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A NEW TYPE OF NEUTRON SPECTROMETER†

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Neutrons are detected in a small $Li^6I(Eu)$ scintillator placed at the center of polyethylene moderating spheres with sizes ranging from 2 to 12 inches in diameter. The efficiency of this neutron counter has been experimentally determined using monoenergetic neutrons from thermal energies to 15 MeV. The counter has excellent energy sensitivity from 0.1 to 2 MeV and is particularly useful for determining the shapes of continuous neutron spectra. The pronounced difference in the efficiencies for the five sizes of spheres which have been calibrated provides a basis for accurate neutron energy determination. The good γ ray discrimination of the counter allows it to be used with a radium-beryllium neutron source. Neutron spectra from a variety of sources have been determined with this counter. These include the two groups of neutrons from the $C^{14}(p,n)N^{14}$ reaction, the evaporation spectrum of the neutrons from the reaction $Rh^{103}(p,n)Pd^{103}$, the energy spectra of inelastically scattered neutrons, and the neutron spectrum from the scattering of fast neutrons by the floor and walls of a building.

1. Design of Counter

Of the many types of neutron counters that have been developed, some can be used as neutron spectrometers[1,2,3]) over a limited range of neutron energies and others[4,5]) have a nearly constant efficiency as a function of neutron energy for fast neutrons. The counter described here can give information about the energy of neutrons over a wide range of energies. The energy sensitivity remains good below 0.5 MeV, which is near the lower limit for most neutron spectrometers. This counter has good γ ray discrimination, is simple in design and application, and has an efficiency of about 0.1%.

Neutrons are detected in a $Li^6I(Eu)$ scintillator after being moderated in polyethylene spheres of various sizes. Moderated neutrons are detected as scintillations resulting from the 4.787 MeV energy release in the $Li^6(n,\alpha)H^3$ reaction. The Li^6I crystal was made by the Harshaw Chemical Company from a sample containing 96.1% Li^6. It is hermetically sealed in an aluminum container with a plate glass window. Al_2O_3 is used as reflector on the walls of the container. Fig. 1 shows the construction of the counter; the scintillation crystal is 4 mm in diameter and 4 mm thick and is optically coupled to a DuMont 6292 photomultiplier by a polystyrene light pipe $\frac{1}{2}$ inch in diameter and 6 inches long. The crystal and light pipe are enclosed in a rigidly mounted brass tube which supports the moderating sphere. The counter has been calibrated with polyethylene spherical moderators with nominal diameters of 2, 3, 5, 8, and 12 inches. Each sphere has a $\frac{5}{8}$ inch hole for insertion of the light pipe, and is positioned so that the Li^6I crystal is at the center of the sphere.

The size and shape of the Li^6I crystal was chosen to provide good γ ray discrimination. About 80% of incident thermal neutrons are absorbed in 1.0 mm of Li^6I, so that thermal neutron detection is essentially a surface effect,

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† Supported in part by the U.S. Atomic Energy Commission.

1) J. L. Fowler and J. E. Brolley, Jr., Revs. Mod. Phys. **28** (1956) 103.

2) C. H. Johnson and C. C. Trail, Rev. Sci. Instr. **27** (1956) 468.

3) L. Cranberg and J. S. Levin, Phys. Rev. **100** (1955) 434.

4) W. D. Allen and R. L. Henkel, Progress in Nuclear Energy, Ser. I, Vol. II (Pergamon Press, New York, 1958); W. D. Allen and A. T. Ferguson, Proc. Phys. Soc. A **70** (1957) 639; W. D. Allen, Chapter in Fast Neutron Physics, Part I, edited by J. B. Marion and J. L. Fowler (Interscience Publishers, Inc., New York, 1960).

5) A. O. Hansen and J. L. McKibben, Phys. Rev. **72** (1947) 673.

whereas the efficiency for detection of γ radiation and fast neutrons is roughly proportional to the volume of the crystal. Consequently, a small (4 mm thick, and 4 mm in diameter) crystal, with large ratio of surface to volume, was used to minimize the proportion of counts not due to thermal neutrons. In addition to reducing the number of γ ray pulses, the small size of the crystal limits the maximum pulse size due to γ rays, and good γ discrimination is obtained. Pulse height spectra obtained with Pu-Be and Ra-Be neutron sources are shown in fig. 2. The pulse height spectrum obtained with the Pu-Be source, which has about 0.6 γ ray per neutron, shows only a well isolated neutron peak with a small low-energy tail. The Ra-Be source has about 30 000 γ rays per neutron which cause the rapid rise below the neutron peak in the pulse height spectrum of Ra-Be. Note that the Ra-Be source was enclosed in 1 inch of lead which attenuates the lower energy γ rays by a considerable amount. Since slow neutrons are predominately counted, the pulse height spectrum is independent of the energy of the incident neutrons. The pulse height spectrum is displayed on a multi-channel analyzer and only pulses greater than the discrimination level indicated by an arrow in fig. 2 are accepted. Proper adjustment of the bias on an integral discriminator would accomplish the same result.

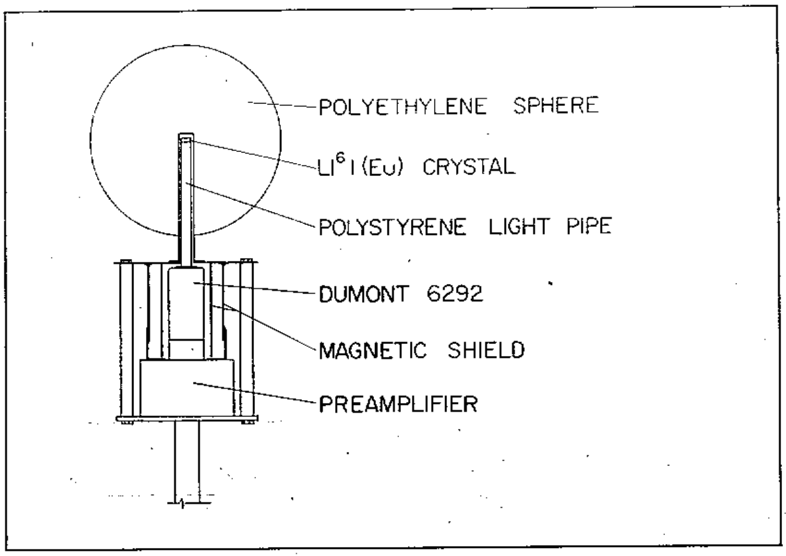

Fig. 1. Schematic drawing of neutron counter.

