Title
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Publication Date
1957-12-16

UCRL 3839 Rev.

UNIVERSITY OF CALIFORNIA

Radiation Laboratory

BERKELEY, CALIFORNIA

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UCRL-3839 Rev.

UNIVERSITY OF CALIFORNIA
Radiation Laboratory
Berkeley, California
Contract No. W-7405-eng-48

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Printed for the U.S. Atomic Energy Commission

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ABSTRACT

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

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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, and Pu-Be have been used as (α, n) sources. Several experiments have been performed to measure the energy spectra from these various sources, but the experiments are quite difficult to do accurately and there has been considerable disagreement on the shapes of some of the spectra. Because of the disagreement and because of the considerable interest in these sources it was decided to calculate the energy spectra of the neutrons emitted from them.

NEUTRON YIELDS

The yield of neutrons from an (α, n) reaction can be calculated in a straightforward fashion. For reasonable values of the inelastic cross sections almost all alpha particles will slow down and stop before interacting. In thickness dx at x we have $n\sigma$ dx interactions, each producing one neutron. If σ is

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*This work was done 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. (London) 149A, 552 (1935).

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 is then

$$Y = \int_0^{R_\alpha} N(x)\, n\sigma\,(E)\, dx = n\, N(0) \int_0^{E_\alpha} [\sigma(E)/(dE/dx)]\, dE. \qquad (1)$$

NEUTRON ENERGY SPECTRA

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

$$E'_n = (M_F/[M_F + M_n])\ (E_\alpha [M_T/(M_T + M_\alpha)] + Q)\ . \qquad (2)$$

Transforming to the laboratory system, we get

$$E_n = E'_n + \left[M_\alpha M_n/(M_T + M_\alpha)^2\right] E_\alpha + [2M_n\, M_\alpha/(M_T + M_\alpha)]\ (E_\alpha E_n/M_\alpha M_n)^{\frac{1}{2}}$$
$$\times \cos\ \theta_{c.m.}\ . \qquad (3)$$

From this we can get the observed neutron spectrum in the laboratory system if we assume that the angular distribution of neutrons emitted in the center-of-mass system 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

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

$$d\Omega = 2\pi \sin \theta_{c.m.} \, d\theta_{c.m.} , \tag{4}$$

therefore the probability $N(E_n)$ of finding a neutron of energy E_n is proportional to $\sin \theta_{c.m.}$. From Eq. (3) and (4) we get the neutron energy distribution (lab) for a monoenergetic alpha particle. (See, for example, Curve A of Fig. 1, which is the spectrum of neutron energies (lab) 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 approximate this slowing down by using several monoenergetic α particles of different energies (instead of the actual continuum of α-particle energies) and calculate the spectrum with this approximation. Then we have

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

$$= n \left[E_1 \left(\frac{\sigma(E)}{(dE/dx)} \right)_{\frac{E_1}{2}} + (E_2 - E_1) \left(\frac{\sigma(E)}{(dE/dx)} \right)_{\frac{E_1 + E_2}{2}} + \dots \right. \tag{5}$$

$$\left. \dots + (E_\alpha - E_m) \left(\frac{\sigma(E)}{(dE/dx)} \right)_{\frac{E_\alpha + E_m}{2}} \right] .$$

We can calculate the spectra for neutron energy (lab) for monoenergetic alpha particles of the several mean energies, E_1, $(E_1 + E_2)/2$, . . . $(E_\alpha + E_m)/2$, used in Eq. (5). The areas under these spectra, which are the neutron yields, are weighted by the factors W:

$$W\left(\frac{E_m + E_{m+1}}{2} \right) = (E_{m+1} - E_m) \left(\frac{\sigma}{(dE/dx)} \right)_{\frac{E_m + E_{m+1}}{2}} . \tag{6}$$

Adding the contributions from the various monoenergetic α particles, we get the neutron energy spectrum (lab). This procedure has been carried out for

the

the several (α, n) sources considered here.

The measured neutron energy spectrum may be somewhat different from the calculated energy spectrum even though 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 because of 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. If elastic scattering (c.m.) is isotropic, 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 the dips in the spectra (such as the one at 6 Mev for Po-α-Be in Fig. 10A) are partially filled in. For typical sources, 20 to 30 % of the neutrons may scatter before emerging.

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 $\sigma_{\alpha + B \rightarrow N + n}$, where n is the number of atoms/gm of B in the source. This cross section has been measured experimentally.[6] 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 I.

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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, Revs. Modern Phys. 25, 790 (1953).

Table I

Yields of (α, n) neutron sources

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

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[a] This yield is for a source containing 4.5 g of Be and 1 g of Ra.

[b] Data calculated in this report.

This yield has been calculated for a natural isotopic mixture of boron; 10% 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 alpha particle (5.30 Mev) emitted by Po. In the final nucleus, N^{14}, the ground level is probably the only energy level that is involved in the reaction $\alpha + B^{11} \to n + N^{14}$. The first excited state of N^{14} at 2.31 Mev may make some contribution. The reaction $\alpha + B^{10} \to n + N^{13}$ also involves only one energy level in the final nucleus, the ground level.

