of the beaker rim (H) above the level of the outer bath at 1.90°K. The time rate of rise of the liquid surface in the beaker was, in all cases, found to be strictly linear with no "end effect" such as was found in certain cases in an emptying process and illustrated in Fig. 2. We note, however, that this end effect of increased transfer rate on emptying always occurred when the inside level was not more than about 2 mm from the top of the beaker. The smallest observed value of H for a filling process (see Table I) was greater than 2 mm and it is possible that for smaller H the end effect would be found for the filling process also. In any event, however, these results completely disagree with Atkins.

In general, at a given temperature, the emptying rate was somewhat larger than the filling rate. We attribute this to evaporation from B, since the latter will tend to increase the emptying rate and decrease the filling rate.** On this view then, an average of the two rates should be the correct one.

A complete summary of our experimental data is given in Table II and in Fig. 3 is a plot of the transfer rate *versus* the temperature. The latter was computed from the vapor pressure of the bath using the Leiden 1932 scale. For the sake of comparison we have also plotted the Daunt-Mendelssohn data (smoothed values) in Fig. 3 and the agreement between the two sets of data is seen to be reasonably satisfactory.

** In our first experiment, it will be recalled, our emptying rate was double the filling rate indicating much poorer thermal isolation in the first apparatus.

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The Angular Distribution of the Photo-Neutrons from Beryllium

B. Hamermesh, M. Hamermesh, and A. Wattenberg
Argonne National Laboratory, Chicago, Illinois

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The angular distribution of the photo-neutrons from beryllium has been studied for γ-ray energies of 1.70, 1.81, and 2.76 Mev. The distribution was found to be spherically symmetrical for the 1.70- and 1.81-Mev γ-rays. The 2.76-Mev gamma-ray yields a distribution of the form $a+b\sin^2\theta$ with $a/b=1.2$.

INTRODUCTION

THE threshold for the photo-disintegration of beryllium is supposed to be 1.63 Mev. Experiments[1] indicate that the (γ,n) cross section of beryllium increases to a maximum in the neighborhood of 1.7 Mev, decreases to a minimum around 2.1 Mev, and is increasing once again at 2.7 Mev. These maxima in the cross section may be explained in a naïve way by saying that the first maximum is caused by the emission of S neutrons, whereas the second maximum is caused by the emission of neutrons of higher angular momentum. One would therefore expect that the angular distribution of the photo-neutrons should be spherically symmetric just above the threshold and then have an asymmetrical component which increases with increasing energy.

Previous studies of the angular distribution of the photo-neutrons from beryllium were carried out by Chadwick and Goldhaber[2] who used γ-rays from a radon source and found a spherically symmetrical distribution. Goloborodko and Rosenkewich[3] used γ-rays from a radium source and came to a similar conclusion. In view of the complexity of the γ-rays from the radium family, it was felt more valuable information might be obtained with monoenergetic γ-ray sources.

APPARATUS

The apparatus shown schematically in Fig. 1 was mounted eight feet above the floor in a large room.

The detector was a BF_3 pulse ion chamber embedded in a paraffin cylinder 20-cm in diameter and 20-cm long. The chamber was filled to a pressure of one atmosphere with enriched BF_3. The amplifier bias was chosen to discriminate between pulses caused by gamma-rays and those caused by neutrons.

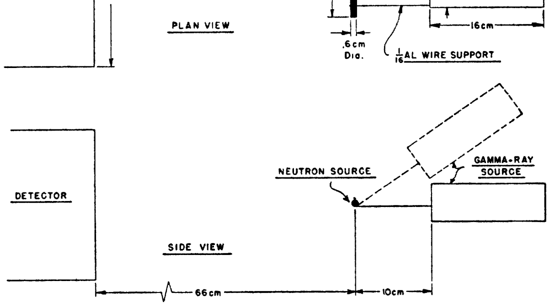

Fig. 1. A schematic diagram of apparatus.

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[1] Russell, Sachs, Wattenberg, and Fields, Phys. Rev. **73**, 545 (1948).

[2] J. Chadwick and M. Goldhaber, Proc. Royal Soc. **A151**, 479 (1935).

[3] Goloborodko and Rosenkewich, Physik. Zeits. Sowjetunion **11**, 78 (1937).