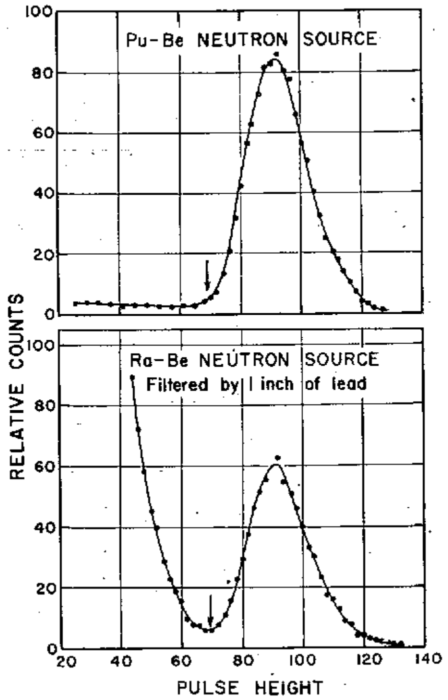

Fig. 2. Pulse spectra obtained with 8 inch counter showing the effect of a large number of γ rays.

2. Calibration of Spectrometer

The counter was calibrated as a function of neutron energy from 0.050 to 15.1 MeV using monoenergetic neutrons from charged particle reactions. The center of the spherical counter was placed at either 20, 40, or 100 cm from the center of the neutron source. Five sizes of spheres were calibrated at each energy. A long counter[4,5]), placed 100 cm from the source at the same angle with the beam of charged particles as the spherical counter, was used to monitor the neutron flux. The spherical counter was removed during the long counter measurements.

The $Li^7(p,n)Be^7$ reaction was used to obtain neutrons in the energy range 0.050 MeV to 0.600 MeV, the $H^3(p,n)He^3$ reaction between 1.0 and 4.0 MeV, and $H^2(d,n)He^3$ reaction for 4.5 to 7.5 MeV neutrons. The $H^3(d,n)He^4$ reaction was used for a source of 15.1 MeV neutrons†. The lithium targets were Li metal evaporated on 0.020 inch tantalum blanks and had a thickness such that protons with an energy of 1.9 MeV lost approximately 0.010 MeV in the target. The $Li^7(p,n)$ threshold was used to calibrate the nuclear magnetic resonance magnetometer used to determine the energy of the bombarding particles. For neutrons of energy less than 0.16 MeV, the counters were moved to 60° with respect to the incident beam of protons.

Gas targets were used for the $H^3(p,n)He^3$ and $H^2(d,n)He^3$ reactions. A small gas target chamber to contain H^3 and H^2 gas was made from a thin walled platinum tube 1.6 cm long and 1 cm in diameter. Fifty curies of tritium gas were stored in an uranium metal trap[6]) which could be heated to about 500°C to evolve tritium gas into the target chamber to a pressure of 1 atmosphere. The energy loss of protons in the tritium gas ranged from 0.04 MeV at $E_p = 4.8$ MeV to 0.06 MeV at $E_p = 1.9$ MeV. The proton beam entered the target chamber through a 2.4 mg/cm² aluminum foil, in which the proton energy loss ranged between 0.15 MeV at $E_p = 4.8$ MeV and 0.26 MeV at $E_p = 1.9$ MeV. When using the $H^2(d,n)He^3$ reaction, the deuteron beam passed through a 2.4 mg/cm² nickel foil into the gas chamber. The energy loss of the deuterons in the foil and in the deuterium gas at a pressure of 1.5 atmospheres was respectively 0.20 and 0.07 MeV at $E_d = 4.04$ MeV, and 0.28 and 0.13 MeV at $E_d = 2.17$ MeV. When using the $H^2(d,n)He^3$ reaction, runs were taken with no gas in the target to determine the background due to other sources of neutrons.

The principle quantity of interest in the calibration of the spherical counter is the counting rate, as a function of neutron energy, from an isotropic point source of constant source strength. In order to obtain this quantity from the experimental data, small corrections must be applied to account for (1) the unequal illumination of different parts of the counter by the neutron source, (2) the background due to scattering of source neutrons in the walls of the room, and (3) the variation in the long counter efficiency. None of these corrections was larger than 16%. Since the neutron energy depends on its angle of emission, there is a spread in energy over the surface of the sphere; thus, the effective neutron energy depends on the sphere size and the distance from the source. The effective neutron energy differed by less than 1% from the energy at the center of the counter.

The illumination correction, due to the angular distribution of neutrons from the source, was obtained by integration of the source reaction cross section over the surface of the sphere. The angular distributions for the source reactions were taken from published data[1,7,8]). Ordinarily, the distance from the center of the counter to the source was 20 cm for the 2 and 3 inch counters and 40 cm for the 5, 8, and 12 inch counters. When using the $H^2(d,n)He^3$ neutron source, which has a strongly peaked angular distribution, data was obtained with the 8 and 12 inch counters at 100 cm in order to obtain more nearly uniform illumination. The corrections for

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† The authors wish to thank Texas Nuclear Corporation for the use of their Van de Graaff accelerator and associated particle neutron monitor for the 15 MeV calibration data.

