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Slow Neutron Velocity Spectrometer Studies of Cu, Ni, Bi, Fe, Sn, and Calcite*

W. W. HAVENS, JR., L. J. RAINWATER, C. S. WU, AND J. R. DUNNING
Pupin Physics Laboratories, Columbia University, New York, New York

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The thermal cross section of Cu is well matched by the curve $\sigma=(7.8+0.54E^{-\frac{1}{2}})$. Microcrystalline interference is observed in the low energy region. The cross section decreases slowly from 8 to 7.3 between 2 and 100 ev, then decreases more rapidly until at zero timing it is 5.3. A small dip is observed near 3000 ev. The thermal cross section of Ni is well matched by the curve $\sigma=(17.0+0.77E^{-\frac{1}{2}})$. Microcrystalline interference effects are observed at low energies. The Ni cross section is approximately constant at 17.2 from 3 to 50 ev. A small dip is observed with a minimum near 100 ev. Above 100 ev the cross section drops rapidly to 8 at zero time of flight. Bismuth shows no $1/v$ slope in the thermal region because of microcrystalline interference effects. The free cross section of Bi is (9.0 ± 0.2) and is constant over the energy region investigated. The thermal cross section of Fe is well matched by the curve $\sigma=(11.0+0.35E^{-\frac{1}{2}})$. Microcrystalline interference effects are observed in the low energy region. The cross section of Fe remains approximately constant at 11 from 3 to 300 ev, then decreases to 4.8 at zero time of flight. The cross section of Sn in the thermal region rises because of microcrystalline interference effects which mask any $1/v$ slope. The free cross section is (4.9 ± 0.1). There is a slight dip in the transmission curve of tin around 6 ev which may or may not be real. Other small dips near 50 and 100 ev are probably real. The cross section increases near zero time of flight indicating that there are probably resonances above 1000 ev. The cross section of a large Nicol Prism decreases from the additive $CaCO_3$ cross section of 20 at short wave-lengths to about 3.5 at 0.005 ev. The residual cross section cannot be explained by theory.

I. INTRODUCTION

IN several previous papers[1-3] the results of investigations of the slow neutron cross section as a function of the neutron energy have been presented for a large number of materials. In order to make available in published form as complete information as possible on slow neutron cross sections the results acquired over the past few years have been re-examined and the data which were considered to be in publishable form are presented in two papers, of which this is the second.

The results presented here were taken with the new system[2] which has been somewhat improved to obtain better resolution, as will be described in detail in a forthcoming paper in the regular series.[2] All of these materials will be investigated more thoroughly in the future, although complete results will probably not be obtained soon. In presenting the results on Cu, Ni, Bi, Fe, Sn and calcite the conventions previously adopted are used,[1,2] in particular:

1. All cross section values are given in units of 10^{-24} cm^2/atom.
2. The resolution function is roughly triangular in shape having a width at its base between 2 and 3 times the timing spacing of adjacent experimental points. The resolution function is usually not shown explicitly on each curve.
3. When a sufficiently strong slow neutron resonance is present in one of the isotopes of the material studied a dip will be observed in the transmission *vs.* slow neutron time of flight at the timing corresponding to the energy of the level. Because of the resolution width of the apparatus, this dip will generally be very much wider and shallower than the "true" transmission dip (infinitely sharp resolution). Thus, in general, the true cross section at exact resonance will be many times larger than the value of σ_{max} corresponding to the bottom of the observed dip in the transmission curve. The position of the dip will give an indication of the position of the resonance if single, but resonances which are closely spaced relative to the resolution width will appear as a single dip. The "area" of a transmission dip, that is, the area between the experimental transmission curve and the transmission of the sample due to the scattering cross section, if the "true" transmission drops to zero, will depend on the sample thickness, the energy E_0, of the resonance and the product $\sigma_0\Gamma^2$, σ_0 being the cross section at exact resonance and Γ the full width of the level at half the maximum cross section.

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[1] L. J. Rainwater and W. W. Havens, Jr., Phys. Rev. **70**, 136–153 (1946); W. W. Havens, Jr. and L. J. Rainwater, Phys. Rev. **70**, 154–173 (1946).
[2] L. J. Rainwater, W. W. Havens, Jr., C. S. Wu, and J. R. Dunning, Phys. Rev. **71**, 65–79 (1947); W. W. Havens, Jr., C. S. Wu, L. J. Rainwater, and C. L. Meaker, Phys. Rev. **71**, 165–173 (1947); C. S. Wu, L. J. Rainwater, and W. W. Havens, Jr., Phys. Rev. **71**, 174–181 (1947).
[3] L. J. Rainwater, W. W. Havens, Jr., J. R. Dunning, and C. S. Wu, Phys. Rev. **73**, 733 (1948).

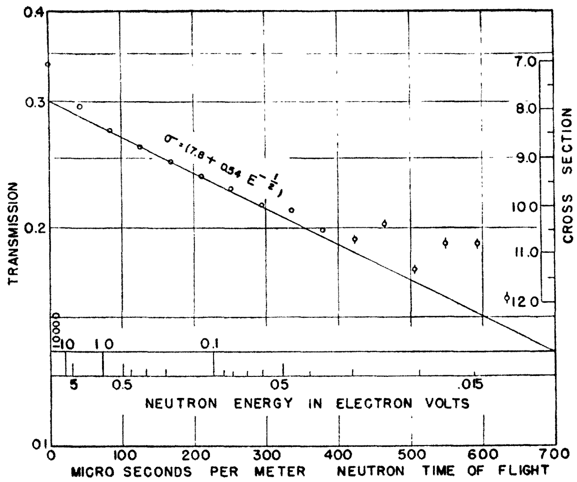

FIG. 1. The slow neutron transmission of 16.3 g/cm² of copper. The best $1/v$ line (0.05 ev to 3 ev) is $\sigma=(7.8+0.54E^{-\frac{1}{2}})$. Crystal interference effects cause the points below 0.05 ev to deviate above the $1/v$ line.

4. The time of flight scale is a $1/v$ scale. When the transmission is plotted on a logarithmic scale the cross section scale is linear and thus a cross sectional dependence linear in $1/v$ will give a straight line on this plot.

