Photo-Neutron Sources and the Energy of the Photo-Neutrons*

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In a preliminary study photo-neutrons were observed to be produced by the γ-rays from Na^{24}, Mn^{56}, Ga^{72}, As^{76}, and La^{140} when these artificially radioactive isotopes were placed in D_2O or Be; F^{20}, Al^{28}, Cl^{38}, In^{116}, and Sb^{124} produced neutrons only in Be. The first group of isotopes must have γ-rays with energy higher than 2.18 Mev, and the second group must have γ-rays greater than 1.63 Mev but less than 2.18 Mev. No photo-neutrons were observed from Co^{60}, Cu^{64}, Ag (225 day $\frac{1}{2}$-life), Pr^{142}, Eu^{151}, Dy^{165}, Ta^{182}, Re^{188}, Ir (19 hours $\frac{1}{2}$-life), and Au^{198} in Be; the intense γ-rays from these isotopes must have energies less than 1.63 Mev. In a second experiment the energy of the photo-neutrons from nine of these sources was determined by measuring the hydrogen scattering cross section of the emitted neutrons. Seven of the sources seem to emit homogeneous groups of neutrons; they are: Sb+Be, Ga+D_2O, La+D_2O, Mn+D_2O, Na+D_2O, La+Be, and Na+Be with neutron energies 0.024, 0.13, 0.13, 0.22, 0.22, 0.62, and 0.83 Mev, respectively, for the particular sized sources studied. Mn+Be emits three groups of neutrons of different energies, but more than 80 percent of the neutrons seem to be in a group at 0.14 Mev. The energy of the γ-rays calculated to produce neutrons of these energies are: for Na^{24}, 2.74 Mev; for Mn^{56}, 1.81 and 2.7 Mev (a third γ-ray is present); for Ga^{72}, 2.50 Mev (at least one other γ-ray is present with an energy between 2.2 and 1.63 Mev); for Sb^{124}, 1.67 Mev; and for La^{140}, 2.49 Mev. The total neutron cross section of carbon is also given for seven of these photo-neutron sources.

INTRODUCTION

HIGH energy γ-rays falling on beryllium or deuterium will cause the emission of neutrons. The threshold for this (γ, n) reaction in beryllium is approximately 1.63 Mev[1–3] and in deuterium is approximately 2.18 Mev.[2–4] Gamma-rays from artificially radioactive sodium, antimony, and yttrium have been used previously to make photo-neutron sources.[5–9]

The heavy water "Pile" at the Argonne Laboratory[10] made available very intense radioactive sources produced by means of (n, γ) reactions. The γ-rays from these radioactive sources were used to produce photo-neutrons.

The photo-neutron sources are of value because γ-rays of a single energy produce a monoenergetic group of neutrons. The energy of the emitted neutrons is from the conservation of energy and momentum

$$E_n=\frac{A-1}{A}\left[E_\gamma-Q-\frac{E_\gamma{}^2}{1862(A-1)}\right]+\delta. \quad (1)$$

E_n is the energy of the neutrons in Mev; A is the atomic weight of the target nucleus; E_γ is the energy of the γ-ray in Mev; and Q is the threshold energy in Mev for the (γ, n) reaction in the nucleus of mass A. δ is a small spread in energy that is a function of the angle θ between the direction of the γ-ray and the direction in which the neutron is emitted.

$$\delta\cong E_\gamma\cos\theta\left(\frac{2(A-1)(E_\gamma-Q)}{931\times A^3}\right)^{\frac{1}{2}}. \quad (2)$$

Part I of this article deals with a preliminary study that was made to determine which of the radioactive elements emit γ-rays energetic enough to produce photo-neutrons in beryllium or deuterium. Part II deals with the determination

* Based on work performed under Contract W-741-eng-37 of the Manhattan District at the Argonne Laboratory, University of Chicago.
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[1] Collins, Waldman, and Guth, Phys. Rev. **56**, 878 (1939).
[2] F. E. Myers and L. C. Van Atta, Phys. Rev. **61**, 19 (1942).
[3] M. L. Wiedenbeck and C. J. Marhoef, Phys. Rev. **67**, 54 (1945).
[4] F. T. Rogers and M. M. Rogers, Phys. Rev. **55**, 263 (1939).
[5] W. E. Ogle and P. G. Kruger, Phys. Rev. **65**, 61 (1944).
[6] Goldhaber, Klaiber, and Scharff-Goldhaber, Phys. Rev. **65**, 61 (1944).
[7] G. S. Klaiber and G. Scharff-Goldhaber, Phys. Rev. **61**, 733 (1942).
[8] G. Scharff-Goldhaber, Phys. Rev. **59**, 937 (1941).
[9] G. R. Gamertsfelder, Phys. Rev. **63**, 60 (1943).
[10] H. D. Smyth, Rev. Mod. Phys. **17**, 419 (1945).

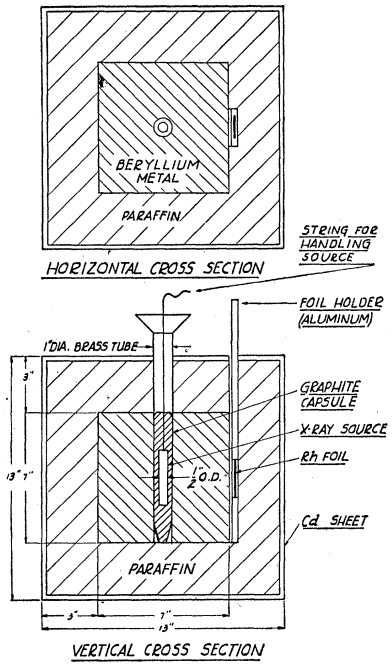

FIG. 1. Geometry used in preliminary study to find (γ, n) sources. For investigations with deuterium, a brass cylinder containing heavy water was substituted for the beryllium.

of the energy of the neutrons emitted by nine of these photo-neutron sources. The actual use of these sources in experiments will be reported in further articles.