[6]) A. B. Lillie and J. P. Conner, Rev. Sci. Instr. **22** (1951) 210.

[7]) R. Taschek and A. Hemmendinger, Phys. Rev. **74** (1948) 373.

[8]) Gabbard, Davis and Bonner, Phys. Rev. **114** (1959) 201.

Table 1
The four largest illumination corrections

Source reaction	Neutron energy (MeV)	Counter diameter (inches)	Distance from source (cm)	Illumination ratio†	Illumination correction factor
$H^2(d,n)He^3$	4.5	12	100	1.11	1.06
$H^2(d,n)He^3$	4.5	3	20	1.13	1.08
$H^2(d,n)He^3$	7.5	12	100	1.22	1.10
$H^2(d,n)He^3$	7.5	3	20	1.31	1.16

† Ratio of illumination at center of detector to that at the edge.

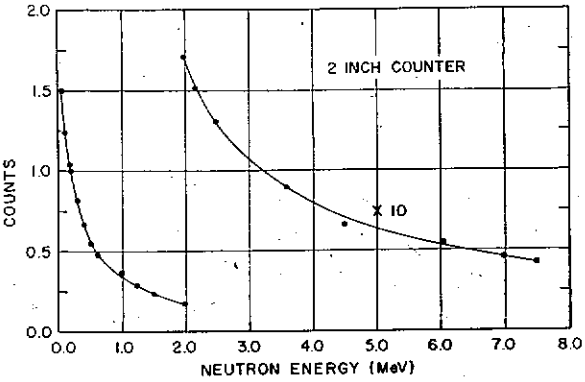

Fig. 3. Results with a 2 inch counter giving the counts per 10^6 neutrons emitted from an isotropic point source 40 cm away.

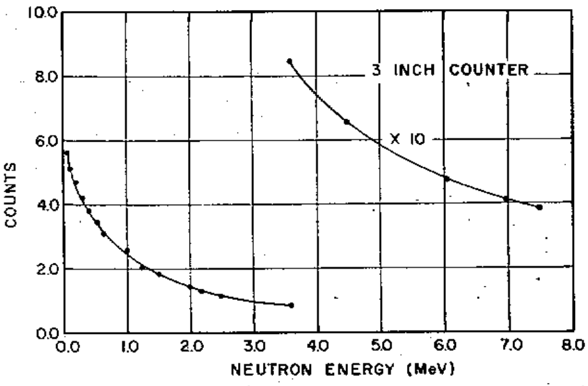

Fig. 4. Results with a 3 inch counter giving the counts per 10^6 neutrons emitted from an isotropic point source 40 cm away.

the large counters at this distance were less than 10%. The corrected count rates at 40 cm were compared to the corrected count rates at 100 cm to check the accuracy of the illumination correction. It was found that, if the correction at 40 cm was less than 20%, the corrected count-rates agreed to 1%. Four of the largest illumination corrections are summarized in table 1. The ratio of the illumination at the center of the detector to that at the edge is given for each case.

The background due to scattering of source neutrons in the walls surrounding the target was investigated in detail. The closest scattering material was the floor, which was 12 feet from the target. The background was assumed to be constant within 100 cm from the target, and was determined by the variation of the counting rate as a function of distance from the target. The contribution of background neutrons was a negligible fraction of the total counts for the 5, 8, and 12 inch counters. The background ranged from 1.5% to 15% for the 2 inch counter, and from 0.7% to 6% for the 3 inch counter; the larger backgrounds were obtained at the higher neutron energies.

A long counter was used in conjunction with the known energy variation of the source reaction cross sections to determine the relative source strength of the calibration reactions. The relative long counter efficiency as a function of energy was taken from Allen *et al.*[4]). This relative long counter efficiency was experimentally compared with the variation in the $H^2(d,n)He^3$ cross section from 4.5 to 7.5 MeV. The relative efficiency and cross section agreed to ± 3%. The error in the relative long counter efficiency in the energy range from 0.1 MeV to 7 MeV is estimated to be ± 4%. The absolute long counter efficiency to ± 5%, was obtained using a calibrated Pu-Be source.

In addition to measurements of the sphere counting rates using neutrons from charged particle reactions, the count rates were measured

Illumination correction factor
1.06
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using thermal neutrons from the graphite column of the Rice Aerojet General 211 reactor. Data taken with the fast chopper at the Materials Testing Reactor† determined the shape of the counting rate curves of the 2 and 3 inch counters in the energy region around 300 eV. This data was very useful when estimating the low energy behavior of the counting rates.

The counting rate due to an isotropic source 40 cm from the center of the spherical counter is shown as a function of the energy of the incident neutrons in fig. 3 through 8. Above 50 keV, the counting rates of the 2 and 3 inch diameter counters decrease rapidly as the energy of the neutrons is increased. The counting rates of the larger counters first increase. reach a maximum, and then decrease. The reduced counting rate of the large spheres at low neutron energies is due to capture of thermalized neutrons in the hydrogen of the moderator. Low energy neutrons, requiring relatively few collisions to be thermalized, are thermalized near the surface of the spherical moderator. Consequently, in the larger spheres, the neutrons must traverse a longer path after thermalization, and they are more likely to be captured before reaching the Li^6I crystal. The complicated structure in the curves shown in figs. 6, 7, and 8 for the 8 inch and 12 inch counters in the neutron energy range 3 to 4 MeV is due to resonances in the elastic scattering cross section of carbon. Similar structure has been observed for a long counter[4]).

An estimate of the counting rates between the experimentally determined values at 0.025 eV and 50 keV is given (dashed curve) in fig. 8. The counting rate of the 3 inch counter attains its maximum at about 300 eV neutron energy, but the absolute efficiency was not determined at this energy. The curve for the 2 inch counter attains its maximum somewhat above thermal energy; this follows from the fact that the bare Li^6I crystal gives 30% more counts in an isotropic flux of thermal neutrons than with the 2 inch polyethylene sphere surrounding it.