II. COPPER

The slow neutron transmission of Cu has been studied using three plates of commercial Cu, each 4.6 mm thick, to give a total sample thickness of 16.3 g/cm². The results of these measurements are presented in Figs. 1 and 2. The results shown in Fig. 1 were obtained when the region above 0.013 ev was investigated using broad resolution and those in Fig. 2 when the region above 3 ev was investigated using higher resolution.

The points in Fig. 1 between 0.06 ev and 1.0 ev are well matched by the $1/v$ relation $\sigma=(7.8+0.54E^{-\frac{1}{2}})$. This relation probably indicates the magnitudes of the free copper scattering cross section (7.8) and the $1/v$ absorption cross section $(0.54E^{-\frac{1}{2}})$ in the thermal region. The points below 0.05 ev are above the $1/v$ line and do not follow a smooth curve. This is to be expected as a result of slow neutron interference effects caused by the microcrystalline nature of the sample. The positions of the discontinuities in the transmission curve at low energies are for neutron wave-lengths which are multiples of the characteristic spacings between crystal lattice planes.

In Fig. 2 the transmission increases gradually with decreasing time of flight to the point corresponding to about 100 ev. For smaller timings (higher energies) there is a more rapid increase in transmission which continues to zero time except for the small dip near 3000 ev. This dip probably represents the lowest resonance level in one of the copper isotopes.

For a proper interpretation of Figs. 1 and 2 it is necessary to consider other information which has been obtained on the interaction of slow neutrons with copper.

Normal Cu consists[4] of 70.13 percent Cu^{63} and 29.87 percent Cu^{65}. Capture of a neutron by Cu^{63} produces Cu^{64} which has a 12.8-hour half-life and decays[4] by β^--emission (0.58 Mev max.), β^+-emission (0.66 Mev max.), or by K capture. Capture of a neutron by Cu^{65} produces β^--active (2.9 Mev max.) Cu^{66} of 5-minute half-life. The partial Cu cross sections due to these separate capture processes have been studied by activation measurements using thermal neutrons. Rasetti[5] obtained $\sigma_{\text{capt.}}=1.8$ due to Cu^{63} and 1.2 due to Cu^{65} giving $\sigma_{\text{capt.}}=3.0$ total. Sinma and Yamasaki[6] found $\sigma_{\text{capt.}}=1.3$ due to Cu^{63} and 1.5 due to Cu^{65} giving $\sigma_{\text{capt.}}=2.8$ total. Goldhaber and O'Neal[7] gave $\sigma_{\text{capt.}}=0.8$ due to Cu^{65}. Total absorption measurements have also been made using thermal neutrons. Coltman[8] obtained $\sigma_{\text{abs.}}=(4.3\pm0.3)$ and Coltman and Goldhaber[9] found $\sigma_{\text{abs.}}=(3.4\pm0.3)$. Volz[10] gave $\sigma_{\text{capt.}}=2.2$ to 2.6. Lichtenberger, Nobles, Monk, Kubetschek, and Dancoff[11] obtained $E_0=570$ ev for the Cu^{65} resonance using the boron method.[12] They also give values for the "activation integrals." These previous results for the absorption cross section are in good agreement with $\sigma_{\text{abs.}}=2.7$ at 0.4 ev from the $1/v$ line in Fig. 1. Previous studies[1,3,13] have indicated that the "effective energy" of previous "thermal neutron"

[4] G. T. Seaborg, Rev. Mod. Phys. 16, 1 (1944).
[5] Franco Rasetti, Phys. Rev. 58, 869 (1940).
[6] K. Sinma and F. Yamasaki, Phys. Rev. 59, 402 (1941).
[7] M. Goldhaber and R. D. O'Neal, Phys. Rev. 59, 109 (1941).
[8] J. W. Coltman, Phys. Rev. 59, 917 (1941).
[9] J. W. Coltman and M. Goldhaber, Phys. Rev. 69, 411 (1946).
[10] H. Volz, Zeits. f. Physik 121, 201 (1943).
[11] H. V. Lichtenberger, R. G. Nobles, G. O. Monk, H. Kubetschek, and S. M. Dancoff, Phys. Rev. 72, 164 (1947).
[12] H. A. Bethe, Rev. Mod. Phys. 9, 69 (1937).
[13] R. F. Bacher, C. P. Baker, and B. D. McDaniel, Phys. Rev. 69, 443 (1946).

measurements was $\sim$0.04 ev rather than 0.025 ev corresponding to kT for room temperature.

The slow neutron cross section values obtained using resonance neutrons (energies above 1 ev) should give the free copper cross section since binding and interference effects should be unimportant in this region. Measurements using thermal neutrons will be markedly influenced by the microcrystalline state of the sample due to interference effects. The following values for the different cross section have been obtained using thermal neutrons: (a) Dunning *et al.*,[14] $\sigma_{\text{tot.}}=7.5$; (b) Mitchell, Murphy, and Whitaker,[15] $\sigma_{\text{scatt.}}=8.3$; (c) Goldhaber and Briggs,[16] $\sigma_{\text{tot.}}=11.9$, $\sigma_{\text{scatt.}}=8.6$; (d) Whitaker and Beyer,[17,18] $\sigma_{\text{tot.}}=(10.5\pm0.4)$; (e) Whitaker and Bright,[19] $\sigma_{\text{tot.}}=10.3$ and $\sigma_{\text{scatt.}}=5.5$. Nix and Clement[20] made a careful study of the effect of microcrystalline structure on the thermal cross section. They obtained $\sigma=(10.84\pm0.03)$ for cold-worked Cu (0.005-mm grain size) and $\sigma=(7.04\pm0.3)$ for a highly annealed (2.4 mm-grain size) sample, with several intermediate values for intermediate grain sizes. They were thus able to obtain a curve of "thermal cross section" *vs.* sample grain size. The value 10.84 is in good agreement with Fig. 1. Hanstein[21] obtained $\sigma_{\text{tot.}}=(8.3\pm0.3)$ using In resonance neutrons (1.44 ev).[1,2] This is in good agreement with the value for this energy in Fig. 1.

