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The Absorption of Resonance Neutrons by Boron, Chlorine, Cobalt and Manganese

W. J. HORVATH AND E. O. SALANT
Department of Physics, New York University, Washington Square, New York, New York

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Measurements are made of the absorption of neutrons by boron and by several elements which capture the neutrons without activity (or with very weak activity). Rh, In, Ag, Mn, Br and I were used as thermal and resonance detectors, and their known boron absorption coefficients were redetermined more carefully. The resonance levels of only Rh and In appeared to be single. It is shown that, by comparing the boron absorption coefficients with the absorption coefficients of the nonradioactive elements, resonance levels of those elements can be located: Resonances are found for Cl^{36} near 1 volt, for Co^{58} near 1 and 30 volts, for Mn below 0.4 volt. Corrections for nonparallelism of the neutron beam are made semi-empirically and neutron scattering by the absorbers is shown to be quite small compared to neutron capture.

INTRODUCTION

As is now well recognized, the cross section of boron for slow neutron capture varies inversely as the velocity of the neutrons, and this law has been used by many experimenters[1] to determine the resonance energies of a number of elements showing induced radioactivity. However, many elements capture neutrons with no activity or with only very weak activity, so that for these substances the boron absorption method fails as a means of detecting resonance levels.

We present here measurements which make possible the detection and rough location of resonance levels of such elements. Suppose that there is available a series of radioactive detectors with known resonance levels. Then our method of finding resonance levels in some element consists of using that element as an absorber of the neutrons activating these different detectors.

Since each detector is (under favorable circumstances) activated by neutrons of a single narrow band of energies, we thus obtain the capture cross section of the absorber for the neutrons of energy corresponding to the energies of the known resonance levels. If the absorber has no levels overlapping those of the detectors, then its capture cross section will vary inversely as the velocity of the neutrons detected,[2] as one finds for boron; if, on the other hand, it has a level overlapping a resonance level of one of the detectors, those resonance neutrons will be absorbed more strongly, relative to the resonance neutrons of the detectors, than would be indicated by the inverse velocity law. If, for example, a certain element captures 5-volt neutrons more strongly than 1-volt neutrons, that element has a resonance level in the neighborhood of 5 volts; or, another example, if an element captures 5- and 10-volt neutrons according to the inverse velocity law, but 1-volt neutrons much more strongly than predicted by that law, the element has a resonance level in the 1-volt region.

Of course, all this presupposes an exact knowledge of the resonance levels of the detectors. The levels of the detectors used by us were redetermined rather carefully, by measuring their boron absorption coefficients. This was done both to insure that the geometrical conditions in the measurements of the absorption with boron and with the element to be investigated were the same, and to discover and allow for multiplicity of the levels in any detector, only rhodium and indium being found to have single levels. The presence or absence of a resonance level of an absorbing element in the neighborhood of the levels of the detectors depends, then, on comparing the element's absorption with the boron absorption of the neutrons inducing the activities in the various detectors.

OBLIQUITY CORRECTIONS IN MEASUREMENTS OF NEUTRON ABSORPTION COEFFICIENTS

It is well known that slow neutrons do not emerge from a paraffin surface as a parallel beam.

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[1] O. R. Frisch and G. Placzek, Nature **137**, 905 (1937); Weekes, Livingston and Bethe, Phys. Rev. **49**, 471 (1936); E. Amaldi and E. Fermi, Phys. Rev. **50**, 899 (1936); H. H. Goldsmith and F. Rasetti, Phys. Rev. **50**, 328 (1936); Norling and Fleischman, Zeits. f. Physik **108**, 483 (1938).

[2] E. Wigner and G. Breit, Phys. Rev. **50**, 1191 (1936).

Fermi[3] has shown that, theoretically, the number of slow neutrons which leave the paraffin in the element of solid angle $d\omega$ is proportional to

$$f(\theta)d\omega=(\cos\theta+\sqrt{3}\cos^2\theta)d\omega.$$

This law was verified experimentally by Hoffman and Livingston[4] for thermal neutrons and has also been applied to slow neutrons of higher than thermal energy, though without very adequate justification.

