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NEUTRONS FROM (α, n) SOURCES

Wilmot N. Hess

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Contents

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ABSTRACT

The neutron energy spectra and yields for several (α, n) neutron sources are calculated and compared with experimental values.

NEUTRONS FROM (α, n) SOURCES*

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INTRODUCTION

In 1932 Chadwick discovered the neutron by studying the (α, n) reaction of polonium alpha particles on beryllium.[1] Shortly after this, the Rome group used alpha particles from radon to make neutrons from the (α, n) reaction on beryllium for their studies.[2] Various (α, n) reactions have been used continuously since 1935 as laboratory sources of neutrons. The most popular sources have been Ra-Be and Po-Be. More recently, in addition to these, Po-B, Po-Li, Pu-Be, and Po-F have been used as (α, n) sources.

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*This work was performed under the auspices of the U.S. Atomic Energy Commission.

[1] J. Chadwick, Nature 129, 312 (1932).

[2] Amaldi, D'Agostino, Fermi, Pontecorvo, Rasetti, and Segrè, Proc. Roy. Soc. 149A, 552 (1935).

NEUTRON YIELDS

The yield of neutrons from an (α, n) reaction can be calculated in a straightforward fashion. The fraction of alpha particles that will travel a distance x from their source without inelastic nuclear collisions will be

$$\frac{N(x)}{N0} = e^{-n\sigma_{in.}\, x} .$$

For reasonable values of the inelastic cross section, we have

$$e^{-n\sigma_{in.}\, x} \approx 1$$

which gives

$$N(x) \approx N0 .$$

In thickness dx at x we will have $n\sigma\ dx$ interactions, each producing one neutron. If σ is the cross section for the (α, n) reaction under consideration, and n is the number of target atoms available, and E_α is the alpha-particle energy, the yield of neutrons will then be

$$Y = \int_0^{R_\alpha} N(x)\, n\sigma(E)\, dx = n\, N0 \int_0^{E_\alpha} \frac{\sigma(E)}{(dE/dx)}\, dE . \qquad (1)$$

NEUTRON ENERGY SPECTRA

For a monoenergetic alpha particle hitting a target nucleus T and producing a neutron and a final nucleus F, there will be a distribution of neutron energies observed in the laboratory corresponding to different directions of emission of the neutron relative to the incident α direction. In the center-of-mass (c.m.) system, the neutron is monoenergetic, with energy E'_n given by

$$E'_n = \frac{M_F}{M_F + M_n} (E'_\alpha + Q) \qquad (2)$$

where E'_α is the α particle energy in the c.m. given by

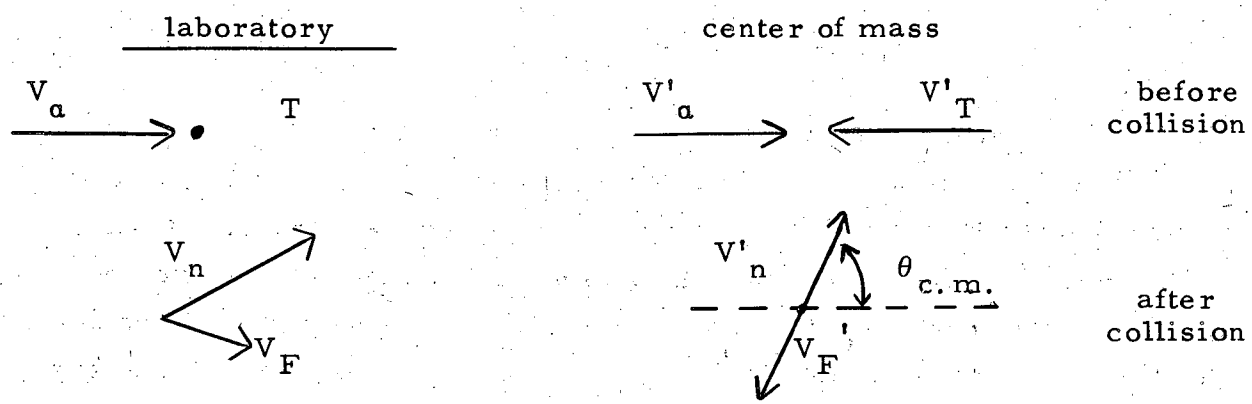
$$E'_\alpha = E_\alpha \left(\frac{M_T}{M_T + M_\alpha} \right) \tag{3}$$

and

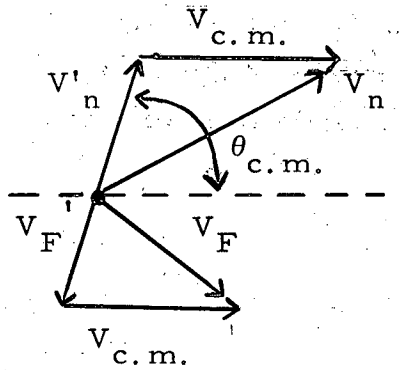
$$Q = \left[M_\alpha + M_T - (M_n + M_F) \right] 932 \text{ Mev} \tag{4}$$

where M_α, M_T, M_n and M_F are the masses of the α particle, target nucleus, neutron, and final nucleus, respectively, in amu.

In order to get the neutron energy in the laboratory, we must add the velocity of the c.m. ($V_{c.m.}$) to the velocity of the neutron (V_n) as follows:



From the c.m. diagram after collision, we can construct the laboratory diagram after collision. Thus we have



$$V_{c.m.} = -V_T' = \left(\frac{M_\alpha}{M_T + M_\alpha} \right) V_\alpha = \left(\frac{M_\alpha}{M_\alpha + M_T} \right) \sqrt{\frac{2E_\alpha}{M_\alpha}}$$

$$V_n' = \sqrt{\frac{2E_n'}{M_n}}$$

$$\delta = 180^\circ - \theta_{c.m.}$$

From this we get

$$V_n^2 = V_n'^2 + V_{c.m.}^2 + 2 V_n' V_{c.m.} \cos \delta , \tag{5}$$

or, rewriting in terms of energies,

$$E_n = \frac{M_n}{2}\left[\frac{2E_n'}{M_n} + \left(\frac{M_a}{M_T + M_a}\right)^2\left(\frac{2E_a}{M_a}\right) + 2\left(\frac{M_a}{M_T + M_a}\right)\sqrt{\frac{2E_a}{M_a}}\sqrt{\frac{2E_n'}{M_n}}\cos\theta_{c.m.}\right] \quad (6)$$

This expression gives the laboratory neutron energies corresponding to different angles of emission $\theta_{c.m.}$. From this we can get the observed neutron spectrum in the laboratory if we assume that the angular distribution of neutrons emitted in the c.m. is isotropic. This is known to be incorrect in several cases for (α, n) emitters,[3] but as will be shown, the calculations are not sensitive to the form of angular distribution used. The solid angle for emission of a neutron in $d\theta_{c.m.}$ at $\theta_{c.m.}$ is

$$d\Omega = 2\pi \sin\theta_{c.m.}\, d\theta_{c.m.}, \quad (7)$$

therefore the probability $N(E_n)$ of finding a neutron of energy E_n is proportional to $\sin\theta_{c.m.}$. From equations 6 and 7, we get the neutron energy distribution in the laboratory for a monoenergetic alpha particle. (See, for example, Curve A of Fig. 1, which is the laboratory neutron energy spectrum for $E_\alpha = 4.8$ for a target of Boron-11). For a nonisotropic angular distribution, the factor $\sin\theta_{c.m.}$ giving the shape of the energy spectrum would be changed.

In an (α, n) neutron source, the alpha particles start at some energy E_α and slow down by ionization loss to $E = 0$ (or occasionally interact). For ease of calculation, we will approximate this situation by using several monoenergetic alpha particles of different energies (instead of the actual continuum of alpha-particle energies) and calculate the spectrum for this case. Then we have:

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[3] J. Perry and G. Haddad, private communication.

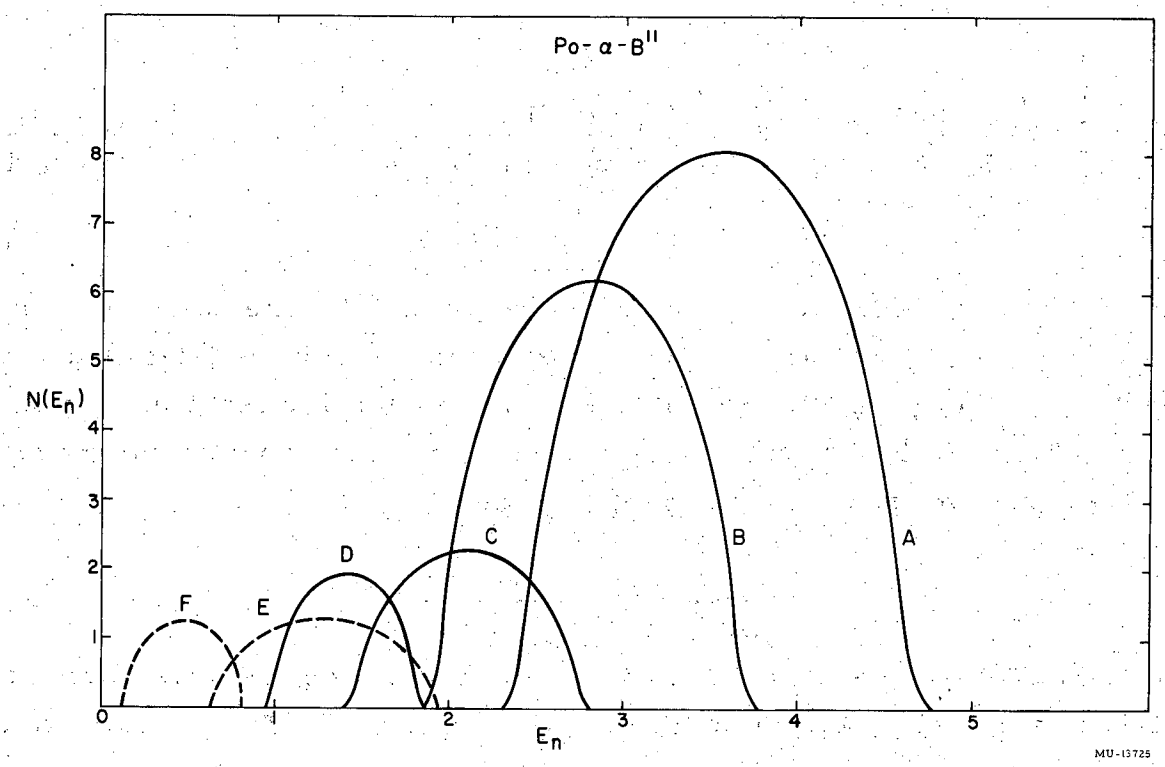

Fig. 1. Neutron energy spectra calculated for various monoenergetic alpha particles incident on B^{11} ($Po-\alpha-B^{11}$ source).