I. PRELIMINARY STUDY

Seaborg's table[11] lists eight isotopes that emit γ-rays sufficiently energetic to produce neutrons in both deuterium and beryllium (i.e., the energy of the γ-ray is greater than 2.18 Mev). There are seven other isotopes that emit γ-rays which will produce neutrons only in beryllium (i.e., the energy of the γ-ray is greater than 1.63 Mev but less than 2.18 Mev). These artificially radioactive isotopes and the energy of their γ-rays as given by Seaborg are listed in Table I.

Method

All of the isotopes of Table I were activated except for those starred. The activity of the sources ranged from 100 to 5000 "millicuries."[12]

A test was made to observe whether neutrons were emitted when these sources were placed in beryllium or heavy water. The sources were set either at the center of a cubical box of beryllium containing 9.5 kilograms of beryllium metal or at the center of a cylinder containing 3.0 kilograms of heavy water. The beryllium and the heavy water were inclosed in paraffin (Fig. 1) in order to slow down the neutrons. A rhodium foil was placed as indicated to detect the neutrons. The activity of the rhodium foil was measured by placing it underneath an Eck and Krebs, glass wall, Geiger counter. An initial counting rate of more than 10,000 counts per minute was observed from the neutrons produced in beryllium by a 100 millicurie source of Na^{24}.

In order to be certain that the γ-ray producing the neutrons was associated with the activity of the isotope being studied and not to another isotope or to some impurity, the decay of the photo-neutrons was followed. All the half-lives observed were in reasonable agreement with those given in column 3 of Table II, which are from Seaborg's table.[11]

Results of Preliminary Study

The relative (neutron induced) activity observed from 100 millicuries of the different elements varied over a factor greater than 1000. The efficiency of the rhodium foil as a neutron detector in a geometrical arrangement of this kind undoubtedly varies with the initial energy of the photo-neutron, and the cross section for the (γ, n) reaction is a function of the energy of

TABLE I. Radioactive isotopes emitting high energy γ-rays, from Seaborg's table.

Isotopes with γ-rays above 2.18 Mev	Energy of γ-ray (in Mev)	Isotopes with γ-rays above 1.63 Mev	Energy of γ-ray (in Mev)
F^{20}	2.2	Al^{28}	1.8
Na^{24}	2.7	Sc^{44*}	1.8
Cl^{38}	2.2	Mn^{56}	2.13 and 1.8
Ga^{72}	2.65	Co^{56*}	1.74
As^{76}	3.2 and 2.2	Sb^{124}	1.75
Y^{88*}	2.8	La^{140}	1.75
In^{116}	2.3	Pr^{142}	1.9
An^{198}	2.5		

* These isotopes cannot be produced by an (n, γ) reaction.

[11] G. T. Seaborg, Rev. Mod. Phys. **16**, 1 (1944).

[12] By a "millicurie" of activity in an artificially radioactive source is meant an activity of 3.7×10^7 disintegrations per second. The activity is calculated using the values of the thermal neutron cross sections for the activation of the isotope in question and the value of the thermal neutron flux as measured by means of a small gold foil.

the γ-rays. These two undetermined factors prevent any accurate quantitative interpretation of the data. However, these two factors do not account for the observed factor of 1000 as the activities observed from the high energy Na+Be neutrons (see Table IV) and the low energy Sb+Be neutrons differed by less than a factor of two. Therefore, the large variation in the relative number of neutrons emitted by different sources must be attributed to the number of energetic γ-rays emitted per disintegration.

Table II gives the radioactive isotopes whose γ-rays were observed to produce neutrons. In order to give some idea of the relative number of neutrons emitted by various sources, the sources are divided into three classes (listed in the last column of Table II). An element in class *A*, as estimated by the relative number of neutrons emitted compared to the sodium sources, emits more than 0.1 useful γ-rays per disintegration; an element in class *B* emits 0.1 to 0.01 γ-rays per disintegration; and an element in class *C* emits less than 0.01 γ-rays per disintegration. Sodium is used as the standard as approximately one γ-ray of 2.8 Mev is emitted per disintegration.[13]

No neutrons were observed from Cl^{38}, In^{116}, or Au^{198} in heavy water. This indicates that if these isotopes emit γ-rays of energy greater than 2.18 Mev that such γ-rays have intensities less than 0.01 γ-ray per disintegration. No neutrons were observed from Pr^{142} or Au^{198} in beryllium indicating that the γ-rays from these elements of energy greater than 1.63 Mev have intensities less than 0.01 γ-ray per disintegration. It is of interest that Mn^{56} and La^{140} both produced neutrons in heavy water; therefore these two isotopes belong with those on the left-hand side of Table I.

Co^{60}, Cu^{64}, Ag (225 day $\frac{1}{2}$ life), Eu^{151}, Dy^{165}, Ta^{182}, Re^{188}, and Ir (19 hr. $\frac{1}{2}$ life) were activated in the hope that the γ-ray literature was incomplete with regard to these elements. However, no neutrons were observed when these sources were placed in beryllium.

This preliminary study showed that one can produce with the aid of a pile at least nine good (class *A*) photo-neutron sources. Those sources with half-lives shorter than one hour have not been found to be very useful.

[13] Elliott, Deutsch, and Roberts, Phys. Rev. **61**, 99 (1942); **63**, 386 (1943); **64**, 321 (1943).

TABLE II. Photo-neutron sources.