Because of the nonparallelism of the beam, the measurement of the transmission of neutrons through a substance in this beam gives us an apparent absorption coefficient which must then be corrected with the aid of the Fermi law to give the true absorption coefficient. This correction is not easily made because the Fermi law holds only for a detector in contact with the paraffin surface. However, under actual experimental conditions, the detector is placed at some convenient height above the paraffin, so that sufficient space is left to insert an absorber. With this arrangement, one must allow for the fact that neutrons emerging at very large angles to the normal to the paraffin will entirely miss the detector, because of its limited size. This, together with the fact that the neutron intensity diminishes in going from the center to the edges of the paraffin, tends to make the obliquity correction smaller than it would be if the detector were placed on top of the paraffin.

Moreover, a different obliquity correction must be applied to each detector, depending on the absorption of neutrons within the detector material. For this purpose we consider only the two ideal cases of "thick" and "thin" detectors. A "thick" detector is one in which all neutrons are captured within a depth from which all electrons emerge; a "thin" detector is one in which only a small fraction of its activating neutrons is captured. It can be shown that the thin detector, because it has a higher probability of capturing neutrons incident obliquely than neutrons incident normally, will, with the same absorber, give a larger absorption coefficient than will a thick detector (for which the probability of neutron capture is independent of the direction). This effect turns out to be quite small in practice.[5]

Undoubtedly, inadequate correction for some of these geometrical effects is one of the chief causes of the many disagreements in boron (and other) absorption coefficients in the literature.

O. R. Frisch[6] has given calculations taking into account these effects. Inasmuch as those neutrons leaving the paraffin surface at a very small angle will miss the detector entirely, he makes the assumption that the Fermi distribution $f(\theta)=\cos\theta+\sqrt{3}\cos^2\theta$ is valid only for angles θ (measured from the normal) less than some critical angle θ_0; and that neutrons making angles greater than θ_0 with the normal will not be detected. In choosing a suitable value of θ_0 one must take into account not only the height of the detector above the paraffin surface but also the shape and size of the detector and of the surface, as well as the distribution of the neutron intensity over the surface. With this assumption, the transmission, T, of an absorber of thickness X is given by

$$T=\frac{\int_0^{\theta_0}\int_0^{2\pi}Je^{-kx}\sin\theta d\theta d\varphi}{\int_0^{\theta_0}\int_0^{2\pi}J\sin\theta d\theta d\varphi},$$

where $J=\cos\theta(1+\sqrt{3}\cos\theta)$ for a thick detector and $J=1+\sqrt{3}\cos\theta$ for a thin detector.

The integrals were evaluated in Frisch's paper, together with f, the ratio of the measured to the true absorption coefficient, for various critical angles θ_0. For a value of θ_0 as large as 60°, f is nearly independent of absorber thickness, so that the absorption is effectively exponential. For θ_0 smaller than 45°, $f=2/(1+\cos\theta_0)$ for both thick and thin detectors.

In making the obliquity corrections in our work, we used this formula for angles smaller than 45°; and, as will be seen, the corrections for larger angles were then obtained experimentally from the results for small angles.

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[3] E. Fermi, Ricerca Scient. **7**, No. 13 (1936).

[4] J. G. Hoffman and M. S. Livingston, Phys. Rev. **53**, 1020 (1938).

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

[6] O. R. Frisch, Kgl. Danske Vidensk. Selskab. Math. Phys. Medd. **14**, 12 (1937).

EXPERIMENTAL PROCEDURE

Our neutron source consisted of a 200-millicurie Ra-Be mixture, placed 3 cm beneath the top of a paraffin cylinder 15 cm high and 25 cm in diameter. The arrangement for irradiating detectors is shown in Fig. 1. Detectors and absorbers were placed on an aluminum platform which moved on steel rails placed on two sides of the paraffin cylinder. This allows the experimenter to place the detectors and absorbers accurately in position while remaining at a safe distance from the source. The platform was centered over the cylinder by means of steel stops which were placed on the rails. This arrangement proved satisfactorily repeatable, the standard deviation of any set of measurements never being more than that expected from the total number of particles counted.

The detectors were kept at a fixed height of 3.8 cm above the paraffin surface by means of an aluminum stand fastened to the sliding platform. With this arrangement we were able to insert absorbers up to a thickness of 2.5 cm on top of the sliding platform.

The absorbers of the elements investigated were generally made up in powder form. For cobalt and manganese we were able to obtain the pure metal, but for boron we used either anhydrous boric acid (pure B_2O_3), or boron carbide (B_4C). The chlorine absorbers were made up of chemically pure carbon tetrachloride.