Following the scheme given earlier, we have calculated the laboratory system 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. 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 resultant neutron energy spectrum is shown in Fig. 2 for 0%, 10%, and 20% of the total yield coming from the excited state of N^{14}. The heights of the curves of Fig. 1 have been added to give the resultant energy spectrum shown in Fig. 2.

The energy spectrum for polonium α particles on B^{10} has been calculated by the same method and is shown in Fig. 3. In the calculation we have assumed $\sigma_{\alpha + B^{n} \to N + n} = \sigma_{\alpha + B^{10} \to N^{13} + n}$.

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. 4. 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 an (NON-) isotropic c.m. angular distribution of the neutrons, the calculations outlined above have been repeated for B^{11} for two quite extreme cases, for a $\cos^2 \theta$ angular distribution and for a $\sin^2 \theta$ angular distribution. These two curves and the curve for an isotropic angular distribution are shown in Fig. 5 normalized to the same height. The widths of the spectra are changed somewhat by the angular distribution, but the effect is small enough that an isotropic angular distribution can be used for all following calculations.

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

POLONIUM-LITHIUM

The spectrum of neutrons from a Po-α-Li source (Fig. 6) has been measured by Barton, using a low-pressure hydrogen-filled diffusion cloud chamber.[9] The average energy of the same source as used by Barton has been measured by Young[10] and found to be about 250 kev by the method of determining the optimum thickness of polyethylene to put around a BF_3 counter. The neutrons from polonium α particles interacting 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 energy of the resulting neutrons is a few hundred kev. The ground state is the only 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 very nearly $1/V_n$ 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

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

$$= 0.437 \; \frac{E_n'}{E_\alpha'} \; .$$

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[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).

where both energies are in the c.m. system. The values of the cross section obtained this way are shown in Fig. 7. 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, and assuming an isotropic c.m. angular distribution, we calculate the lab spectra. These spectra are weighted and added to get the resultant neutron spectrum for Po-Li shown in Fig. 6.

Good-geometry attenuation measurements with polyethylene attenuators and a Hansen and McKibben counter and using a Po-α-Li source have been performed by Hess and Smith.[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. First, polonium does not alloy with Li (or B or Be), therefore a mechanical mixture is used in these sources. If the diameter of a polonium particle is an appreciable fraction of an alpha-particle range, then fewer high-energy alpha particles are available to make the (α, n) reaction than has been assumed. This results in a decreased yield of high-energy neutrons. Secondly, in Barton's experiment there is the problem of wall scattering. If neutrons that had scattered from the walls of the cloud chamber (and had lower energies than the unscattered neutrons) had been detected, the spectrum would be in error. These scattered neutrons cannot, in general, be separated from unscattered neutrons. The fraction of such events is hard to estimate, but is probably significant.

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

POLONIUM-BERYLLIUM

This is one of the most frequently used neutron sources for laboratory work, because of the high yield and relatively small number of γ rays. Sources containing Po, which has a 138-day half life, do not last very long.

For this source, the reaction involved is

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

The final nucleus C^{12} can be in the ground state or the 4.43- or 7.65-Mev energy level. Risser, Price, and Class give cross-section values 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.[14] Halpern gives values for the cross section for the reaction $Be^9 (\alpha, n)C^{12}$ for all conditions of the final nucleus C^{12}.[15] The difference between the Halpern and Risser cross sections is then the cross section for the reaction in which the C^{12} nucleus is left in the 7.65-Mev level or in some other highly excited condition. The cross sections obtained in this way are shown in Fig. 8. The related branching ratios are shown in Fig. 9. 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. 10. The difference cross section may be due to multibody breakup of the compound nucleus C^{13} rather than the effect of the 7.65-Mev level of C^{12}. This multibody breakup is an appreciable effect for the reaction $p + C^{12} \rightarrow 3He^4$ at 30 Mev.[16] In our work, we may have been observing neutrons from the reaction $He^4 + Be^9 \rightarrow n + Be^8 + He^4$. This three-body breakup 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. 9, and assuming that 80% of the difference cross section goes into three-body breakup and the remaining 20% goes to excite the 7.65-Mev C^{12} level, we derive Curve B of Fig. 10.

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

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

[15] I. Halpern, Phys. Rev. <u>76</u>, 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.

Smith show that Curve A of Fig. 10 is nearer the correct spectrum than Curve B.[13] This says that for 5.3-Mev α particles on Be the "difference" cross section is accounted for by C^{12} left in the 7.65-Mev excited state rather than by three-body breakup of the C^{12} nucleus.