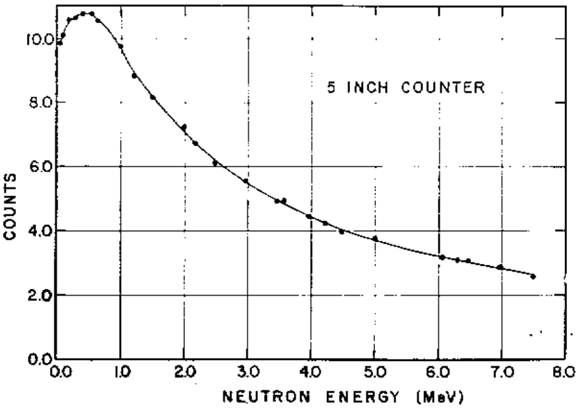

Fig. 5. Results with a 5 inch counter giving the counts per 10^6 neutrons emitted from an isotropic point source 40 cm away.

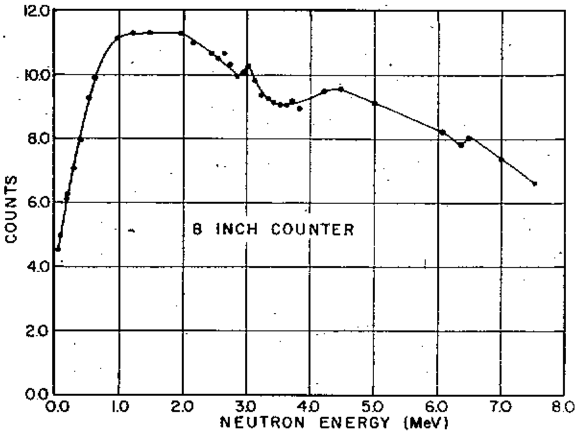

Fig. 6. Results with an 8 inch counter giving the counts per 10^6 neutrons emitted from an isotropic point source 40 cm away.

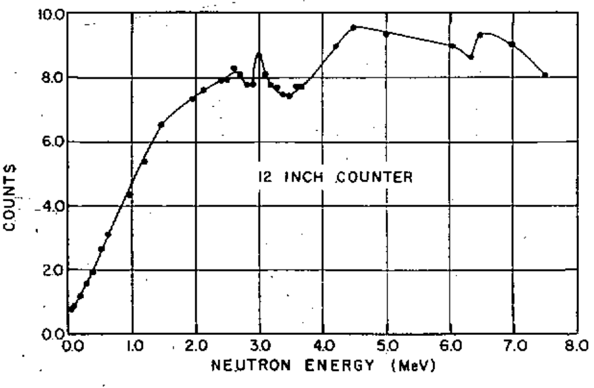

Fig. 7. Results with a 12 inch counter giving the counts per 10^6 neutrons emitted from an isotropic point source 40 cm away.

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† The authors wish to thank the Atomic Energy Division of Phillips Petroleum Company for the use of the fast chopper.

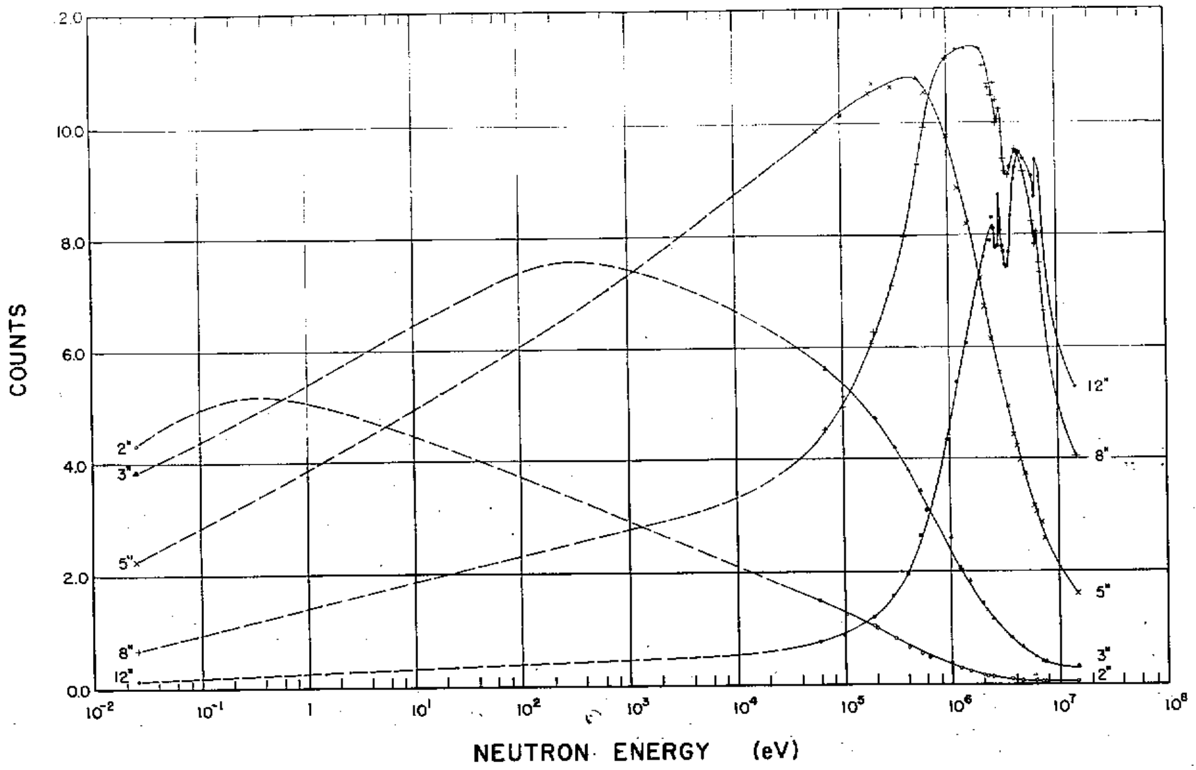

Fig. 8. Results with all counters giving the counts per 10^6 neutrons emitted from an isotropic point source 40 cm away.