The powdered absorbers were placed in thin aluminum cans, of the same cross section as the paraffin cylinder. No absorption of slow neutrons by the empty cans could be detected, and, indeed, calculations with the known total cross section of aluminum showed that, in the thicknesses used by us, the absorption was negligible. The cans were carefully filled to insure a uniform thickness of absorbing material throughout the whole area. The containers for the carbon tetrachloride were of soldered iron, of the same size as the aluminum cans. The effect of the iron was allowed for experimentally by leaving the empty cans in place when the counts without absorber were taken. In order to simplify the geometrical corrections, the absorbers were always inserted directly beneath the detectors rather than on the top surface of the moving platform. The purpose of this arrangement was to minimize the effect of scattering; a discussion of the magnitude of this effect is given in the section on experimental results.

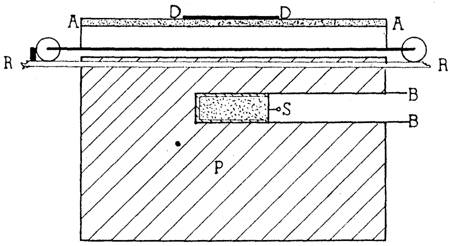

FIG. 1. Neutron source and arrangement for irradiating detectors. *D*—detector, *A*—absorber, *R*—steel rail, *B*—brass tube, *S*—source, *P*—paraffin.

Only six resonance detectors gave sufficient intensity with our source: rhodium, indium, silver, manganese, bromine and iodine. The rhodium, indium and silver were used as rolled foils of the pure metal. The other detectors were in powder form and cast into thin slabs by mixing with a dilute solution of "Duco cement," the amount of slowing produced by the hydrogenous material introduced this way being completely negligible. The iodine, bromine and manganese detectors were used as compounds; for iodine we used lead iodide, PbI_2, and iodoform, CHI_3; for bromine we used lead bromide, $PbBr_2$, and hexabromethane, C_2Br_6; for manganese we used the oxide MnO_2, as well as the pure metal powder. The results obtained with different compounds for the same detector were always consistent with one another and with results obtained using detectors without binder.

All of the resonance detectors except manganese fitted our criterion for "thick" detectors. Manganese and the thermal detectors had such small neutron absorption coefficients that they may be considered "thin."

We found that the most efficient way of using a detector was to cut it into four rectangular pieces, each piece 22 mm by 40 mm. These were placed on the irradiating platform so as to form a detecting surface 44 mm by 80 mm. After irradiation, they were removed and fastened to a rectangular frame, fitting over the Geiger counter, which was thus surrounded on all sides by the activated material. This procedure was carefully standardized, so that the same part of the frame was always opposite the same part of the Geiger counter.

The recording apparatus consisted of an amplifier with a Neher-Harper circuit, a stabilized high voltage supply and a scale-of-eight counter. All electrical parts were checked to insure stability. Sufficient resolving power was provided so that, even at the highest counting rates used, the number of particles missed was less than 0.1 percent.

Experimental Results

I. Determination of corrections

With the detector at a height of 3.8 cm above the paraffin, evaluation of the critical angle θ_0 from the geometrical arrangements is not very easy. However, by measuring the intensity of neutrons over the surface and by a rather complicated numerical integration, the value $\theta_0 \simeq 65°$ was obtained for iodine and rhodium resonance neutrons. Since the calculation of f (the ratio of measured to true absorption coefficient) under these circumstances would not be very accurate, we proceeded to evaluate this factor experimentally.

With rhodium, there was sufficient intensity to place the detector 14.3 cm above the paraffin and to reduce the aperture of the emitting surface of the paraffin to a 10-cm square (by means of a diaphragm of 1.2 g/cm² of boron). The critical angle was carefully evaluated by taking into account the variation of neutron flux from different parts of the surface and was found to be 27°. For this value of θ_0 the correction factor f is accurately determined by the Frisch relation $f=2/(1+\cos\theta_0)$. We obtained a value of 1.06 (±0.01). Thus, by measuring the boron absorption of Rh resonance neutrons with this good geometry, the true absorption coefficient of B for these neutrons was found to be $K=5.37$ and the same value, to within 1 percent, was found for indium resonance neutrons.