Radioactive isotope	Target	Half-life	Class
F^{20}	Be	12 sec.	*A*
Na^{24}	Be	14.8 hr.	*A*
Na^{24}	D_2O	14.8 hr.	*A*
Al^{28}	Be	2.4 min.	*A*
Cl^{38}	Be	37 min.	*A*
Mn^{56}	Be	2.59 hr.	*A*
Mn^{56}	D_2O	2.59 hr.	*C*
Ga^{72}	Be	14.1 hr.	*A*
Ga^{72}	D_2O	14.1 hr.	*A*
As^{76}	Be	26.8 hr.	*B*
As^{76}	D_2O	26.8 hr.	*C*
In^{116}	Be	54 min.	*B*
Sb^{124}	Be	60 days	*A*
La^{140}	Be	40 hr.	*B*
La^{140}	D_2O	40 hr.	*B*

II. ENERGY OF THE PHOTO-NEUTRONS

Method

The neutron scattering cross section of hydrogen (σ_H) varies with the energy of the neutrons (E_n). E. Fermi suggested that the energy of the neutrons emitted by the photo-neutron sources be determined by measuring σ_H and using the relationship between σ_H and E_n. In the experiments being described σ_H was determined by measuring the transmissions of the different photo-neutrons through thin pieces of paraffin.

All of the photo-neutron sources investigated emit neutrons with energies lying between 0.01 and 1.0 Mev. The theoretical formula for the curve of σ_H as a function of E_n is given by Kittel and Breit.[14] This curve, at energies less than 1 Mev, is caused by *S* scattering and depends mainly upon the value of σ_H at $E_n=0$, hereafter designated by $\sigma_H(0)$. Kittel and Breit used the value $\sigma_H(0)=14.5\times10^{-24}$ cm^2. It now seems that the best values of $\sigma_H(0)$, as obtained from conditions of good collimation, approach $21\pm1\times10^{-24}$ cm^2.[15–18] S. Dancoff has used Kittel and Breit's Eqs. (11) and (12)[14] and has calculated three curves of σ_H *versus* E_n for values of $\sigma_H(0)$ equal

[14] C. Kittel and G. Breit, Phys. Rev. **56**, 744 (1939).
[15] Cohen, Goldsmith, and Schwinger, Phys. Rev. **55**, 106 (1939).
[16] Cohen, Goldsmith, and Hanstein, Phys. Rev. **57**, 352 (1940).
[17] Hanstein, Phys. Rev. **59**, 489 (1941).
[18] H. Carroll, Phys. Rev. **60**, 702 (1941).

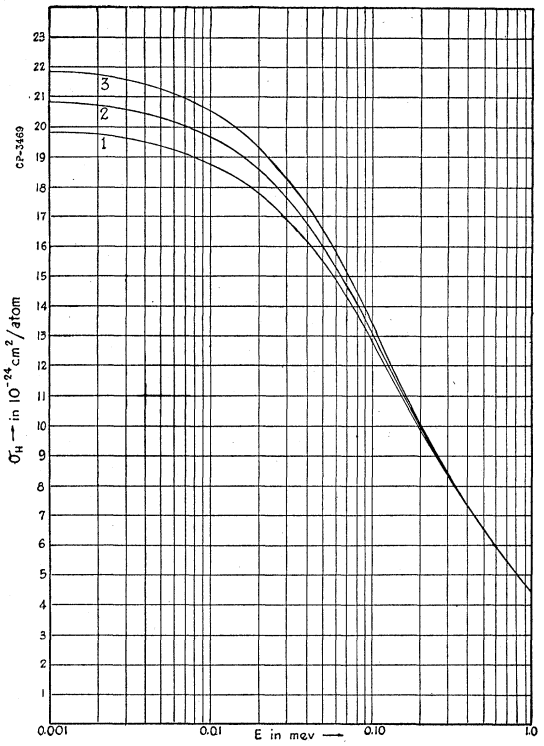

FIG. 2. Theoretical curves for the variation of hydrogen scattering cross section with the energy of the neutrons. Curves 1, 2, and 3 are for the assumed values of σ_H (at $E_n=0$) equal to 20, 21, and 22×10^{-24} cm^2, respectively.

to 20, 21, and 22×10^{-24} cm^2. These curves have been adjusted to join smoothly to a curve at higher energies that took into consideration the tensor forces.[19] Dancoff's curves are shown in Fig. 2.

In determining E_n for a measurement of σ_H, one introduces an uncertainty in E_n due to the uncertainty in the value of $\sigma_H(0)$. This uncertainty in E_n is greatest at low neutron energies (i.e., for $\sigma_H\sim20\times10^{-24}$ cm^2). However, for σ_H less than 12×10^{-24} cm^2, the uncertainty in E_n is less than 7 percent. This uncertainty is considered for each source separately in the sections of this article dealing with the individual sources.

Description of Photo-Neutron Sources

The γ-ray emitting elements were activated at the center of the heavy water pile. The activity of the sources ranged from 1 to 75 curies. The activity that could be induced in an isotope depended upon the thermal neutron activation cross section for that isotope.

In order to keep the sources as small as possible, metal castings of the element were used in every case except that of sodium. In this case fused NaF was used in order to get the highest density of sodium atoms; the fluorine half-life is so short that the fluorine activity caused no trouble.

The γ-ray sources, in the form of cylinders 1.25 cm in diameter and 5 cm long, were encased in graphite cylinders. A thin string or wire was attached to the graphite for handling the source. The graphite cylinder containing the source was pulled up into a thin walled brass tube on which was mounted a cylinder of beryllium metal (Fig. 3) or a brass container of D_2O. The cylinders of Be or D_2O were 0.79 cm thick and 5.08 long and weighed 69.7 g and 34.5 g, respectively.