Curve A. E_α = 4.80 going to ground state of N^{14}

Curve B. E_α = 3.80 going to ground state of N^{14}

Curve C. E_α = 2.80 going to ground state of N^{14}

Curve D. E_α = 1.80 going to ground state of N^{14}

Curve E. E_α = 4.71 going to first excited state of N^{14}

Curve F. E_α = 3.54 going to first excited state of N^{14}.

$$\frac{Y}{N_0} = n \int_0^{E_a} \frac{\sigma}{(dE/dx)}\, dE$$

$$\frac{Y}{N_0} = n \int_0^{E_1} \frac{\sigma(E)}{(dE/dx)}\, dE + n \int_{E_1}^{E_2} \frac{\sigma(E)}{(dE/dx)}\, dE + \cdots n \int_{E_m}^{E_a} \frac{\sigma(E)}{(dE/dx)}\, dE$$

$$= n \left[E_1 \left(\frac{\sigma(E)}{(dE/dx)} \right)_{\frac{E_1}{2}} + (E_2 - E_1) \left(\frac{\sigma(E)}{(dE/dx)} \right)_{\frac{E_1+E_2}{2}} + \cdots (E_a - E_m) \left(\frac{\sigma(E)}{(dE/dx)} \right)_{\frac{E_a+E_m}{2}} \right] \quad (8)$$

In the last line of Eq. 8 above, we have approximated the value of the integrals of the previous equation by taking the average value of the integrand and multiplying it by the width of the energy interval under consideration.

We can calculate the laboratory neutron energy spectra for monoenergetic alpha particles of the several mean energies

$$E_1, \quad \frac{E_1 + E_2}{2}, \quad \cdots \quad \frac{E_x + E_m}{2}$$

used in Eq. 8 above. We weight the areas under these spectra, which are the neutron yields, by the factors indicated in Eq. 7. The weights are given by the expression:

$$W\left(\frac{E_m + E_{m+1}}{2} \right) = \left(E_{m+1} - E_m \right) \left(\frac{\sigma}{(dE/dx)} \right)_{\frac{E_m + E_{m+1}}{2}} . \quad (9)$$

Adding the heights of the curves at various neutron energies, we get the laboratory neutron-energy spectrum. This procedure has been carried out for the several (α, n) sources considered here.

Experimental measurements of the neutron spectrum from (α, n) sources are hard to perform. One needs a fairly efficient neutron detector that will count neutrons from ~ 0.1 Mev to 10 Mev. The detector should be directional to insure that the neutrons detected come from the source and not from local

scattering material. Perlman, Richards, and Speck[4] used nuclear emulsions and observed recoil protons. They used neutrons from the $Li^7(p, n)Be^7$ reaction of 0.6, 0.9, 1.3, and 1.8 Mev to calibrate the emulsions. The results of these calibrations with monoenergetic neutrons are shown in Fig. 2. These calibration curves are wide enough so that fine structure in the neutron spectrum will be covered up.

The measured neutron energy spectrum may be somewhat different than the calculated energy spectrum even through the calculated spectrum is correct. This is due to scattering of the neutrons on their way out of the source. Scattering, which is mostly elastic for these energies, decreases the neutron energies due to the recoil of the struck nucleus. When the scattering material is a light nucleus such as Li or B or Be, the energy loss is larger than that for a heavy nucleus. Assuming isotropic elastic scattering in the c.m., a monoenergetic neutron group of energy E_n is changed into a flat distribution of neutrons from E_n to $(A-1/A+1)^2 E_n$. In this way the average neutron energy is decreased, and dips in the spectra (such as the one at 6 Mev for Po-α-Be in Fig. 3A) are partially filled in. For typical sources, 20 to 30% of the neutrons may scatter before emerging. The source container is normally made of a heavy material so that elastic scattering does not change the neutron energy much. For several sources used at UCRL, the fraction of neutrons that scatter before emerging has been calculated and is given in Table I below.

Table I

Source	Source dimensions diam. (in.)	Length	Average distance travelled by emerging neutron (in.)	σ (barns)	Fraction of neutrons scattered
Po-α-Li	0.50	0.50	0.20	2	0.04
Po-α-Be	0.50	0.50	0.20	3	0.17
Pu-α-Be	0.85	0.90	0.35	3	0.27
Ra-α-Be	0.70	0.95	0.28	3	0.22

Container walls have been neglected in these calculations. For the Po-α-Li source, the fraction of neutrons scattered is small, but for the Po-α-Be, Pu-α-Be, and Ra-α-Be sources the fractions scattered are appreciable. Assuming 20% of the neutrons of all energies scatter once in the source,

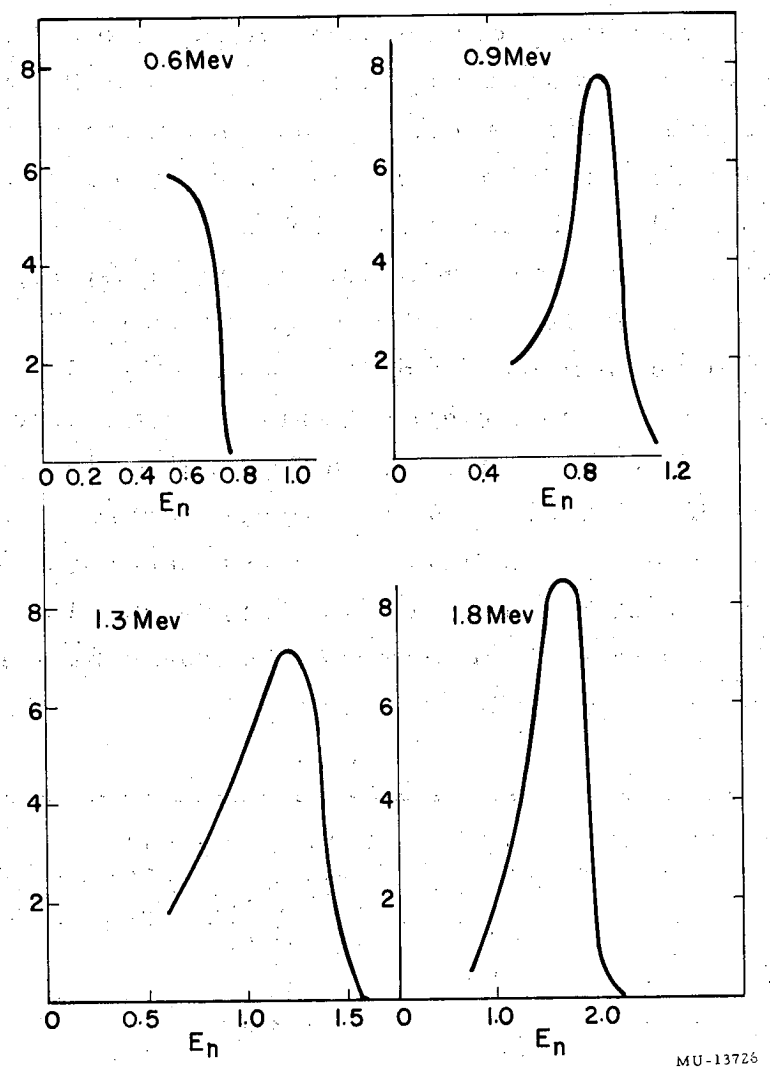

Fig. 2. Calibration curves for detecting monoenergetic neutrons by nuclear emulsions.

we have calculated the energy spectrum modified by scattering for a Po-α-Be source; this is shown in Fig. 3C. The spectrum is changed only slightly by the scattering calculation.

POLONIUM-BORON

Sources made of Po–B have been studied by several workers. Measurements on the neutron energy spectrum have been made[4] and the yield of neutrons has been measured.[5]

The yield of a Po–B source can be calculated from Eq. 1. In this case σ becomes

$$\sigma_{\alpha+B \longrightarrow N+n'}$$

where n is the number of atoms/gm of B in the source. This cross section has been measured experimentally. Values of dE/dx have been obtained[7] and the equation integrated graphically. There is so little Po in a Po–B source (about 1% by weight) that it has been neglected here in dE/dx. Values for this and other yields are given in Table II.

This yield has been calculated using a natural isotopic mixture of boron. Ten percent of the yield has been assumed to come from B^{11}, and the rest from B^{10}.[8]

The energy spectrum from a Po–B source is quite simple. There is one monoenergetic (5.30-Mev) alpha particle emitted by Po. In the final nucleus, N^{14}, the ground level is probably the only energy level that is involved in the reaction $\alpha + B^{11} \longrightarrow n + N^{14}$. The first excited state of N^{14} at 2.31 Mev may contribute some. The reaction $\alpha + B^{10} \longrightarrow n + N^{13}$ also involves only one energy level in the final nucleus, the ground level.

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[4] Perlman, Richards, and Speck, "The Neutron Spectra of Po–B and Po–Be" MDDC-39, July, 1946; H. Staub, "The Neutron Spectrum of Boron Bombarded by Polonium-Alphas", MDDC-1490, Dec. 1947; and R.G. Cochran and K.M. Henry, Rev. Sci. Instr. 26, 757 (1955).

[5] James H. Roberts, "Neutron Yields of Several Light Elements Bombarded with Polonium Alpha Particles", MDDC-731 (date unknown). See also E. Segrè and C. Wiegand, "Thick Target Excitation Functions for Alpha Particles," MDDC-185, Sept. 1944.

[6] R.L. Walker, Phys. Rev. 76, 244 (1949).

[7] S.K. Allison and S.D. Warshaw, Rev. Mod. Phys. 25, 790 (1953).

[8] T.W. Bonner and L.M. Mott-Smith, Phys. Rev. 46, 258 (1934).

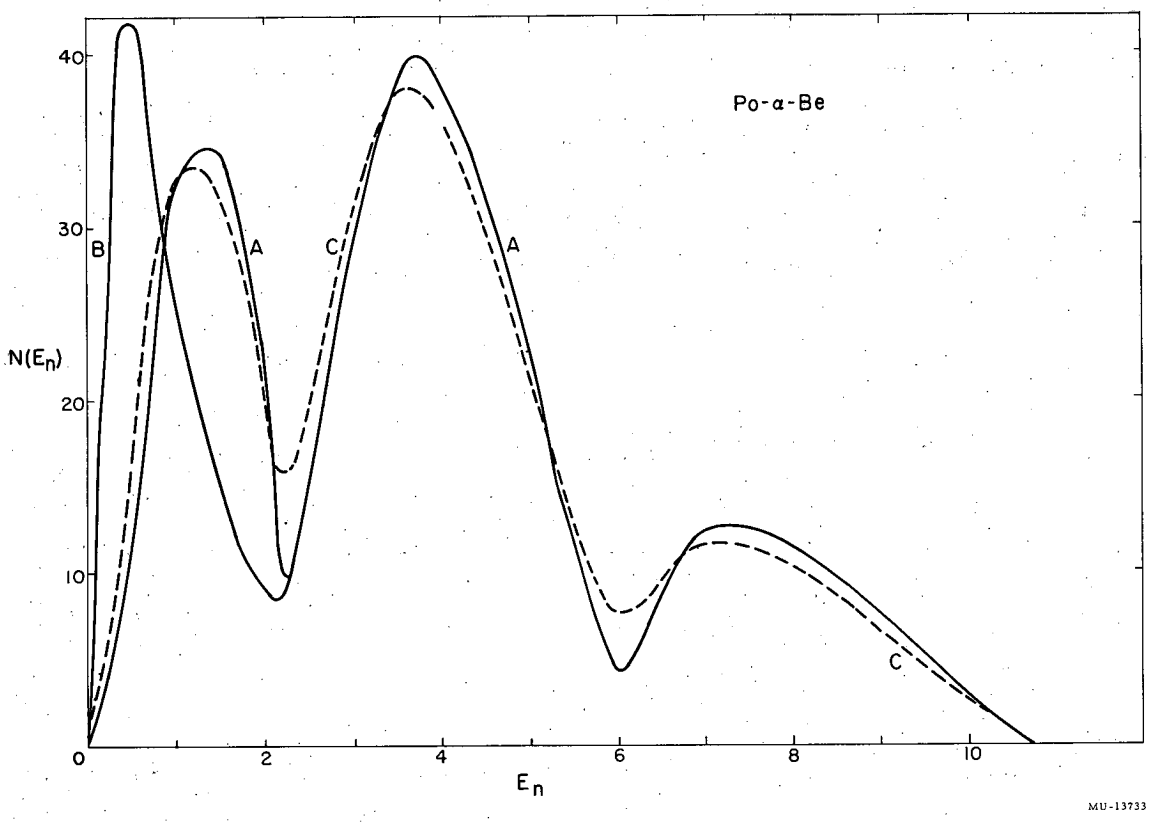

Fig. 3. Calculated neutron energy spectrum for a Po–Be source.