A similar procedure with thermal neutrons gave a true boron absorption coefficient $K_{th}=30.2$ (±0.3).

Having found the true boron absorption coefficient, we then measured the absorption coefficient with the Rh detector at 3.8 cm above the paraffin, without any diaphragm (that is, under geometrical conditions to be employed in all our other absorption measurements). The ratio of this value to the previously determined true boron absorption coefficient then gave the value of f for the detector at 3.8 cm. Since f, under a fixed geometry, depends, for resonance neutrons, only on the geometry, this value of f, 1.32, could then be used to correct all the absorption measurements with other detectors and other absorbers.

The method employed is, thus, semi-empirical; the true absorption coefficient for boron is obtained under conditions where the Frisch theory is reliable and the correction factor f, under the conditions of our other experiments, is obtained experimentally by comparison with this true coefficient.

The results of the boron absorption measurements with the Rh detector on the 3.8-cm platform appear in Table I. A filter of 0.5 g/cm² of Cd was used to distinguish the thermal neutrons. All transmissions are good to about ±0.5 percent of the transmission value.

Curves of these values are plotted in Figs. 2 and 3. As predicted by Frisch for a critical angle of about 65°, these curves are closely exponential. However, because of their inhomogeneity, thermal neutrons are not expected to be absorbed exponentially at still lower transmissions; this effect is discussed below.

The two corrected transmission curves appear in Figs. 4 and 5, together with theoretical curves of Frisch for various effective angles θ_0. It will be noticed that the curve for resonance neutrons falls in between Frisch's theoretical thick detector curves for $\theta_0=60°$ and $\theta_0=71°$. In fact, it

Table I. *Transmission through boron.*

δ, g/cm² Boron	% Trans. Rh (44 sec.) Detector	% Trans. Mn Detector
	Thermal Neutrons	
0.0047	80.0	78.7
0.0143	57.3	53.9
0.0230	40.2	37.6
0.0299	32.2	29.2
0.108	—	2.9
	Resonance Neutrons	
0.0143	90.0	
0.0230	84.1	
0.0299	80.4	
0.108	46.5	
0.207	23.2	

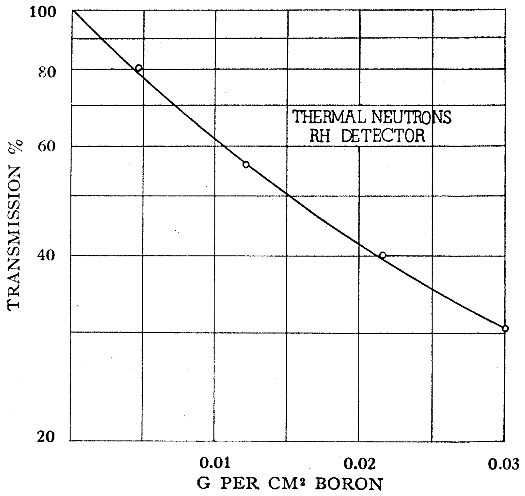

FIG. 2. Transmission of thermal neutrons through boron.

corresponds very closely to the $\theta_0 \simeq 65°$ which we had previously estimated for our geometry by an independent method. Our curve for thermal neutrons coincides with Frisch's thin detector curve for $\theta_0 = 60°$. One can understand that thermal neutrons should have a smaller critical angle than resonance neutrons because their longer mean free path in paraffin gives rise to a different intensity distribution over the surface. (The effect is to make the paraffin surface appear larger to a thermal detector than to a resonance detector.)

In order to study the boron absorption of thermal neutrons at low transmission values, we prepared some manganese thermal detectors. These enabled us to follow the curve down to 2.9 percent transmission. Here the observed deviation from the exponential law was equal to the deviation calculated with a Maxwellian distribution of neutron velocities; its amount was such as to make the absorption coefficient at 2.9 percent transmission 1.32 times the absorption coefficient at 53.9 percent transmission. (See Table I.)

It will be noticed that the transmissions measured with the Mn detector are always lower than those measured with the Rh detector. Ag and In, used as thermal detectors, did not show this behavior, their transmissions being in agreement with the Rh values. We were thus led to suspect a resonance level for Mn in the energy region of C neutrons (those not transmitted by cadmium). For this reason, an investigation of manganese as an absorbor was made.

