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ON THE SELECTIVE CAPTURE OF SLOW NEUTRONS

BY

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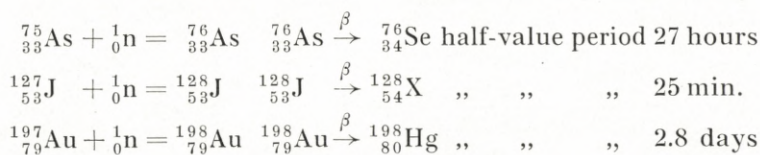
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We deal in this paper with the selective capture of slow neutrons (1, 2) in arsenic, iodine, and gold (3). On capturing a neutron, the nuclei of these elements are transformed into unstable ones, which revert to stable nuclei again by the emission of a beta-particle:



These elements were selected because they show the phenomenon of selective capture in a marked degree, because only one stable isotope is known in each case, and because the corresponding unstable isotopes have periods which are convenient for measurement.

Samples of the substance under investigation were exposed under various conditions to the neutrons emerging from a block of paraffin wax, containing a source of fast neutrons (Ra + Be or radon + Be). The samples were then transferred to a GEIGER-MÜLLER counter, and the activity shown by the counter was taken as a measure of the number of neutrons captured within the sample.

The observations have been interpreted on the assumption (4, 5) that the capturing nucleus together with the incoming neutron forms a "compound nucleus" with well

defined energy levels whose width is small compared with their separation, in the energy region concerned. In the first instance, however, we shall only assume one such level in each case, and the evidence for and against this assumption will be discussed.

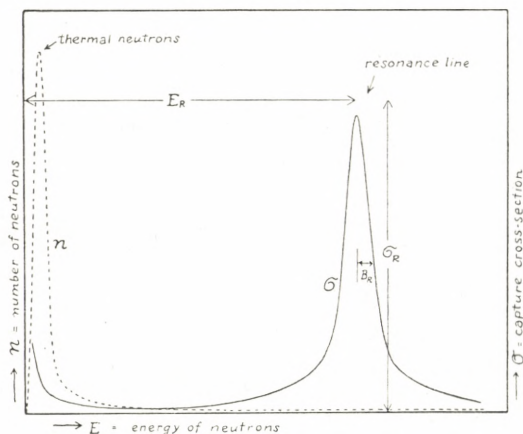


Fig. 1.

The conditions in the one level case are shown schematically in fig. 1. The full line indicates the dependence of the capture cross-section σ on the kinetic energy E of the incoming neutrons; this dependence (5) is given by the formula

$$\sigma = \frac{\sigma_R}{1 + \left(\frac{E - E_R}{B_R}\right)^2} \cdot \sqrt{\frac{E_R}{E}} \left(\begin{array}{l} E_R = \text{Resonance energy} \\ \sigma_R = \text{Resonance cross-section} \\ 2B_R = \text{Half-value width of re-} \\ \text{sonance line.} \end{array} \right)$$

In all cases so far investigated the "resonance cross-section" σ_R is much larger than the corresponding value of σ for neutrons of thermal energy; still the thermal neutrons contribute considerably to the activation of the sample, on

account of their large number (the estimated energy distribution of the neutrons emerging from a paraffin block (6, 7) is indicated by the dotted line). A screen of cadmium was therefore used to remove the thermal neutrons in the usual way; the main part of the activity is then due to neutrons with energies near E_R . In what follows, these neutrons will simply be called "resonance neutrons".

In order to determine the resonance energy E_R , the absorption of the resonance neutrons in boron was compared with the absorption of thermal neutrons in boron (8). Theoretical arguments have been given for the assumption that the absorbing cross-section of boron is inversely proportional to the velocity of the neutrons (8, 9). This " $\frac{1}{v}$ -law" should hold for neutron velocities up to at least 10^7 cm./sec. (energies of ≈ 50 eV.) when the capture cross-section becomes of the order of ordinary nuclear cross-sections. Experimental checks are in qualitative agreement with this assumption (10, 11). In this paper the validity of the $\frac{1}{v}$ -law will be taken as established. We have made no attempt to verify it.

The resonance cross-section σ_R was determined by measuring the absorption of the resonance neutrons in the element under investigation. Absorption curves under various geometrical conditions have been obtained and compared with theory.

Two different ways of obtaining an estimate of the width of the resonance level are discussed in the case of gold. An attempt has been made to discover a broadening of the absorption line on increasing the temperature of the absorber (thermal Doppler-effect) but no conclusive result has been obtained so far.

1. Determination of Resonance Energies.

Experimental procedure. The neutron source (500 mg. radium in the form of RaSO_4 , mixed with beryllium) was placed at the centre of a cube of paraffin wax of side 13 cms. To investigate the resonance energy of gold, four gold discs (15 mms. diameter, 0.1 mm. thick) were placed 2 cms. below the lower face of the cube and arranged at the corners of a square of 3 cms. sides, situated symmetrically with respect to the cube. Absorbers of 3 cms. in diameter of amorphous boron (pressed without binding material) were placed on three of the gold plates, the absorber thicknesses being 0.10, 0.20, and 0.40 gr./cm.², respectively. On comparing the activities induced in the four gold plates, an absorption curve, in boron, of the resonance neutrons of gold is obtained. A shield of 0.4 gr./cm.² cadmium was placed immediately below the paraffin to cut off the thermal neutrons, and a double shield (0.4 gr./cm.² cadmium + 0.5 gr./cm.² gold) against stray neutrons was placed under the gold. After two days exposure the activity of the gold plates was measured by means of GEIGER-MÜLLER counters having a 10 mms. diameter window of mica (0.0065 gm./cm.²). In order to reduce the time necessary for a sufficiently high count three counters were used simultaneously; small differences in the counting rates of the counters were eliminated by measuring the activity of every disc on each of the three counters and taking the average.

Information on the behaviour of neutrons filtered through about 0.15 gr./cm.² gold was obtained by measuring the activity both of the lower and the upper sides of the gold plates; since the electrons emitted by gold are very

soft the activity of the lower side is almost entirely due to neutrons which have penetrated nearly the whole thickness of the gold plate.