Table 2
Maxima of the counting rate curves

Counter diameter (inches)	Position of maximum (eV)	Counts per 10^6 neutrons†	Absolute efficiency†† in per cent
2	0.3	5	0.5
3	3.0×10^2	8	0.3
5	4.5×10^5	10.8	0.172
8	1.7×10^6	11.3	0.069
12	5.0×10^6	9.4	0.025

† Counts per 10^6 neutrons emitted from an isotropic source 40 cm away.

†† The percentage of the neutrons which strike the surface of the counter which result in a count.

Table 2 gives the maximum of the counting rate curve for each sphere and the position of the maximum. For comparison, the counting rate per 10^6 neutrons emitted from a source 40 cm from the paraffin face of the long counter used at Rice is about 160. The BF_3 tube used in the Rice long counter is 1 inch in diameter, 34 cm long, and contains 96% $B^{10}F_3$ at 40 cm Hg pressure.

The errors in the counting rate curves between 0.050 and 7.5 MeV are of two types: absolute error due to uncertainty in the absolute calibration of the long counter (± 5%), and relative errors, which include all other than absolute errors. On a relative basis, the principle source of uncertainty is the long counter efficiency as a function of energy (± 4%). The statistical counting error was about 1% for all cases. Error in both the illumination and background corrections is estimated to be ± 1% for all except the 2 inch counter, for which the illumination correction error is negligible and the background correction error is estimated to be ± 2%. Consequently, the relative error of each curve is estimated to be less than ± 6%. At any incident neutron energy the ratios of the counting rates of the various counters was reproducible to ± 3%. The error of the data points at 0.025 eV and 15 MeV is estimated to be ± 10%.

The ratios of the counting rates of spherical

TABLE 3
Counter sensitivity

Neutron energy (MeV)	Percent change in counter ratio corresponding to 1% increase in neutron energy					
	12" & 5" counters	12" & 3" counters	12" & 3" counters	8" & 3" counters	8" & 2" counters	5" & 2" counters
0.10	0.29	0.46	0.56	0.36	0.46	0.27
0.50	0.88	1.23	1.56	0.84	1.16	0.67
1.00	1.26	1.58	1.79	0.71	0.93	0.53
2.00	1.01	1.30	1.58	0.79	1.06	0.57
5.00	0.53	0.68	0.83	0.42	0.57	0.30

counters of different size are sensitive functions of the neutron energy. The percentage change in the ratio of counts of several pairs of counters corresponding to a 1% change in neutron energy is shown in table 3. The counting ratio most sensitive to a change in neutron energy is that of the 12 inch to the 2 inch counter. The range of maximum sensitivity of the counting ratios for all the pairs of counters in table 3 is from 0.5 to 2 MeV.

TABLE 4
Counting rate for Pu-Be source
(1.34 ± 0.05) × 10^6 neutrons/sec.
Nearest scattering material 12 feet away

Nominal counter diameter (inches)	Measured counter diameter† (inches)	Distance from counter to source (cm)	Counting rate (counts/sec)
bare		6.69	2.03
2	1.992	6.69	10.07
3	3.00	10.07	27.4
5	4.98	16.71	40.9
8	7.98	26.78	25.3
12	11.91††	40.00	9.15

† The density of the polyethylene used was 0.924 g/cm³.

†† The 12 inch counter was flattened on the bottom surface to facilitate mounting. The effective diameter given here compensates for the flattening.

For the convenience of those who might like to check the calibration of a similar set of counters, the counting rate of each counter at a specified distance from the center of a Pu-Be source is given in table 4. The distances were such that each sphere subtended the same solid angle from the source. The source strength was (1.34 ± 0.05) × 10^6 neutrons per second. The measured diameters of the polyethylene spheres are also given in table 4.

A quantity of incidental interest is the absorption of thermal neutrons by the spherical polyethylene moderators. The counting rate for thermal neutrons is given as a function of the diameter of the counter in fig. 9. About 30% of the incident thermal neutrons are absorbed before detection in the 2 inch diameter counter; whereas the 12 inch polyethylene sphere absorbs about 98% of the incident thermal neutrons.

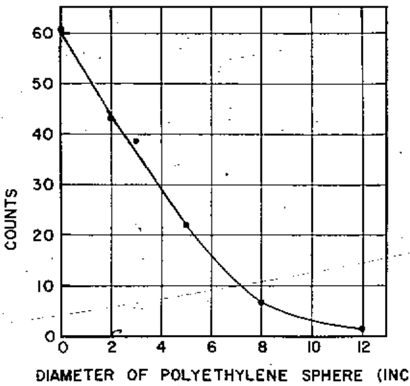

Fig. 9. Relative counting rates of the 2, 3, 5, 8, and 12 inch counters in a thermal neutron flux, showing absorption of the thermal neutrons.

Experiments to determine the energy distribution of neutrons from isotropic sources should be carried out with the source to detector distance as small as possible to reduce background effects and increase the counting rate; but errors are introduced in applying the curves of fig. 3 through 8 if the solid angle subtended by the counter is too large. An experiment was performed using a Pu-Be source to determine the maximum solid angle that can be used without introducing error. The counting rate of the 12 inch counter was determined as a function of the distance to the source. It was found that the counting rate, after taking into account a background of 6% at 1 m, was proportional (± 1%) to the total solid angle subtended by the 12 inch sphere, for distances greater than 40 cm. At a distance of 25 cm between the source and the center of the polyethylene sphere, the counting rate divided by the solid angle was 2.5% lower than at 40 cm, and at 20 cm the counting rate divided by the solid angle was 14% lower than at 40 cm. Hence, the 12 inch counter could be used at 30 cm without introducing an error greater than 1%. This distance corresponds to a half angle of 30°.