Neutron Detector

The neutron detector used in these experiments consisted of a BF_3-filled ionization cham-

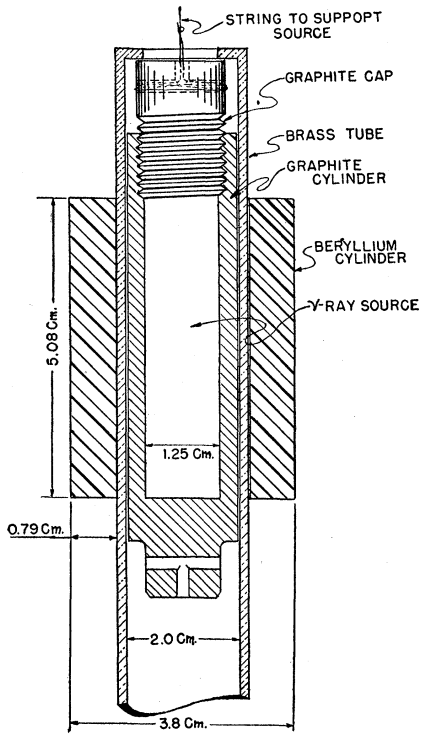

FIG. 3. Photo-neutron sources used in determining the energy of the emitted neutrons. For sources employing deuterium, an identically shaped thin walled brass cylinder of heavy water was substituted for the beryllium.

[19] Bohm and Richman (unpublished).

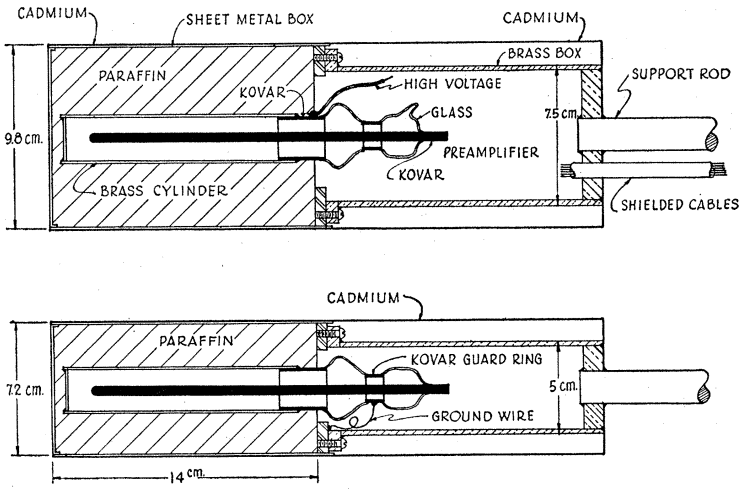

FIG. 4. Photo-neutron detector. The pulse ionization chamber was filled with BF_3 at a pressure of one atmosphere.

ber embedded in paraffin (Fig. 4). The paraffin increased the efficiency of the detector by slowing down the neutrons to a point at which the BF_3 has a high neutron absorption cross section. The electrical circuits were arranged to count the pulse produced when a neutron was absorbed and caused an (n, α) reaction in B^{10}.

The outer cylinder of the ionization chamber was made of brass and was 12.5 cm long and had a 2.5 cm I.D. The central electrode was a Kovar rod 0.50 cm O.D. At the back of the chamber the brass cylinder was insulated from the central rod by a Kovar-glass seal. In the middle of the Kovar-glass there was a grounded guard ring of Kovar metal. The chamber was filled with BF_3 to a pressure of one atmosphere. The paraffin block in which the chamber was embedded was 7.5 cm $\times$ 10 cm $\times$ 15 cm long. The paraffin was encased in a sheet metal box. The box was covered by a 0.5 mm thickness of cadmium in order to shield the detector from any slow neutrons that may have been present.

A preamplifier was attached directly to the back of the detector. A stabilized high voltage supply, a storage battery filament supply, an amplifier, an oscilloscope, and a counting unit (scale of 64) were connected to the preamplifier by shielded cables 20 feet long. These long cables permitted the person making measurements to be shielded from the γ-radiation of the sources by four feet of concrete.

It was found possible to make the scaler count only neutron pulses even when a 75-curie source was 50 cm from the face of the detector. Before making neutron measurements with any source, a test was run to make certain that no γ-rays would be counted.

Even though no counts were being produced by the γ-rays, it was feared that the presence of a large amount of ionization in the chamber due to the γ-rays might affect the counting of neutrons. To investigate this, a cylinder of lead was placed in front of the ionization chamber, and several neutron transmissions were measured. The average values of the transmissions with and without the lead were the same; this indicated that the γ-rays were not affecting the measurements of neutron transmissions.

The neutron counting rate of this detector varied slowly with changes in the high voltage; the counting rate increased by 15 percent in going from 600 to 1100 volts. The voltage normally used across the chamber was 700 volts.

Scatterers

Paraffin is supposed to be a mixture of straight-chain hydrocarbon compounds with formulas of the type C_nH_{2n+2}. The paraffin scatterers used in these transmission measurements were made from material that had a density of 0.901 at 20°C and a melting point of 56°C. For the purpose of calculations the paraffin was considered to have the formula $C_{24}H_{50}$.

In order to determine σ_H from measurements of the transmission of neutrons through paraffin, one must correct for the neutron scattering due

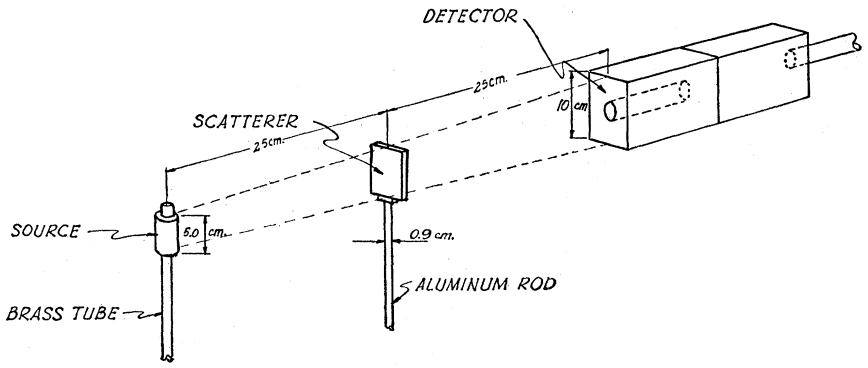

FIG. 5. Geometry used in measuring transmissions. Source and detector are detailed in Figs. 3 and 4, respectively.

to the carbon in the paraffin. To get this correction the transmission of pure carbon in the form of graphite had to be measured for each source of neutrons.

