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The Slowing Down of Low Energy Neutrons in Water.
II. Determination of Photo-Neutron Energies

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A new method for determining neutron energies which should be particularly useful below 500 kev has been developed and applied. The method consists in slowing down the neutrons from the source in water and measuring the distribution of D group neutrons. The arrangement is calibrated with neutron sources of known energy. The energies of the photo-neutrons emitted from Y(100*d*)+Be and Sb(60*d*)+Be have been determined and found to be 220±20 kev and 100±20 kev respectively. This is in agreement with previous measurements by other methods. This method has the advantage of great simplicity and should be applicable to neutron energies below 100 kev, which cannot be studied by other known methods.

INTRODUCTION

PHOTO-NEUTRON energies above 100 kev have been determined by measuring the energy of recoil protons in a hydrogen-filled ionization chamber.[1,2] However, it is not possible to use this method for photo-neutrons of energy less than about 100 kev, since the amplifier noise level and the γ-ray background obscure the measurement of such low energy recoil protons. It is desirable, therefore, to have a method which could be employed for energies below as well as above 100 kev. As is well known, the distribution of C neutrons and also group neutrons in water varies with neutron energy since the number of collisions necessary to reduce the neutron energy to some particular value increases with initial energy. A theoretical deduction of the distribution curve for a given energy is not exact enough to be used for the inverse problem of determining the energy from a measured curve. An empirical calibration is therefore necessary.

As was shown in a previous report,[3] the distribution curves for resonance neutrons (D, I groups) fall off much more rapidly than the C neutron curve. One might therefore expect that the curves for resonance neutrons will vary more sensitively with the initial energy than will the C neutron curves which are spread out by the diffusion of the C neutrons.

APPARATUS AND PROCEDURE

The apparatus used is quite simple. The photo-neutron sources were placed in a soft glass tube centrally in a tank of water 100 cm long and 60 cm wide which was filled to a depth of 60 cm. Six different photo-neutron sources were used: 100 mC Ra+Be; 100 mC Ra+D_2O; 8 mC

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* This paper was received for publication on the date indicated but was voluntarily withheld from publication until the end of the war.

[1] G. Scharff-Goldhaber, Phys. Rev. **59**, 937A (1941).

[2] G. S. Klaiber and G. Scharff-Goldhaber, Baltimore meeting (1942).

[3] M. Goldhaber and R. D. O'Neal, Phys. Rev. **60**, 834L (1941).

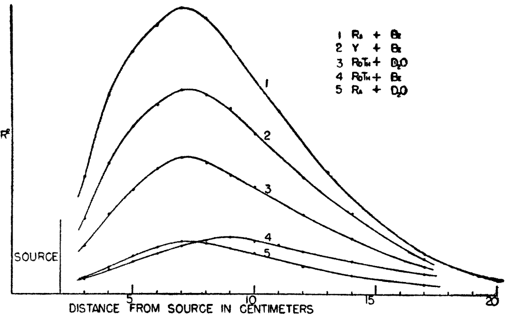

FIG. 1. C neutron distribution in water. Ordinates =activation×square of distance from center of source. Curve 2 drawn to ½ and curve 1 drawn to ¼ scale of ordinates for curves 3, 4, and 5.

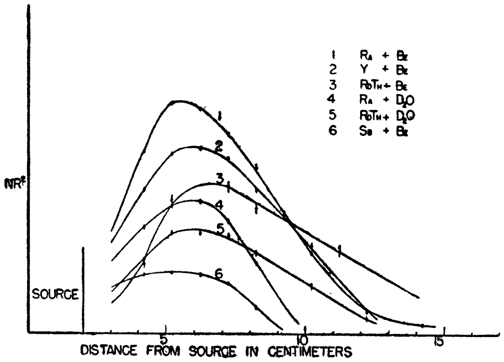

FIG. 2. D neutron distribution in water. Ordinates =activation×square of distance from center of source. Curve 1 is drawn to ¼ and curve 2 to ½ the scale of ordinates for curves 3, 4, 5, and 6. Vertical lines give probable errors.

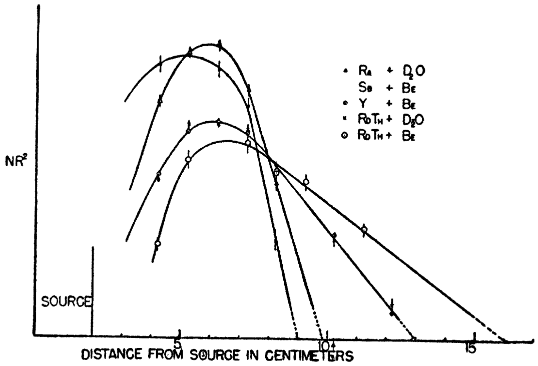

FIG. 3. D neutron distribution in water. Ordinates =activation×square of distance from source. The units of the ordinates are chosen so that each curve includes the same area. Vertical lines give probable errors.

