SOME EXPERIMENTS WITH NEUTRONS SLOWED DOWN AT DIFFERENT TEMPERATURES

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I. Introduction

Fermi and his collaborators* have shown that the efficiency of neutrons in producing certain nuclear transformations is very much increased in the presence of large amounts of paraffin or water, and they attribute this to a loss of energy by the neutrons in repeated elastic collisions with hydrogen nuclei. The number of such collisions which a neutron might undergo before it is absorbed was not known, but Bjerge and Westcott† advanced reasons for believing that this number would be sufficient to reduce the velocity of the neutrons to the gas kinetic velocity corresponding to the temperature of the scattering hydrogenous body. In this case the effects observed might be expected to depend on that temperature, but Fermi‡ had been unable to detect any change between room temperature and 200° C. Later, however, Moon and Tillman§ announced a considerable increase in the radioactivity induced in several substances when the temperature of the paraffin wax through which the neutrons passed was lowered from ordinary temperatures to the temperature of liquid oxygen (90° K.). A similar effect was also found by Dunning, Pegram, Fink, and Mitchell||, and recently Fermi¶ has also been able to obtain the effect, in addition to making a more direct estimation of the velocity of the neutrons, which agrees with the hypothesis of kinetic equilibrium.

The present paper describes some further experiments on neutrons slowed down at low temperatures. In view of the considerable increases in the effects obtained at liquid air temperature, we decided to attempt similar measurements not only at the temperature of liquid nitrogen (77° K.), but also at that of liquid hydrogen (20° K.), particularly as very large increases at the latter temperature were thought possible.

* Amaldi, D'Agostino, Fermi, Pontecorvo, Rasetti and Segrè, *Proc. Roy. Soc.* A, 149 (1935), 522.

† *Proc. Roy. Soc.* A, 150 (1935) 709. ‡ *Loc. cit.*

§ *Nature*, 135 (1935), 904.

|| *Phys. Rev.* 47 (1935), 796 (Abst. 54) and 888; 48 (1935), 265.

¶ Amaldi, Fermi, and others, *La Ricerca Scientifica*, (6), 1 (1935), no. 11–12.

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II. MEASUREMENTS WITH INDUCED RADIOACTIVITY

Most of the measurements were made using the artificial radioactivity induced in various substances by slow neutrons. The apparatus used for exposing the samples to the neutrons is shown in Fig. 1. The neutron source (beryllium + radon, 20–100 millicuries) is placed just outside the Dewar vessel, since if it were cooled, condensation of the radon would probably change its efficiency. A large annular block of paraffin wax serves as a preliminary scatterer for the

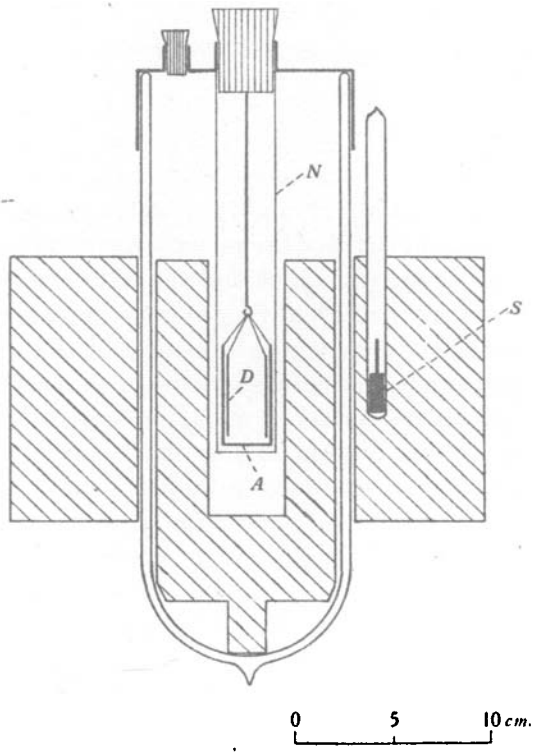


Fig. 1. Section of arrangement used for inducing activity. Diagonal shading—paraffin wax: *S*, neutron source; *D*, detector; *A*, absorber (when used); *N*, nickel tube.