II. Boron absorptions with various resonance detectors

Having determined the geometrical correction with one resonance detector, we measured the boron absorption coefficients with our other detectors under this standard geometry. All absorption coefficients given in this and the following sections are, accordingly, corrected, true absorption coefficients. It is well to note here that our measurements give us only the total absorption coefficient, which includes not only the capture but also a fraction of the scattering coefficient as well; nevertheless, the scattering by boron is sufficiently low[7] to justify equating the total absorption and the capture coefficients of boron, and this equality is assumed throughout this work. A further discussion of scattering is given below.

A more careful investigation of the boron absorption of In resonance neutrons than that mentioned previously appears in Table II.

Thus the absorption coefficient for In, 5.30 ±0.02 cm²/g, as compared with 5.37±0.02 cm²/g for Rh, indicates that the In resonance level is at a slightly higher energy. As an added check, Hg was used as an absorber with these two detectors;

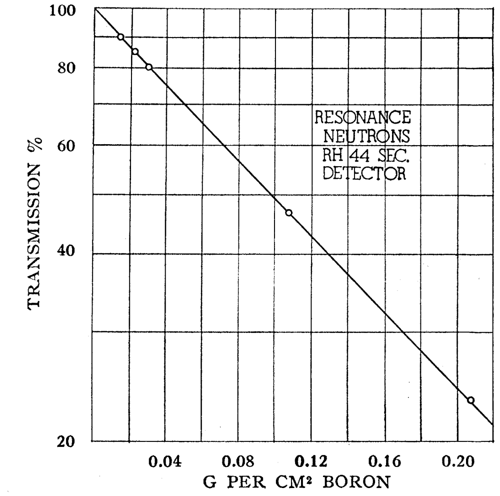

FIG. 3. Transmission of resonance neutrons through boron.

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[7] F. Norling and R. Fleischman, Zeits. f. Physik **108**, 483 (1938).

following Goldsmith and Manley,[8] we assume that its absorption varies inversely as the fifth power of the neutron velocity, and hence is more sensitive to energy differences in this region. In this way it was found that the In resonance energy was higher than the Rh by the amount indicated by the boron absorptions, the energy values from these measurements being 0.82 ev for Rh and 0.84 ev for In. These energies differ somewhat from the values of other authors[1] using similar methods, but the values reported by Bacher[9] agree well with ours. The order of the energies is in agreement with those of Goldsmith and Rasetti,[1] though they find a somewhat greater separation. Since the boron absorption curves for both detectors are good exponentials, both In and Rh must have single levels.

The boron absorption coefficients of the silver 22″, manganese 150′, iodine 25′ and bromine 20′ resonance activities are in Table III.

In all four cases the absorption coefficient decreases steadily as the absorber thickness increases, precisely the behavior to be expected if the neutrons are absorbed at two or more separate energy levels. Since we wish to compare the absorption coefficient of some other element with the boron absorption coefficient, we encounter the difficulty, then, of knowing which boron coefficient to choose.

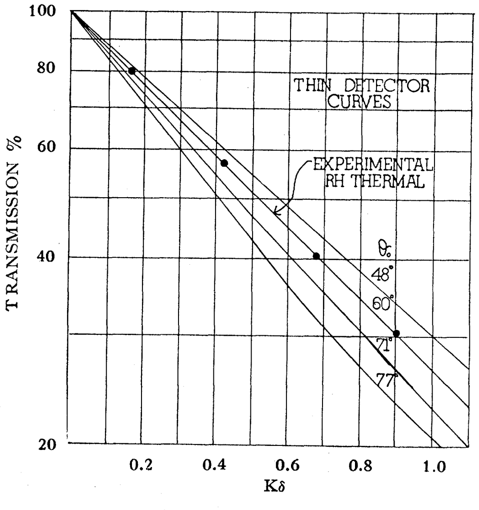

FIG. 4. Corrected transmission values for thermal neutrons with a thin detector and theoretical curves of Frisch for various angles.