Paraffin and graphite scatterers 5.6 cm wide, 6.9 cm high, and of various thicknesses were prepared. Thin paraffin scatterers of a uniform thickness were produced by allowing molten paraffin to solidify on a water surface. The graphite and thicker paraffin scatterers were machined to size. Micrometer calipers were used to check that the thickness of a scatterer did not vary from point to point by more than 2 percent.

Geometrical Arrangement

In order to minimize the number of stray neutrons being scattered into the detector, the source and the detector were mounted two meters above the ground in the center of a large room. During the neutron measurements, nothing was near the source, the scatterer, or the detector except their means of support.

The source was supported on the brass tube shown in Fig. 3, and the brass tube was attached to a horizontal pipe 60 cm below the source. The iron rod sticking out the back of the detector (Fig. 4) was the only support for the detector. This rod was attached to a vertical pipe 60 cm behind the detector. The scatterers were supported on a small aluminum platform on top of a 1 cm aluminum rod. The platform was $1\times2\times0.2$ cm. The scatterers were held in position on the platform by two small pins that fitted into holes in the scatterers.

The source was 50 cm from the front face of the detector, and the scatterers were placed midway between the two. The scatterers completely blocked the detector's view of the source (Fig. 5). Every time a scatterer was mounted, this geometrical arrangement was checked by means of a straight edge. The center of the source and the axis of the ionization chamber were at the same height. In order to make sure that the face of a scatterer was perpendicular to this horizontal line of centers, the edges of the scatterer were brought into alignment with two vertical strings attached to plumb-bobs.

Measurements

The measurements of transmissions were made in cycles. A cycle consisted of:

1. A measurement without anything between the source and the detector (open beam reading).
2. A measurement with a paraffin or graphite scatterer.
3. A measurement with a lead plug between the source and the detector to determine the number of neutrons being scattered into the detector from the ground and walls (plug reading).
4. Another open beam reading.

These cycles were repeated several times. The natural background of the detector was measured at least every third cycle and was about one count per minute. The open beam readings ranged from 3000 to 50 counts per minute. Counts were taken for five minutes at the highest counting rates. The longest time interval used was 30 minutes, except when background or plug readings were being taken; the counting rates of the plug readings were about 10 percent of the open beam readings.

The lead plug was 30 cm long and was tapered in such a way that at any point along its length it had a cross-sectional area that would just prevent the detector from seeing the source.

The plug was mounted on the scatterer platform and aligned with a straight edge.

The natural background was subtracted from all readings first. As a check, the open beam readings from all the cycles were plotted on semi-log paper against time. The half-lives found from these graphs checked the values of Table II within our experimental accuracy.

Within each cycle all the readings were corrected for the decay of the source from the half-lives given in Table II. The two open beam readings were then averaged, and the observed transmissions (T_{obs}) were calculated from

$$T_{obs}=\frac{\text{Scatterer reading—plug reading}}{\text{Average open beam reading—plug reading}}.$$

The average values of T_{obs} and their standard errors are given in column 6 of Table III. The number of independent determinations used in calculating each average is given in column 5. The total number of counts taken with each scatterer is given in column 4. The standard errors (column 7) are listed in order to give an idea of the spread in the observed values of the transmissions.

Calculation of Hydrogen Cross Sections

Some of the neutrons that are scattered suffer only a small change in direction. Some of these (small scattering angle) neutrons will still hit the detector and be recorded as if they had not been scattered. A correction to the transmission for the neutrons scattered into the detector (scattering-in-effect) has been calculated. The

TABLE III. Observed transmissions and hydrogen cross sections.

Source	Scattering material	Scatterer g/cm²	Total counts	No. of independent determinations	Observed transmission	Standard error	Calculated transmission of hydrogen	Hydrogen cross section (in 10^{-24} cm²)
$Na^{24}+Be$	$C_{24}H_{50}$	0.654	40,000	6	0.710	0.007	0.743	5.1
	$C_{24}H_{50}$	.890	50,000	7	.639	.004	.679	4.9
	C	3.003	40,000	5	.653	.003		
$Na^{24}+D_2O$	$C_{24}H_{50}$	.258	61,000	9	.780	.004	.796	10.0
	$C_{24}H_{50}$	.449	84,000	10	.670	.005	.693	9.2
	$C_{24}H_{50}$	.654	33,000	7	.565	.005	.590	9.1
	C	1.513	54,000	7	.736	.003		
$Mn^{56}+Be$	$C_{24}H_{50}$	.258	56,000	5	.757	.004	.770	11.4
	$C_{24}H_{50}$	.421	114,000	13	.638	.004	.653	11.4
	$C_{24}H_{50}$	.449	67,000	5	.626	.004	.642	11.1
	$C_{24}H_{50}$	.654	53,000	5	.514	.005	.529	10.9
	$C_{24}H_{50}$	.890	52,000	5	.413	.003	.422	10.9
	C	1.513	100,000	22	.729	.004		
$Mn^{56}+D_2O$	$C_{24}H_{50}$	.449	12,000	7	.656	.007	.677	9.6
	C	1.513	1,200	2	.74			
$Ga^{72}+Be$	$C_{24}H_{50}$	.449	30,000	10	.686	.004	.708	8.7
	$C_{24}H_{50}$	.654	30,000	9	.566	.002	.587	9.1
	C	1.513	41,000	12	.750	.003		
$Ga^{72}+D_2O$	$C_{24}H_{50}$	.258	42,000	10	.750	.003	.762	11.9
	$C_{24}H_{50}$	.449	50,000	13	.605	.003	.617	12.0
	$C_{24}H_{50}$	.546	23,000	4	.553	.003	.565	11.8
	C	1.513	63,000	14	.731	.004		
$Sb^{124}+Be$	$C_{24}H_{50}$	.172	110,000	8	.757	.003	.758	18.1
	$C_{24}H_{50}$	.258	110,000	12	.659	.003	.659	18.2
	$C_{24}H_{50}$	.449	100,000	15	.503	.002	.497	17.5
	C	1.513	150,000	10	.710	.004		
	C	2.034	40,000	5	.640	.003		
$La^{140}+Be$	$C_{24}H_{50}$	.449	14,000	6	.769	.007	.799	5.6
	$C_{24}H_{50}$	.654	20,000	7	.664	.006	.699	6.1
	C	1.513	32,000	8	.779	.007		
$La^{140}+D_2O$	$C_{24}H_{50}$	.258	15,000	5	.752	.009	.766	11.7
	$C_{24}H_{50}$	.449	30,000	9	.606	.004	.618	12.0
	C	1.513	38,000	10	.732	.007		