According to the theory of Feshbach, Peaslee, and Weisskopf[22] the scattering cross section should be very nearly equal to the value $4\pi R^2$ due to potential scattering (where R is the nuclear radius) when the neutron energy differs from that of the nearest resonance level by an amount which is not small compared to the spacing between levels. Since Cu may be considered a relatively light element, the spacing between neutron resonance levels would be expected[12] to be of the order of hundreds to thousands of ev. Therefore, the energy region below $\sim$10 ev can be considered narrow compared to the average level spacing. Using the value $R=6.75\times10^{-13}$ cm for Cu given by Amaldi and Cacciapuoti[23] gives $4\pi R^2=5.7$ for the expected Cu cross section due to potential scattering. This is somewhat larger than the value $4\pi R^2=4.5$ given by Feshbach, Peaslee, and Weisskopf.[22] The observed value $\sigma=7.8$ in Figs. 1 and 2 probably indicates that the scattering cross section of one of the Cu isotopes is larger than $4\pi R^2$ as a result of the interference between potential and resonance scattering. Weisskopf's[22] theory predicts this effect when the neutron energy is near and just above the energy of the nearest resonance. On this basis the shape of the curve in Fig. 2 should be explained as due to the presence of a virtual level[1,12] with a resonance energy near zero neutron kinetic energy. The decrease in cross section above 100 ev would be interpreted as a return to the "potential" scattering cross section value at larger distances from the resonance. The shape of the increase also suggests that the virtual level is near -500 ev energy. Since there are two isotopes, each with non-zero spin, the level near 3000 ev in Fig. 2

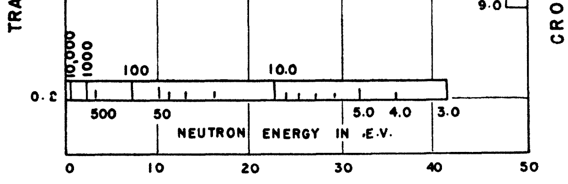

FIG. 2. The slow neutron transmission of 16.3 g/cm² of copper. This curve shows the small dip in transmission at 1.5 μsec./meter which indicates the presence of one or more resonance levels near 3000 ev.

[14] J. R. Dunning, G. B. Pegram, G. A. Fink, and D. P. Mitchell, Phys. Rev. 48, 265 (1935).
[15] A. C. G. Mitchell, E. J. Murphy, and M. D. Whitaker, Phys. Rev. 50, 133 (1936).
[16] M. Goldhaber and G. M. Briggs, Roy. Soc. Proc. 162A, 127 (1937).
[17] M. D. Whitaker and H. G. Beyer, Phys. Rev. 55, 1101 and 1124 (1939).
[18] H. G. Beyer and M. D. Whitaker, Phys. Rev. 57, 976 (1940).
[19] M. D. Whitaker and W. C. Bright, Phys. Rev. 60, 155 (1941).
[20] F. C. Nix and G. F. Clement, Phys. Rev. 68, 159 (1945).
[21] Henry B. Hanstein, Phys. Rev. 59, 489 (1941).
[22] H. Feshbach, D. C. Peaslee, and V. F. Weisskopf, Phys. Rev. 71, 145 (1947).
[23] E. Amaldi and B. N. Cacciapuoti, Phys. Rev. 71, 739 (1947).

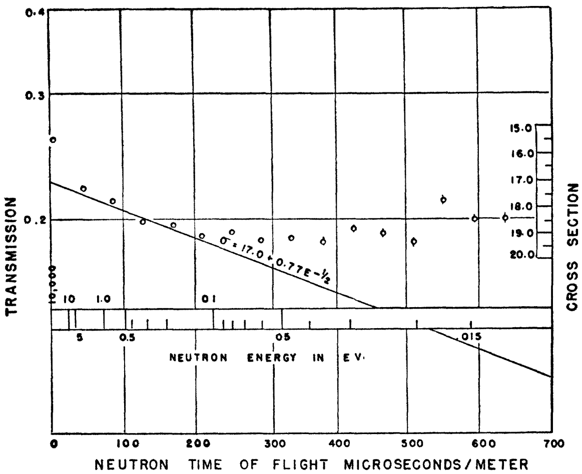

FIG. 3. The slow neutron transmission of 8.47 g/cm² of nickel. The best $1/v$ line (0.1−5 ev) is $\sigma=(17.0+0.77E^{-\frac{1}{2}})$. Crystal interference effects cause the points below 0.1 ev to deviate above the $1/v$ line.

may not correspond to the same compound nucleus which is responsible for the large scattering.

Measurements by Fields, Russell, Sachs, and Wattenberg[24] using photo-neutrons indicate that the cross section averages nearer $4\pi R^2$ at higher energies. They obtained $\sigma=8.0$, 6.2, 5.9, 5.3, and 3.8 at 24, 130, 140, 220, and 830 kev. Since the measurements in Fig. 2 were not taken with the highest resolution of the spectrometer, it is planned to study the resonance region above 50 ev again using much better resolution.

III. NICKEL

The slow neutron transmission of Ni has been studied using three plates of commercial Ni each 3.3 mm thick for a total sample thickness of 8.47 g/cm². The results shown in Fig. 3 were obtained when the region above 0.013 ev was studied using broad resolution and those in Fig. 4 when the region above 3 ev was investigated using better resolution.

The points in Fig. 3 between 0.1 and 3 ev may be used to locate the $1/v$ slope in the thermal region although it is less well defined than the similar region for Cu in Fig. 1. The "best straight line" indicated in Fig. 3 corresponds to $\sigma=(17.0+0.77E^{-\frac{1}{2}})$ in which the two terms may be interpreted as giving, respectively, the scattering and absorption cross sections. The points for energies below 0.1 ev lie above the $1/v$ line due to the microcrystalline interference effects as discussed for Cu. The points in Fig. 4 indicate that the cross section is relatively constant below 50 ev since the points lie close to the $1/v$ line of Fig. 3 in this region. The dip at 7μ sec./meter indicates that one or more unresolved resonance levels are present near 100 ev. For still higher energies the cross section decreases with the first point shown approaching the value of $4\pi R^2=5.7$ as discussed for Cu.