The effect of neutrons scattering on the way out of the source material (discussed earlier) has been calculated on the assumption that 20% of the emerging neutrons scatter once. The neutron spectrum modified by scattering is shown in Curve C of Fig. 10. 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. 11. 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 Po-α-Be neutron energy spectrum at about 6 Mev. 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. 10). 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. 10.

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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; Eilliot, McGarry, and Faust, 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, Revs. Modern Phys. 24, 321 (1952). See also Guier, Bertini, and Roberts, Phys. Rev. 85, 426 (1952).

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 I) by use of Eq. (1) and the cross section from Halpern.[15]

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 whereas Po and Ra can only be mechanically mixed.

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, whereas Po has one alpha particle 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. 12. Also shown is the spectrum measured by Stewart, which agrees reasonably well.[20] In these calculations the "difference" cross section is assumed to be attributable to the 7.65-Mev excited state of C^{12}. The dip in the energy spectrum for Po-α-Be at 6 Mev must also exist for Pu-α-Be. In fact, the dip must be deeper here because the alpha-particle energies are lower.

The neutron yield from Pu-α-Be has been measured[20] and also is calculated here. There is enough Pu in the source 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. The yield is thus decreased.

In this case, Eq. (1) becomes

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

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[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).

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

Taking $(dE/dx)_{Pu}/(dE/dx)_{Be} = K$, and assuming that K is independent of energy, we can rewrite Eq. (1) for a Pu-Be$_{13}$ source as

$$Y/N_0 = [1.0/(1.0 + 2.0\ K)]\ n_{Be} \int_0^{E_\alpha} [\sigma/(dE/dx)_{Be}]\ dE.$$

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

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 in 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 in Table II. 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) or originally pure radium all the decay chain is in equilibrium except the part from Pb^{210} on. The Pb^{210} activity builds up exponentially according to the relationship.

$$(dN/dt)_{Pb^{210}} / (dN/dt)_{Ra^{226}} = 1 - \exp(-0.036\ T),$$

where T is in years. From Pb^{210} on the decay chain is in equilibrium with the Pb^{210}, sotthat the Po^{210} particle activity builds up with a 19.4-yr half life. A Ra-Be source increases its neutron yield because of this effect, and reaches equilibrium in about 100 years. The neutron energy spectrum has been calculated for a new (1-month-old) Ra-Be source. The cross sections of Fig. 8 and the branching ratios of Fig. 9 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 extrapolations of the branching ratio curves are based on the fact that there is a

Table II

Decay chain for radium

Element	Particle emitted	α-Particle kinetic energy (Mev)	$T_{\frac{1}{2}}$
Ra^{226} Rn^{222}	α	4.79* 4.59	1622 yr
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} Pb^{206}	α	5.30	138 day

*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.

considerable yield of low-energy neutrons from Ra-Be which does not seem to be present in Po-Be.[13, 21] Using the branching ratios above 5.3 Mev as shown in Fig. 9 and assuming that the "difference" cross section is accounted for by three-body breakup gives the energy spectrum shown in Fig. 13 shown for comparison are the data of Hill.[22] This spectrum is consistent with the CH_2 attenuation measurements by Hess and Smith[13] and also has about the right average neutron energy. The branching ratios could be changed somewhat without altering the agreement of the spectrum with experiments, but not too much. Also included in the above spectrum is a 3% contribution of photoneutrons in the energy range 0 to 0.6 Mev. The neutrons in the low-energy peak should, if anything, be lowered in energy for better agreement with the CH_2 attenuation curves.[13] Figure 14 shows various measured spectra for Ra-α-Be.[22, 23]

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 gram of Be due to the gamma rays from Ra and its decay products at a distance of 1 cm.[24] 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.

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[21] J. DePangher, private communication.

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

[23] 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. Physik 129, 365 (1951).

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

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 g Ra and 4 g Be. We 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-g sphere of Be around the Ra. The radius of this sphere is 0.80 cm. We must weigh 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

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

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 × 1 × 4 × (1/0.25) = 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

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

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Figure Captions

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

Curve A. $E_{\alpha} = 4.80$ going to ground state of N^{14}
Curve B. $E_{\alpha} = 3.80$ going to ground state of N^{14}
Curve C. $E_{\alpha} = 2.80$ going to ground state of N^{14}
Curve D. $E_{\alpha} = 1.80$ going to ground state of N^{14}
Curve E. $E_{\alpha} = 4.71$ going to first excited state of N^{14}
Curve F. $E_{\alpha} = 3.54$ going to first excited state of N^{14}.

Fig. 2. Neutron energy spectrum calculated for a Po-B^{11} source.

Fig. 3. Neutron energy spectrum calculated for a Po-B^{10} source.

Fig. 4. Neutron energy spectrum calculated for a Po-natural B source and several experimental spectra.

Fig. 5. Neutron energy spectrum calculated for a Po-B^{11} source for three different angular distributions of neutrons in the c.m. system.

Fig. 6. Calculated and measured neutron energy spectra for a Po-Li source.