Curve A. Calculated spectrum assuming C^{12} energy levels of 0 Mev, 4.43 Mev and 7.65 Mev enter into the reaction.

Curve B. Calculated spectrum assuming C^{12} energy levels of 0 Mev and 4.43 Mev and also three-body break up of C^{13} enter into the reaction.

Curve C. Calculated spectrum using assumptions of curve A as modified by neutron scattering in the source.

Following the scheme given in Section III, we have calculated the laboratory-neutron energy spectra for B^{11} for α energies of E = 4.8, 3.8, 2.8, and 1.8 Mev. These spectra are shown in Fig. 1, Curves A, B, C, and D. The neutron energies for the four α particles are given by

$$E_n = 3.52 + 1.08 \cos \theta_{c.m.}, \quad \text{for } E_\alpha = 4.8,$$
$$E_n = 2.80 + 0.85 \cos \theta_{c.m.}, \quad \text{for } E_\alpha = 3.8,$$
$$E_n = 2.10 + 0.64 \cos \theta_{c.m.}, \quad \text{for } E_\alpha = 2.8,$$

and

$$E_n = 1.40 + 0.42 \cos \theta_{c.m.}, \quad \text{for } E_\alpha = 1.8 .$$

The height of the energy spectrum $N(E_n)$ for the different values of E_α are given by $W_i \sin \theta_{c.m.}$. The weights (W_i) are calculated by using Eq. (9). The heights of the curves of Fig. 1 have been added to give the resultant energy spectrum shown in Fig. 4. Curves E and F of Fig. 1 are the monoenergetic α-particle neutron spectra for two values of E_α for N^{14} left in the 2.31-Mev excited state. The calculated neutron energy spectrum is shown in Fig. 4 for 0%, 10%, and 20% of the total yield coming from the excited state of N^{14}.

The energy spectrum for polonium α particles on B^{10} has been calculated by the same method and is shown in Fig. 5.

In order to get the energy spectrum for natural boron, we have added 10% of the B^{10} spectrum to the B^{11} spectrum[8] to get the resultant spectrum shown in Fig. 5. The experimental results of Perlman, Staub, and Cochran are shown for comparison.[4] The agreement of the calculated curve with the experimental results is quite good.

In order to show the effect of a non isotropic angular distribution of the neutrons in the c.m., the calculations outlined above have been repeated for B^{11} for two quite extreme cases, for a $\cos^2\theta$- and for a $\sin^2\theta$-angular distribution. These two curves and the curve for an isotropic angular distribution are shown in Fig. 6 normalized to the same height. The widths of the spectra are changed slightly by the angular distribution, but the effect is small enough so that an isotropic angular distribution will be used for all following calculations.

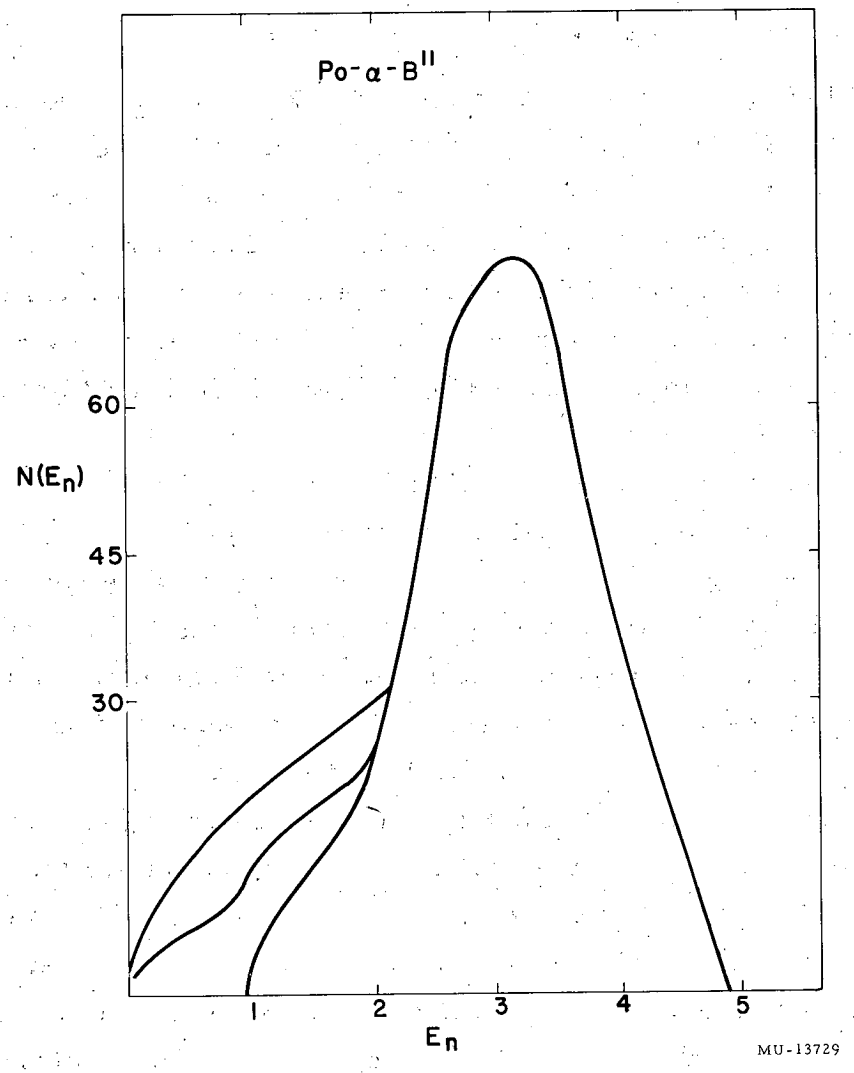

Fig. 4. Neutron energy spectrum calculated for a Po–B^{11} source.

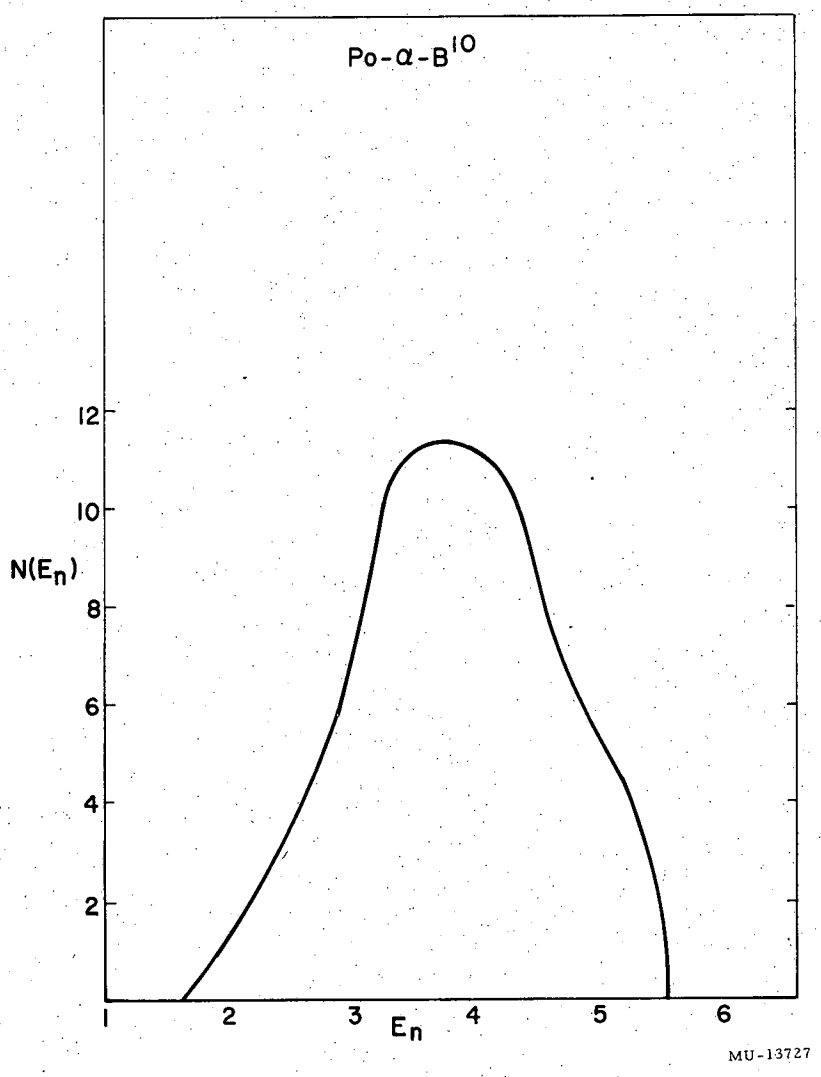

Fig. 5. Neutron energy spectrum calculated for a Po–B^{10} source.

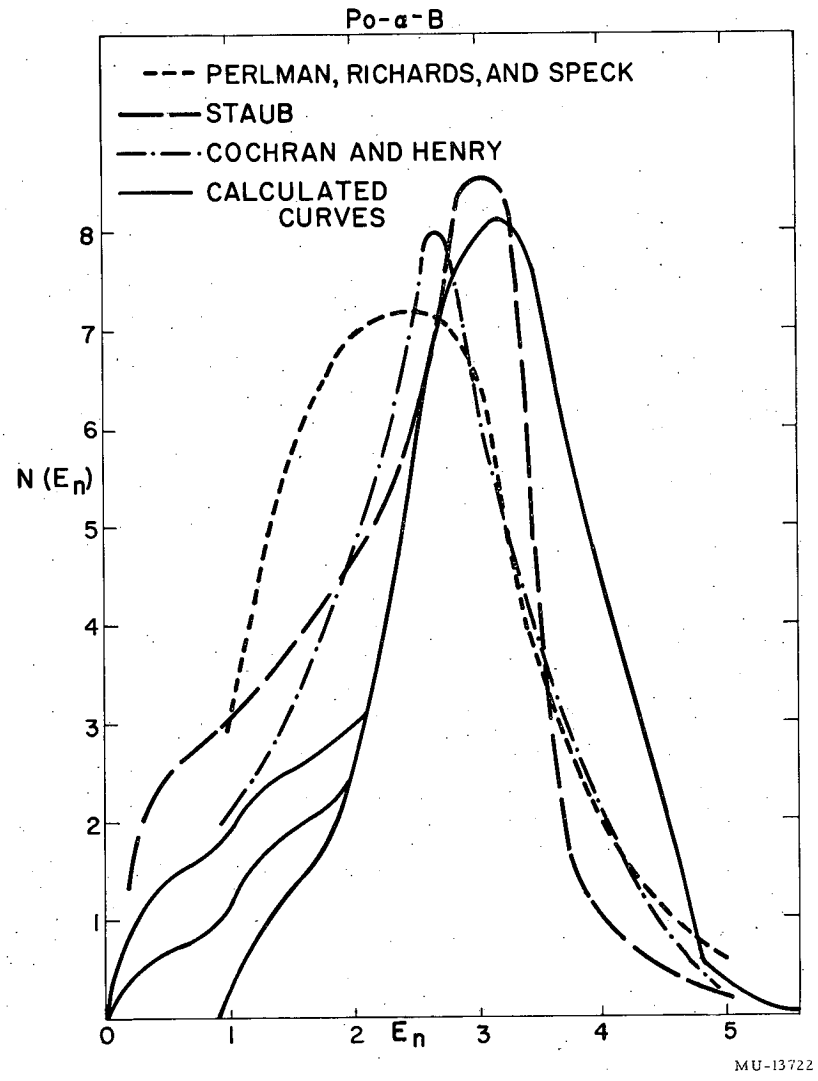

Fig. 6. Neutron energy spectrum calculated for a Po–natural B source and several experimental spectra.