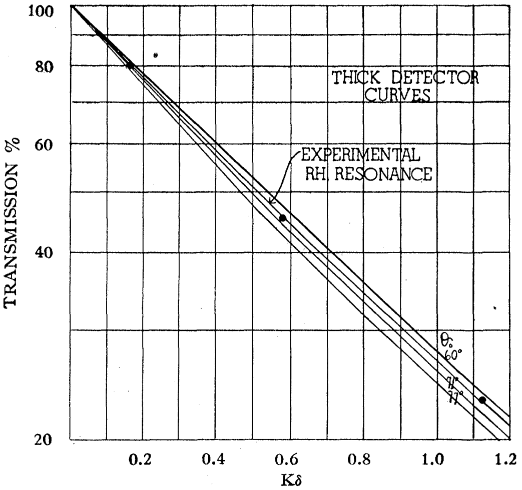

FIG. 5. Corrected transmission for resonance neutrons with a thick detector and theoretical curves of Frisch for various angles.

We are interested in determining whether the absorption of our other element follows the $1/v$ law, that is, the same law as does boron. If both boron and this element follow this law, then their absorption, with a multi-level detector, will vary with absorber thickness in exactly the same way. Thus if we compare their absorption coefficients for any pair of identical values of the transmission, the ratio should be constant. Hence, in comparing the chosen element's absorption coefficient with that of boron, the boron coefficient chosen was the one for the same percentage transmission shown by the element; this was done for several values of the transmission, except with iodine and bromine detectors, where the geometrical arrangements did not permit more than one thickness of absorber.

With boron coefficients selected in this way, the ratio of coefficients for two different detectors, compared to the same ratio with the other element as absorber, will show whether that element follows the $1/v$ law or has resonances, even if the detector has more than one level.

III. Absorption by chlorine, cobalt and manganese

We selected chlorine and cobalt for this work because both elements exhibit a large total cross section for thermal neutrons. Despite their large

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[8] H. H. Goldsmith and J. H. Manley, Phys. Rev. **51**, 382A (1937).

[9] C. P. Baker and R. F. Bacher, Phys. Rev. **57**, 1076A (1940).

TABLE II. *Percent transmissions* Rh *and* In *resonance neutrons.*

DETECTOR	δ, 0.030 G/CM² B	δ, 0.108 G/CM² B
Rh	80.4±0.3	46.5±0.2
In	80.8±0.3	46.9±0.2

cross sections we were able to induce only a very weak 40-minute period in chlorine (previously identified as Cl^{38})[10] and a still weaker 11-minute period in Co (Co^{58}).[10] If these activities were to be ascribed to the large neutron capture cross sections, then the activity in Cl should have been 100 times greater than found, and that in Co 600 times greater. Since each element has only two stable isotopes, we concluded that the large capture cross sections are involved in the production of Cl^{36} and Co^{60}. A similar argument has been advanced by Kikuchi[11] on the basis of the cross section for the production of capture γ-rays. Recent work[12] has shown that Co^{60} has a half-life of several years and some unpublished work of Grahame[10] shows a similar behavior for Cl^{36}. Our absorption method is peculiarly suited to the study of their resonance levels, since it is not feasible with a natural source to look for them by the usual method of studying the effect of boron absorbers on the induced radioactivity.

We have already mentioned the reason for investigating the absorption of manganese.

The absorption of neutrons by these elements was measured with the six detectors whose boron absorption coefficients had already been determined. Wherever practicable, several different thicknesses of absorber were used; the absorption coefficients of Cl and Co were good to better than 1 percent, the coefficient of Mn to only 2–3 percent, because of its much weaker absorption.

Rh and Ag served as thermal neutron detectors, and in all cases the same value of absorption coefficient was obtained with both detectors. When Mn was tried as a thermal detector, higher values of the absorption coefficients of Cl, Co, and Mn were found, just as with the boron absorber.

The results of typical runs are given in Table IV, showing the good agreement attainable for different thicknesses when neutrons of homogeneous energy are detected.

Table V shows the absorption coefficients of B, Cl, Co, and Mn, as measured with the various detectors. As already pointed out, the boron absorption coefficients for all neutrons except those of the Rh and In resonances really refer to more than one resonance energy. However, to fix the order of the resonance energies of the different detectors, and to facilitate discussion, the energy corresponding to each boron absorption coefficient is calculated as if due to a single energy and it is in this way that the column of resonance energies in Table V is evaluated.

The following features in Table V are to be noticed, under the assumption, for the moment, that the total absorption coefficient K is not sensibly different from the capture coefficient, K_c, and with our discussion confined to K.