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

Fig. 8. Cross sections for the reaction $He^{4} + Be^{9} \rightarrow C^{12} + n$.

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

Fig. 10. 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.

Fig. 11. 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.

Fig. 12. Calculated and measured neutron energy spectra for a Pu-Be source.

Fig. 13. Calculated neutron energy spectrum for a Ra-Be source. Shown for comparison are the data of D. L. Hill.[21]

Fig. 14. 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.

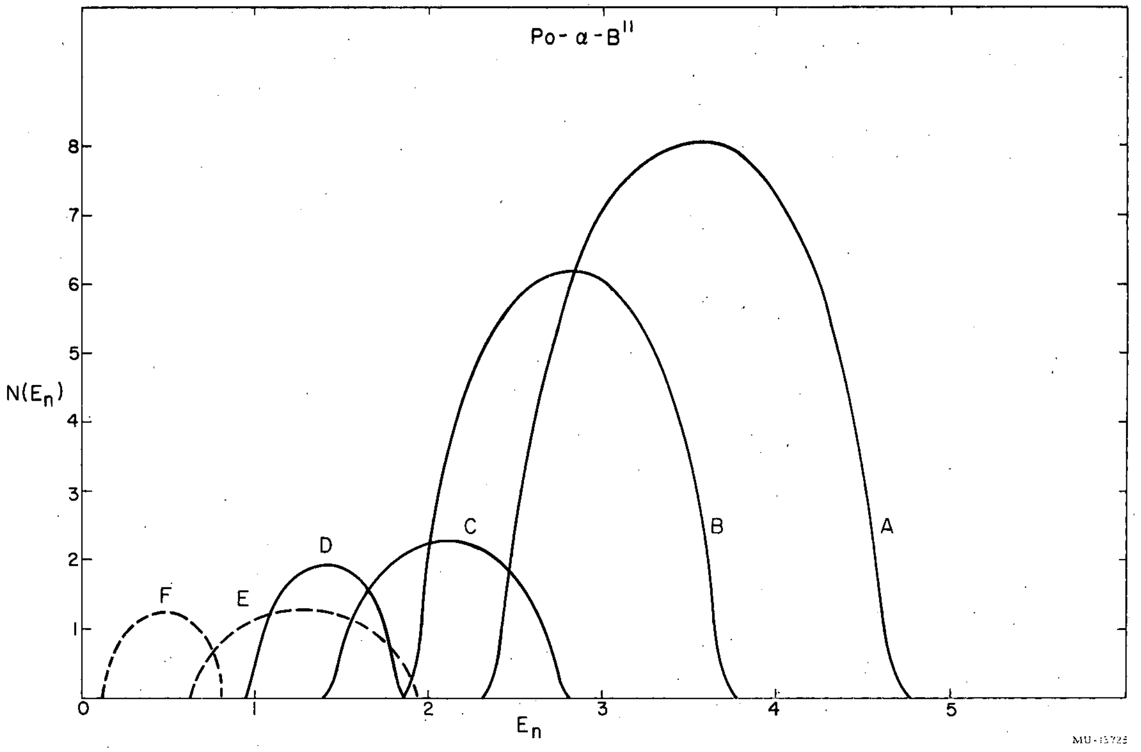


Fig. 1.