In the case of arsenic this simple method could not be used since the electrons emitted by active arsenic are much harder. Eight plates of As_2O_3 of 15 mms. diameter, each containing 0.200 gr. As_2O_3 , were therefore placed in pairs,

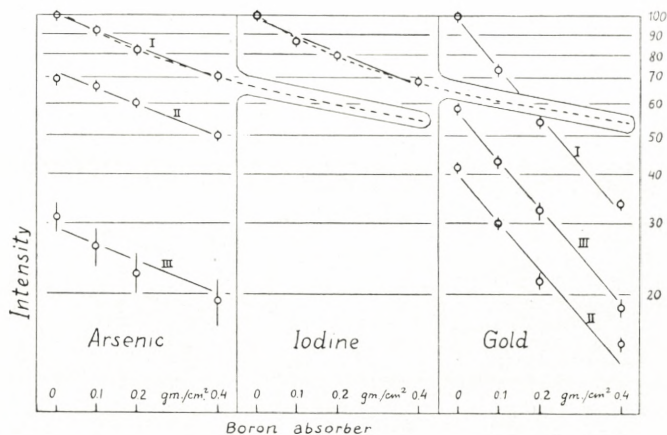


Fig. 2.

one on top of another, at the corners of a square, as in the case of the gold. The boron absorbers and the upper cadmium shield were the same, but there was no shield underneath; there are, however, reasons to believe that this makes little or no difference in the case of arsenic. Only the activity of the upper sides of the plates was measured.

With iodine, similar plates, each containing 0.500 gm. I_2O_5 were used; only one plate was placed under each boron filter. The lower shield consisted of 0.4 gm./cm.² cadmium + 2 gm./cm.² iodine. Only the activities of the upper sides were measured.

Results of measurements. The results are summarized in fig. 2 where the activities are plotted on a logarithmic scale against the thickness of the boron absorber; the units are such that the intensity without any absorber is always 100. (I = unfiltered neutrons, II = filtered, III = I - II).

In the case of gold, the absorption in boron is seen to be fairly well exponential, and the ratio of the activities of the upper and lower sides does not change appreciably with increasing boron thickness. This supports the view that most of the activity in gold is produced by one narrow range of neutron velocities, or in other words, that one nuclear level is responsible for most of the activation.

In the case of arsenic, the reduction in activity by the thickest boron absorber used was only 30 %, so no definite conclusion can be drawn from the straightness of the absorption curves. Furthermore the difference between curves I and II is only a small one (the arsenic filter was too thin) so too much weight should not be laid on the constancy of their ratio. In the case of iodine the points might suggest a slight curvature in the absorption curve.

Absorption of thermal neutrons in boron. The absorption of thermal neutrons in boron was determined using, as detector, a boron lined ionisation chamber, connected to a linear amplifier and mechanical counter. The sensitive boron layer covered a circle of 15 mms. diameter and was brought into the same position relative to the paraffin as the plates to be activated in the foregoing experiments; in this way identical geometrical conditions were secured¹. A screen of cadmium was used to discriminate between thermal and faster neutrons. The pro-

¹ The chamber was placed above instead of below the paraffin block.

cedure was the usual one: counts were made (*a*) without absorber, (*b*) with 0.4 gm./cm.² cadmium, (*c*) with 0.020 gm./cm.² boron, (*d*) with cadmium and boron. The ratio (*c* - *d*):(*a* - *b*) gives the transmission in boron of the neutrons stopped by cadmium (C-neutrons); it was found to be $(51.5 \pm 1.5) \%$.

Some doubt may arise as to the degree of temperature equilibrium of the neutrons defined in the way described above, although a large part of the C-neutrons has certainly got thermal velocities as may be deduced from temperature variation (12, 13) and rotating wheel (14) experiments. The following experiment was therefore carried out: counts were taken, in the way described above, with the difference that the cadmium was not placed on top of the paraffin but at a certain depth below the surface. The ratio (*c* - *d*):(*a* - *b*) then gives the absorption, in boron, of those neutrons which were slow enough at that depth to be stopped by cadmium but had, however, to diffuse through a certain layer of paraffin wax before reaching the boron absorber and the ionisation chamber. We should expect those neutrons to be more nearly in temperature equilibrium than the C-neutrons. As a matter of fact, the ratio (*c* - *d*):(*a* - *b*) was found to be unchanged, for depths up to 3 cms. of paraffin, within the limit of error of about 5%. It seems therefore reasonable to assume that this ratio would be essentially the same for a beam of neutrons in perfect temperature equilibrium.

The effective velocity of neutrons with a Maxwellian velocity distribution, that is, the velocity of homogeneous neutrons showing the same absorption in boron, depends somewhat on the thickness of the boron absorber used. For thin boron absorbers it corresponds to an energy of

$\frac{\pi}{4}kT$; when about 50 % of the neutrons are absorbed a slightly higher energy of very nearly kT has to be used (15).

Oblique Incidence. Under the geometrical conditions employed, oblique neutrons from directions forming angles up to about 70° with the normal were involved. The determination of the mass absorption coefficient of boron would therefore require a serious correction and thereby become rather inaccurate. The determination of E_R , however, requires a knowledge of the ratio only of two mass absorption coefficients, which is, in the first instance, equal to the inverse ratio of the respective boron thicknesses required to obtain equal absorption.

The geometrical conditions are, however, not quite identical since the different detectors used respond in a different way to oblique neutrons so that a small correction has to be applied. In the boron chamber, the probability of a neutron being counted is larger for oblique neutrons since their path inside the effective boron layer (that is, the layer from which disintegration alpha-particles may escape into the chamber) is longer ("thin detector"). In gold, however, most of the resonance neutrons are absorbed in a layer which is thin compared with the mean range of the electrons emitted by the active gold; therefore, the probability of a resonance neutron being counted is almost independent of the angle of incidence ("Thick detector"). In the case of gold, therefore, a correction of 5 % has been applied (see appendix I) while in the case of arsenic and iodine the detectors used were regarded as thin, and consequently the uncorrected values were taken.