Normal Ni consists[4] of 67.4 percent Ni^{58}, 26.7 percent Ni^{60}, 1.2 percent Ni^{61}, and 3.8 percent Ni^{62}. Capture of a neutron by Ni^{62} produces β-active Ni^{63} of 2.6-hr. half-life. Capture of a neutron by the principal isotope Ni^{58} produces Ni^{59} which is β^+-active with a 15-year half-life,[25] while absorption by Ni^{60} and Ni^{61} produces stable isotopes. The total absorption cross section of Ni and the partial cross section for the production of the Ni^{63} activity have been measured using thermal neutrons. Sinma and Yamasaki[6] obtained $\sigma_{\text{capt.}}=0.35$ for the production of the Ni^{63} activity. Goldhaber and O'Neal[7] found $\sigma_{\text{capt.}}$

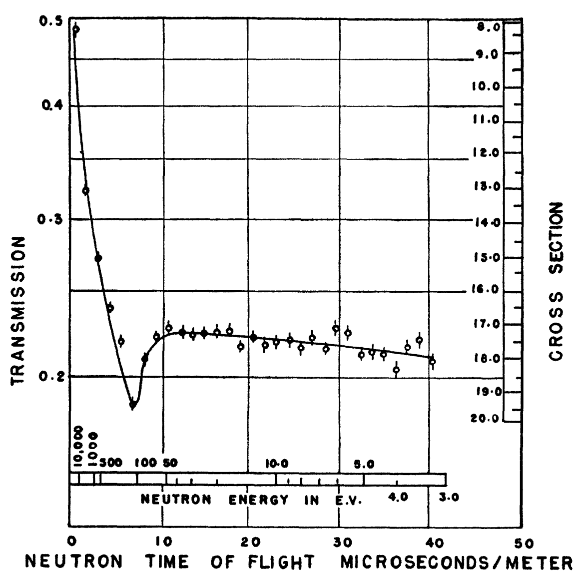

FIG. 4. The slow neutron transmission of 8.47 g/cm² of nickel. This curve shows the dip in transmission at 7 μsec./meter which indicates the presence of one or more resonance levels near 100 ev.

[24] R. Fields, B. Russell, D. Sachs, and A. Wattenberg, Phys. Rev. 71, 508 (1947).

[25] Isotope Committee, Science 103, 697 (1946).

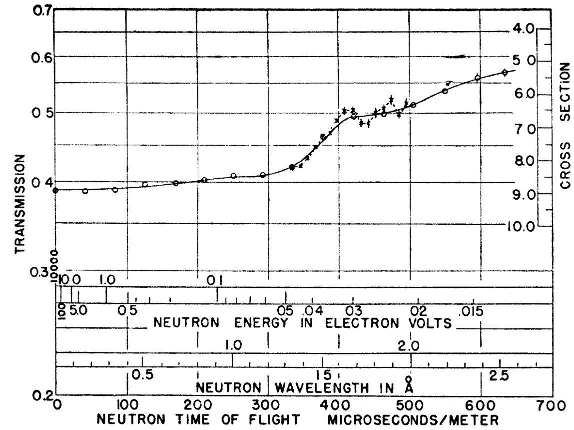

FIG. 5. The slow neutron transmission of 36.72 g/cm² of bismuth. The presence of the crystal interference effects makes the determination of the $1/v$ line impossible.

<0.03 for the same process. Coltman[8] gave $\sigma_{abs.}=(6.2\pm0.5)$. Coltmann and Goldhaber[9] obtained $\sigma_{abs.}=(5.6\pm0.5)$. Volz[10] gave $\sigma_{abs.}=3.6$. The $1/v$ line in Fig. 3 corresponds to $\sigma_{capt.}=3.8$ at 0.04 ev which is in agreement with the results of Volz[10] but is lower than those of Coltman and Goldhaber.[8, 9]

The results given in Figs. 3 and 4 may be compared with previously measured values of $\sigma_{tot.}$ and $\sigma_{scatt.}$ using thermal and resonance neutrons. It should be remembered that the value of the "thermal" cross section depends on the microcrystalline structure of the sample as discussed under Cu. The following values of the different cross sections have been obtained using thermal neutrons: (a) Dunning *et al.*,[14] $\sigma_{tot.}=15.4$; (b) Mitchell, Murphy, and Whitaker,[15] $\sigma_{scatt.}=18$; (c) Goldhaber and Briggs,[16] $\sigma_{tot.}=19.7$ and $\sigma_{scatt.}=12.4$; (d) Whitaker and Beyer,[19] $\sigma_{tot.}=(19.8\pm0.5)$ for polycrystalline nickel and $\sigma_{tot.}=(14.1\pm1.2)$ for a single crystal of Ni (both 4.4 g/cm²): (e) Whitaker and Bright, $\sigma_{tot.}=21.2$ and $\sigma_{scatt.}=13.9$. Laslett[26] found no change in the Ni cross section when Ni was heated to above the Curie point. (This measurement was to test the possibility that the high scattering cross section is partly of ferromagnetic origin.) Mitchell and Varney[27] obtained $\sigma_{scatt.}=19.2$ for thermal neutrons, 11.9 for In resonance neutrons (1.44 ev), 13.5 for Ag resonance neutrons[2] (~5 ev) and 12 for I resonance neutrons[2] (~40 ev). Kimura[28] obtained $\sigma_{scatt.}=19$ for In resonance neutrons and 20 for thermal neutrons. Hanstein[21] obtained $\sigma_{tot.}=(16.1\pm0.8)$ using In resonance neutrons. The results of Figs. 3 and 4 are in agreement with the previous results for Ni to the extent that they indicate a definite value.

The value of scattering cross section as indicated in Fig. 4 is very large compared to the value $4\pi R^2=5.7$ for potential scattering. According to the theory of Feshbach, Peaslee, and Weisskopf[22] this would indicate the presence of a virtual level near zero energy (near relative to the level spacing) and the cross section should drop to $4\pi R^2$ for most of the region to the next level. In Fig. 4 the high value of the scattering cross section continues up to, and perhaps above, the level near 100 ev. Although this at first seems to contradict the theory, the fact that there are several isotopes probably means that one isotope is responsible for this level, while another (probably the principal Ni^{58} isotope) is responsible for the large scattering cross section. The extent of the region over which the scattering is large indicates an average level spacing of about 50,000 ev. which is not unreasonable for such a light nucleus. It is planned to investigate the region above 50 ev with much higher resolution to study this matter more carefully. The above conclusions are in agreement with the results of Fields, Russell, Sachs, and Wattenberg[24] using photo-neutrons. They obtained $\sigma=23$, 6.2, 4.2, 5.8, 3.7, and 3.5 at 24, 130, 140, 220, 620, and