3. Application to Experiments

As a simple example of the use of the spherical counter, consider the case of two monoenergetic groups of neutrons of known energy but unknown intensities. For example, this situation occurs in neutron producing reactions where the emergent neutron can leave the residual nucleus in either its ground state or its first excited state. If the neutron groups have known energies, the relative intensities of the two groups can be determined from the counting rates in two different size counters. For example, if the two neutron energies are 0.5 and 4.0 MeV and the groups are of about equal intensity, then a 1% change in the ratio of the counting rates corresponds to a 1% change in the relative intensity.

The above method can be extended to determine the parameters of a continuous spectrum for which there is a theoretical or empirical form. If an assumed energy spectrum is multiplied by each of the counting rate curves of fig. 3 through 7 and the products are integrated over the energy range of interest, the result is a set of count rates for the particular spectrum that is assumed. If this procedure is carried out for several values of the parameters of the theoretical distribution, the parameters best fitting the observed counting ratios can be determined. A given spectrum fits the data if the calculated counting ratios fall within the experimental error for each independent sphere ratio. The best fitting spectrum is the one with the least root-mean-square deviation of the calculated ratios from the experimental ratios.

3.1. NEUTRONS RESULTING FROM PROTON BOMBARDMENT OF C^{14}

Neutrons produced in the reaction $C^{14}(p,n)N^{14}$ have been studied9) over the range of proton bombarding energies from 2.8 to 5.5 MeV using the polyethylene moderated neutron detector. Protons from the Rice 5.5 MeV van de Graaff accelerator were used to bombard a carbon target which was isotopically enriched to 25% C^{14}. The yield of monoenergetic neutrons was measured, using the 8 inch counter, from 2.8 MeV to the threshold for the second group of neutrons at 3.1 MeV. Between the neutron thresholds at 3.1 and 4.9 MeV, two monoenergetic groups of neutrons are energetically possible. The intensities of these two groups of neutrons were determined at 0° and 90° to the beam of protons from 3.4 to 4.9 MeV. For this purpose, the counting rate of the 8 inch counter at 20 cm from the target was obtained from 3.1 to 4.9 MeV. After removing the 8 inch counter, the 3 inch counter was positioned to subtend the same solid angle as the 8 inch at 20 cm, and the 3 inch counting rate was obtained. By using the same solid angle for each counter, effects due to rapid changes in the neutron angular distributions are eliminated. Analysis of the counting rates obtained using the known efficiencies of each counter shows that the ratio of the number of neutrons from the high energy group to the number of lower energy neutrons varies from 8.3 on the resonance at 3.40 MeV to 0.28 in a region where there were no resolved resonances.

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9) Hanna, Bonner, Bramblett and St. Romain, to be published.

Above the threshold for the third group of neutrons, three counters were used to determine the intensities of the three groups of neutrons.

3.2. THE CONTINUOUS SPECTRUM OF NEUTRONS FROM $Rh^{103}(p,n)Pd^{103}$

The spectrum of neutrons resulting from bombardment of several intermediate weight nuclei with 5.30 MeV protons was investigated[10]). The counting rates of the 2, 3, 5, 8, and 12 inch diameter counters were obtained. Table 5 shows the fit of the neutron spectrum from $Rh^{103}(p,n)Pd^{103}$ with two energy distributions having one unknown parameter: the evaporation spectrum, $E \exp(-E/\tau)$; and the Maxwellian distribution, $E^{\frac{1}{2}} \exp(-E/\theta)$. If the neutron spectrum is assumed to be of the evaporation form, the parameter, τ, can be determined from the ratio of the counting rates of two counters. Since five sizes of counters were used, there are four independent determinations of τ. If these independent determinations agree, the algebraic form assumed is correct. If they do not, another form must be chosen. The first column of table 5 shows the ratio under consideration, the second column gives the value of τ determined by the ratio. The average value of τ is 0.568 MeV and the largest deviation is 0.009 MeV, which is less than the estimated experimental error of about 0.014 MeV. It is concluded that the spectrum of neutrons from $Rh^{103}(p,n)$ fits the evaporation spectrum.

TABLE 5

Values of parameters required to fit experimental neutron spectrum from $Rh^{103}(p,n)$

Counters used	Assumed spectrum	
	Evaporation $Ee^{-E/\tau}\tau$ (MeV)	Maxwellian $\sqrt{E}e^{-E/\theta}$ θ(MeV)
12″ and 8″	0.582	0.792
12″ and 5″	0.592	0.844
12″ and 3″	0.581	0.856
12″ and 2″	0.591	0.912
8″ and 3″	0.577	0.908
8″ and 2″	0.593	0.983
5″ and 2″	0.587	1.042
Average	0.586	0.905

Another form that might fit the neutron spectrum is the Maxwellian distribution, with parameter θ. The attempt to fit this spectrum is shown in the third column of table 5. This spectrum does not fit the experimental data. The values of θ determined by the ratios differ by as much as 0.14 MeV from the average of 0.90 MeV. The expected experimental error in this case is about 0.03 MeV. The ratios are listed in a meaningful order, starting with ratios of large counters at the top and ending with small counters at the bottom. When arranged in this order, a misfit to the neutron spectrum results in a trend in the values of the parameters indicated by the ratios. The trend for the Maxwellian form is apparent. Even though there are only four independent ratios, the use of more than four ratios in this manner makes the analysis easier. The evaporation and Maxwellian spectra are very similar distributions, and the differentiation between these two types by the spectrometer shows its inherent sensitivity.