Discussion of Resonance Energies. The final results are summarised in table 1. The results of H. H.

Table 1.

| | C-neutrons | Arsenic | Iodine | Gold | Units |
|---|--------------------|-----------------|-----------------|-----------------|----------------------|
| Half-value thickness H . . . | 0.0205 ± 0.001 | 0.75 ± 0.07 | 0.71 ± 0.07 | 0.25 ± 0.01 | gr./cm. ² |
| $\frac{H_R}{H_C} = q'$ | | 37 ± 3.5 | 35 ± 3.5 | 12.2 ± 0.5 | |
| $q_{\text{corr}} = \frac{\mu(C)}{\mu(R)} \dots$ | | 37 ± 4 | 35 ± 4 | 11.6 ± 0.7 | |
| $E_R = kT \cdot q^2 \dots$ ($kT = 0.026$) | | 35 ± 8 | 32 ± 8 | 3.5 ± 0.5 | eV. |
| E_R (GOLDSMITH and RASETTI) | | 84 | 80 | 2.5 | eV. |

GOLDSMITH and F. RASETTI (15) which were published after our measurements were finished have been included for comparison. While in the case of gold the agreement is tolerable the authors find considerably higher energy values for arsenic and iodine than we do. This difference seems to indicate that, in fact, more than one level contributed to the activation, both in arsenic and iodine. The difference between the values obtained by GOLDSMITH and RASETTI and our values is then probably due to the fact that GOLDSMITH and RASETTI used thicker boron absorbers than we, and thereby suppressed the low energy levels relative to the higher ones. In fact the introduction of their values into our fig. 2 (a rather arbitrary procedure, on account of the different geometrical conditions) suggests a definite curvature of the absorption curves (indicated by the dotted lines) which is, however, quite compatible with the points measured by us. It would therefore appear that the energy values given both by GOLDSMITH and RASETTI and in this paper are just different average values, and that at least one level somewhat below 30 eV. and at least one above 80 eV. are involved (and possibly levels in between), both in arsenic and iodine.

It seems very doubtful whether much additional information may be expected from this type of experiments since the boron absorption method is rather ineffective as soon as more than one component is involved, like all methods where absorption curves are analysed into exponentials (e. g. gamma ray analysis by absorption).

2. Determination of Resonance Cross Sections.

Determinations of resonance cross sections by different authors have so far not been very consistent among themselves. This is probably due to the phenomenon of self-reversal (16): neutrons with velocities near to the centre of the absorption line are quickly absorbed, those at the sides showing a smaller absorption. The apparent absorption coefficient will, therefore, depend on the thickness of the absorber used, decreasing with increasing absorber thickness; in other words, the absorption curve is not exponential but flattens out at large absorber thicknesses.

We shall first discuss the shape of the absorption curve theoretically and then compare it with experiment. Our calculation is based on the assumptions that only one resonance level is involved the width of which is small compared with the resonance energy, and that the neutrons have a uniform energy distribution in the energy region concerned. The first assumption permits us to neglect the $\frac{1}{v}$ -factor in the capture cross section which becomes important, anyhow, only for very slow neutrons which in the experiments have been removed by a cadmium screen. We take therefore

$$\sigma = \frac{\sigma_R}{1 + \left(\frac{E - E_R}{B_R} \right)^2}$$

or, introducing the mass absorption coefficient

$$\mu = \frac{\sigma \cdot N}{A} \quad \left(\begin{array}{l} N = \text{Avogadro's number} \\ A = \text{Atomic Weight} \end{array} \right)$$

$$\mu = \frac{\mu_R}{1 + \left(\frac{E - E_R}{B_R} \right)^2}.$$

Assuming that $n \cdot dE$ neutrons of energies between E and $E + dE$ fall normally on a plate of the absorber, the number present after passage through a thickness x will be $n \cdot e^{-\mu x} dE$. The number of neutrons which are absorbed between x and $x + dx$ is then found by differentiating the last expression. Finally one has to integrate over all neutron energies, to obtain the total number of neutrons absorbed in a thin detector of thickness dx behind an absorbing layer of thickness x . We find this to be

$$\text{const. } e^{-z} \cdot J_0(iz) \left(z = \frac{\mu_R x}{2}, J_0 = \text{Bessel function of order zero} \right).$$

This function is tabulated in column A of table 2 and shown graphically in fig. 3. The function starts off like an exponential, the corresponding absorption coefficient μ_0 being, however, only half the value μ_R at resonance. For larger absorber thicknesses the curve flattens out and approaches asymptotically the function $\frac{1}{\sqrt{\pi \mu_R x}}$.

The same calculation has been carried out numerically in the case where the neutrons do not enter the plate normally but are distributed in angle according to a cosine law. (B in table 2 and fig. 3.) For completeness the figures corresponding not to a resonance line but to a fixed absorption coefficient μ_0 are included (C and D), both for normal and cosine incidence.

Table 2.

| $\mu_0 x$ | A | B | C | D |
|-----------|-------|-------|-------|-------|
| 0.01 | 0.990 | 0.950 | 0.990 | 0.950 |
| 0.2 | 980 | 914 | 980 | 913 |
| 0.5 | 951 | 832 | 951 | 828 |
| 1 | 907 | 737 | 905 | 723 |
| 2 | 827 | 629 | 819 | 574 |
| 3 | 758 | 546 | 741 | 467 |
| 4 | 697 | .. | 670 | .. |
| 5 | .. | .. | 607 | 327 |
| 6 | 600 | 395 | 549 | 275 |
| 8 | 523 | .. | 449 | .. |
| 1.0 | 466 | 296 | 368 | 148 |
| 1.5 | 367 | 234 | 223 | .. |
| 2 | 308 | 198 | 135 | 038 |
| 3 | 243 | 158 | 050 | 011 |
| 4 | 207 | 137 | 018 | .. |
| 5 | 183 | 122 | 007 | .. |
| 6 | 166 | 111 | 003 | .. |
| 7 | 152 | 099 | 001 | .. |