(1) The Cl coefficient is greater at 0.84 ev than at 0.82 ev, just the inverse of the B coefficient; thereafter, the Cl absorption coefficient decreases steadily with increasing energy. We conclude, therefore, that there is a Cl resonance level near 1 ev, somewhat beyond the In resonance level. Additional evidence for this is obtained by com-

TABLE III. *Boron absorption.*

δ, G/CM² BORON	% TRANS.	K, ABS. COEFF. CM²/G
	Silver detector	
0.030	89.0	2.75
0.108	67.4	2.70
0.207	51.5	2.39
0.268	44.9	2.24
0.420	30.7	2.13
	Manganese detector	
0.108	82.5	1.25
0.207	69.2	1.25
0.268	63.2	1.21
0.420	56.8	0.97
0.560	48.0	0.95
0.980	36.5	0.74
	Iodine detector	
0.108	86.9	0.97
0.207	76.8	0.94
0.420	64.9	0.79
0.980	37.9	0.75
	Bromine detector	
0.108	86.2	0.99
0.207	76.0	0.97
0.420	63.5	0.81
0.980	37.1	0.78

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[10] For a summary of induced radioactivities see J. J. Livingood and G. T. Seaborg, Rev. Mod. Phys. **12**, 30 (1940).

[11] Kikuchi, Takeda, and Ito, Proc. Math.-Phys. Soc. Japan **19**, No. 1 (1937).

[12] J. Risser, Phys. Rev. **52**, 768 (1937).

paring the ratio K_{th}/K_{Rh} of Cl and of B; this ratio is 4.1 for Cl, and 5.6 for B. In other words, as one goes from thermal energy to 1 volt, the Cl absorption does not diminish as much as does a nonresonance, inverse velocity capture.

(2) In the region of 1 volt, Co behaves like Cl; its absorption coefficient for thermal neutrons is 4.6 times its absorption coefficient at 0.82 volt and the coefficient increases from 0.82 to 0.84 volt. Unlike Cl, the Co coefficient increases again at the Br and I resonance energies, indicating that it has another resonance level beyond the I energy, 27 volts. Downing and Ellis[13] using the method of slowing curves, reported Co resonances at 1 and 40 volts, in good agreement with these results.

(3) For Mn, the ratio of the absorption coefficients at 0.028 and 0.82 volt is 6.5, greater than the ratio 5.6 of the boron absorption coefficients. This indicates a resonance level of Mn below the limit of the Cd cut-off (less than 0.4 volt).

IV. Effect of scattering

We have based our discussion so far on the total coefficients, whereas in actuality the inverse velocity law applies to the capture coefficients only. We shall see, however, that in our experiments the scattering is so small that it does not change the conclusions drawn.

The evaluation of the effects of scattering is based on measurements of absorption by MnO_2. The total absorption coefficient of Mn having already been determined, we can find the effect of oxygen alone by assuming the additivity of cross section. (This is certainly valid at the higher energies.) Oxygen is known[14] to exhibit negligible capture, its effect on the neutron beam being due almost entirely to scattering. Our values of the total coefficient for oxygen are shown in Table VI.

Table IV. *Absorption coefficients for* Co *and* Cl.

δ, g/cm²	% Trans.	K, Abs. Coeff. cm²/g
	Thermal neutrons by Co	
0.960	67.0	0.313
1.94	44.8	0.312
3.00	28.8	0.315
	Rh *Resonance neutrons by* Cl	
1.00	82.6	0.150
1.94	67.5	0.149
2.94	55.3	0.149

We see that the coefficient is constant for different energies, as to be expected if it represents scattering only. But our value is only one-tenth the value, $K_s=0.15$, found by Goldhaber and others[15] for thermal neutrons. This is not unexpected, since in our arrangement there is considerable scattering into the beam, so that only a fraction of the true scattering coefficient is effective in our experiments. Pb and Fe showed a similar effective fraction of scattering of one-tenth, when their absorption was allowed for, and a rough theoretical evaluation of this effect showed that we might expect a factor of about $\frac{1}{8}$. By taking one-tenth the scattering coefficients of Goldhaber, then, we obtain the scattering coefficients effective in our experiments; these come out to be $K_s=0.005$ cm²/g for Co, $K_s=0.003$ cm²/g for Mn, and since only an upper limit has been given for the scattering of Cl, we can only say that $K_s<0.01$ cm²/g for Cl. These values are to be subtracted from the K values to obtain the coefficients K_c, and are, it is seen, quite unim-

Table V. *Absorption coefficients for* B, Cl, Co *and* Mn.