The source holder supported the beryllium target by means of two $\frac{1}{16}$-inch aluminum wires. The beryllium target was a cylinder 5.5-cm long and 0.6-cm in diameter. The source holder could be rotated about an axis that coincided with the axis of the target so as to change the angle between the bombarding gamma-rays and the detected neutrons. Readings were taken at 0°, 20°, 40°, 55°, 75°, and 90°. A set of electrical contacts on the rotating arm attached to the source holder made it possible to make an accurate setting of the angles. The source and detector subtended half-angles of less than 9° at the target.

The sources used were approximately 20 curies in strength. As gamma-ray sources Sb^{124} (γ-ray energy 1.70 Mev), Mn^{56} (γ-ray energies 1.81 and 2.13; nearly 80 percent of the neutron intensity is caused by the 1.81-Mev γ-rays), and Na^{24} (γ-ray energy 2.76 Mev) were used. The source materials were in thin walled aluminum cans for the purposes of handling and irradiation in the heavy water pile at this laboratory. The aluminum activity was allowed to die out before measurements were started. By the use of mirrors, pulleys, and strings all operations during the experiments were carried out with the experimenters located behind adequate shielding material.

EXPERIMENTAL PROCEDURE

The counting rate at any angle included in addition to the desired beryllium photo-neutron intensity, (E), a background consisting of four components—namely:

b—the natural background of the counter.

S—the room scattered neutrons, i.e., those neutrons that reach the counter because they have been scattered by the walls, floor, and ceiling of the room.

C—the neutrons that were produced in the paraffin surrounding the counter. These arise from the photo-disintegration of the deuterium contained in the paraffin in its natural isotopic abundance.

W—the wall-produced neutrons. These arise from the photo-disintegration of the deuterium contained in the walls, floor, and ceiling.

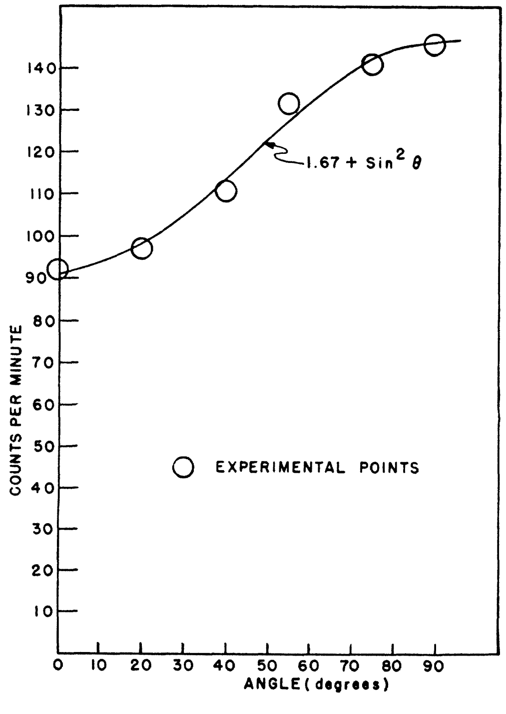

FIG. 2. The angular distribution of photo-neutrons from beryllium at 2.76 Mev.

C and W are only present to an appreciable extent when the Na^{24} source was used.

The counting rate, due to the room scattered neutrons, S, was determined by interposing a tapered lead plug 30-cm long between the target and detector. The plug prevented the detector from seeing any portion of the beryllium target.

The experimental procedure was to go through a cycle of four measurements at each angle. The natural background, b, was determined at the beginning and end of a run. The cycle was as follows:

I—Beryllium target present, no lead plug,
II—No target, no lead plug,
III—Beryllium target present, lead plug in,
IV—No target, lead plug in.

These four measurements are related to E, C, W, S, and b in the following way:

$$\begin{aligned} \mathrm{I} &= E+S+C+W+b, \\ \mathrm{II} &= C+W+b, \\ \mathrm{III} &= S+W+b, \\ \mathrm{IV} &= W+b. \end{aligned}$$

The effect we are interested in is $E=\mathrm{I}-\mathrm{II}-(\mathrm{III}-\mathrm{IV})$. When W and C are zero or negligible, only measurements I and III are necessary.

DATA

(1) Sb^{124} and Mn^{56} gamma-rays.

The angular distribution of the photo-neutrons was found to be spherically symmetrical within the limits of the experimental errors for both Sb^{124} and Mn^{56} gamma-rays.

(2) Na^{24} gamma-rays.