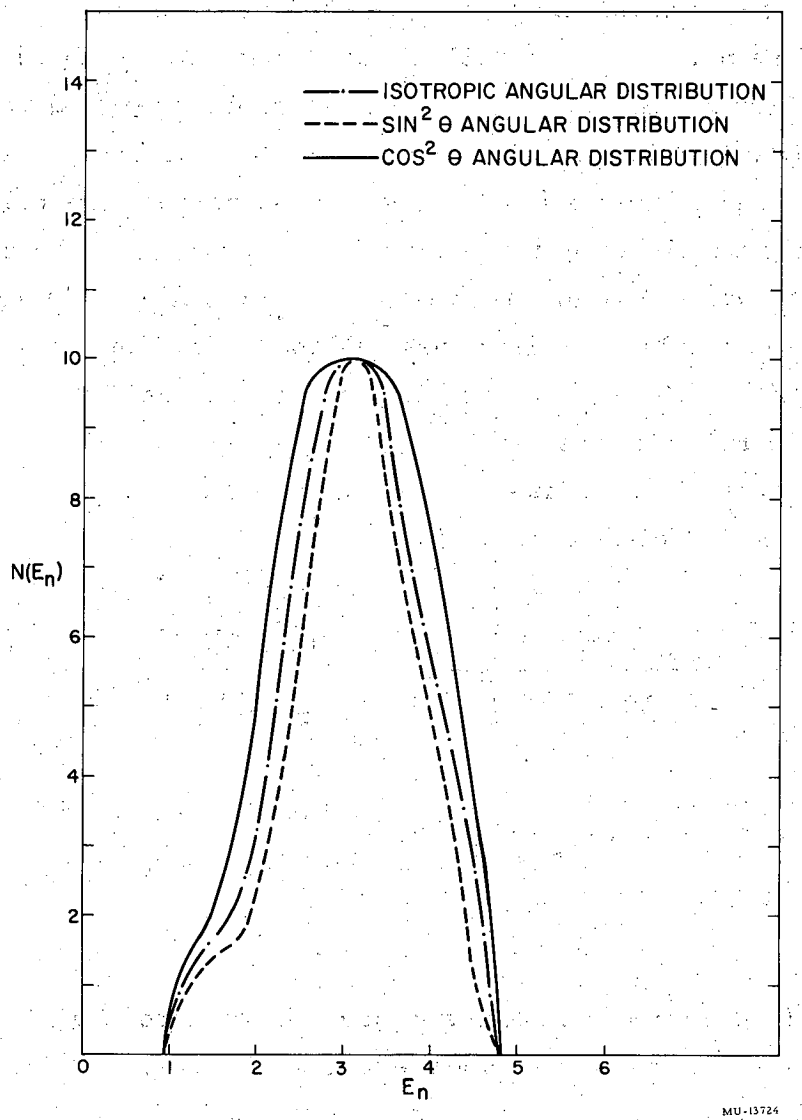

Fig. 7. Neutron energy spectrum calculated for a Po–B^{11} source for three different angular distributions of neutrons in the c.m. system.

POLONIUM-LITHIUM

The spectrum of neutrons from a Po-α-Li source (Fig. 8) has been measured by Barton using a low pressure hydrogen-filled diffusion cloud chamber.[9] The average energy of the same source used by Barton has been measured by Young[10] and found to be about 250 kev by the method of finding the optimum thickness of (polyethylene) to put around a BF_3 counter. The neutrons from polonium α particles with Li come from the Li^7 only. The reaction with Li^6 requires more energy than is available.

For the reaction with Li^7, Q =-2.78 Mev and the resulting neutrons have a few hundred kev energy. The ground state is the only energy level energetically possible for the residual nucleus B^{10}. The cross section for this reaction has not been measured, but by detailed balancing on the inverse reaction we can calculate the cross section. For the inverse reaction, $B^{10} + n \rightarrow Li^7 + \alpha$, the cross section is known to be closely $1/V_n$ over a considerable range of energy.[11]

This cross section has also been measured for neutron energies from 0.1 to 2 Mev.[12] Detailed balancing gives

$$\frac{\sigma_{\alpha + Li^7 \rightarrow B^{10} + n}}{\sigma_{B10 + n \rightarrow Li^7 + \alpha}} = \frac{p_n^2 (2I_{B10} + 1)(2I_n + 1)}{p_\alpha^2 (2I_{Li7} + 1)(2I_\alpha + 1)}$$

$$= 0.437 \frac{E_n'}{E_\alpha'},$$

---

[9] David M. Barton, "Measurement of the Neutron Spectrum from a Po-Li^7 Low Energy Neutron Source", LA-1609, July 1953.

[10] D. S. Young, "Paraffin Cylinders to Measure Neutron Energies", LA-1938, July 1955.

[11] D. J. Hughes and J. A. Harvey, "Neutron Cross Sections", BNL-325, July 1955.

[12] Petree, Johnson, and Miller, Phys. Rev. 84, 1138 (1951).

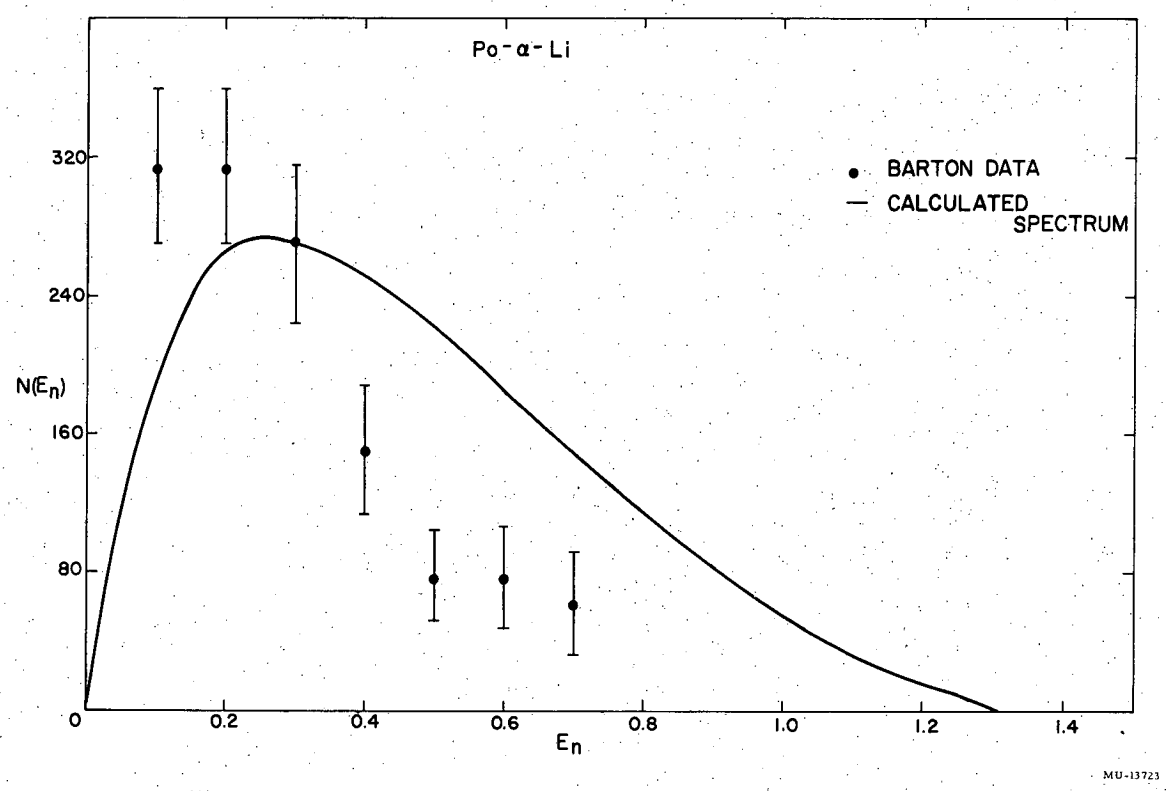

Fig. 8. Calculated and measured neutron energy spectra for a Po–Li source.

where both energies are in the c.m. system. The values of the cross section obtained this way are shown in Fig. 9. Using this cross section, we proceed as before. Using monoenergetic α particles of 5.2, 5.0, 4.8, 4.6, and 4.43 Mev, we calculate the lab spectra assuming an isotropic angular distribution in the c.m. These spectra are weighted and added to get the resultant neutron spectrum for Po-Li shown in Fig. 7. The yield has also been obtained from Eq. 1 and is shown in Table II.

Good-geometry attenuation measurements using polyethylene attenuators and a Hansen and McKibben counter have been performed by Hess and Smith using a Po-α-Li source.[13] Their results give a mean neutron energy of about 480 kev in agreement with the spectrum calculated here.

There are two possible explanations for the difference between this work and Barton's experiment. Polonium does not alloy with Li (or B or Be) so a mechanical mixture is used in these sources. If the particle size of polonium is an appreciable fraction of an alpha-particle range in diameter, then fewer high-energy alpha particles will be available to make the (α, n) reaction than has been assumed. This will result in a decreased yield of high energy neutrons. Secondly, there is the problem of wall-scattering in Barton's experiment. Neutrons that had scattered from the walls of the cloud chamber could have been detected and would have had lower energies than the non scattered neutrons. These scattered neutrons cannot, in general, be separated from non scattered neutrons. The fraction of such events is hard to estimate, but is probably significant.

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[13] W. Hess and A. Smith, private communication.