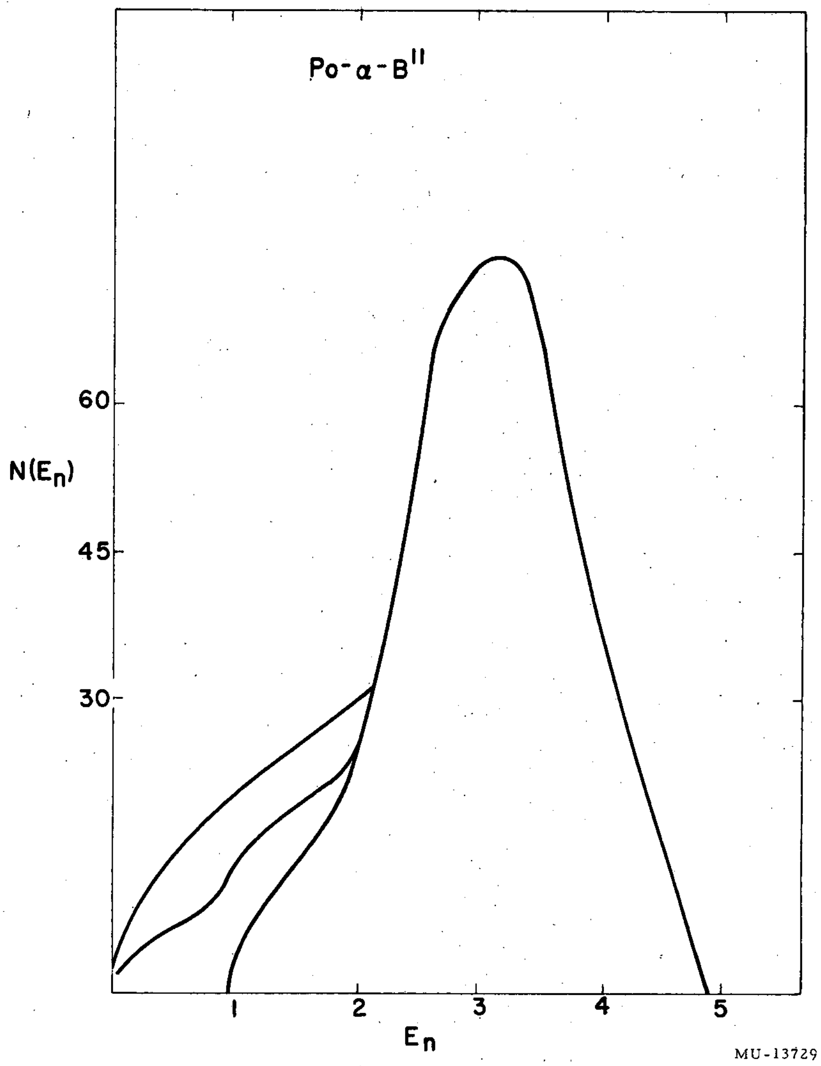
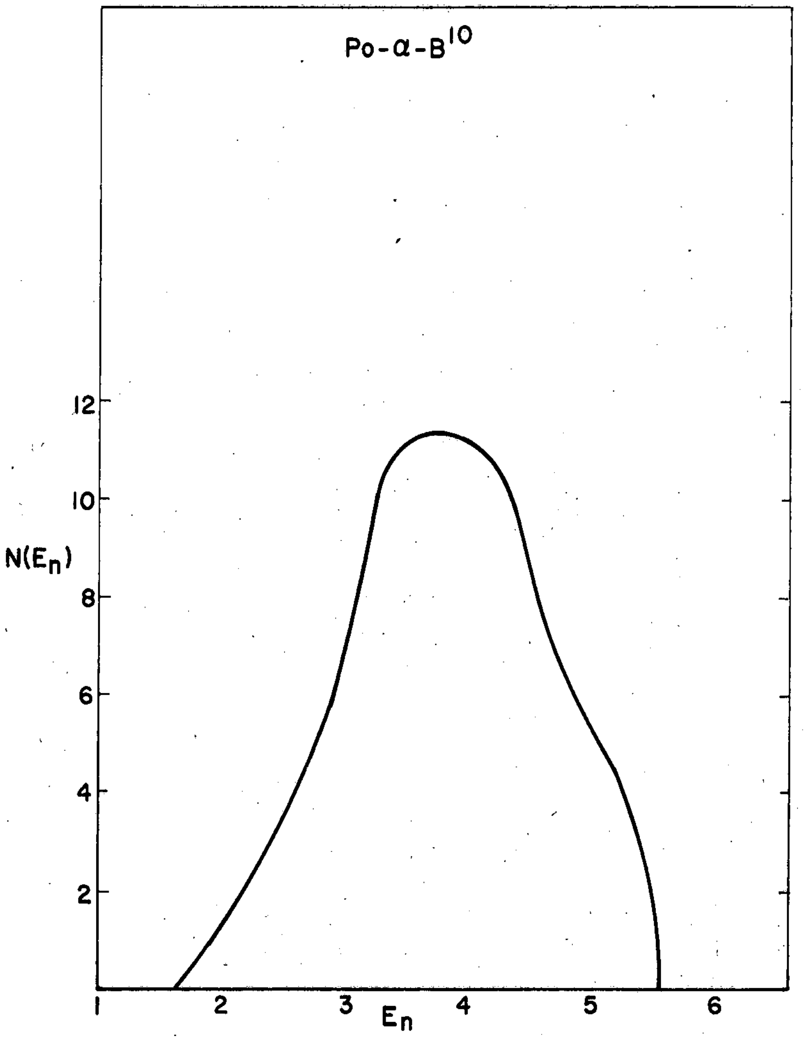


Fig. 2.



MU-13727

Fig. 3.