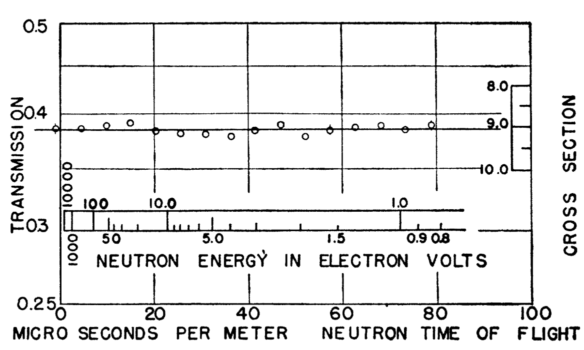

FIG. 6. The slow neutron transmission of 36.72 g/cm² of bismuth. The cross section is constant where crystal interference effects are not important to within the accuracy of the results.

[26] L. Jackson Laslett, Phys. Rev. 51, 72 (1937).
[27] A. C. G. Mitchell and R. N. Varney, Phys. Rev. 52, 282 (1937).
[28] N. Kimura, Phys. and Math. Soc. Japan, Proc. 22, 391 (1940).

830 kev. This indicates that there is a strong resonance near 24 kev and shows that the cross section is close to the potential scattering value at the other energies.

IV. BISMUTH

The slow neutron transmission of Bi has been studied using a sample of 36.72 g/cm^2 thickness cast from C.P. Bi metal. The results of the transmission measurements are shown in Figs. 5 and 6. The results shown in Fig. 5 were obtained when the region above 0.013 ev was studied using broad resolution and those in Fig. 6 when the region above 0.8 ev was studied with higher resolution. There is no evidence of a 1/v slope in Fig. 5 since the curve rises after the first three points due to microcrystalline interference effects. In Fig. 6 the cross section is constant over the entire region to within the accuracy of the measurements and is equal to (9.0 ± 0.2). This may be interpreted as the free Bi scattering cross section in the region studied. There is no evidence of any resonance dips although an investigation using higher resolution is planned and may indicate the presence of weak resonances.

Normal Bi consists[4] entirely of the 100 percent Bi^{209} isotope of spin 9/2. Capture of a neutron produces β^--active Bi^{210} (RaE) of 5 days half-life. Several measurements have been made of the absorption and activation capture cross sections

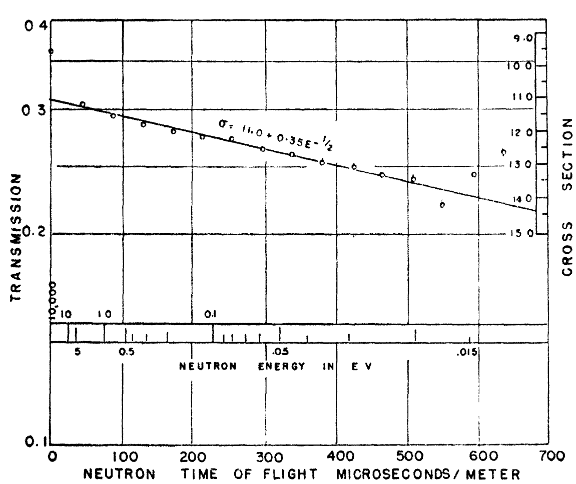

FIG. 7. The slow neutron transmission of 9.93 g/cm^2 of iron. The best $1/v$ line is $\sigma=(11.0+0.35E^{-\frac{1}{2}})$. The last three points deviate from the straight line because of the neutron interference due to the microcrystalline structure of the sample.

for thermal neutrons. Goldhaber and O'Neal[7] obtained $\sigma_{capt.}<0.1$ for the production of the RaD activity. Volz[10] found $\sigma_{abs.}=0.33$, Meulhause and Goldhaber[29] gave $\sigma_{abs.}\sim 10^{-2}$ or less for the production of RaE. Considering all of the results it seems that the higher value of Volz may represent the effect of impurities in his sample since the capture should result entirely in the production of RaE. It is therefore not surprising that no $1/v$ slope was observed in the present measurements. Lead and bismuth are known to have abnormally low radiative capture cross sections for fast neutrons[22,30] relative to neighboring elements, thus indicating that there is an anomalous level pattern for these nuclei probaby due to the relatively small binding energy of the captured neutron. The total cross section and the scattering cross sections should thus be essentially equal over a wide range of energies.

The following values of the different cross sections have been obtained using thermal neutrons: (a) Dunning *et al.*,[14] $\sigma_{tot.}=8.2$; (b) Mitchell, Murphy, and Whitaker,[15] $\sigma_{scatt.}=10.2$; (c) Goldhaber and Briggs,[16] $\sigma_{tot.}=8.9$ and $\sigma_{scatt.}=8.9$; (d) Rasetti,[31] $\sigma=6.6$ for a single crystal and $\sigma=8.3$ for the liquid. He subsequently obtained $\sigma=6.39$ for a single crystal using a room temperature source and 5.94 using a source at 80°K. Kimura[28] obtained $\sigma_{scatt.}=7.5$ for thermal neutrons and 8.3 for In resonance neutrons. Hanstein[21] obtained $\sigma=(8.7\pm 0.5)$ using In resonance neutrons. Anderson, Fermi, and Marshall[32] obtained $\sigma=6.68$ using thermal neutrons and only 1.03 using the very low energy neutrons ($\sim$0.0015 ev or 7.15A wave-length) obtained by filtering pile neutrons through graphite. Fields, Russell, Sachs, and Wattenberg[24] obtained $\sigma=12.1$, 10.2, 9.7, 8.0, and 5.9 using 24, 130, 140, 220, and 830 kev photoneutrons.

The above values are in essential agreement with the results shown in Figs. 5 and 6 considering that the thermal values are structure dependent. The value $\sigma=9.0$ obtained from Fig. 6

[29] C. O. Muehlhause and M. Goldhaber, Phys. Rev. **57**, 976 (1940).
[30] D. J. Hughes, Phys. Rev. **70**, 106 (1946).
[31] Franco Rasetti, Phys. Rev. **58**, 321 (1940).
[32] H. L. Anderson, E. Fermi, and L. Marshall, Phys. Rev. **70**, 815 (1946).

is close to the value of $4\pi R^2=10$ for potential scattering.