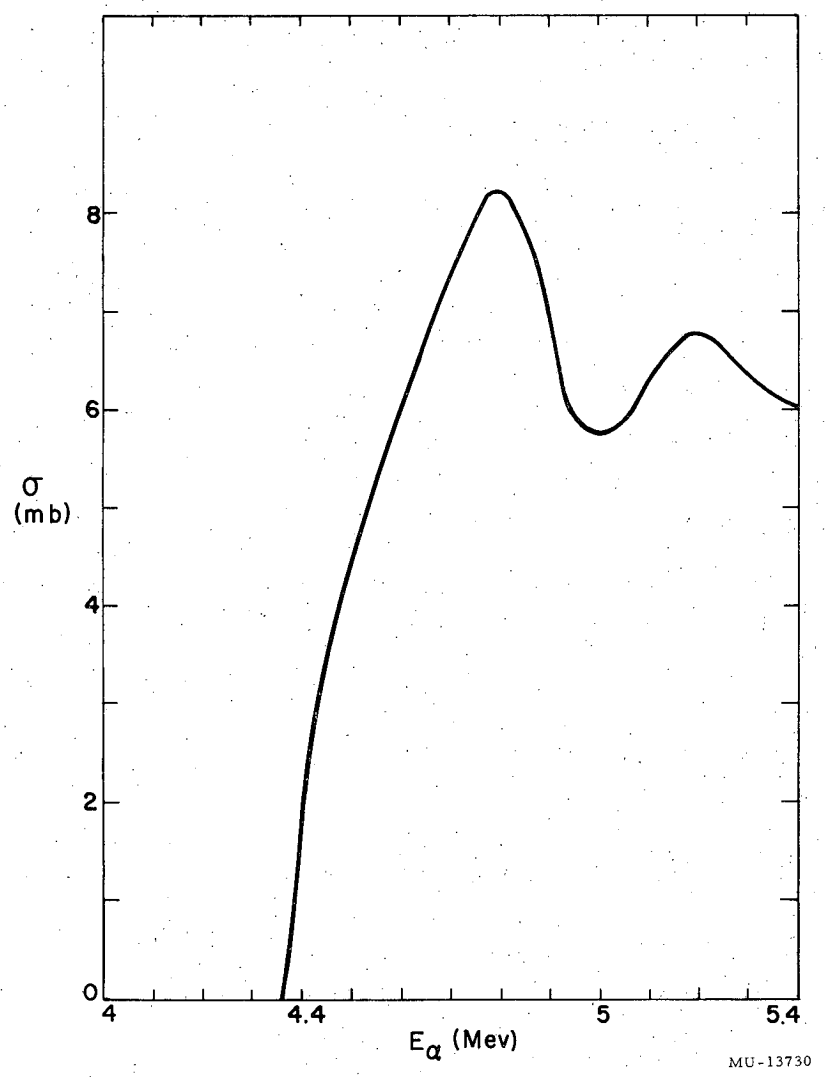

Fig. 9. Calculated cross section for $He^4 + Li^7 \rightarrow B^{10} + n$.

Table II

Yields of (α, n) neutrons sources

Source	Measured yield Neutrons/10^6 alphas	Reference	Calculated yield Neutrons/10^6 alphas	Reference
Po-α-Li	2.4	Roberts (5)	2.6	Roberts (5)
	4.7	Segrè and Wiegand (5)	2.5	Hess**
Po-α-Be^9	72	Roberts (5)	80	Roberts (5)
	73	Segrè and Wiegand (5)	58	Hess***
Po-α-B	21	Roberts (5)	24	Roberts (5)
	19	Segrè and Wiegand (5)	24	Hess**
Po-α-BF_3	13.5	Richards (24)	15.4	Hess**
Po-α-F^{19}	10.4	Roberts (5)	12	Roberts (5)
Pu-α-Be	42	Stewart (20)	35	Hess**
Ra-α-Be^9	1.4×10^7 neutrons/sec* per gm Ra (new source)	Anderson (19)	1.35×10^7 neutrons /sec per gm Ra (new source)	Hess**
			1.56×10^7 neutrons /sec per gm Ra (old source)	Hess**

*This yield is for a source containing 4.5 gms of Be and 1 gm of Ra.

**Data calculated in this report.

POLONIUM-BERYLLIUM

This is one of the most frequently used laboratory neutron sources because of the high yield and relatively small number of γ rays. Sources using Po have the disadvantage that Po has a 138-day half life, so these sources do not last too long.

For this source, the reaction involved is

$$He^4 + Be^9 \longrightarrow C^{12} + n .$$

The final nucleus C^{12} can be in the ground state or the 4.43- or 7.65-Mev energy levels. Risser, Price, and Class[14] give values for the cross section for the reactions $Be^9(\alpha, n)C^{12}$, for C^{12} left in the ground state, and $Be^9(\alpha, n)C^{12*}$, for C^{12} left in the 4.43-Mev level. Halpern[15] gives values for the cross section for the reaction $Be^9(\alpha, n)C^{12}$ for all conditions of the final nucleus C^{12}. The difference between the Halpern and Risser cross sections is then the cross section for the reaction where the C^{12} nucleus is left in the 7.65-Mev level or in other highly excited conditions. The cross sections obtained this way are shown in Fig. 10. The related branching ratios are shown in Fig. 11. Assuming that all of this difference cross section is due to the 7.65-Mev excited state of C^{12} we have calculated the energy spectrum for a Po-α-Be source. This is shown as Curve A of Fig. 3. The difference cross section might be due to multibody break up of the compound nucleus C^{13} rather than the effect of the 7.65-Mev level of C^{12}. This multibody break up is an appreciable effect for the reaction $p + C^{12} \longrightarrow 3He^4$ at 30 Mev.[16] In our case, we might be observing neutrons from the reaction $He^4 + Be^9 \longrightarrow n + Be^8 + He^4$. This three-body break up results in low-energy neutrons. The neutron spectrum for this reaction in the c.m. system has been calculated by phase-space arguments which give $N(E) = k \sqrt{E}\sqrt{E^{max} - E}$.[16] This c.m. spectrum has been transformed to the laboratory system. Using the branching ratios of Fig. 11, and assuming that 80% of the difference cross section goes into three-body break up and the remaining 20% goes to excite the 7.65-Mev C^{12} level, we derive Curve B of Fig. 3.

Curves A and B are radically different and, the real spectrum may be something intermediate between them. The CH_2 attenuation curves of Hess

[14] Risser, Price, and Class, Phys. Rev. 105, 1288 (1957)

[15] I. Halpern, Phys. Rev. 76, 248 (1949).

[16] H. B. Knowles, The Differential Cross Sections of the Alpha Particles from Carbon Induced by 31.8-Mev Protons, UCRL-3753, April, 1957.

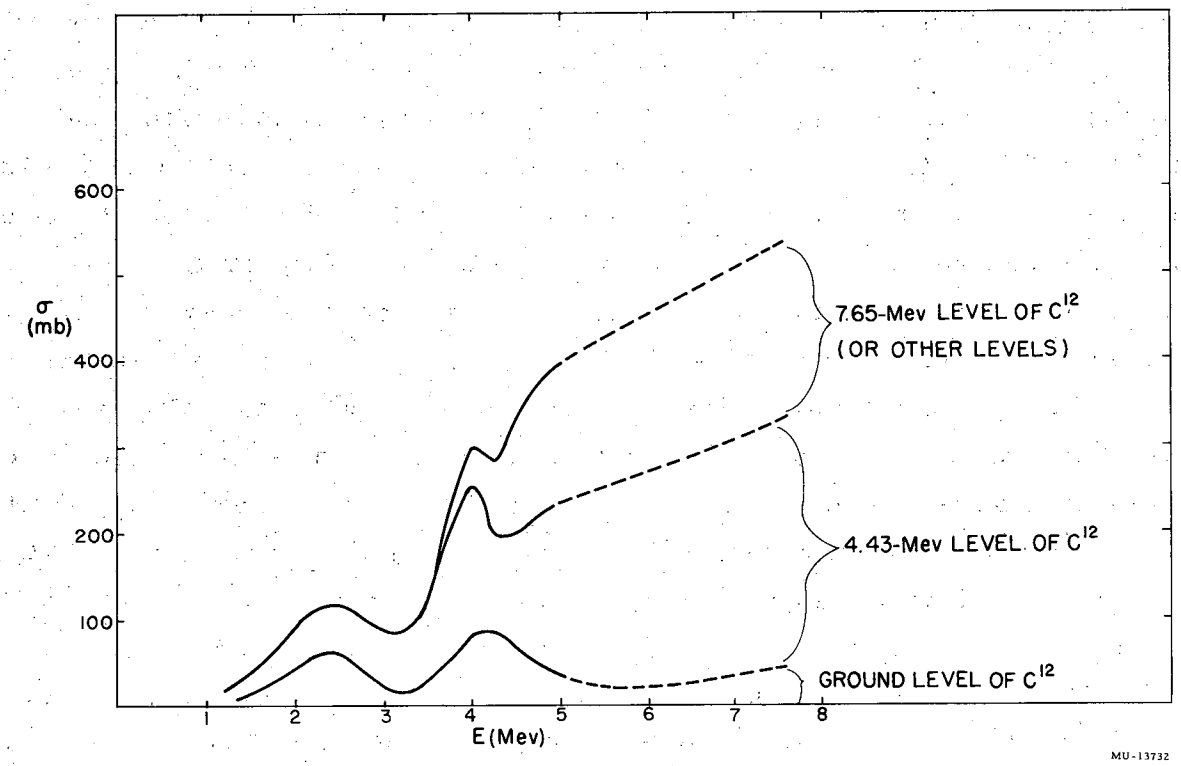

Fig. 10. Cross sections for the reaction $He^4 + Be^9 \rightarrow C^{12} + n$.

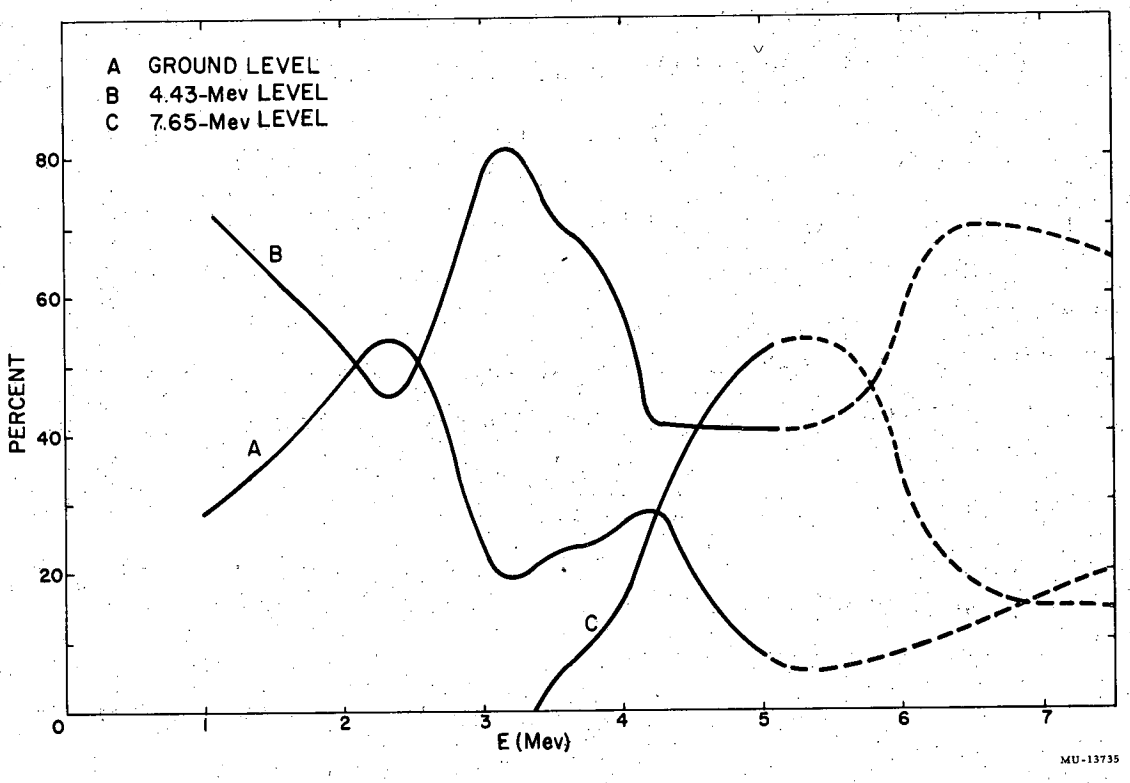

Fig. 11. Branching ratios for the reaction $He^4 + Be^9 \rightarrow C^{12} + n$.

and Smith cannot distinguish between these two spectra.[13]

The effect of neutrons scattering on the way out of the source material as discussed in Section III has been calculated, assuming 20% of the emerging neutrons scatter once. The neutron spectrum modified by scattering is shown in Curve C of Fig. 3. It may be seen that scattering does not change the spectrum much. It should be remembered that clumping of the Po atoms can further modify this spectrum. There have been several attempts to measure the Po-Be spectrum;[17] the results of a few of them are shown in Fig. 12. The agreement of the various spectra is not startling. Various authors have suggested that there are other energy levels in C^{12} than the commonly accepted ones. Ajzenberg and Lauritsen conclude that there are no energy levels lower than the 7.65-Mev level other than the 4.43-Mev and ground levels.[18] If there is no energy level between 0 and 4.43 Mev, there must be a big dip in the neutron energy spectrum at about 6 Mev. This can be seen from the following argument. The spectrum of neutrons resulting only in the 4.43-Mev level of C^{12} has a peak at about 4 Mev and falls to zero at 6.5 Mev (see Fig. 3). The spectrum of neutrons for C^{12} in the ground state has a peak at about 8 Mev and falls to zero at 5.2 Mev. Regardless of the form of the angular distribution of neutrons in the c.m. system or regardless of the branching ratio, combining these two spectra results in a neutron spectrum that has a decided dip at about 6 Mev as shown in Fig. 3.