In plotting the experimental points one has to add to each absorber thickness a certain fraction of the detector thickness, the effective depth of the detector. For a thin detector this is just half its thickness; for a thick detector

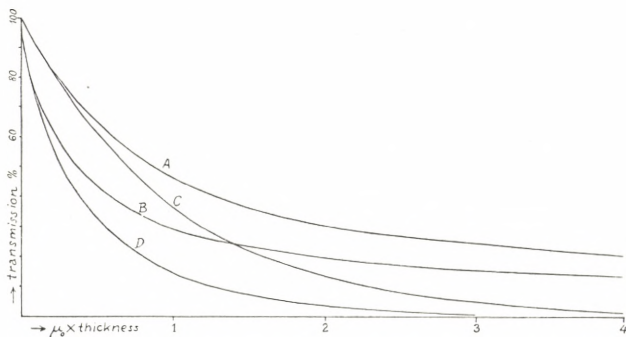


Fig. 3.

of thickness a the absorption of the electrons emitted in the detector has to be taken into account. We have done this in a rough way by measuring the absorption coefficient μ_e of the electrons in the detector material and by using for the effective depth the expression $\frac{1}{\mu_e} \left(1 - a\mu_e \frac{e^{-a\mu_e}}{1 - e^{-a\mu_e}} \right)$.

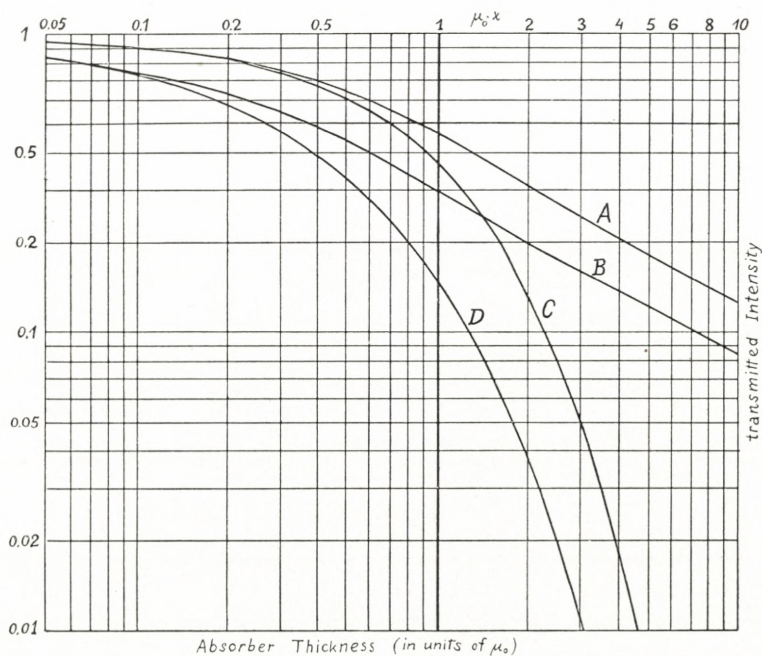


Fig. 4.

In comparing the theoretical curves with the experiments we must remember the following point. The scales of the ordinate and abscissa of the theoretical and experimental curves are not the same. The adjustment of the scales can be most easily effected by plotting both the ordinate and abscissa logarithmically, for then a change of scale merely causes a shifting of the origin. The theoretical curves are

first plotted (fig. 4); comparison is then carried out by plotting the experimental points on the same scale on a piece of transparent paper and by attempting to obtain coincidence by means of vertical and horizontal translations of the paper.

Experimental procedure. A nearly parallel beam of neutrons would obviously be the best for measuring their absorption, but intensity considerations force one to content oneself with rather bad geometrical arrangements. We have used two types. In one of them, a block of paraffin wax shaped like a cone was used as a source of slow neutrons, and the detector was placed in such a way that only neutrons forming angles of about 45° , or less, with the normal were able to reach it. In the other one, the absorbers and the detector were placed immediately on top of a flat paraffin block. For the determination of the initial absorption coefficient the "conical" arrangement was always used; the "flat" arrangement, yielding larger intensity, was used to obtain, in some cases, the shape of the absorption curve up to higher absorbing thicknesses.

In the case of iodine, plates of 15 mms. diameter, each containing 0.200 gr. I_2O_5 , were used as detectors; the absorber plates consisted also of I_2O_5 . The activity of both sides was measured in all cases and the average was taken (the difference was always small); the effective depth could then be taken as equal to half the thickness of the detector, corresponding to 0.043 gr./cm.² iodine. On plotting the points, this amount was always added to the absorber thickness. The distance of the detector from the paraffin varied by about one mm.,

depending on the absorber used; to allow for this, a small correction of 4 % at most was applied.

The points obtained are plotted, on a double logarithmic scale, in fig. 5. The effective absorber thickness (in gr./cm.²) has been written under each point while the corrected intensity is written on top of it, in arbitrary units. On comparing the points with different curves of type A (see fig. 4) one sees that none of them fits all the observed points. Doppler

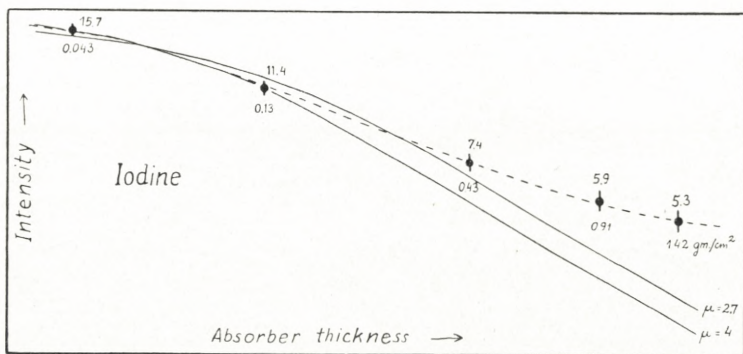


Fig. 5.

broadening of the line would make the absorption still steeper and thereby make the discrepancy still worse. The only possibility seems again to be to assume that more than one level is involved. If we assume, for example, that about 20 % of the activation of the detector without absorber is due to some group of neutrons which are only weakly absorbed in iodine and that 80 % is due to a line with $\mu_0 = 5$ cm.²/gr. ($\sigma_R = 2.1 \cdot 10^{-21}$ cm.²) then we get the dotted line which fits the observed points perfectly. It should be emphasized that, of course, many other combinations of neutron groups with different absorption

coefficient could be found which would fit the points equally well. A small part of the activation might be due to the primary neutrons from the (Ra + Be) source; this might account for some of the weakly absorbable neutrons.