3.3. ENERGY SPECTRA OF INELASTICALLY SCATTERED NEUTRONS

The energy spectra of neutrons inelastically scattered from Fe, Cd, Sn, Ta, and W have been investigated with the neutron spectrometer. Monoenergetic neutrons with energies of 1.00, 2.44, and 5.0 MeV were obtained with the Van de Graaff accelerator. These neutrons were scattered from samples which were placed at 0° to the bombarding beam. The dimensions of the scatterers were $1\frac{1}{2} \times 2\frac{3}{8} \times 2\frac{3}{8}$ inches. The neutron spectrometer was placed so that it counted neutrons which were scattered through an angle of 90° by the sample. The counter was shielded from the neutrons that came directly from the target. The number of counts due to neutrons scattered from the sample is equal to the difference of the counts with the scatterer in place and removed. Counts with the scatterer removed amounted to 35% to 60% of the number with a

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[10]) Richard L. Bramblett and T. W. Bonner, Nuclear Physics **20** (1960) 395.

TABLE 6
Data on the energies of inelastically scattered neutrons

Spherical counters	Energy of bombarding neutrons in MeV								
	1.00			2.44			5.0		
	8/3	5/3	8/5	8/3	5/3	8/5	8/3	5/3	8/5
Fe ratio †	2.6	2.9	0.91	5.6	4.2	1.32	4.9	3.9	1.28
E_i ††	0.14	0.13	0.15	—	—	—	1.26	0.99	1.15
T †††	—	—	—	—	—	—	0.99	0.85	0.82
Cd ratio	3.2	3.3	0.98	3.6	3.3	1.09	4.1	3.5	1.17
E_i	0.33	0.32	0.35	0.63	0.56	0.70	0.85	0.77	0.92
T	0.18	0.26	0.15	0.43	0.42	0.43	0.61	0.62	0.60
Sn ratio	4.3	4.1	1.05	4.1	3.5	1.18	4.2	3.6	1.15
E_i	—	—	—	0.69	0.60	0.80	0.86	0.84	0.90
T	—	—	—	0.48	0.45	0.52	0.62	0.69	0.58
Ta ratio	2.6	3.0	0.87	3.0	3.1	0.97	3.5	3.3	1.05
E_i	0.31	0.31	0.31	0.52	0.49	0.55	0.67	0.65	0.70
T	0.15	0.22	0.13	0.33	0.36	0.32	0.45	0.50	0.42
W ratio	3.2	3.2	1.02	3.3	3.2	1.02	3.02	3.4	1.10
E_i	0.57	0.44	0.70	0.53	0.49	0.57	0.74	0.70	0.78
T	0.38	0.33	0.42	0.33	0.36	0.33	0.51	0.55	0.48

† The ratios listed are the experimental ratios of the counting rates in the 8, 5, and 3 inch spherical counters due to both elastically-scattered and inelastically-scattered neutrons. The statistical probable errors in the ratios ar 10%, 8% and 6% on the 1.00, 2.44, and 5.0 MeV data respectively.

†† E_i is the indicated energy of the inelastically scattered neutrons in MeV.

††† T is the evaporation temperature in MeV.

scatterer in place. Data were obtained with spherical counters with diameters of 8 inches, 5 inches, and 3 inches.

Since the sample scatters neutrons into the detector by both elastic and inelastic processes, analysis was necessary to separate the counts due to the two processes. The energy of the elastically scattered neutrons is known and the cross sections for elastic scattering at 90° and for inelastic scattering are also known. The indicated energy, E_1, of the inelastically scattered neutrons was obtained for each of the counting rate ratios: 8 to 3, 5 to 3, and 8 to 5. If the inelastically scattered neutrons all had the same energy, as would be the case for scattering by a single level, then the indicated energies would all have the same value. However, if the neutrons have a continuous evaporation spectrum, then the indicated energies from each of the ratios should differ. The nuclear temperature, T, which corresponds to the most probable neutron energy in an evaporation spectrum, was determined from each of the ratios. When the three calculated values of T agree within the experimental error, the spectrum agrees with the theoretical evaporation spectrum.

The results of these experiments are summarized in table 6. The experiment with 1.00 MeV neutrons scattered from Sn serves as a check on the method, since there are no inelastically scattered neutrons. The observed counting ratios are those expected for elastically scattered neutrons. The inelastic scattering from Fe is from a single level at 0.845 MeV, and the calculated energy of the single group of inelastically scattered neutrons is 0.14 MeV. The experimental results with 1.00 MeV neutrons on Cd and Ta are similar in that a nearly constant indicated energy, E_i, is obtained. This shows that a large fraction of the neutrons are of the indicated

;.0	
/3	8.5
.9	1.28
.99	1.15
.85	0.82
.5	1.17
.77	0.92
.62	0.60
.6	1.15
.84	0.90
.69	0.58
.3	1.05
.65	0.70
.50	0.42
.4	1.10
.70	0.78
.55	0.48

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energies and the distribution does not approximate an evaporation spectrum. The results with W at this energy are consistent with an approximate evaporation spectrum with a nuclear temperature of 0.38 MeV.

The results at 2.44 MeV and 5.0 MeV for Cd, Sn, Ta, and W show that the distributions are close to evaporation spectra. In all of these cases the nuclear temperature increases with the bombarding energy of the neutrons as predicted by theory. The results with Fe at 5.0 MeV agree within the experimental error with an evaporation spectrum and a nuclear temperature of 0.91 ± 0.10 MeV.