The yield of Po-α-Be has been measured by Roberts and by Segrè and Wiegand[19] and calculated by Roberts, and is also calculated here (see Table II) using Eq. 1 and the cross section of Halpern.[15]

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[17] B.G. Whitmore and W.B. Baker, Phys. Rev. 78, 799 (1950); Gursky, Winnemore, and Cowan, Phys. Rev. 91, 209 (1953); Pierre Demers, "Photographic Emulsion Study of Po-Be Neutrons" MP-74 Jan. 1949; Elliot, McGarry, and Fanst, Phys. Rev. 93, 1348 (1953); R.G. Cochran and K.M. Henry, Rev. Sci. Instr. 26, 754 (1955); Perlman, Richards, and Speck, "The Neutron Spectra of Po-B and Po-Be," MDDC-39, July 1946.

[18] F. Ajzenberg and T. Lauritsen, Rev. Mod. Phys. 24, 321 (1952). See also Guier, Bertini, and Roberts, Phys. Rev. 85, 426 (1952).

[19] H.L. Anderson, Preliminary Report, No. 3, Nuclear Science Series, National Research Council (1948), and James H. Roberts, "Neutron Yields of Several Light Elements Bombarded with Polonium Alpha Particles", MDDC 731 (date unknown).

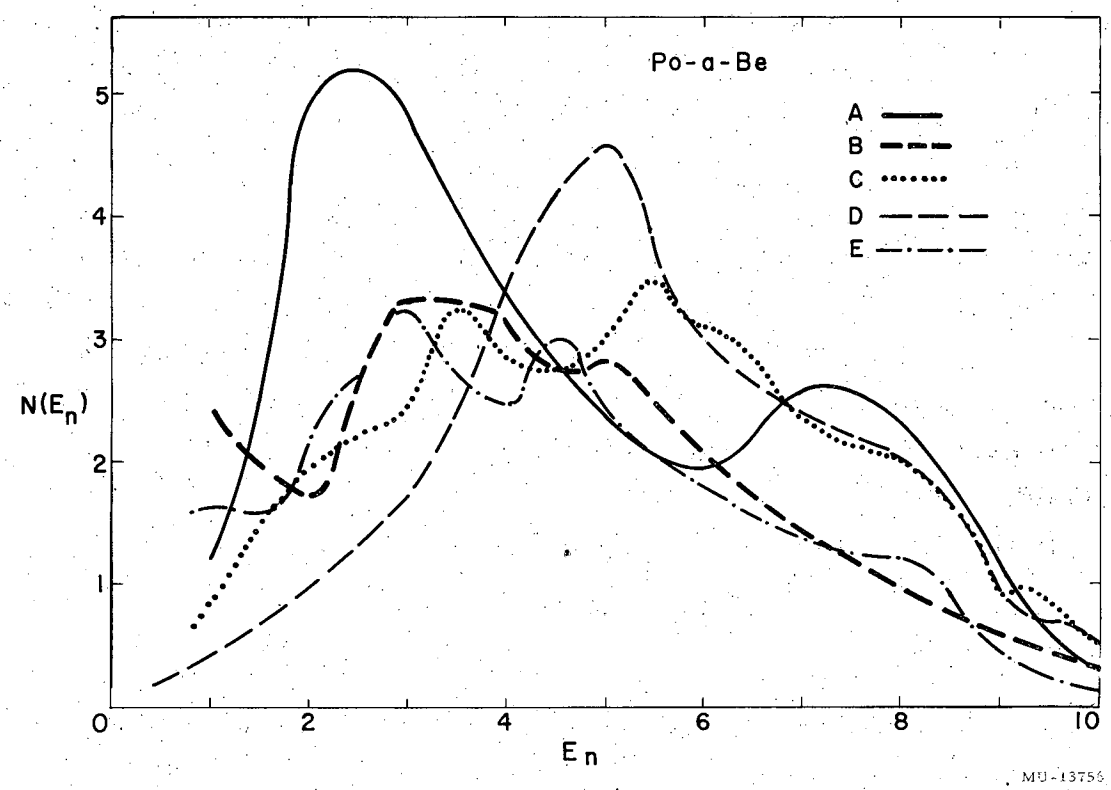

Fig. 12. Measured neutron energy spectra for a Po–Be source.[17]

Curve A. Data of Perlman, Richards, and Speck.

Curve B. Data of Cochran and Henry.

Curve C. Data of Elliott, McGarry, and Faust.

Curve D. Data of P. Demers.

Curve E. Data of Whitmore and Baker.

PLUTONIUM-BERYLLIUM

Plutonium is now used quite frequently with beryllium as a neutron source. It is long-lived. The source has very few γ rays. In addition, Pu can be alloyed with Be to form $PuBe_{13}$ which gives essentially atomic mixing while Po and Ra can only be mixed mechanically.

The neutron spectrum from Pu-α-Be must be very similar to the spectrum from Po-α-Be. The alpha particles from Pu have energies of 5.15, 5.137, and 5.09 Mev, while Po has one alpha of 5.30 Mev. This slight difference in α energy results in only a slight difference in the energy spectra of the two sources. The calculated spectrum for Pu-α-Be is shown in Fig. 13. Also shown is the measured spectrum measured by Stewart, which agrees reasonably well.[20] The argument given for Po-α-Be about the existence of the dip in the energy spectrum at 6 Mev applies equally well here. In fact, the dip must be deeper here because the alpha particle energy is lower.

The yield of Pu-α-Be has been measured[20] and also is calculated here. There is enough Pu in the source now so that it must be considered in the calculation because, in slowing down, alpha particles spend an appreciable part of their time near Pu atoms rather than Be atoms. This effect decreases the yield.

In this case, Eq. 1 becomes

$$\frac{Y}{N_0} = N_{Be} \int_0^{E_\alpha} \frac{\sigma}{(dE/dx)_{Be}} \left[\frac{dE_{Be}}{dE_{Be} + dE_{Pu}} \right] dE,$$

where the added term in brackets is to take care of the decreased yield due to the non productive energy loss of alpha particles while near Pu atoms. For a source of $PuBe_{13}$ we have

$$\frac{\text{gm/cm}^3 \text{ of Be}}{\text{gm/cm}^3 \text{ of Pu}} = \frac{13 \times 9}{1 \times 239} = \frac{117}{239},$$

from which we derive the fraction of Be in gm/cm^3,

$$\frac{117}{117 \times 239} = \frac{117}{356},$$

[20] Leona Stewart, Phys. Rev. 98, 740 (1955).

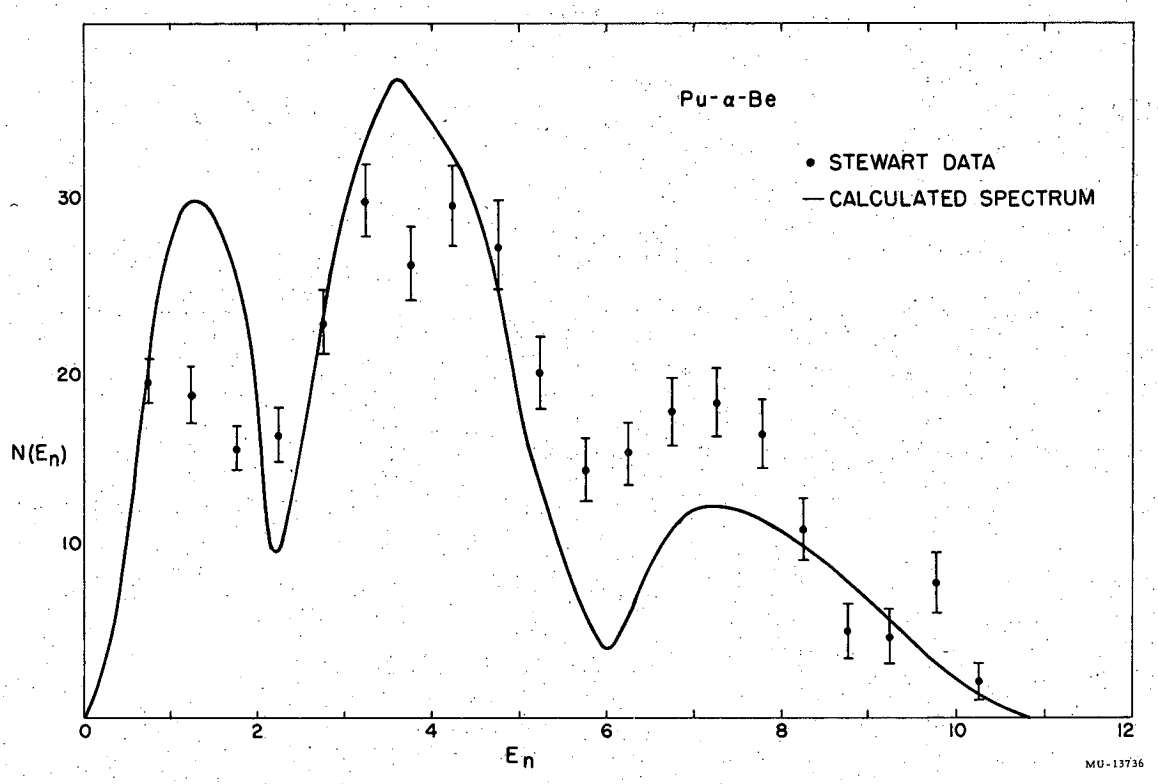

Fig. 13. Calculated and measured neutron energy spectra for a Pu–Be source.

and the fraction of Pu in gm/cm^3,

$$\frac{239}{117 + 239} = \frac{239}{356} .$$

Now we can write

$$dE_{Be} = (dE/dx)_{Be} \left(\frac{117}{356}\right) dx ,$$

$$dE_{Pu} = (dE/dx)_{Pu} \left(\frac{239}{356}\right) dx .$$

Taking $\frac{(dE/dx)_{Pu}}{(dE/dx)_{Be}} = K$, and assuming K is independent of energy, we can rewrite Eq. 1 as

$$\frac{Y}{N_0} = \left[\frac{(117/356)}{(117/356) + K\,(239/356)}\right] n_{Be} \int_0^{E_a} \frac{\sigma}{(dE/dx)_{Be}}\, dE .$$

This equation has been evaluated and the yield is given in Table II.