In the case of arsenic, the absorption coefficient was determined in a similar way, using detectors of 15 mms.

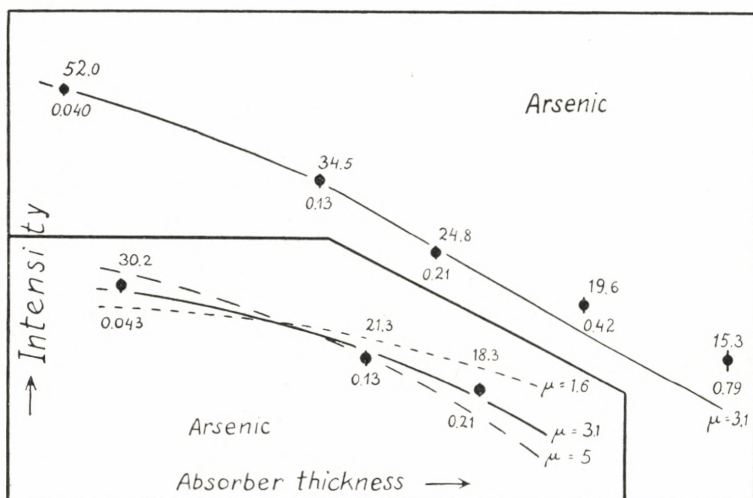


Fig. 6.

diameter, each containing 0.200 gr. As_2O_3 , and the conical paraffin arrangement. The results are plotted in fig. 6. An additional experiment in which larger absorbing thicknesses were employed was carried out with the flat arrangement. The first three points of this fit the corresponding curve with the same value of μ_0 ($3.1 \text{ cm}^2/\text{gr.}$) determined in the conical arrangement. The other two points deviate from the curve in a similar way to the case of iodine, but the deviation seems to be smaller.

Both with arsenic and iodine, the oxygen contained in

the absorbers had no measurable influence; this was checked by special experiments.

In the case of gold, the initial absorption coefficient μ_0 was determined by using gold foils of about 0.004 mm. thickness as detector and absorber. Two such foils (of 15 mms. diameter) were simultaneously exposed to the neutrons with the conical arrangement, on top of one another, and the activity induced in both of them was measured. A small correction of 3 % was applied to the activity ratio measured since in a preliminary experiment it had been found that one of the foils showed 3 % more activity when both had been exposed under identical conditions. Since only two points are measured and the intensity ratio is small one may work out the absorption coefficient assuming an exponential absorption law. In this way one gets $\mu_0 = 41 \text{ cm.}^2/\text{gr.}$ (oblique incidence having been allowed for). Some uncertainty, however, arises from the inhomogeneity of the gold foils used; if, instead of 3 %, a correction of 7 % is applied to the ratio measured, in view of the fact that there was a 7 % difference in weight between the foils, one gets $\mu_0 = 35 \text{ cm.}^2/\text{gr.}$ As a safe estimate we would propose the value $\mu_0 = (40 \pm 5) \text{ cm.}^2/\text{gr.}$ (corresponding to $\sigma_R = 2.6 \cdot 10^{-20} \text{ cm.}^2$).

On account of this high value, together with the high density of gold, it has been possible to follow the absorption curve of gold for a very large range of thicknesses, varying in ratio from 1 to 5000. For this purpose, a pile of 29 gold plates of different thickness, the total thickness being about 6 mms., was placed on top of the flat paraffin block. To prevent neutrons from entering the pile from the sides, a "guard ring" of gold, of 15 mms. internal and 25 mms. external diameter, was placed round the pile. After three