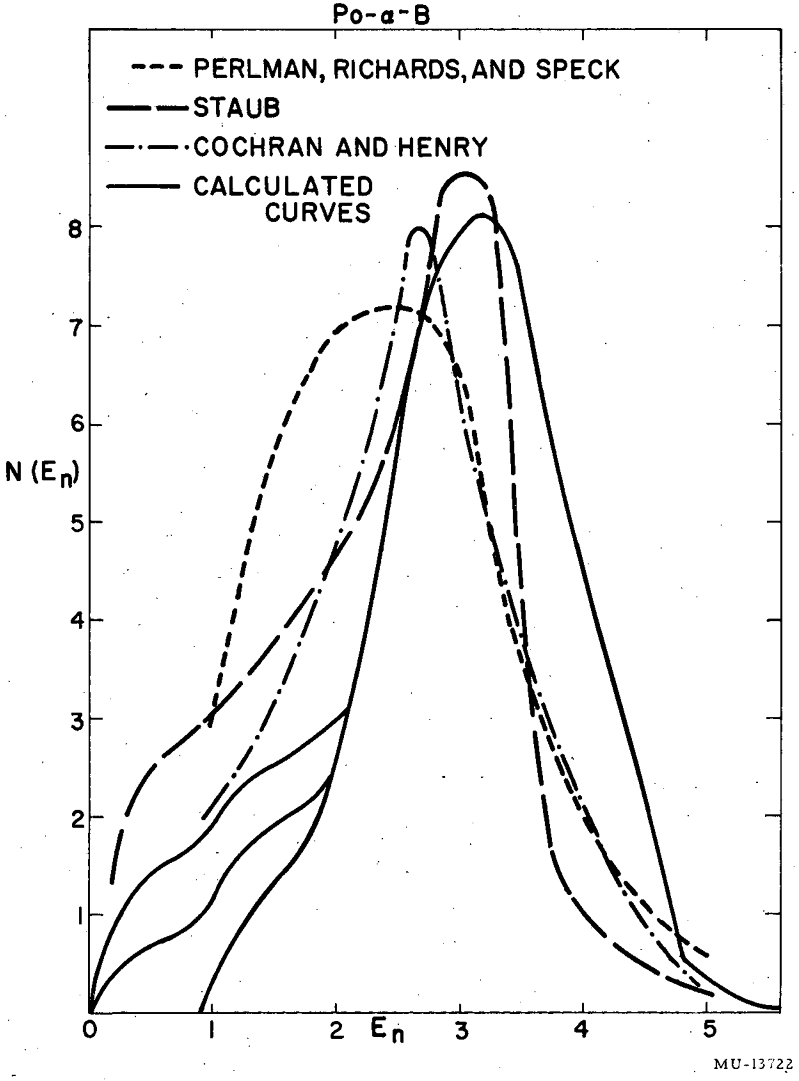

Po-α-B
PERLMAN, RICHARDS, AND SPECK
STAUB
COCHRAN AND HENRY
CALCULATED CURVES
N (E_n)
E_n
0
1
2
3
4
5
6
7
8
MU-13722

Fig. 4.

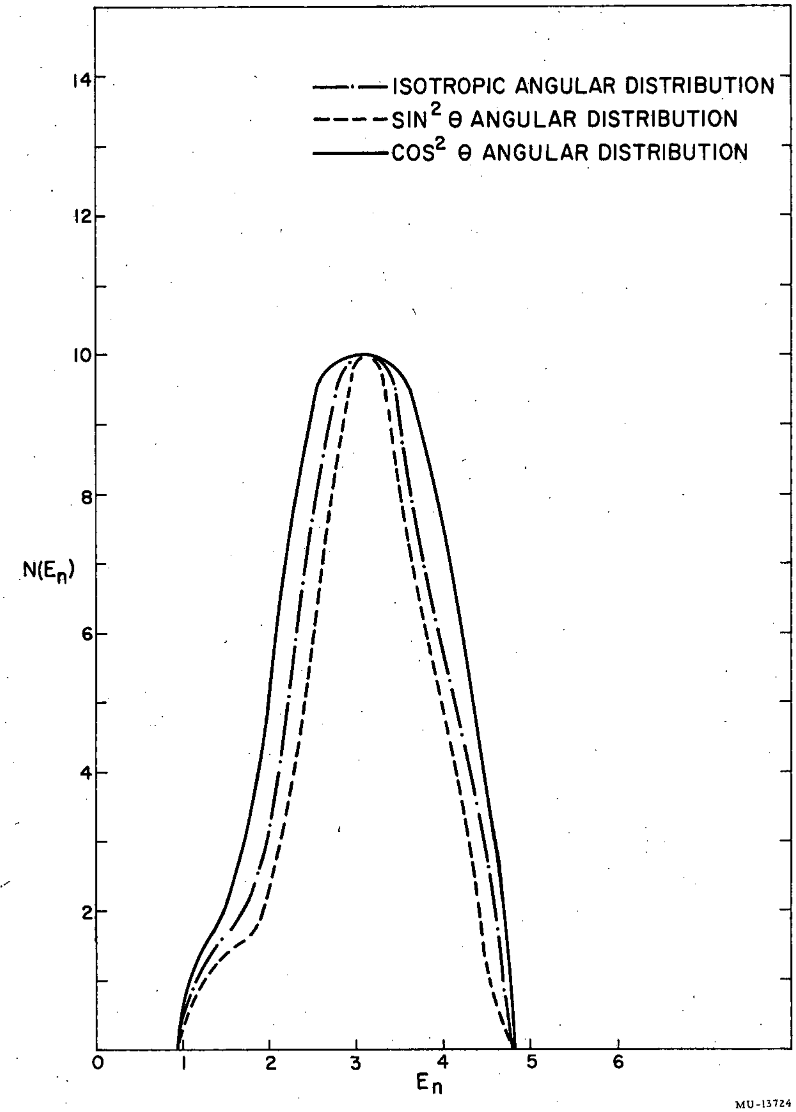

ISOTROPIC ANGULAR DISTRIBUTION
$\sin^2 \theta$ ANGULAR DISTRIBUTION
$\cos^2 \theta$ ANGULAR DISTRIBUTION
N(E_n)
14
12
10
8
6
4
2
0
1
2
3
4
5
6
E_n
MU-13724

Fig. 5.