neutrons. The block of paraffin inside the Dewar could be cooled by pouring in liquid nitrogen or hydrogen, in the latter case being generally first cooled by the gases from the liquefier before the liquid began to form. During the measurements the level of the liquid was always well below the bottom of the cylinder being exposed to the neutrons. Owing to the high specific heat and low thermal conductivity of the paraffin wax, it took a long time to cool the blocks right through, but of course the deeper layers took correspondingly longer to warm up. It was usual to refill the Dewar fairly frequently between measurements until

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the level of the liquid was as high as could be allowed, and it was noticed during this operation that the first part of the liquid put in evaporated very fast, thus showing that the temperature of the surface layers of the upper part of the block was considerably above that of the liquid.

The metal cap of the Dewar served to prevent contact with the air when liquid hydrogen was used and also carried a tube of thin (0·1 mm.) nickel, which is believed to be fairly transparent to slow neutrons; the cylinders of metal to be irradiated were introduced into this tube as shown in Fig. 1. The Dewar vessel itself had to be of glass free from boron in order to allow the neutrons to enter freely.

The procedure for the measurements was the same as that employed in previous investigations*, viz. to expose a cylinder of a suitable substance to the neutrons for a fixed time, and then to transfer it to a Geiger counter (kept at some distance from the source), and after allowing a known interval to elapse, to record the number of particles within a fixed period of time. It was necessary

TABLE I

	Copper	Silver	Rhodium
Periods of induced activities	5 m. (10 h.)	22 s., 2·4 m.	44 s., 4 m.
Time of irradiation, min.	10	$\frac{1}{2}$	$\frac{2}{3}$
Interval allowed, min.	1	$\frac{1}{2}$	1
Time of counting, min.	8	3	4
Thickness of detector, mm.	0·45	0·11	0·10
Thickness of absorber, mm.	1·5	0·50	—

to have the sample at room temperature and dry before placing it over the Geiger counter, so the interval allowed was sufficiently long to permit the cylinder to be warmed in a Bunsen flame and dried in a stream of warm air from a hair drier.

Using this arrangement, measurements were made with copper, silver, and rhodium, under the conditions given in Table I. In the case of copper and silver, measurements were also made with a cylindrical absorber of the same substance fitting over the detector during irradiation, as shown in Fig. 1; this enabled changes of the effect induced and of the absorption coefficient to be measured independently. It is not claimed that this method gives an absolute value for the absorption coefficient, owing to varying obliquity of the neutrons, and the possibility of multiple passage through the absorber, but for relative measurements it would seem sufficient. The values for the absorption cross-sections are calculated on the assumption that the absorption is exponential, and the figures for the effects induced are also corrected from these measurements for the finite

* Bjerge and Westcott, *loc. cit.*

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thinkness of the detecting cylinder used*. In the case of copper, the activity due to the long period was subtracted, but in other cases the total activity was used. No absorber of rhodium was available, and the activities observed could therefore not be corrected for the finite thickness of the detector, but in any case the detector did not form a complete cylinder, and its thickness was only about equal to the half-value thickness of the β-rays which it emits, so the correction could not have been large. Measurements of the absorption coefficient of cadmium were also made, using an absorber 0·045 mm. thick, and the silver detector, but the results are of doubtful value since a large proportion of the effect remaining with this absorber must have been due to faster neutrons, and it was not possible to obtain a thinner absorber.

III. MEASUREMENTS WITH THE BORON CHAMBER

It was unfortunately impossible to use a boron chamber in the same arrangement without special modifications, since it would have to be placed in the cavity at the low temperature, so a different arrangement was used. The flat chamber described by Bjerge and Westcott† was employed, and as a substitute

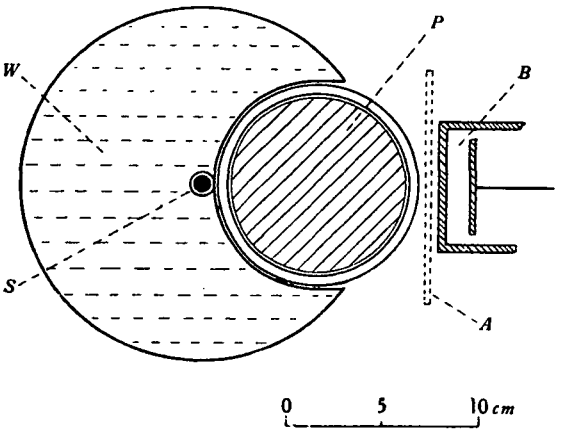


Fig. 2. Plan of arrangement used with boron chamber. Height of water and paraffin layers 20 cm. *W*, tin containing water; *P*, Dewar flask containing paraffin wax; *S*, neutron source; *B*, boron chamber; *A*, absorber.