V. IRON

The slow neutron transmission of iron has been measured using a 9.93 g/cm² thick sample of ordinary cold-rolled iron sheet. A spectrographic analysis of the sample by the Bureau of Standards indicated 0.01 to 1 percent Cr, Cu, and Mn and less than 0.01 percent of Ca, Co, Ge, Mg, Ni, Si, and Sn. The results of the transmission measurements above 0.013 ev using broad resolution are shown in Fig. 7. The experimental results between 0.02 ev and 2 ev are well matched by the straight line $1/v$ relation

$$\sigma=[11.0+0.35E^{-\frac{1}{2}}].$$

This indicates that the iron scattering cross section in this energy region is (11.0±0.2) and the capture cross section is $0.35E^{-\frac{1}{2}}$. The deviation of the last three points in Fig. 7 from the straight line is due to microcrystalline interference effects.

The results of the transmission measurements above 3 ev using better resolution are shown in Fig. 8. The points for energies below about 200 ev closely follow the 1/v line of Fig. 7. For higher energies the cross section decreases rapidly to about 4. The scattering cross section for Fe is considerably higher than the value[22, 23] $4\pi R^2=5.5$ for pure potential scattering. The explaination in this case is probably the same as for Cu and Ni. Normal Fe contains[4] mainly the 91.57 percent Fe^{56} plus 6.04 percent Fe^{54}, 2.11 percent Fe^{57}, and 0.28 percent Fe^{58}. On the basis of the theory of Feshbach, Peaslee, and Weisskopf[22] the large scattering cross section is probably the result of the interference between potential and resonance scattering due to a relatively near virtual level in Fe^{56}. The decrease in cross section above 200 ev is then due to the increased distance from the virtual level indicating that it is probably several thousand ev. below zero neutron energy. The level spacing[22] on this basis would be greater than 10,000 ev. This next resonance cannot be observed in Fig. 8. Further investigation of this sample above 50 ev. is planned using much better resolution.

The value of the capture cross section indicated from the 1/v slope in Fig. 7 may be compared with the results of absorption measurements using thermal neutrons. Coltman[8] obtained $\sigma_{abs.}=(2.1\pm0.2)$, Coltman and Goldhaber[9] found $\sigma_{abs.}=(2.05\pm0.15)$, and Volz[10] gave $\sigma_{abs.}=1.6$. These values are in good agreement with the result $\sigma_{abs.}=1.8$ at 0.04 ev from Fig. 7.

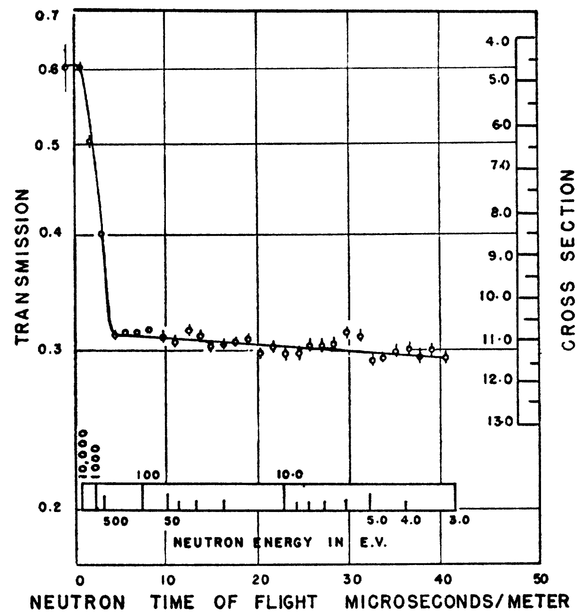

FIG. 8. The slow neutron transmission of 9.93 g/cm² of iron. The points for energies below 200 ev closely follow the $1/v$ line obtained from the results in Fig. 7.

It is also of interest to compare the results of Figs. 7 and 8 with previous measurements of $\sigma_{tot.}$ and $\sigma_{scatt.}$ cross sections using thermal and resonance neutrons, remembering that the resonance neutron cross sections should be directly comparable and the thermal values are structure sensitive. Dunning *et al.*[14] obtained $\sigma_{tot.}=12.0$ using thermal neutrons. Mitchell, Murphy, and Whitaker[15] found $\sigma_{scatt.}=10.6$ using thermal neutrons. Goldhaber and Briggs[16] gave $\sigma_{tot.}=13.6$ and $\sigma_{scatt.}=10.3$ using thermal neutrons. Whitaker and Beyer[17, 18] obtained $\sigma=(12.0\pm0.2)$ for a 1.6 g/cm² thick sample of polycrystalline iron, (7.0±0.1) for a 1.6 g/cm² single crystal of iron and (6.1±1) for an 8.8 g/cm² single crystal of iron. Powers, Goldsmith, Beyer, and Dunning[33] obtained $\sigma=(12.0\pm0.4)$ using "room temperature" neutrons and (12.0±1.0) using "liquid air" temperature neutrons. Whitaker and Bright[19]

[33] P. N. Powers, H. H. Goldsmith, H. G. Beyer, and J. R. Dunning, Phys. Rev. **53**, 947 (1938).

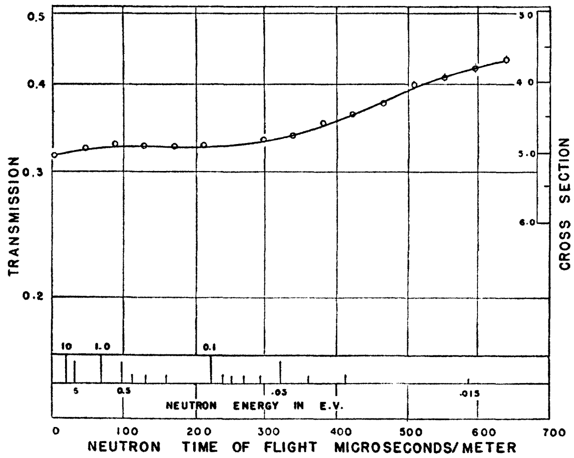

FIG. 9. The slow neutron transmission of 45.15 g/cm² of tin. The presence of crystal interference effects makes the determination of the $1/v$ line impossible.