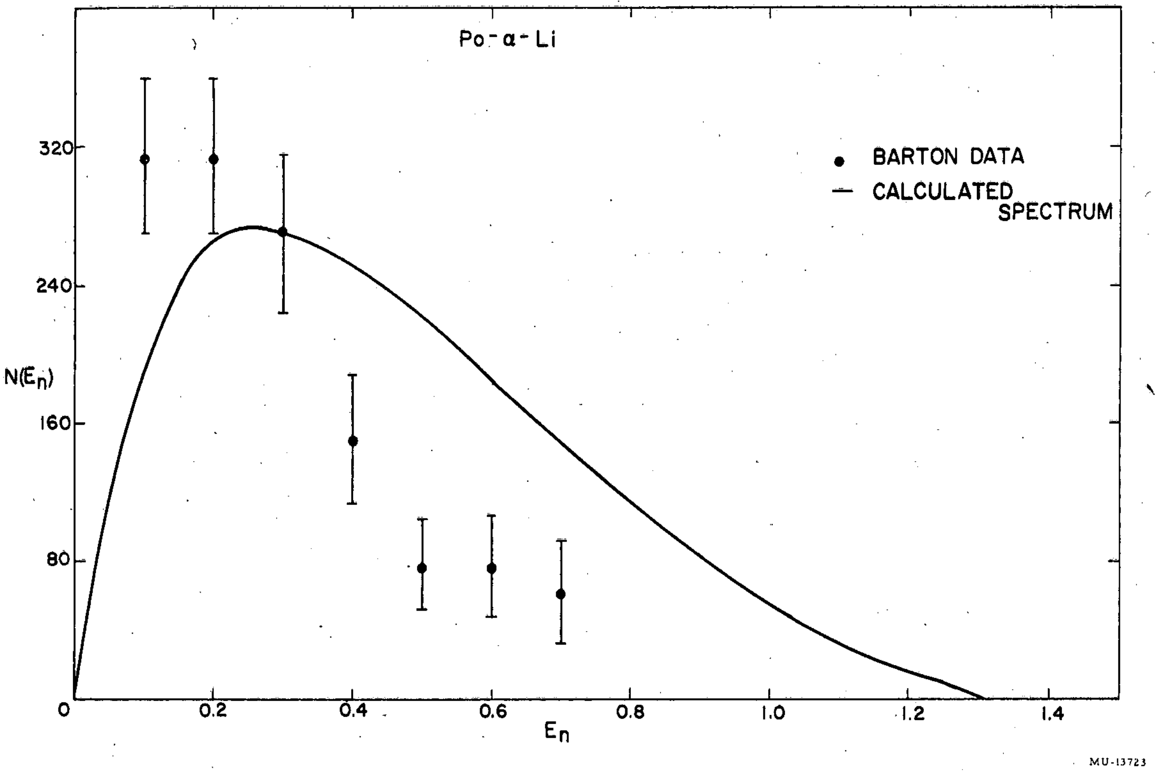

Po-α-Li
● BARTON DATA
— CALCULATED SPECTRUM
N(E_n)
320
240
160
80
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
E_n
MU-13723

Fig. 6.