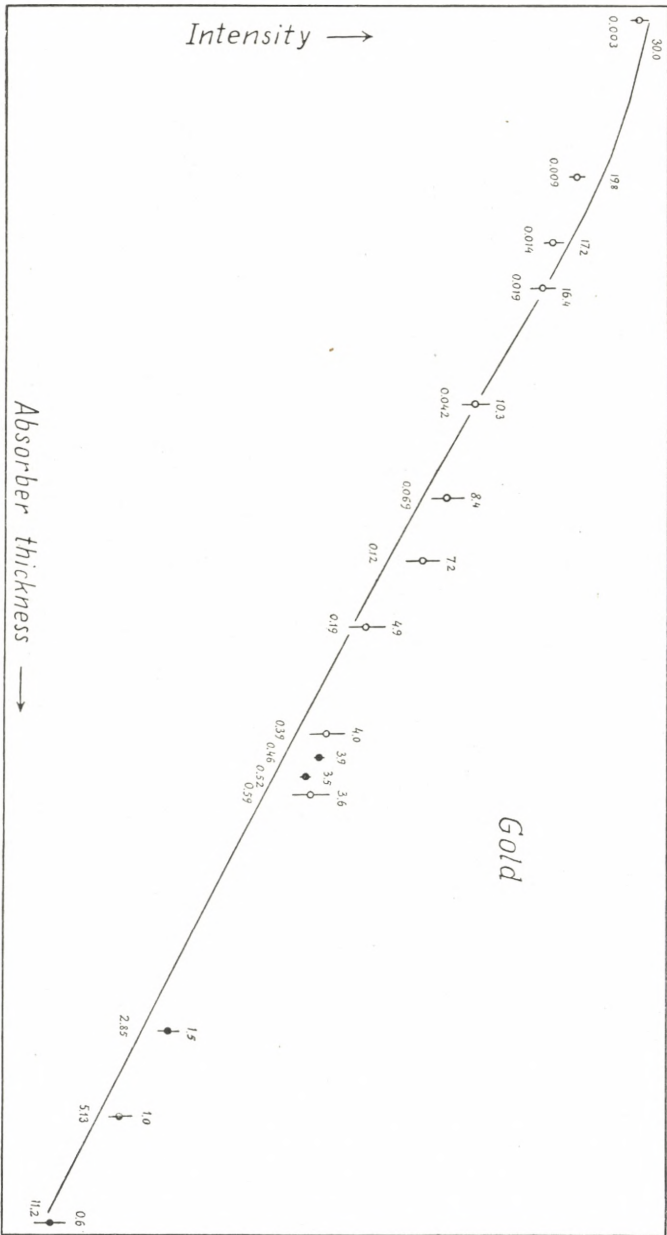


Fig. 7.

days exposure the activities of a suitable selection of foils were measured, the corresponding absorbing thicknesses having a fairly uniform distribution on a logarithmic scale.

Ten of the gold foils selected for measurement were of nearly equal thickness (0.004 mm.); small differences in thickness were allowed for by dividing the measured activity by the weight of each foil. For thicker absorbing layers, however, the intensity becomes too small to be measured by such thin detectors; plates of 0.1 mm. thickness were therefore used and their activity was divided by the empirical figure seven, to match them with the thin detectors. The results are shown in fig. 7. The curve drawn through the points is a curve of type B (see fig. 4), for $\mu_0 = 40 \text{ cm.}^2/\text{gr.}$ The fit is remarkably good, considering the great range of thickness, and offers a very conclusive proof of the "resonance shape" of the absorption line. The deviations present are too small to offer a basis for discussion.

3. Width of Resonance Level.

From the formula $\mu = \frac{\mu_R}{1 + \left(\frac{E - E_R}{B_R}\right)^2} \cdot \sqrt{\frac{E_R}{E}}$ the half-value

width $2B_R$ can be calculated if E_R , μ_R and the absorption coefficient at another velocity, e. g. for thermal neutrons (μ_T) is known. In the case of gold, taking $E_R = 3.5 \text{ eV.}$, $\mu_R = 2\mu_0 = 80 \text{ cm.}^2/\text{gr.}$, and $\mu_T = 0.29 \text{ cm.}^2/\text{gr.}$, we obtain $2B_R = 0.12 \text{ eV.}$ This result is, however, uncertain because other levels might contribute to the absorption coefficient μ_T at thermal energies, possibly also levels below "zero", that is, levels with smaller energies than would correspond to an incoming neutron with zero velocity.

From measurements on the relative intensity of activation due to thermal and resonance neutrons one may obtain information on the width of resonance (17, 11) without assuming only one level. A very rough estimate on this basis gave a width of about 0.1 eV. which is the same order of magnitude as had been obtained in silver and rhodium (11).

In the case of such narrow absorption lines the Doppler broadening, due to the thermal agitation of the capturing nuclei, is not at all negligible. For a infinitely sharp level the Doppler half-value width of the absorption line would be $4\sqrt{\ln 2} \cdot \sqrt{kT \cdot \frac{E_R}{A}}$ (A = atomic weight) which, in the case of gold at room temperature, is equal to 0.06 eV. An attempt was therefore made to find an influence of temperature on the width of the absorption line.

Gold foils of 0.01 mm. thickness were exposed to slow neutrons filtered with cadmium, the gold being either at room temperature or at a faint red glow (about 600° C). Since neutrons near the centre of the absorption line are almost completely absorbed in that thickness of gold the broadening of the line with increasing temperature was expected to result in increased activity. The experiments are rendered laborious by the smallness of the differences to be measured and by the inhomogeneity of the gold foils. Still, from four runs carried out with different gold foils and arrangements, a difference in activity, in favour of the hot foil, of $(7.5 \pm 1.5)\%$ seemed to be fairly well established.

A check experiment, however, in which the cadmium screen was removed, showed about the same difference in activity between the hot and the cold foil. Since about

three-quarters of the activity obtained under these conditions was due to thermal neutrons, this result is hard to understand. For thermal neutrons the rate of capture per unit time should be independent of the velocity ($\frac{1}{v}$ -law!) and consequently there should be no temperature effect. It is therefore doubtful whether the effect observed with the cadmium screen present is genuine, and it may be that all the effects observed are due to some still undetected source of error.

APPENDIX I.

Obliquity Corrections.

Calculations have been carried out regarding the absorption curve of radiation with a given absorption coefficient μ , under geometrical conditions roughly the same as those actually used. For the directional distribution of the neutrons emerging from the paraffin, the expression

$$J_2 \sin \vartheta d\vartheta d\varphi = (\cos \vartheta + \sqrt{3} \cdot \cos^2 \vartheta) \sin \vartheta d\vartheta d\varphi$$

was taken (11). This is also the number of neutrons from different directions, indicated by a "thick" detector which responds equally well to neutrons from all directions. In a "thin" detector, however, oblique neutrons have a probability of being detected, larger by a factor $1/\cos \vartheta$. In this case, the directional distribution of indicated neutrons is given by

$$J_1 \sin \vartheta d\vartheta d\varphi = (1 + \sqrt{3} \cdot \cos \vartheta) \sin \vartheta d\vartheta d\varphi.$$