found $\sigma_{\text{tot.}}=12.8$ and $\sigma_{\text{scatt.}}=9.5$ using thermal neutrons. Nix and Clement[20] investigated the effect of sample grain size on the thermal cross section and obtained $\sigma=(13.06\pm0.4)$ for cold-worked Fe (0.077-mm grain size), and (11.39 ± 0.3) for annealed Fe (0.127-mm grain size). Laslett[26] observed no change in the thermal neutron cross section when a sample was heated above the Curie point during an investigation to see if the large cross sections of Fe and Ni are due to their ferromagnetic properties. Mitchell and Varney[27] obtained $\sigma_{\text{scatt.}}=9.8$ using thermal neutrons, 10.0 using Rh resonance neutrons, 11.6 using Ag resonance neutrons, and 10.8 using I resonance neutrons. Kimura[28] found $\sigma_{\text{scatt.}}=9.7$ using thermal neutrons, and 8.5 using In resonance neutrons. Hanstein[21] obtained $\sigma=(11.1\pm0.3)$ using In resonance neutrons. Using photoneutrons Field, Russell, Sachs, and Wattenberg[24] obtained $\sigma=2.2$, 4.1, 3.9, 3.3, and 2.7 using 24, 130, 140, 220, and 830 kev neutrons. These results suggest that there is a resonance above 24 kev and show that the cross section is nearer the potential scattering value at higher energies.

VI. TIN

The slow neutron transmission of tin has been measured using a sample of 45.15g/cm² thickness which was made by melting mossy C.P. tin and molding to the desired shape. A quantitative spectrographic analysis of the sample showed an indium impurity of (0.03 ± 0.01) percent. A qualitative spectrographic analysis showed a Pb impurity of the order of 0.05 percent; Sb impurities of the order of 0.005 percent. 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. The results of the measurements above 0.013 ev using broad resolution are shown in Fig. 9. The rise in transmission for larger timings is due to microcrystalline interference effects and probably masks any $1/v$ type slope[34] that may be present. The points between 0.09 and 1 ev all have essentially constant cross section values equal to (4.9 ± 0.1). A "thermal" neutron absorption cross section of (0.53 ± 0.05) has been observed by Coltman and Goldhaber[9] and a value $\sigma_{\text{abs.}}=0.4$ was obtained by Volz.[10] On the basis of these values for the thermal absorption cross section an increase of 0.2 in σ should be observed between 1 ev and 0.09 ev in Fig. 9.

The results of the measurements above 0.8 ev using higher resolution are shown in Fig. 10. The dip near 1.4 ev is probably due to a slight In impurity in the sample. From the size of the dip an In impurity of about 0.05 percent is indicated which is in agreement with the spectroscopic measurements. The small dip near 6 ev may be

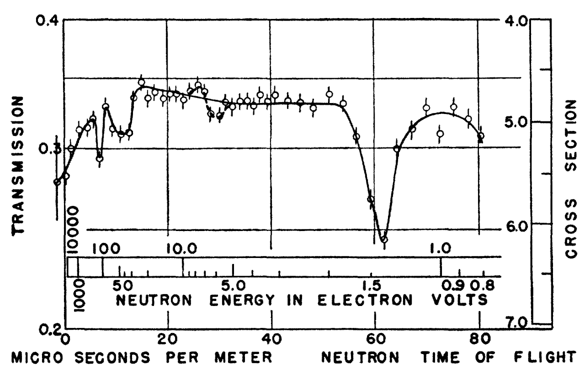

FIG. 10. The slow neutron transmission of 45.15 g/cm² of tin. The transmission dip at 1.44 ev is caused by a 0.03 percent indium impurity in the sample. The small dip at 6 ev may be spurious. The dips near 50 ev and 100 ev are probably real, although exact location of the resonances is difficult with these data.

[34] M. E. Nahmías, Comptes rendus **202**, 1050 (1936); R. Naidu, Nature **137**, 578 (1936); G. T. Livingood and J. J. Seaborg, Phys. Rev. **55**, 667(1939); H. Volz, Zeits. f. Physik **121**, 201 (1943).

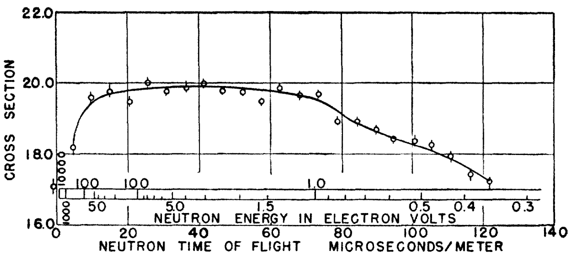

FIG. 11. The slow neutron cross section of calcite. The cross section begins to decrease just below 1.0 ev because of the crystal structure of the sample.

spurious or may represent a weak resonance level for one of the ten stable isotopes of Sn. The dips near 50 and 100 ev are probably real although the exact location of the resonance or resonances is difficult with the present data. Higher resolution will be used to determine more accurately the position and magnitude of these dips. The fact that the cross section increases near zero time of flight is also of interest as it indicates that there are probably levels above 1000 ev.

The results of Figs. 9 and 10 may be compared with values previously obtained for the total and scattering cross sections. Dunning *et al.*[14] obtained $\sigma_{\text{tot.}}=4.0$ using thermal neutrons. Mitchell, Murphy, and Whitaker[15] found $\sigma_{\text{scatt.}}=4.1$, and Goldhaber and Briggs[16] gave $\sigma_{\text{scatt.}}=4.9$ using thermal neutrons. Hanstein[21] obtained $\sigma_{\text{tot.}}=(5.7\pm 0.3)$ using In resonance neutrons. Fields, Russell, Sachs, and Wattenberg[24] obtained $\sigma=5.9$, 6.4, 6.4, 6.3, 6.8, and 6.7 using 24, 130, 140, 220, 620, and 830 kev photoneutrons. The value of $4\pi R^2$ for potential scattering of 6.6 given by Feshbach, Peaslee, and Weisskopf[22] is in better agreement with the above experimental results than the value 9 obtained using the value of Amaldi and Cacciapuoti[23] for the Sn nuclear radius.