RdTh+Be; 8 mC RdTh+D_2O; 35 mC Y(100*d*) +Be; and 2.5 mC Sb(60*d*)+Be. The γ-ray sources were of somewhat different sizes, but were all cylindrical and from 1 to 2.5 cm long. The beryllium block was 7 cm long and 3 cm in diameter and had a hole along the axis 4.5 cm long and 1 cm in diameter. It weighed 85 g. Forty-five grams of D_2O were contained in a soft glass vessel of outer diameter 3.5 cm and 5.5 cm high. The γ-ray source was placed in a recess at the center of this cylinder 4 cm long and 0.4 cm in diameter.

Thin indium foils placed in water-tight aluminum containers were used for detecting the slow neutrons. The 54-minute β-activity of these foils (corrected for infinite bombardment time and to initial activity) was measured by wrapping them around a thin-wall Geiger counter in a standard position. The group neutron activity of indium was measured by placing the foils in a water-tight cadmium container of thickness 0.17 cm. The indium foil during bombardment was folded into a target of dimensions 4.5 cm by 2 cm. Lead iodide was used as a detector for the iodine group neutrons. The sample used was the same size as the indium sample.

RESULTS

C Neutron Curves

In Fig. 1 are shown the distribution curves for C neutrons. In these curves N is the difference in the induced activity of the indium foil without and with cadmium surrounding it. The distance is measured from the center of the source. One might use either of two criteria for measuring the initial energy of the neutrons—(1) position of maxima or (2) falling-off or decay of the curve. It may readily be seen that the maxima do vary with energy; i.e., RdTh+Be (900-kev neutrons) has a maximum about 1.5 cm farther out than RdTh+D_2O (220-kev neutrons) while the maximum for the latter agrees very well with that for Y(100*d*)+Be, and the maximum for Ra+Be is in still closer (strongest γ-ray gives rise to 120 kev neutrons). However, as can be seen from these curves, and easier still by normalizing them, the slow neutron curves do not offer a very sensitive method for determining energies.

D Neutron Curves

While the C neutron curves may be measured rather easily and rapidly, the group neutron curves are more tedious to measure, since the activities here are roughly only 1/10 the activities one gets for C neutrons. The curves as measured are shown in Fig. 2 and these curves normalized to equal area are shown in Fig. 3. It may be seen that both the maxima and especially the manner in which these curves fall off are rather sensitive functions of the initial neutron energy. One may extrapolate the very nearly straight line portion of the curve to the axis (actually it must fall off approximately exponentially) and use this "apparent intercept" as a criterion of neutron energy. This has been done and we have 3 calibration points as shown in Table I. As can be seen from Fig. 2 and Fig. 3, the distribution of the neutrons from RdTh+Be has not been so accurately measured. There are two reasons for this—(1) the source is so weak that counting at distances far from the source is very difficult and (2) fewer data were taken in this case since this energy region can be better investigated by the recoil proton method.

In Table I the neutron energies are calculated from the γ-ray energies on the basis of 1.62 as the binding energy for beryllium[4, 5] and 2.17 as the binding energy for the deuteron.[4] If one were interested in the exact neutron distribution instead of the "apparent intercepts" one might prefer to use the root-mean-square of the distance that neutrons travel in getting from source to detector instead of the measured distance from the center of the source. This can easily be done when one knows the dimensions of the source and detector. This, of course changes the shape of the curve somewhat, but adds little to the use of the curves as criteria of initial neutron energy.

TABLE I. Neutron energies from Fig. 3.

Source	γ-ray energy (Mev)	Neutron energy* (Mev)	Apparent intercept (cm)	Neutron energy from Fig. 3 (kev)
RdTh+D_2O	2.62	220	13.0	Standard
Y(100*d*)+Be	1.87,[a] 1.89,[b] 1.92[c]	220, 240, 270	13.0	220±20
Ra+D_2O	2.42	120	9.8	Standard
Sb(60*d*)+Be	1.75,[d] 1.72,[e] 1.82[f]	115, 90, 180	9.0	100±20
RdTh+Be	2.62	900	16.0	Standard

* Calculated from γ-ray energy or taken from previous work.

[a] See reference 1.