RADIUM-BERYLLIUM

The neutrons from a Ra–Be source result from the same reaction as for a Po–Be source

$$He^4 + Be^9 \rightarrow C^{12} + n$$

where the C^{12} nucleus can be left in the ground state, or the 4.43-Mev, 7.65-Mev or even higher excited levels. For radium, the situation is more complicated because there are several different α particles from the radium decay chain causing (α, n) reactions. The decay chain for Ra is shown below:

Table III

Decay chain for radium

Element	Particle emitted	α-Particle kinetic energy	T 1/2
Ra^{226}	α	4.79*	1622 Yr
Rn^{222}		4.59	
Po^{218}	α	5.48	3.8 day
Pb^{214}	α	6.00	3.0 min
Bi^{214}	β		26.8 min
Po^{214}	β		19.7 min
	α	7.68	164 μsec
Pb^{210}	β		19.4 Yr
Bi^{210}	β		5.0 day
Po^{210}	α	5.30	138 day
Pb^{206}			

*The 4.79-Mev α decay occurs 94.2% of the time, and the 4.59-Mev α decay occurs 5.7% of the time.

From this we see that α particles of energies 4.79, 5.48, 6.00, 7.68, and 5.30 Mev are produced. The 5.30 Mev α particles from Po^{210} decay do not appear until the Pb^{210} activity has built up appreciably. For a young source (≈1 month old) of originally pure radium all of the decay chain is in equilibrium except the part from Pb^{210} on. The Pb^{210} activity builds up exponentially according to the relationship

$$\frac{(dN/dt)_{Pb^{210}}}{(dN/dt)_{Ra^{226}}} = 1 - e^{-0.036\, T_{(yrs)}}.$$

From Pb^{210} on the decay chain is in equilibrium with the Pb^{210}, so that the Po^{210} particle activity builds up with a 19.4-yr half life. A Ra–Be source will increase in its neutron yield due to this effect and will reach equilibrium in about 100 years. The neutron energy spectrum has been calculated for a new (1-month-old) Ra–Be source. The cross section of Fig. 10 and the branching ratio of Fig. 11 have been used in this calculation. The extrapolations of both curves above 5.3 Mev are estimates. The extrapolation of the cross-section curve has been made to give the correct total yield. The extrapolation of the branching ratio curve is based on the fact that the measured mean energy of a Ra-Be source is 4.1 Mev.[13] If the branching ratios at 5.3 Mev are assumed to remain constant up to 7.5 Mev, the calculated Ra–Be spectrum has a mean energy of 3.8 Mev. Measurements of the mean energy give higher values. Therefore the fraction of the time that the reaction leaves C^{12} in the ground state and the 4.43 Mev-level must increase. The branching ratios that have been chosen are not unique, but they do give the correct mean energy. The calculated Ra–Be spectrum is shown in Fig. 14 with the measured spectrum of Hill.[21] Also included in the above spectrum is a 3% contribution of photoneutrons in the energy range 0 to 0.6 Mev. Figure 15 shows various measured spectra for Ra-α-Be.[21,22]

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[21] D. L. Hill, "Studies with the Ranger", AECD-1945 (rev.), April 1947.

[22] U. Schmidt-Rohr, Z. Naturforsch. 8a, 470 (1953); Pierre Demers, "Energy Distribution of Neutrons from Ra-Be Mixed Source", MP-204, Nov. 1948; and F. G. Houtermans and M. Teucher, Z. fur Physik 129 365 (1951).

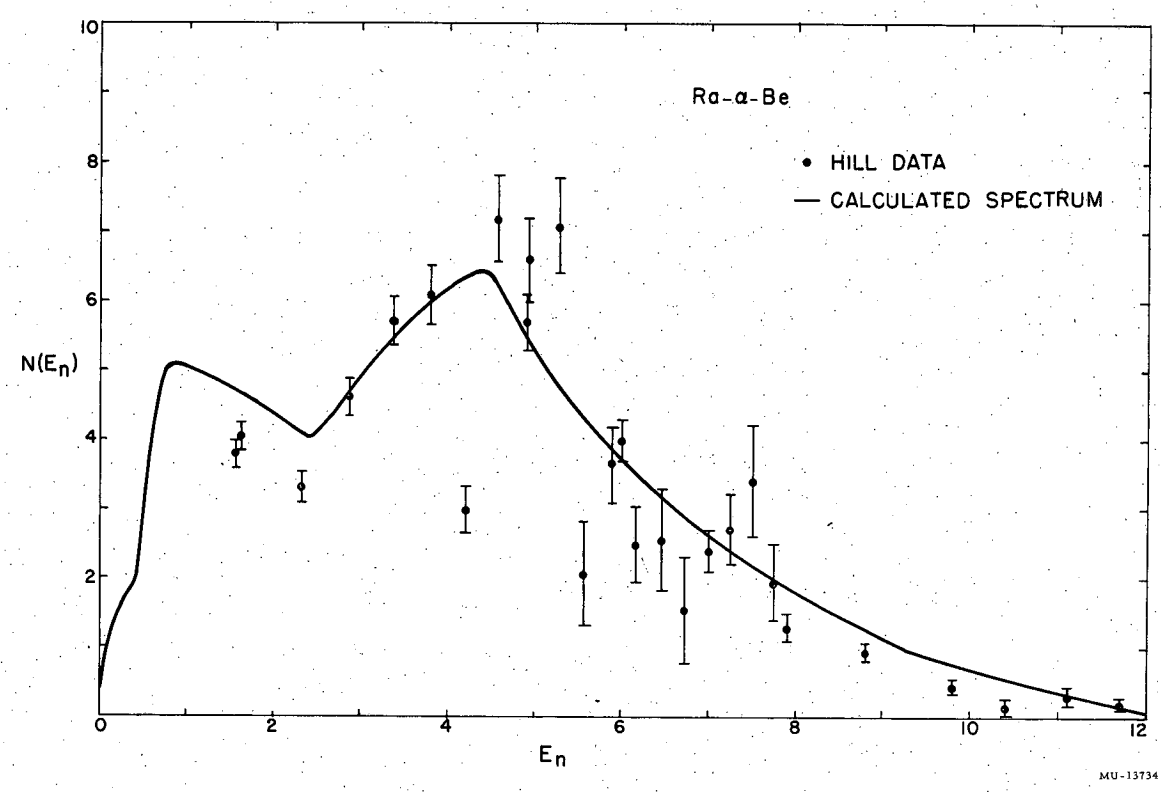

Fig. 14. Calculated neutron energy spectrum for a Ra–Be source. Shown for comparison is the data of D. L. Hill.[21]

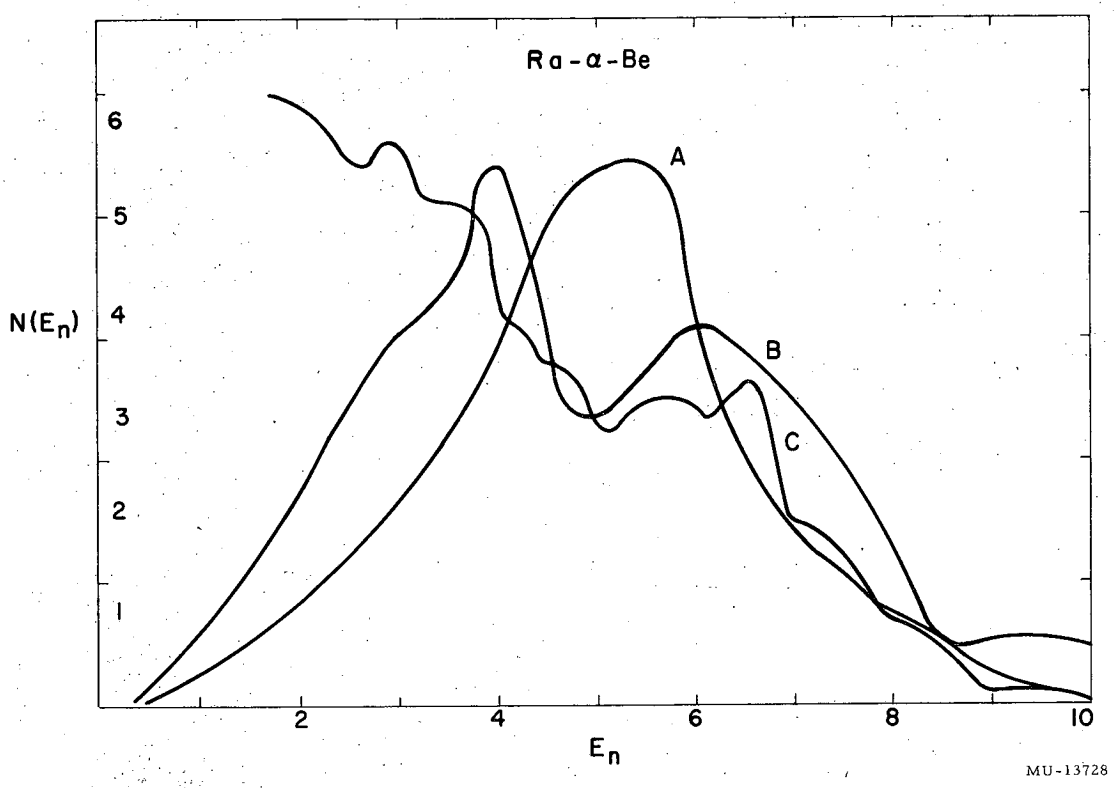

Fig. 15. Measured spectra for a Ra–Be source.[22]
Curve A. Data of P. Demers.
Curve B. Data of F. Houtermans and M. Teucher.
Curve C. Data of U. Schmidt-Rohr.

It is known that photoneutrons contribute part of the yield from a Ra–Be source. Feld and Fermi found 30,000 neutrons per gram of Ra per gm of Be due to the gamma rays from Ra and its decay products at a distance of 1 cm.[23] The threshold for a (γ, n) reaction on Be is 1.63 Mev. There are gamma rays of 1.76 Mev and 2.20 Mev to make photoneutrons of energies up to 0.6 Mev.

When the Ra and Be are intimately mixed, the yield of photoneutrons increases because the flux of gamma rays seen by the Be is increased. To estimate how large an effect this is, let us consider a source made of 1 gm Ra and 4 gms of Be. We will assume no attenuation of the gammas through the Be; this is reasonable because the mean free path for 2-Mev gamma rays in Be is about 20 g/cm^2. We can find the mean distance from the Ra source to the Be for a 4-gm sphere of Be around the Ra. The radius of this sphere is 0.80 cm. We must weight the distance to the element of volume under consideration by the magnitude of the gamma flux F at the point, because the number of neutrons formed is proportional to this flux. Accordingly, we have

$$\overline{R^2} = \frac{\int r^2 F\, dV}{\int F\, dV} = \frac{\int_0^{0.80} r^2 \left(\frac{k}{r^2}\right) 4\pi r^2\, dr}{\int_0^{0.80} \left(\frac{k}{r^2}\right) 4\pi r^2\, dr} = 0.21 .$$

If we put all the Be in a hemisphere on one side of the Ra source, we get $\overline{R^2} = 0.34$. The average situation is intermediate between these. We will take $\overline{R^2} = 0.25$. This gives the yield of photoneutrons from our source, 30,000 x 1 x 4 x (1/.25) = 480,000 neutrons/sec. The total output of a 1-g Ra–Be source is 1.5×10^7 neutrons/sec. Therefore the photoneutron yield is 3% of the total yield.