VII. CALCITE

The slow neutron transmission of a calcite crystal has been measured using the Tyndall Nicol Prism of Columbia University which has a sample thickness of 24.53 g/cm². The results of these transmission measurements using broad resolution are presented in Figs. 11 and 12. The effective $CaCO_3$ cross section decreases from about 20 in the energy region where the nuclei should scatter independently to about 3.5 in the lowest energy region studied.

Using the values $\sigma=3.7$ and 4.8, respectively, for the free oxygen and carbon cross sections, a value of 4.1 is indicated for the free Ca cross section. This is in good agreement with Rassetti's value[31] of (4.4 ± 0.2) using thermal neutrons. The values $\sigma_{\text{tot.}}=11.0$ obtained by Dunning *et al.*[14] and $\sigma_{\text{scatt.}}=9.5$ obtained by Goldhaber and Briggs[16] for Ca were probably due to hydrogenous impurities in the samples.

Carbon and oxygen each have only one important stable isotope, each with zero spin. They both have very small capture cross sections as is indicated by their use as moderator materials in graphite and heavy water piles. Thus, for example, Anderson, Fermi, Wattenberg, Weil, and Zinn[35] obtained $\sigma_{\text{abs.}}=0.0049$ for graphite using thermal neutrons and Muehlhouse and Goldhaber[29] obtained $\sigma_{\text{abs.}}\sim 10^{-2}$ or less for

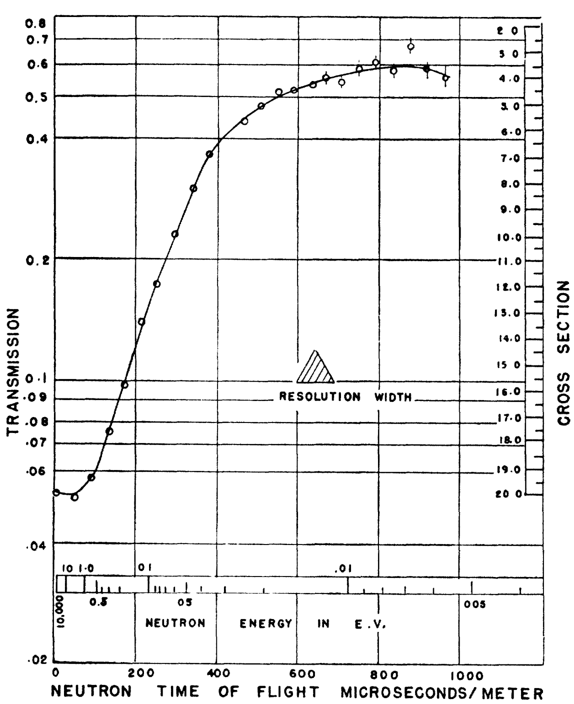

FIG. 12. The slow neutron transmission of calcite. The effective cross section of calcite decreases from 20 where the nuclei should scatter independently to about 3.5 at 0.008 ev. The principle charge occurring between 1.0 ev and 0.02 ev.

[35] H. L. Anderson, E. Fermi, A. Wattenberg, G. L. Weil, and W. H. Zinn, Phys. Rev. 72, 16 (1947).

oxygen. Although there are seven stable Ca isotopes,[4] normal Ca consists mainly of the 96.96 percent Ca^{40} isotope which forms radioactive Ca^{41} of 8.5-day half-life on neutron capture. Measurements of the absorption cross section for Ca for thermal neutrons show that it is small compared to the residual $CaCo_3$ cross section of 3.5. Coltman[8] obtained $\sigma_{abs.}=(0.50 \pm 0.04)$ and Coltman and Goldhaber[9] obtained (0.37 ± 0.04). Volz[10] gave $\sigma_{abs.}=0.28$. Subtracting the value $\sigma_{abs.} \sim 0.3$ to 0.4 from Rassetti's value $\sigma_{tot.}=(4.4 \pm 0.2)$ gives a result in good agreement with the value 4.1 from Fig. 11 obtained as described above.

The most extensive previous investigation of the effective $CaCo_3$ cross section for calcite at low energies was made by Rasetti[31] who obtained $\sigma=6.6$ for a 10.0 g/cm^2 thick sample of optical grade iceland spar using thermal neutrons. He showed that $\sigma_{eff.}$ increases with decreasing crystal size in ground crystals and showed that the thermal neutrons transmitted through calcite have their average energy lowered.

The transparency of crystalline materials to low energy neutrons has been investigated experimentally using the thermal neutrons from RaBe sources and using monochromatic neutrons.[32] The theory of the scattering of neutrons by crystals has been given by Wick[36] and by Halpern, Hammermesh, and Johnson.[37] A simple qualitative explanation can be given in terms of wave scattering usually applied to x-rays. When the slow neutron wave-length is comparable to the crystal lattice spacing there is strong scattering only when the conditions are satisfied for Bragg reflection by the different sets of crystal planes. This gives complete scattering of certain very narrow wave-length regions and very little for the other wave-lengths. When the neutron wave-length is more than twice the spacing of the crystal planes the Bragg condition cannot be satisfied so the total cross section should be due only to capture and incoherent scattering.

The incoherent scattering at long neutron wave-lengths must be ~ 2.5 after a value of ~ 1.0 is subtracted for the Ca capture cross section (note the $1/v$ factor increase from the "thermal" value). This measurement was made at the request of Professor Otto Halpern and the cross section was found to be unexpectedly large and difficult to explain on the basis of present theories. The residual cross section can, perhaps, be accounted for by the following causes of incoherent scattering.

1. Isotope effects: The elements all have only one main isotope each and these each have zero spin, so this effect should not be important.
2. Temperature effects: The temperature of the sample is not small compared to its Debye temperature.
3. Crystal imperfections: This should not be important for the Tyndall Nicol.

The exact manner in which the effective cross section decreases in Fig. 12 is of interest. It is seen that the main change in cross section occurs between about 1 ev and 0.02 ev with the half-value point near 0.1 ev. It is evident from Fig. 11 that a calcite crystal filter will lower the energy of a transmitted beam of thermal spectrum neutrons as observed by Rasetti.[31]

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[36] G. C. Wick, Phys. Zeits. 38, 403, 689 (1937).
[37] O. Halpern, M. Hammermesh, and M. H. Johnson, Phys. Rev. 59, 981 (1941).