for a sphere of cooled paraffin round the source we used the arrangement shown in Fig. 2. The thickness of water or paraffin surrounding the source is here practically the same in all directions as it would be for a cylindrical tin of height and diameter both 20 cm. We performed a subsidiary experiment with the

* In some preliminary experiments we were unable to detect any increase of activity at low temperatures on the inner surface of a cylinder of silver 0·5 mm. thick, owing to the increased absorption of the neutrons in the sample itself.

† *Loc. cit.*

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Dewar filled with a 2 % solution of boric acid (which absorbs the neutrons), and found that the effect at the boron chamber was practically the same whether water or the same solution was placed in the tin: this shows that practically all the neutrons which reach the chamber have passed through the Dewar flask.

As before, measurements were also made of the absorption coefficient of boron, in the form of a flat sheet of pyrex (1 mm. thick) interposed in front of the counter, and corrections were applied for the absorption in the boron layers of the counter, as well as in the brass cap which covered it. It was also found that the Dewar was not quite free from absorbing material (presumably boron), and the absorption of this was estimated and the corresponding correction applied.

IV. Results and discussion

The results of the induced radioactivity measurements are given in Table II.

Table II

Temperature	Copper	Silver	Cadmium (Ag det.)
Increase in absorption coefficient:			
77° K.	1·50 ± 0·14	1·22 ± 0·04	1·07 ± 0·04
20° K.	1·98 ± 0·13	1·38 ± 0·04	1·12 ± 0·05
Increase in activity (26 mm. paraffin layer):			
	Copper	Silver	Rhodium
77° K.	1·25 ± 0·03	1·09 ± 0·02	1·09 ± 0·02
20° K.	1·54 ± 0·04	1·22 ± 0·02	1·17 ± 0·02
Increase in "number of neutrons" (26 mm. paraffin layer):			
77° K.	0·82 ± 0·07	0·89 ± 0·03	—
20° K.	0·78 ± 0·05	0·88 ± 0·03	—
Increase in activity (13 mm. paraffin layer):			
77° K.	1·60 ± 0·05	1·27 ± 0·03	1·16 ± 0·03
20° K.	1·77 ± 0·04	1·44 ± 0·04	1·23 ± 0·03
Increase in "number of neutrons" (13 mm. paraffin layer):			
77° K.	1·05 ± 0·09	1·04 ± 0·04	—
20° K.	0·89 ± 0·06	1·04 ± 0·04	—

The figures given represent the ratio by which the effects induced, or the absorption coefficients (and therefore the absorption cross-sections), are increased when the paraffin is cooled from room temperature to the temperatures attained with liquid nitrogen or hydrogen, the errors shown being calculated mean square errors.

It would be anticipated that the increase in the effects induced would be proportional to the increase in the absorption cross-section; the fact that this is not so presumably means that the number of neutrons escaping from the paraffin depends on the temperature. By dividing the factor for the increase of the effect by that for the increase of the absorption coefficient, we obtain the factor representing the increase (or decrease) of the "number of neutrons", which

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is also given in the above table. However, it should be borne in mind that these figures are not absolute, owing to the selective efficiency of the detectors for neutrons of different velocities.

Tillman and Moon* have pointed out that if the absorption of slow neutrons in paraffin depends on their velocity, the effects induced should depend on the thickness of the layer of cooled paraffin used. We therefore repeated the measurements of Fig. 1, with a cylinder of paraffin of larger internal diameter, having walls only 13 mm. thick instead of 26 mm. It will be seen from Table II that with this arrangement the effects (though initially smaller, due to the smaller amount of wax present) increased by larger factors. It is of course possible that systematic errors may occur in the measurement of the absorption coefficient, so that too much importance must not be attached to the fact that the number of neutrons did not seem to decrease at all for this thickness, but it is satisfactory to observe that the change of this number was smaller for the smaller thickness of wax.