Detector	Energy, ev	Abs. Coeff., K, cm²/g			
		B	Cl	Co	Mn
Rh thermal	0.026	30.2	0.610	0.314	0.123
Rh 44 sec.	0.82	5.37	0.149	0.068	0.019
In 54 min.	0.84	5.30	0.161	0.070	0.019
Ag 22 sec.	3.3	2.70	0.110	0.039	0.014
Mn 150 min.	15	1.25	0.065	0.023	(0.79)*
Br 18 min.	25	0.97	0.058	0.032	0.020
I 25 min.	27	0.94	0.054	0.043	0.014

* Abs. coeff. at exact resonance measured with thin detector and thin absorber.

Table VI. *Oxygen scattering.*

Detector	K_s, Scattering Coeff. cm²/g
Rh thermal	0.015
Rh 44 sec.	0.011
In 54 min.	0.012
Ag 22 sec.	0.012
Br 18 min.	0.012
I 25 min.	0.013

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[13] A. E. Downing and C. D. Ellis, Nature **142**, 793 (1938).

[14] M. Goldhaber and G. H. Briggs, Proc. Roy. Soc. **A162**, 127 (1937).

[15] H. Carroll and J. R. Dunning, Phys. Rev. **54**, 541 (1938).

portant, except in the case of Mn, where the ratio of K_c for thermal and 0.82-volt neutrons becomes 7.5 instead of the 6.5 for B, thus making still more prominent the resonance in the thermal region.

It must be realized that, while the method outlined in this paper can show, and has shown, resonances in nuclei which are not activated, it has two drawbacks. One is that, with the few practicable detectors available, the chances are slight that the resonance bands of detectors and absorber will overlap sufficiently for a marked effect, and the other is that, if the absorbing element scatters strongly, the scattering correction is neither unimportant nor accurately calculable.

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The X-Ray Spectra Arising from the Valence Band—*L* Transitions of Tungsten, Tungsten Oxide (WO_3) and Platinum*

J. A. Bearden and T. M. Snyder
Rowland Physical Laboratory, The Johns Hopkins University, Baltimore, Maryland

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X-ray emission lines and absorption edges arising from transitions between the *L* levels and the valence bands of tungsten, tungsten oxide (WO_3) and platinum were studied with a double crystal spectrometer. Manning and Chodorow's calculation of the density of states in the 5*d* and 6*s* bands of tungsten is found to be in good agreement with the observed shapes of the tungsten absorption edges. The tungsten emission lines, on the other hand, do not have the structure expected from their calculation and are 4.5 ev narrower than the region of occupied states calculated for these bands. A comparison of the spectra of tungsten metal with those of its oxide shows: (1) the initial absorption maximum of the L_{II} and L_{III} edges is both broader and higher in the oxide, (2) the *L* edges of the oxide are shifted 2.5 ev to higher frequencies, (3) the emission lines of the oxide are about 3 ev wider than those of the metal. These differences between the spectra of the oxide and the metal are explained qualitatively in terms of the high electronegativity of oxygen. The platinum absorption edge structures observed are in agreement with what is qualitatively expected from the other properties of this metal. A marked difference in the relative intensity of corresponding structure features of the L_{II} and L_{III} edges is ascribed to a spin-orbit coupling of the valence electrons.

Introduction

PREVIOUS workers[1–5] have shown that the experimentally observed shapes of x-ray absorption limits and of those emission lines which arise through transitions from the valence bands characteristic of elements in a solid may be interpreted in terms of the density of states in the unfilled and filled portions of these bands. In the present work, the *L*-absorption edges and *L*-emission lines which involve transitions from the valence bands of tungsten and tungsten oxide and the *L* edges of platinum were studied. The shapes of the tungsten spectra are compared with that of the density-of-states of the 5*d* and 6*s* electrons of tungsten calculated by Manning and Chodorow.[6] The WO_3 and W spectra are compared and their differences explained in terms of the high electronegativity of oxygen. The shapes of the *L* edges of platinum are shown to be compatible with band structure expected for this metal from its other properties.

Experimental

The spectrometer, crystals, high voltage supply and intensity measuring apparatus used in this work have already been described elsewhere.[7] For absorption studies, the target of

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