assumption is made that the carbon scattering is spherically symmetrical in the laboratory system of coordinates. The transmission of carbon corrected for the scattering-in-effect is given by

$$(T_c)_{\text{corrected}}=\frac{(T_c)_{\text{obs}}-\epsilon_c}{1-\epsilon_c}.$$

ϵ_c is a function of the solid angles subtended by the graphite at the source, by the detector at the source, and by the detector at the graphite. ϵ_c for the standard geometry (Fig. 5) is 0.026.

The scattering-in-effect for paraffin is complicated by the presence of hydrogen and carbon nuclei in the same scatterer. Whereas the carbon scattering is assumed spherically symmetrical in the laboratory system, the hydrogen scattering is spherically symmetrical in the center of gravity system of the hydrogen nucleus and the neutron. With these assumptions it is found convenient to calculate directly the transmission of the hydrogen alone (T_H). The formula used is

$$T_H=\frac{(T_{Pf})_{\text{obs}}-\epsilon_{Pf}}{(1-\epsilon_{Pf})(T_c)^K_{\text{corrected}}}, \qquad (3)$$

where Pf is used to denote paraffin. The exponent K is needed to correct $(T_c)_{\text{obs}}$ for the ratio of carbon atoms present in the paraffin scatterer and the graphite scatterer. Using $C_{24}H_{50}$ for paraffin, we get

$$K=0.851\times\frac{\text{g/cm}^2\text{ of Pf scatterer}}{\text{g/cm}^2\text{ of C scatterer}}.$$

ϵ_{Pf} is a function of the same solid angles as ϵ_c and is also a slowly varying function of the ratio of σ_H and σ_c (the neutron scattering cross section for carbon). ϵ_{Pf} varies from 0.078 to 0.088 when the neutron energy varies from 0.80 to 0.02 Mev.

The values of T_H calculated from Eq. (3) are given in column 7 of Table III.

As a check on the correction for the scattering-in-effect, the area of a paraffin scatterer was doubled and the transmission measured. An appropriate ϵ_{Pf} was calculated for the larger scatterer and Eq. (3) was used. No significant difference in the value of T_H was observed.

Several measurements were made with the source and scatterer separated by distances appreciably different from the standard 50 cm (Fig. 5). The values of T_H found were independent of the distance between the source and the detector.

From the values of T_H and the thicknesses of the scatterers (Table III), σ_H has been calculated using

$$\sigma_H=\frac{11.25\times(-\ln T_H)}{\text{g/cm}^2\text{ of Pf scatterer}}.$$

These values of σ_H are listed in the last column of Table III.

Results

Some of the neutrons suffer collisions within the sources before they escape; these collisions slow down the neutrons. This effect broadens the energy distribution of the neutrons on the low energy side. S. Dancoff has estimated that, on the average, the neutrons are decreased in energy by 20 percent in sources of the size and shape shown in Fig. 3. The amount of broadening can be decreased by using smaller sources; however, there will always be a certain amount of spread in the energy distribution because of the angular dependence term, δ, in Eq. (1).

In passing through a piece of paraffin the neutrons of lower energy are more readily scattered than those of higher energy because of the inverse variation of σ_H with E_n. The mean energy of the transmitted neutrons will therefore be higher than that of the original distribution. This effect is referred to as "hardening." As greater thicknesses of paraffin are used, the amount of hardening increases. The values of σ_H found with the thicker paraffin scatterers should be lower than those found with the thinner scatterers. This manifestation of the hardening seems to be present in the value of σ_H listed in Table III. Unfortunately, the hardening cannot be studied quantitatively because of multiple scattering. The number of neutrons suffering two or more collisions within a scatterer increases with decreasing transmission. Equation (3) assumes single scattering, and it is not valid if there is appreciable multiple scattering. The effect of multiple scattering can probably be neglected for transmissions greater than 0.60.

Because of multiple scattering and hardening, only those cross sections obtained from transmissions greater than 0.60 are used in calculating

TABLE IV. Energy of neutrons and γ-rays.