The results of the measurements with the boron chamber are given in Table III.

TABLE III

	77° K.	20° K.
Increase in absorption coefficient	$1{\cdot}51 \pm 0{\cdot}13$	$1{\cdot}69 \pm 0{\cdot}14$
Increase in activity	$0{\cdot}99 \pm 0{\cdot}03$	$1{\cdot}09 \pm 0{\cdot}04$
Increase in "number of neutrons"	$0{\cdot}67 \pm 0{\cdot}06$	$0{\cdot}65 \pm 0{\cdot}06$

Considering that the thickness of cooled paraffin wax was much larger in this case than in the previous measurements, the larger decrease observed in the number of neutrons is what might be expected.

Finally, a few measurements were made replacing paraffin wax cooled to liquid hydrogen temperature by liquid hydrogen itself. Unfortunately the density of hydrogen is some 40 % less in the latter substance, which disturbs the rate at which fast neutrons are slowed down. However, it was thought possible that the absence of carbon might increase the number of neutrons by a factor sufficiently large to be obvious in spite of this difficulty.

The first measurements were made with the arrangement of Fig. 2. It had been observed that if the Dewar were empty, an effect some 25 % greater was obtained than if the paraffin block were inserted—the latter scattering away more slow neutrons than would compensate for the extra ones produced. It was therefore thought that changing the density of the hydrogen present in the Dewar from 0·11 to 0·07 would not by itself increase the effect by more than 10 %. However, on substituting liquid hydrogen for paraffin wax (without

* *Nature*, 136 (1935), 66.

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changing the temperature) a 47 % increase of the effect was observed, which suggested that much of the absorption in paraffin wax at 20° K. was due to carbon, and that removal of the carbon was responsible for most of the increase observed.

It was therefore decided to try a similar experiment using the apparatus of Fig. 1. Here three arrangements were compared: first the original measurements with a 26 mm. layer of paraffin cooled with liquid hydrogen; secondly, a 13 mm. layer as used for the previous experiments, but covered with liquid hydrogen, so that the 14 mm. space between the paraffin and the detector was full of liquid hydrogen; and thirdly, with the Dewar full of liquid hydrogen alone (layer 3 cm. thick). The effects induced were found to depend to a marked degree on the level of the liquid hydrogen, which was evaporating away continuously, but it is believed that the mean values obtained are fairly reliable.

TABLE IV

	Copper	Silver	Rhodium
14 mm. hydrogen + 13 mm. wax	1·06 ± 0·03	1·03 ± 0·03	1·00 ± 0·03
30 mm. hydrogen	0·98 ± 0·03	1·05 ± 0·03	0·88 ± 0·03

Both relative to 26 mm. wax = 1·00.

It will be seen from this table that with this arrangement little difference resulted from the substitution of liquid hydrogen for paraffin, which is in apparent disagreement with the earlier result. However, the discrepancy may possibly be explained by the difference in the thicknesses of the layers used in the two experiments, in the same way as the differences in the figures for the number of neutrons in Tables II and III.

Finally, it may be noted that the few absorption measurements which were made when liquid hydrogen was used showed no sign of any large systematic difference from those obtained with paraffin cooled with liquid hydrogen: such might have been expected if the temperature in the latter case had been so much higher as to cause serious errors in the other readings.

No claim to more than a very moderate accuracy is made in respect of the detailed numerical results of this paper, which is only intended to give a general picture of the processes occurring. It is hoped to continue experiments on these lines with a view to greater accuracy.

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SUMMARY

Experiments are described comparing the effects of neutrons slowed down in paraffin wax at the temperatures of liquid nitrogen and liquid hydrogen with those obtained at ordinary temperatures. It is found that the absorption produced by certain substances increases as the temperature is lowered. The transformations produced in these substances also increase, but generally to a smaller extent, probably owing to more neutrons being absorbed in the paraffin: the exact figure depends on the thickness of the layer of cooled paraffin.

A few experiments were also made substituting liquid hydrogen for paraffin wax (without change of temperature). The effect of this also appears to depend on the thickness of the layer, but it is not yet possible to draw definite conclusions.

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