If the detector is not placed directly on top of the paraffin, no neutrons emerging at a very flat angle will hit the detector. The directional distribution of indicated

$$F_1 = \frac{e^{-k} [2 + \sqrt{3}(1-k)] - e^{\frac{-k}{a}} [2a + \sqrt{3}(a^2 - ak)] - \left[E(k) - E\left(\frac{k}{a}\right) \right] (2k - \sqrt{3} \cdot k^2)}{2(1-a) + \sqrt{3}(1-a^3)}$$

$$F_2 = \frac{e^{-k} [3(1-k) + \sqrt{3}(2-k+k^2)] - e^{\frac{-k}{a}} [3(a^2 - ak) + \sqrt{3}(2a^3 - a^2k + ak^2)] + \left[E(k) - E\left(\frac{k}{a}\right) \right] (3k^2 - \sqrt{3} \cdot k^3)}{3(1-a^2) + 2\sqrt{3}(1-a^3)}$$

$$\left(a = \cos \theta_0, \quad k = \mu x, \quad E(y) = \int_y^{\infty} \frac{e^{-z}}{z} dz \right).$$

neutrons becomes, then, very complicated, depending on the shape of the paraffin surface and the distribution of neutron brightness along it. In the calculation the assumption was made, for the sake of simplicity, that for $\vartheta < \vartheta_0$ the directional distribution given above is valid while for $\vartheta > \vartheta_0$ no neutrons are indicated at all, where ϑ_0 is a suitably chosen angle.

The relative number of neutrons indicated behind an absorbing plate of thickness x is then given by

$$F = \frac{\int_0^{\vartheta_0} \int_0^{2\pi} J \cdot e^{-\frac{\mu x}{\cos \vartheta}} \cdot \sin \vartheta \, d\vartheta \, d\varphi}{\int_0^{\vartheta_0} \int_0^{2\pi} J \cdot \sin \vartheta \, d\vartheta \, d\varphi}.$$

If the integration is carried out, taking either J_1 or J_2 for the distribution of indicated neutrons, the expressions on page 24 are obtained.

These formulae have been kindly evaluated by Mr. FRODE HJERTING; the results are given in table 3.

For practical purposes, the set of curves given in fig. 8 may be found convenient. Each curve corresponds to a value of ϑ_0 ; the abscissae are the observed transmissions (absorptions), and the ordinate gives, then, the factor f by which one has to multiply the absorber thickness in order to obtain a thickness which would, in the case of a parallel beam, give the transmission observed. In other words: if one has calculated the "apparent" absorption coefficient from an absorption experiment, neglecting obliquity, then one has to divide it by f in order to obtain the true one. For not too bad geometrical conditions (ϑ_0 not larger than about 60°) the absorption is nearly exponential and, there-

Table 3.

| | | $\mu x = 0.01$ | 0.02 | 0.05 | 0.1 | 0.2 | 0.5 | 1.0 | 2.0 |
|---------------------------------|------------------|----------------|-------|-------|-------|-------|-------|-------|-------|
| F_1 thin de- tector | 90° 0 | 0.964 | 0.936 | 0.866 | 0.774 | 0.634 | 0.381 | 0.181 | 0.048 |
| | 84° 0.1 | 978 | 957 | 899 | 812 | 671 | 404 | 193 | 051 |
| | 77° 0.2 | 982 | 964 | 913 | 835 | 703 | 432 | 207 | 055 |
| | 71° 0.333 | 985 | 969 | 929 | 856 | 734 | 470 | 232 | 062 |
| | 60° 0.5 | 987 | 973 | 934 | 874 | 764 | 512 | 267 | 080 |
| | 48° 0.667 | 988 | 976 | 942 | 886 | 786 | 548 | 302 | 093 |
| | 0° 1 | 990 | 980 | 951 | 905 | 819 | 607 | 368 | 135 |
| F_2 thick de- tector | 90° 0 | 983 | 967 | 920 | 849 | 728 | 471 | 240 | 068 |
| | 84° 0.1 | 984 | 968 | 922 | 852 | 731 | 474 | 242 | 069 |
| | 77° 0.2 | 985 | 970 | 926 | 858 | 739 | 481 | 246 | 070 |
| | 71° 0.333 | 986 | 972 | 931 | 867 | 753 | 498 | 257 | 074 |
| | 60° 0.5 | 987 | 974 | 937 | 878 | 771 | 525 | 279 | 082 |
| | 48° 0.667 | 988 | 977 | 942 | 888 | 788 | 553 | 307 | 096 |
| | 0° 1 | 990 | 980 | 951 | 905 | 819 | 607 | 368 | 135 |

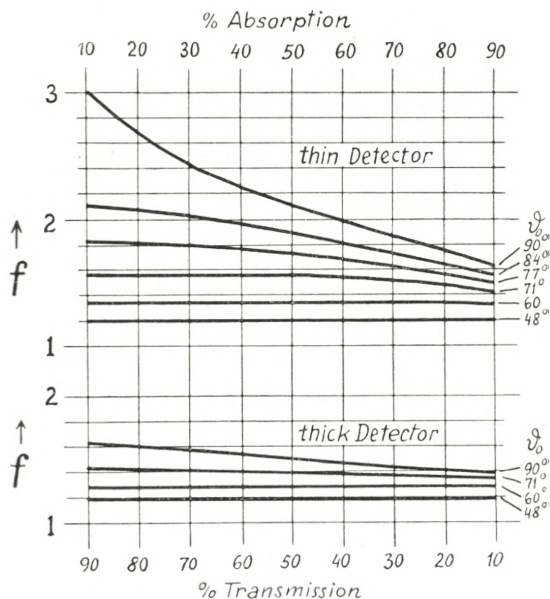


Fig. 8.

fore, f is fairly independent of the absorber thickness. For ϑ_0 smaller than 45° , f is nearly equal to $\frac{2}{(1 + \cos \vartheta_0)}$, both for thin and thick detectors.

In applying the obliquity correction to the experiments with the paraffin cube, a value of $\vartheta_0 = 71^\circ$ has been adopted. Consequently the apparent absorption coefficient has to be divided by 1.42 in the case of gold, and by 1.52 in the case of the other detectors used. This would result in a correction of 7 % in the value of q , for gold; for various reasons, this correction was lowered to 5 %.

APPENDIX II.

Cut-off Energy of Cadmium.