The yield for Ra-α-Be has been calculated for the several different particles present using the cross section of Halpern extrapolated up to 7.7 Mev. As with Pu-α-Be, the yield is decreased because of the relatively large amount of Ra in the source. Here the yield is

$$Y = \left(\frac{4}{4+K}\right) n_{Be} \int_0^{E_\alpha} \frac{\sigma}{(dE/dx)\, dE} .$$

[23] B. Feld, and E. Fermi "Neutrons Emitted by a Radium-Beryllium Photosource." MDDC-1438, Nov. 1948.

POLONIUM-FLUORINE

Fluorine has been used as a neutron source both as Po-α-BF_3 and as one component in a "mock fission" source. The energy spectrum and yield of a Po-α-BF_3 source has been measured by Richards.[24] His source was a cylinder coated inside with Po and filled with BF_3 gas.

Using the already described technique, we calculated the spectrum of a Po-α-F source. This spectrum, shown in Fig. 16, can be combined with the spectrum shown in Fig. 6 for Po-α-B to get the spectrum of a BF_3 source, using yields from Table I of 22 for B and 11 for F. This is shown in Fig. 17 and compared with the data of Richards for comparison.

The yield of Po-α-F has been measured by Roberts[5] (see Table II) and the yield of Po-α-BF_3 has been measured by Richards.[24] From the neutron yield from F and from B, we can get the yield from BF_3. Somewhat more than half of the alphas from Richards' source did not get into the BF_3 gas but hit the cylinder walls (let us assume 60% do not get into the gas). Therefore, for Richards 30-mC source giving 0.6×10^4 neutrons/sec, we get 13.5 neutrons/10^6 alphas. Weighting the yield from B and from F according to their individual yields and the number of atoms of each present, we get

$$Y_{BF_3} = 0.60\ Y_F + 0.40\ Y_B = 15.4\ \frac{\text{neutrons}}{10^6\ \alpha}\ .$$

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[24] H. T. Richards, "Po Alphas on BF_3 as a Neutron Source" MDDC-472, May 1944.

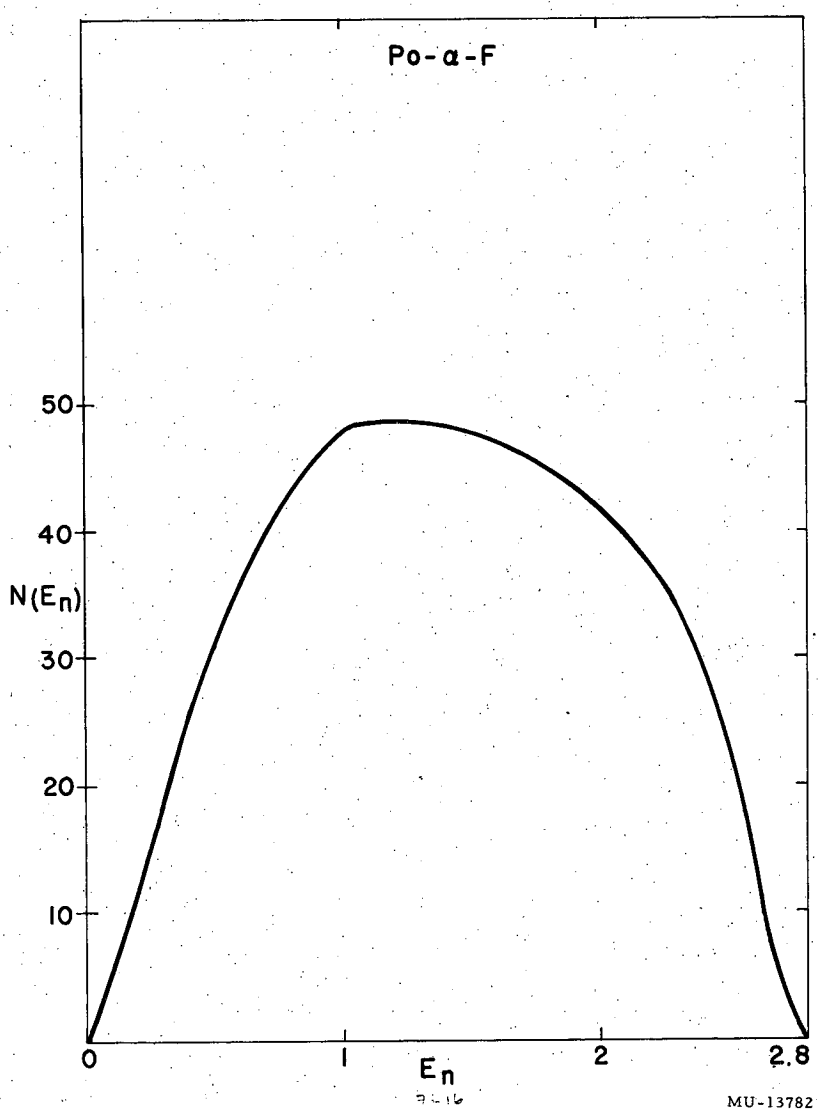

Fig. 16. Calculated neutron energy spectrum for a Po–F source.

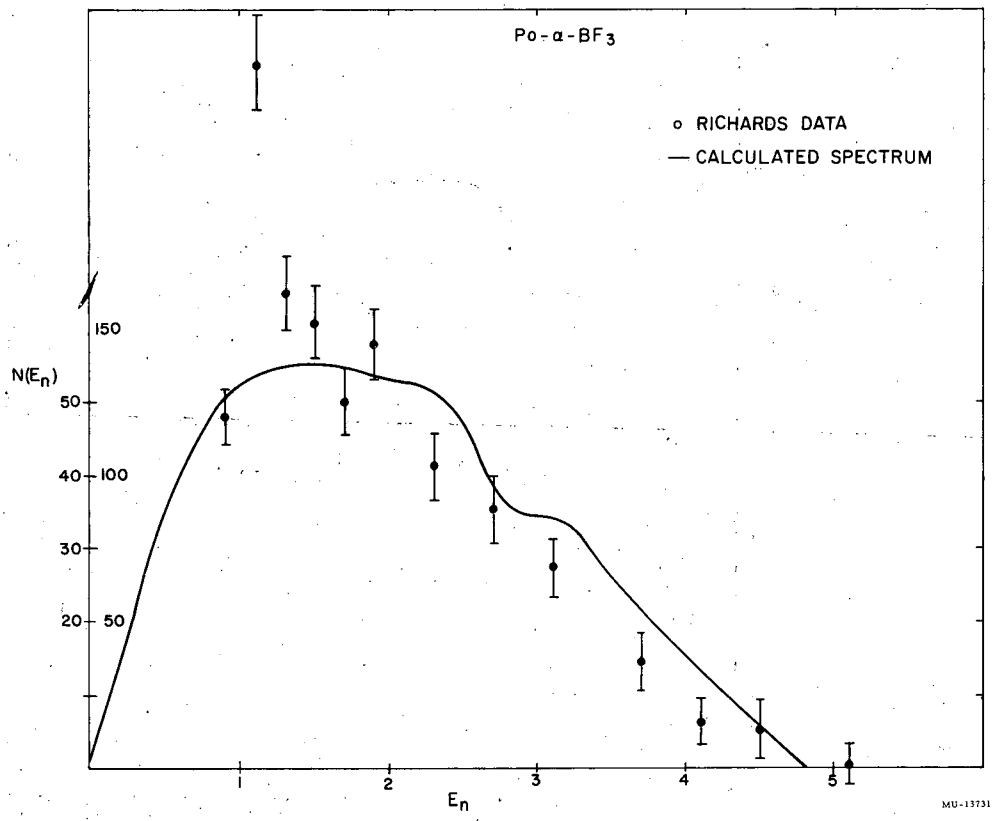

Fig. 17. Calculated and measured neutron energy spectra for a Po-BF_3 source.

MOCK FISSION

Neutron sources are now made having a neutron energy spectrum resembling a fission source. These sources use Po as the alpha emitter and a mixture of light elements to get the proper neutron spectrum. Using the manufacturer's data about the relative yields of the different components in one such source,[25] and using the neutron energy spectra calculated in this report, we have computed the neutron energy spectrum of a mock fission source. This is shown in Fig. 18. Shown for comparison is the fission neutron energy spectrum.[26] The agreement is fairly good. Above 5 Mev there are considerably too few neutrons in the mock fission source.

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[25] Private communication to Mr. W. Phillips from J. L. Richmond. A Mound Laboratory mock fission source (Mix A) had the following yields

Element	Neutrons/10^6 alphas
Be	0.28
B	2.28
Li	0.90
F	6.72

[26] B. E. Watt, Phys. Rev. 87, 1037 (1952).

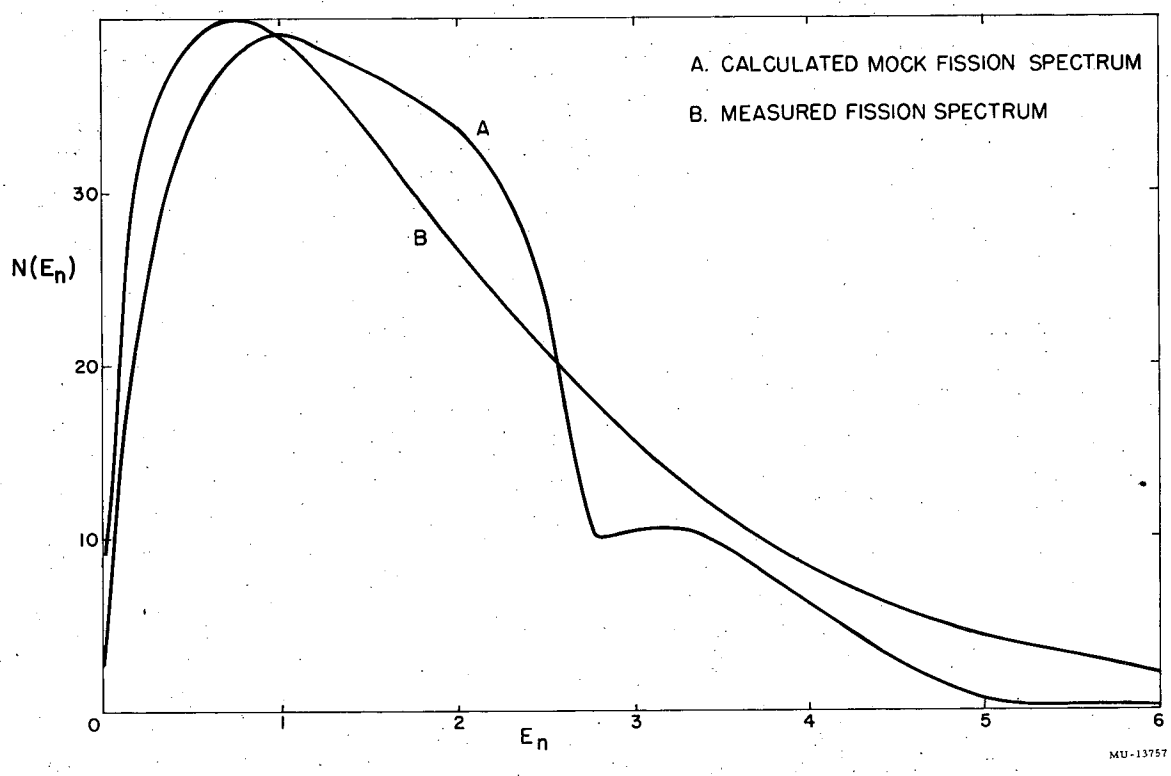

Fig. 18. Calculated neutron energy spectrum of a mock fission neutron source. Shown for comparison is the energy spectrum of fission neutrons.