 5 percent Ca; 0.5 percent Zn, Si, Sr; 0.05 percent Mg, Ti, Mn, Fe, Cu, Al; 0.005 percent Be, B; traces of Sc, Y, V, Cr, Mo, Ni, Sn, Pb, Sb. For all other metals the prominent lines were not apparent. In all cases a constant cross section of 4.1 has been deducted for the oxygen.[5]

The results of measurements with wide resolution over the entire energy region are shown in Fig. 12. This shows that levels are present above 1 ev and that the results for lower energies are well matched by the $1/v$ curve $\sigma=(6.8+0.74E^{-\frac{1}{2}})$.

The region above 0.6 ev was investigated with better resolution as shown in Fig. 13. The dips indicated that there were single levels at 1.09 ev and 2.3 ev and perhaps a double level near 7 ev. The region 4 to 10 ev was then investigated with highest resolution as shown, and the dip seems to be resolved into two dips at 7.6 ev and 4.7 ev. There are no indications of other resonances.

Zirconium has 5 stable isotopes of which Zr^{91}

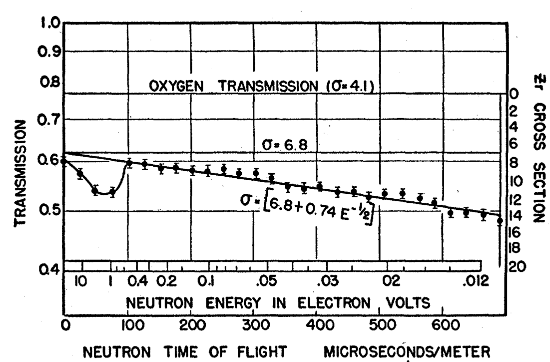

FIG. 12. The slow neutron transmission of 6.45 g/cm² of ZrO_2. This curve shows the $1/v$ type cross section for Zr in the thermal region with $\sigma=(6.8+0.74E^{-\frac{1}{2}})$ after 4.1 has been deducted for the oxygen cross section.

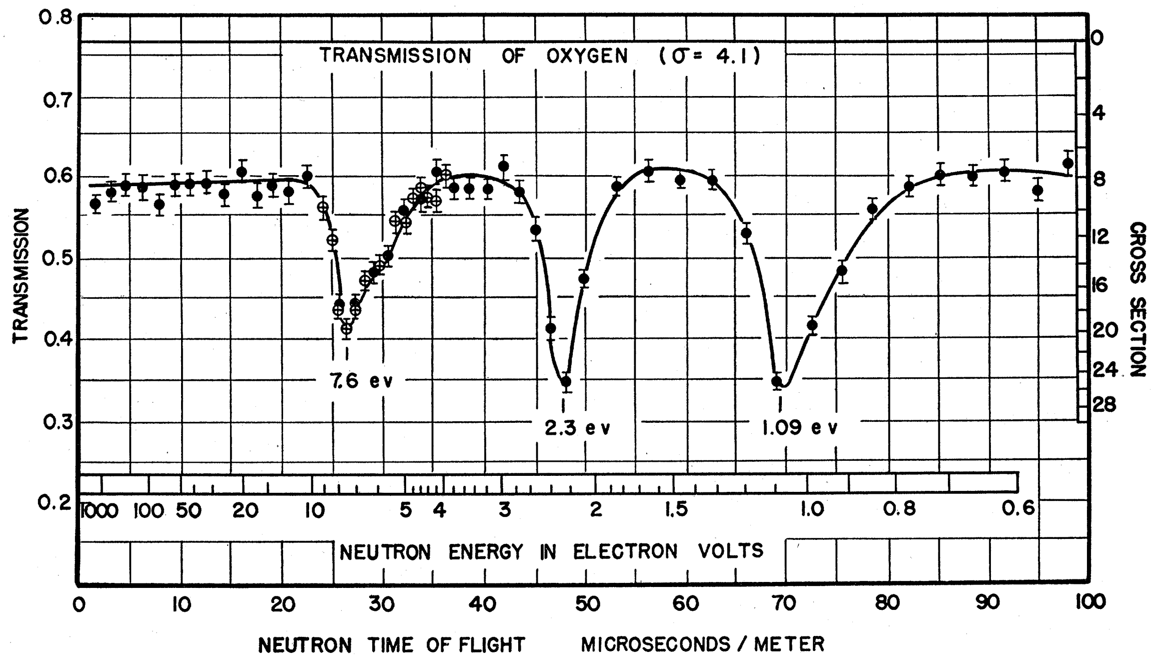

FIG. 13. The slow neutron cross section of 6.45 g/cm² of ZrO_2. This curve shows the transmission dips at 1.09 ev and 2.3 ev and the odd shaped dip in the vicinity of 7 ev which might be the sum of two dips at 5.7 ev and another at 7.6 ev.

(11.5 percent abundance) is the only odd isotope and, therefore, should be responsible for the stronger levels.[8] The weakness of the levels suggests that one or more may be owing to slight impurities in the sample. The induced activities in zirconium by (n, γ) reactions are not yet definitely assigned.

The results for Zr may be summarized as follows:

1. Below 0.6 ev the results are well matched by the $1/v$ curve $\sigma=[(6.8\pm0.3)+(0.74\pm0.10)E^{-\frac{1}{2}}]$.
2. There is a partially resolved level at $E_0=(1.09\pm0.03)$ ev $\sigma_0\Gamma\sim5$.
3. The second level is at $E_0=(2.30\pm0.07)$ ev $\sigma_0\Gamma\sim8$.
4. There is bulge on the next dip indicating a level at $E_0=(5.7\pm0.5)$ ev with $\sigma_0\Gamma\sim10$ (uncertain).
5. The next level is at $E_0=(7.6\pm0.4)$ ev $\sigma_0\Gamma\sim40$.

We take pleasure in acknowledging our indebtedness to Professor J. R. Dunning for his valuable suggestions and stimulating discussions. We wish to thank Miss Miriam Levin, who assisted with the numerous calculations involved in this paper, and the other members of the cyclotron staff who aided with these measurements.