3.4. PENETRATION OF 15 MeV NEUTRONS THROUGH A SHIELD

The energy spectrum of neutrons resulting from penetration of 15 MeV neutrons through a shield of concrete blocks has been determined. Neutrons were produced by the $T(d,n)He^4$ reaction, using the Texas Nuclear Corporation 2 MeV Van de Graaff accelerator. A wall, 40 cm thick, which was made of concrete blocks, served as a neutron shield. The counter was positioned 6.41 m from the target and 30 cm behind the concrete wall. The other walls of the target room were also about 6 m from the target, which was 3.5 m above a concrete floor. The counting rates of the 12, 8, 5, 3, and 2 inch counters were obtained. The results of these measurements were analyzed to determine the neutron spectrum. Agreement with the experimental data was obtained with a neutron intensity inversely proportional to the neutron energy from about 0.5 eV to 2.5 MeV. In this energy range there are 90 neutrons/cm²-sec. Below 0.5 eV, there are 50 neutrons/cm²-sec. From 2.5 to 15 MeV neutron energy there are 32 neutrons/cm²-sec. The distribution of the 32 neutrons/cm²-sec over the latter energy range is not accurately determined by this experiment. Both a spike of 14–15 MeV neutrons and a flat distribution from 2.5 to 15 MeV fit the data. The actual spectrum probably lies between these two extremes.

The absolute yield of 15 MeV neutrons from the primary source was about 1.0×10^9 neutrons/sec. Without a shield, the flux of 15 MeV neutrons at the counter would be 194 neutrons/cm²-sec. The number of neutrons above 2.5 MeV was reduced by the concrete wall to $\frac{1}{6}$ of this value, but comparison with the total flux of neutrons behind the shield shows that nearly all of the 15 MeV neutrons penetrate the shield, although at a much reduced energy.

3.5. BACKGROUND NEUTRONS FROM A NUCLEAR REACTOR

Measurements were made on the background neutrons in a working area of the Materials Testing Reactor at Idaho Falls, Idaho. The counting rates of the 8, 5, 3, and 2 inch counters were obtained under normal operating conditions of the reactor, and at a power level of 25 megawatts. The results of this experiment indicated that the number of neutrons per unit energy internal is inversely proportional to the neutron energy from about 0.5 eV to 0.9 MeV and the intensity above 0.9 MeV decreases rapidly. The neutron flux below 0.5 eV was 15 neutron/cm²-sec as compared with 20 neutrons/cm²-sec in the neutron energy range from 0.5 eV to 0.9 MeV. An independent measurement of the number of thermal neutrons was made by covering the counters with cadmium about 1 mm thick. This latter determination of the number of thermal neutrons agreed with the determination made with the counting ratios to within the experimental error of about 20%.

3.6. BACKGROUND NEUTRONS IN A VAN DE GRAAFF TARGET AREA

The neutron spectrum resulting from scattering of fast neutrons by the floor and walls surrounding the Rice Van de Graaff accelerator has been determined using the polyethylene moderated neutron detector. The primary source of neutrons was from the break-up of deuterium by proton bombardment at an energy of 4.5 MeV. The primary neutron spectrum at this bombarding energy ranges from 0 to 2.0 MeV with an average energy of about 0.7 MeV. The yield of neutrons from this reaction decreases very rapidly with angle; at 90° to the incident beam of protons, the yield is less than 2% of that at 0°. The absolute yield from the primary source was 1.4×10^8 neutrons/sec. The counting rate of each spherical counter due to background neutrons was determined from the counting rates at two distances from the target at 90° to the beam of bombarding protons. That portion of the count not decreasing proportional to the solid angle subtended by the counter from the source was due to background neutrons. At a distance of 100 cm, over 75% of the counts in each sphere was due to background neutrons. Data was obtained with the 2, 3, 5, 8, and 12 inch counters. The results indicate that the background neutron intensity is inversely proportional to the neutron energy from 0.5 eV to 0.1 MeV. In this energy interval there are 22 neutrons/cm^2-sec. There are 7 neutrons/cm^2-sec in the energy range below 0.5 eV. From 0.1 MeV to 0.7 MeV there are 11 neutrons/cm^2-sec. The distribution of the 11 neutrons/cm^2-sec over the latter energy range is not accurately determined by this experiment. Both a spike of 0.5 to 0.7 MeV neutrons and a uniform distribution from 0.1 to 0.7 MeV fit the data. The actual spectrum probably lies between these two extremes.

3.7. APPLICATION OF THE COUNTER TO NEUTRON DOSIMETRY

Since the neutron detector described herein is sensitive to all energies of neutrons, it might well be applied to problems in neutron dosimetry. For example, the previously discussed neutron spectrum in a working area at the Materials Testing Reactor can be converted into units of radiation exposure using the published data[11]) on the relative biological effectiveness of neutrons. Using this data, the radiation exposure to neutrons was found to be 0.54 millirem per hour, of which 0.06 was due to thermal neutrons.

For some purposes, a neutron counter whose response is the same as the sensitivity of the human body to neutrons would be very useful. Such a counter might be used to monitor neutron exposure without regard to the actual spectrum of neutrons. The 12 inch diameter counter has approximately the same response to neutrons as the human body from thermal neutron energy to 15 MeV. This is shown in table 7, which gives, as a function of neutron energy, the number of counts in the 12 inch counter per millirem of neutron exposure. The variations in the number of counts per millirem given in table 7 are not much greater than the uncertainty in the neutron flux equivalent to one millirem.

TABLE 7

Response of 12 inch counter to neutron dose

Neutron energy (MeV)	Neutrons equivalent to 1 millirem† (10^3 neutrons/cm^2)	Response of 12 inch counter (3.2×10^3 counts/millirem)
2.5×10^{-8}	965	0.80
0.0001	720	1.62
0.01	430	1.31
0.1	115	0.62
0.5	43	0.62
1.0	26	0.72
2.0	29	1.26
3.0	26	1.23
15.0	25	0.77

† Taken from ref.[11]).

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[11]) U.S. National Bureau of Standards Handbook No. 63 (1957).