[b] See reference 6.

[c] See reference 7.

[d] See reference 2.

[e] E. B. Hales and E. B. Jordan, private communication. Determined from difference in end-points of β-ray spectra. 2.43±0.07 Mev—0.71 ±0.03 Mev gives 1.72±0.07 Mev.

[f] A. C. G. Mitchell, L. M. Langer, and P. W. McDaniel, Phys. Rev. **57**, 1107 (1940).

TABLE II. Neutron energies from Ra+Be.

Gamma energy of radium (Mev)	Relative[a] intensity	Neutron energy (Kev)
1.62	0.54	0
1.69	0.40	60
1.75	2.42	120
1.82	0.41	180
2.09	0.37	420
2.20	1.0	510
2.42	0.5	710

[a] A. I. Alichanow, Comptes Rendus Acad. Sci. U.S.S.R. **20**, 429 (1938).

One may see from the curves that the "apparent intercepts" for RdTh+D_2O and Y(100*d*)+Be are not distinguishable from one another. This is in excellent agreement with the measurements[1] of the energy of the recoil protons for these two and the energy of the γ-ray of yttrium that one deduces from these measurements is in good agreement with independent measurements of the γ-ray energy.[6, 7] Small discrepancies might be accounted for by a slight error in the values used for the binding energies of beryllium and the deuteron.

As is seen in Table II the Ra+Be source is not homogeneous, its main intensity being around 100 kev. One sees in Fig. 2 how the higher energy neutrons push the curve out.

There is no indication in the curve for Ra+D_2O of neutrons by the 2.20 Mev γ-ray. This may be caused by the small cross section for photo-disintegration of the deuteron near the threshold. The neutrons from Ra+D_2O are probably mainly caused by the 2.42 Mev γ-ray line, but one should not exclude the possibility that a small contribution is made by very weak high energy γ-ray lines. The measurement of this curve was made more difficult by the neutrons from the radium source itself. However, this was an exceptionally good source as the neutron activity of the γ-ray source itself was less than 1 percent of the neutron activity when surrounded by the beryllium block. This activity and its different distribution had to be taken into account in all measurements with radium

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[4] F. E. Myers and L. C. Van Atta, Phys. Rev. **61**, 19 (1942).

[5] L. S. Skaggs, Phys. Rev. **56**, 24 (1939).

[6] J. R. Downing, M. Deutsch, and A. Roberts, Phys. Rev. **60**, 470L (1941).

[7] J. R. Richardson, Phys. Rev. **60**, 188 (1941).

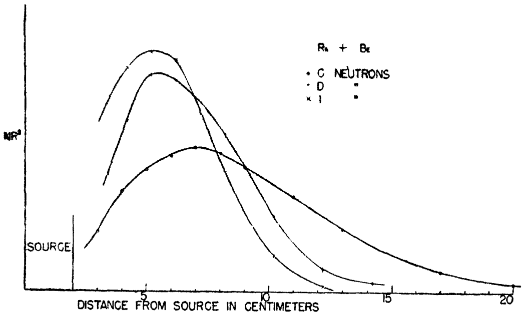

FIG. 4. Ordinates = activation × square of distance from center of source. The units of the ordinates are chosen so that each curve includes the same area.

and the "apparent intercept" of this curve has been determined rather accurately. From this "apparent intercept," that of RdTh+D_2O, and the fact that zero energy neutrons must have an "apparent intercept" near zero, the initial energy of the neutrons from Sb+Be was deduced to be 100 kev with an estimated error of about 20 kev. This is in essential agreement with the energy determination by the proton recoil method.

Comparison of Curves

Previously a comparison has been made[3] between the C, D, and I curves for the initially low energy monokinetic neutrons from a Y(100*d*) +Be source. This comparison brought out the important fact that, unlike the case for neutrons of high initial energy, there was no region at some distance from the source where the two curves decayed at the same rate, but that here at some distance from the source the ratio of group neutrons to C neutrons decreased and so at fairly large distances from the source there are principally C neutrons left.

In Fig. 4 is shown a comparison of the C, D, and I curves for the most commonly used source, Ra-γ-Be. Conclusions similar to those above may be drawn from this comparison, but the presence of the higher energy neutrons makes these conclusions less obvious here.

The accuracy of these measurements and the ease with which they can be carried out can of course be increased by using stronger sources. For convenient measurements of neutron energies of approximately 100 kev, a source of at least 5 millicuries strength should be used if beryllium is being disintegrated and one of at least 10 millicuries if deuterium is being disintegrated.

ACKNOWLEDGMENT

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