Table I gives the average of a set of cycles obtained with a source of Na^{24} gamma-rays. The last column gives the counting rate caused by the effect we are trying to study after all the backgrounds have been subtracted. (In this table an average of (III–IV) for all angles was used in calculating the last column, E.)

Figure 2 shows a least square fit of the data to a curve of the form $A+B\sin^2\theta$. There seems to be good correlation between the experimental data and the curve. If one accepts the conclusion that the angular distribution is of the above form, then the most important parameter that is desired is the ratio A/B. This ratio can be most readily obtained by obtaining good data at 0° and 90°. An average of three runs, each extending over periods greater than fifteen hours, gave $A/B=1.58$. This value is not the value for the actual distribution emitted by the beryllium nuclei; one must correct for two important effects.

CORRECTIONS

The observed angular distribution, $A+B\sin^2\theta$ requires correction for the following:

(1) The geometry employed, i.e., the finite size of the target, source, and detector result in a spread around the listed central angle.

(2) Neutron scattering effect, i.e., a small percentage of the neutrons undergo scattering in the beryllium target, and these neutrons are shifted from one angular range to some other before escaping from the beryllium.

The geometrical effect, (1), is comparatively small and can be estimated by numerical integration. It turns out that if the angular distribution of the neutrons leaving the beryllium target is of the form $a'+b'\sin^2\theta$, then with the geometry employed here, the distribution that will be observed is

$$A+B\sin^2\theta,$$

where $A=a'+0.034b'$ and $B=a'+0.99b'$.

The effect on the distribution of those neutrons that are scattered before leaving the target is more difficult to estimate. It tends to make the observed neutron distribution appear more spherically symmetric. The correction was estimated graphically for the targets employed here and has been roughly checked experimentally in the course of similar experiments on D_2O which are still incomplete.

If the probability distribution for the emission of the neutrons by a nucleus is of the form $a+b\sin^2\theta$ and due to the scattering within the target the neutrons leaving the beryllium target have a distribution of the form $a'+b'\sin^2\theta$, then the relationships between these quantities are

$$a'=1.02a+0.12b, \quad b'=0.90b,$$

for the targets employed in these experiments and for the neutrons from $Na^{24}+Be$.

Applying the above correction to the experimentally observed values of A/B, we obtain a corrected value of a/b of 1.22 for the $Na^{24}+Be$ source.

TABLE I. Average counting rate obtained from Na^{24} source.

	I	II	III	IV	E
Angle	Be target (counts/min.)	No target (counts/min.)	Be target and lead plug (counts/min.)	No target and lead plug (counts/min.)	Effect (counts/min.)
0°	213.5	98.6	36.1	11.4	91.6
20°	239.6	116.2	37.6	11.8	97.4
40°	266.4	129.7	36.9	9.7	110.7
55°	298.4	140.5	39.1	11.3	131.9
75°	322.4	154.6	42.6	18.8	141.1
90°	352.1	180.3	54.8	25.4	145.8

COMPARISON WITH THEORY

For the lower energy γ-rays an isotropic distribution is expected because of their proximity to the photodisintegration threshold.

The angular distribution can be calculated for the simple model discussed by Guth and Mullin.[4] The Be^9 is regarded as an inert Be^8 (2α-particle) core, with a "valence" neutron in the ground $P_{3/2}$ state. On this model, no magnetic dipole transitions are possible. Electric dipole transitions to S states will give a spherically symmetric distribution, while transitions to D states lead to a distribution of the form $a+b\sin^2\theta$, with $a/b=17/12\simeq 1.4$. The rise in total cross section is ascribed[4] to the $P-D$ transition; the residual effect of the transition to S states increases slightly the expected a/b value.

A splitting of the D levels will decrease the value of a/b for the $P-D$ transition. In this way Guth and Mullin[5] obtain a value that is in agreement with the value for Na^{24} γ-rays found in this experiment.

ACKNOWLEDGMENTS

It is a pleasure to acknowledge the valuable assistance of John Dalman in the construction of the equipment employed in this experiment and his help in obtaining the data. We also wish to thank Rena Levy for carrying out the numerical integration needed to determine the corrections.

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[4] E. Guth and C. J. Mullin, Phys. Rev. **74**, 833 (1948).

[5] E. Guth and C. J. Mullin, Phys. Rev. **76**, 682 (1949).