Source	σ_H $\times(10^{-24}$ cm^2)	E_n (sources of Fig. 3) (Mev)	Av. E_n (sources of Fig. 3) (Mev)	Estimated E_n (very small source) (Mev)	Energy of γ-ray (Mev)
Na+Be	5.1	0.80	0.83	1.00	2.75
	4.9	0.86			
Na+D_2O	10.0	0.200	0.22	0.27	2.72
	9.2	0.245			
Mn+Be	11.4	0.145	(0.15)*	(0.18)	(1.83)
	11.4	0.145			
	11.1	0.157			
Mn+D_2O	9.6	0.220	0.22	0.26	2.7
Ga+Be	8.7	0.270	(0.27)	(0.32)	(1.99)
Ga+D_2O	11.9	0.130	0.13	0.16	2.50
	12.0	0.126			
Sb+Be	18.1	0.024	0.024	0.029	1.67
	18.2	0.024			
La+Be	5.6	0.066	0.62	0.75	2.47
	6.1	0.058			
La+D_2O	11.7	0.135	0.13	0.16	2.50
	12.0	0.126			

* Energies given in parentheses are not correct because of the presence of more than one γ-ray. (See section on these individual sources.)

the energy of the neutrons emitted by the sources. The values of E_n corresponding to the observed values of σ_H are given in column 3 of Table IV. Curve 2 of Fig. 2 (i.e., $\sigma_H(0)=21\times10^{-24}$ cm^2) has been used in calculating these values. The values in column 4 are the averages of the values in column 3. These two columns are characteristic only of the sources shown in Fig. 3. The estimated average energy of the neutrons which would be emitted by extremely small sources is given in column 5 of Table IV. These values are based upon Dancoff's estimate of a 20 percent average energy decrement.

Equation (1) (with $\delta=0$) has been used to calculate the energy of the γ-ray needed to produce the neutrons of the energy listed in column 5. It will be noticed that the γ-ray energies for Mn^{56} (column 6 of Table IV) obtained from Mn+Be and Mn+D_2O disagree. The same thing is true for Ga+Be and Ga+D_2O. These disagreements can be explained if more than one high energy γ-ray is emitted by Mn^{56} and Ga^{72}. If such is the case, then the Ga+Be and Mn+Be sources each emit at least two groups of neutrons of different energies.

Consideration of the Individual Sources

Na^{24}

Previous to these experiments measurements on Na^{24} indicated a single high energy γ-ray. The energy was given as 2.87 Mev by Goldhaber, Klaiber, and Scharff-Goldhaber,[20] as 2.76 Mev by Elliott, Deutsch, and Roberts[21] and as 2.94 by Mandeville.[22] Recently Ogle and Kruger[23] have reported four intense γ-rays of energy 2.56, 2.68, 2.76, and 2.89 Mev and a weak γ-ray of 3.24 Mev.

The γ-ray energy found in this experiment is 2.74 Mev (Table IV); the agreement with Elliott, Deutsch, and Roberts is good. It is possible that the amount of slowing down within the sources has been underestimated; however, this does not seem very likely as the Na+Be and Na+D_2O γ-ray values and the La+Be and La+D_2O γ-ray values agree fairly well.

Confirmative studies have been made by D. Hughes and C. Eggler with a cloud chamber.[24] The proton recoils produced by the neutrons from Na+Be and Na+D_2O were investigated. Only one energy group of neutrons was observed from each of these sources, and the average energies agreed with the values in column 4 (Table IV). The cloud-chamber studies showed that the Na+Be neutron had an energy distribution with a width of about 30 percent (at half maximum). The distribution from Na+D_2O had a width of about 25 percent.

The three curves of Fig. 2 do not visibly differ for the Na+Be source. For the Na+D_2O, the extreme values of E_n differ by about 0.012 Mev from the value of curve No. 2.

The counting rate observed from the Na+Be source was almost the same as that observed from the Na+D_2O source. Both are relatively efficient sources, apparently, of homogeneous neutrons.

Mn^{56}

The previous work on the Mn^{56} high energy γ-rays indicated two γ-rays of 1.81 and 2.13

[20] Goldhaber, Klaiber, and Scharff-Goldhaber, Phys. Rev. **65**, 61 (1944).
[21] Elliott, Deutsch, and Roberts, Phys. Rev. **63**, 386 (1943).
[22] C. E. Mandeville, Phys. Rev. **63**, 387 (1943).
[23] G. Kruger and W. E. Ogle, Phys. Rev. **67**, 273 (1945).
[24] D. Hughes (unpublished).

Mev.[25,26] From the energy of the Mn+D_2O neutrons observed in the present work, another γ-ray at roughly 2.7 Mev must exist. The counting rate from the Mn+D_2O source is only one twenty-fifth of that from the Mn+Be source. The 2.7 Mev γ-ray therefore must have a very low intensity.

Studies of the hardening of the neutrons from Mn+Be were made by employing thicker scatterers. It will be noticed (Table III) that no exceptional amount of hardening appeared. This led us to believe that the spectrum from Mn+Be might be composed of mainly one energy group of neutrons. A cloud chamber investigation was undertaken by D. Hughes and C. Eggler.[27] They found that the ratio of the number of neutrons from the 1.8 Mev and from the 2.1 Mev γ-ray was 10:1. Three energy groups of neutrons are emitted by the Mn+Be source, and probably more than 80 percent of the neutrons are in the lowest energy group.

Upon the assumption that 10 percent of the neutrons are in a 0.4 Mev group and 4 percent in a 0.8 Mev group, a calculation was made using $\sigma_H=11.3$ as the effective cross section for all the neutrons from Mn+Be. This leads to a value of 0.14 Mev for E_n for the main group of neutrons. The corresponding γ-ray energy is 1.82 Mev, which is in good agreement with the previous work.[25,26]

The counting rate per curie from the Mn+Be source is one-fourth of that from the Na+Be source. Very little work was done with the Mn+D_2O source because of its poor yield of neutrons.