In order to obtain some information on the energy limit up to which the high absorbing power of cadmium extends (cut-off energy) the absorption in boron of those neutrons which penetrate through cadmium (as detected by a boron chamber) has been compared with the absorption of thermal neutrons in boron (9). The residual neutrons were found to be about six times less absorbable than the thermal ones, and it was concluded from this that cadmium is fairly transparent for neutrons with energies as small as 1 eV.

These experiments have been repeated and extended over a large range of boron thicknesses without, however, changing very much the result which was obtained first. In table 4 the results of an experiment are collected where the absorption in boron of neutrons detected by a boron chamber was studied with and without a screen of 1 gr./cm.² cadmium. The source of neutrons was a tin can filled with water (17 cms. diameter and 18 cms. high), with 200 mgr.

Table 4.

| boron absorber thickness in gr./cm. ² | A | B | C | D |
|--|--------------------|--|---|-----------|
| | without cadmium | with a screen of 1 gr./cm. ² Cd (unit as in A) | same as B | A - B |
| | | | (unit changed to make first value = 100) | |
| 0 | 100 ± 2 | 6.9 ± 0.15 | 100 ± 2 | 100 ± 2 |
| 0.020 | 59 ± 2 | (6.6) | .. | 56.5 ± 2 |
| 0.030 | 45 ± 2 | (6.4) | .. | 41.5 ± 2 |
| 0.049 | 32 ± 1.5 | 6.1 ± 0.2 | 89 ± 3 | 28 ± 1.5 |
| 0.10 | 13.3 ± 0.6 | 5.6 ± 0.2 | 81 ± 3 | 8.3 ± 0.7 |
| 0.20 | .. | 4.4 ± 0.2 | 64 ± 3 | .. |
| 0.40 | 3.1 ± 0.3 | 2.9 ± 0.15 | 42 ± 2 | 0.2 ± 0.4 |
| 1.0 | .. | 1.8 ± 0.15 | 26 ± 2 | .. |

Ra + Be placed in its centre; the detecting boron layer had a diameter of 15 mms., as in the experiments described above, and was placed 8 cm. above the water surface.

The absorption curves both for the residual neutrons and those stopped by the cadmium screen are shown in fig. 9. The fact that the half value thickness for the residual

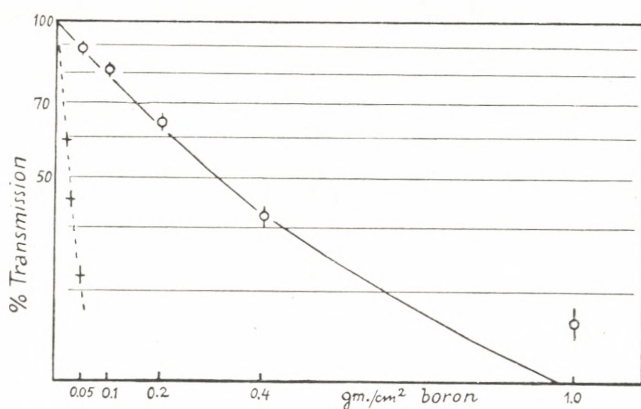


Fig. 9.

neutrons is seen to be about 15 times larger than for thermal neutrons shows that they are absorbed like a homogeneous group of about 5 eV. energy. This value may be regarded as a kind of average energy of the residual neutrons.

As a rough approximation to the velocity distribution of the residual neutrons one may assume that no neutrons are present with velocities below a certain limit v_L , while above this limit the number of neutrons entering the boron chamber per unit time with velocities between v and $v + dv$ is proportional to $\frac{dv}{v}$ (7, 11).

The absorption curve for this distribution has been calculated, taking into account the $\frac{1}{v}$ -sensitivity of the boron chamber, and the result is

$$J = J_0 \frac{1 - e^{-\mu_L \cdot x}}{\mu_L \cdot x} \left(\begin{array}{l} x = \text{boron thickness} \\ \mu_L = \text{absorption coefficient of boron} \\ \text{for neutrons of velocity } v_L \\ \text{(energy } E_L). \end{array} \right)$$

Taking E_L equal to 0.87 eV. we obtain the curve shown in fig. 9. From the good agreement of this curve with the points measured we may deduce that the cut-off energy of a screen of 1 gr./cm.² cadmium is slightly below one volt. Of course, the cut-off is not a sharp one; there will be still lower energies transmitted, to some extent, and higher energies will still be somewhat absorbed. A careful study of the cadmium absorption curve combined with measurements of the absorption in boron of the transmitted neutrons may give more information on this point.

SUMMARY

The selective capture of slow neutrons in gold can be attributed mainly to one resonance level. The resonance

energy is found to be 3.5 ± 0.4 eV. (using the "boron absorption method"), the resonance cross-section is $(2.6 \pm 0.3) \cdot 10^{-20}$ cm.². The half-value width of the absorption line is estimated to be of the order of 0.1 eV. An attempt of finding an influence of temperature on the line width (thermal Doppler effect) gave no conclusive results.

In the case of arsenic and iodine there are indications that more than one level contributes to the activation; in both cases, the boron absorption method gives a value of about 30 eV. for the average resonance energy if fairly thin boron absorbers are used, while GOLDSMITH and RASETTI find a value of about 80 eV., using thicker absorbers. It is concluded that at least one level below 30 eV. and one above 80 eV. contribute to the activation both of arsenic and iodine.

Absorption curves obtained in the element under investigation also indicate the presence of more than one level in the case of arsenic and iodine, while the absorption curve of gold is in accord with the assumption of one level only.

The influence of oblique incidence on absorption measurements is discussed in detail, and a diagram is given by means of which the corrections can be carried out readily.

The "cut-off" energy of a screen of 1 gr./cm². cadmium is found to be nearly 1 eV.

In conclusion, I wish to thank Prof. Dr. N. BOHR for his kind interest in this work, and Dr. G. PLACZEK, Dr. V. WEISSKOPF and Dr. G. WICK for many helpful and stimulating discussions. Furthermore, my thanks are due to the Rask-Ørsted foundation for a grant which enabled me to carry out this investigation at the Institut for teoretisk Fysik at Copenhagen.

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