Ga^{72}

A single high energy γ-ray of 2.65 Mev was reported by Mandeville for Ga^{72}.[28] The results listed in column 6 of Table IV can be explained if there are at least two high energy γ-rays from Ga^{72}. The counting rate observed from Ga+Be was slightly more than double that from Ga+D_2O. By comparison with the counting rates from the La and Na sources, the ratio for the Ga sources indicates γ-rays of approximately equal intensity lie above and below the deuterium threshold energy. That some γ-ray or γ-rays must be below the D threshold is substantiated by the value of the γ-ray energy calculated from the Ga+Be value of E_n. From these considerations and experiments to be reported elsewhere, it is believed that the neutrons emitted by Ga+D_2O are homogeneous. In this case the energy of the γ-ray is 2.5 Mev. The uncertainty in E_n due to the uncertainty in $\sigma_H(0)$ is about 0.010 Mev.

Ga+D_2O is only a moderately efficient source of neutrons; the counting rate per curie from the Ga+D_2O source is one-fourth of that from the Na+D_2O source.

Sb^{124}

The high energy γ-ray from Sb^{124} has been reported as 1.82 Mev[29] and 1.70 Mev.[23] The energy of the γ-ray as determined in this experiment is 1.67 Mev.

Klaiber and Scharff-Goldhaber[30] studied the neutrons emitted by an Sb+Be source. They measured the proton recoils and determined the energy of the neutrons to be 0.115 Mev. The energy of the neutrons found in this experiment (column 5, Table IV) is 0.029 Mev. If one uses curve 3 (i.e., assumes $\sigma_H(0)=22\times10^{-24}$ cm^2) of Fig. 2 instead of curve 2, the value of E_n would be 0.038 Mev. There is thus a serious disagreement between the value of E_n determined in this experiment and the value determined by Klaiber and Scharff-Goldhaber. The percentage spread in energy due to δ of Eq. (2) is greater in the Sb+Be source than in any other Be source employed. The extreme energy variation on either side of the mean is 0.0017 Mev (i.e., $\cos\theta=\pm1$ in Eq. (2)).

D. Hughes and C. Eggler recently studied the recoil protons from Sb+Be neutrons. The cloud chamber was operated at a low pressure.[31] Their results showed a single group of neutrons are emitted with an average energy of 0.035 ± 0.010 Mev, which is in agreement with the energy determined in this experiment.

[25] M. Deutsch and A. Roberts, Phys. Rev. **60**, 362 (1941).
[26] L. G. Elliott and M. Deutsch, Phys. Rev. **63**, 321 (1943).
[27] D. Hughes (unpublished).
[28] C. E. Mandeville, Phys. Rev. **64**, 147 (1943).
[29] Mitchell, Langer, and McDaniel, Phys. Rev. **57**, 1107 (1940).
[30] G. S. Klaiber and G. Scharff-Goldhaber, Phys. Rev. **61**, 733 (1942).
[31] D. Hughes (unpublished).

TABLE V. Energy of photo-neutrons and the total cross section of carbon.

Source	E_n of sources of this experiment	Cross section of carbon $\times 10^{24}$ cm^2
Sb+Be	0.024±0.015	4.55
Ga+D_2O	0.13 ±0.02	4.3
La+D_2O	0.13 ±0.03	4.3
Mn+Be	0.14 ±0.03*	4.3
Na+D_2O	0.22 ±0.02	4.1
La+Be	0.62 ±0.07	3.4
Na+Be	0.83 ±0.04	2.9

* There are also two less intense groups of neutrons emitted by this source.

The Sb+Be source is a very efficient one; the counting rates per curie observed from the Sb+Be and Na+Be sources were about the same.

La^{140}

All previous measurements of the La^{140} high energy γ-ray indicated an energy of about 2.0 Mev.[32,33] The value of the γ-ray obtained in this experiment is 2.49 Mev. The agreement between the γ-ray energy values obtained from the La+Be and La+D_2O sources indicate that there is only one high energy γ-ray emitted by La^{140}. Therefore, both of these sources emit homogeneous neutrons. The uncertainty in E_n due to the uncertainty in $\sigma_H(0)$ is negligible for the La+Be source. For the La+D_2O source it is about 0.010 Mev.

Unfortunately these sources are relatively inefficient ones. The counting rates per curie from the La+Be source and La+D_2O sources are about one-fiftieth of those observed from the Na+Be and Na+D_2O sources, respectively.

Summary

There are seven sources that probably emit homogeneous groups of neutrons; they are: Na+Be, Na+D_2O, Mn+D_2O, Ga+D_2O, Sb+Be, La+Be, and La+D_2O. Mn+Be emits three groups of neutrons of different energies, but more than 80 percent of the neutrons seem to be in the group at 0.14 Mev.

Table V lists the most useful sources in order of increasing neutron energy. Column 2 gives the values of E_n determined for the particular sized sources employed in this experiment. The author's estimate of the uncertainty in the value of E_n also is given. (In the case of Sb+Be this uncertainty is almost entirely caused by the uncertainty in $\sigma_H(0)$.) These particular sources probably all have energy distributions with widths (at half maxima) of at least 25 percent. From Table V it will be seen that there are sources of neutrons of five distinct energies between 0.024 and 0.83 Mev.

The total neutron cross section of carbon has been calculated for these energies from the data on the graphite scatterers (Table III). The values of σ_c are listed in Table V.

The data on the γ-rays (above 1.63 Mev) are summarized in Table VI.

TABLE VI. Energy of γ-rays.

Isotope	Energy of γ-ray (in Mev)	Remarks
Na^{24}	2.74±0.05*	A single γ-ray
Mn^{56}	1.81±0.05	There is a third γ-ray present;
	2.7 ±0.2	the 2.7 Mev γ-ray is weak
Ga^{72}	2.50±0.05	There are other γ-rays present with energies below 2.2 Mev
Sb^{124}	1.67±0.02	A single γ-ray
La^{140}	2.49±0.07	A single γ-ray of low intensity

* Author's estimate of the uncertainty.

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[32] Mounce, Pool, and Kurbatov, Phys. Rev. **61**, 389 (1942); **63**, 67 (1943).
[33] C. E. Mandeville, Phys. Rev. **63**, 387 (1943).