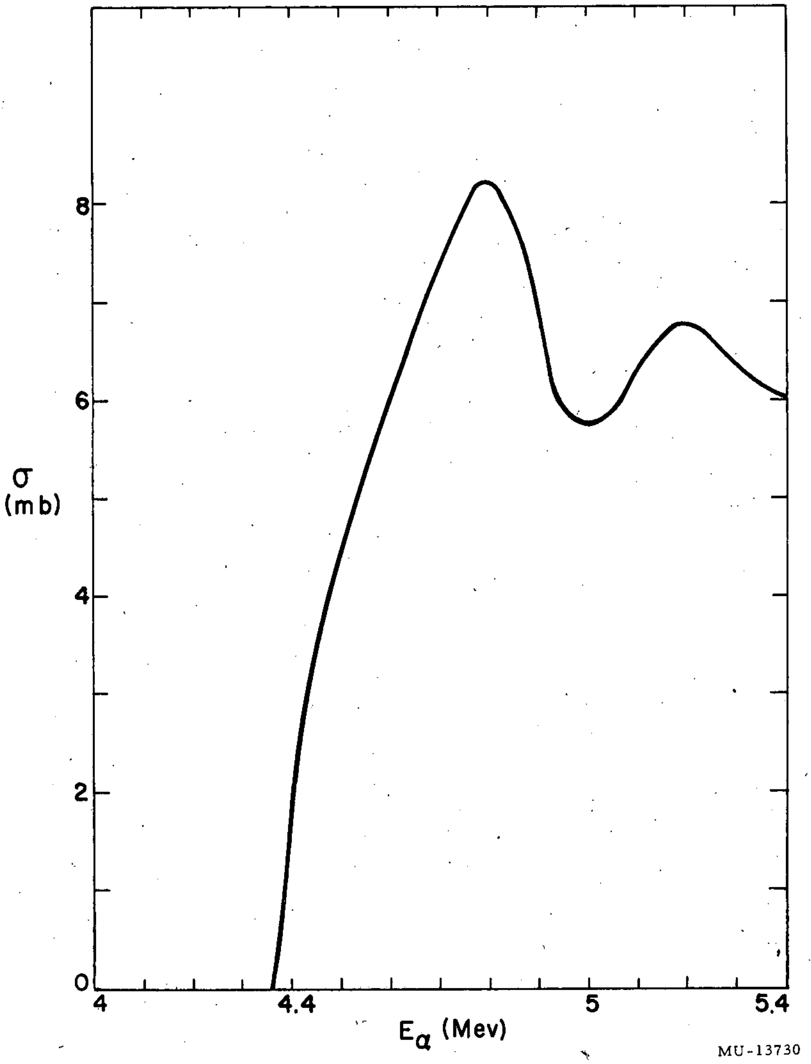


Fig. 7.

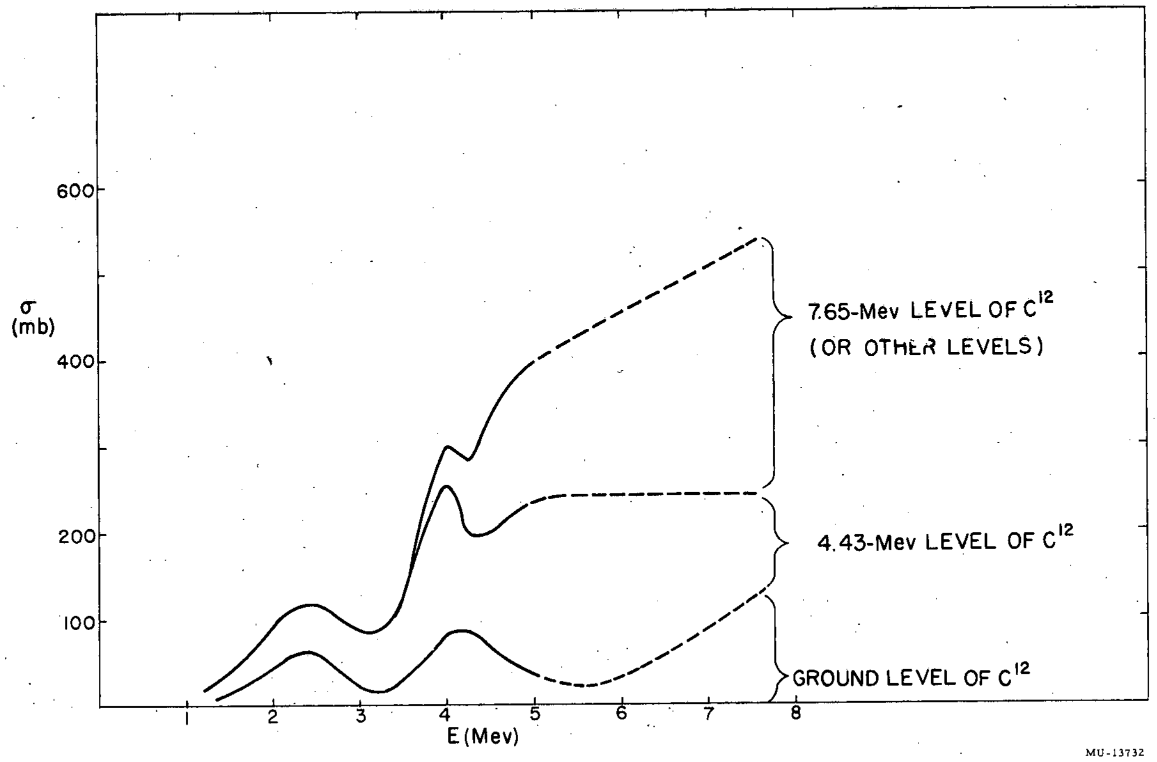

σ (mb)
600
400
200
100
1
2
3
4
5
6
7
8
E (Mev)
7.65-Mev LEVEL OF C12 (OR OTHER LEVELS)
4.43-Mev LEVEL OF C12
GROUND LEVEL OF C12
MU-13732

Fig. 8.

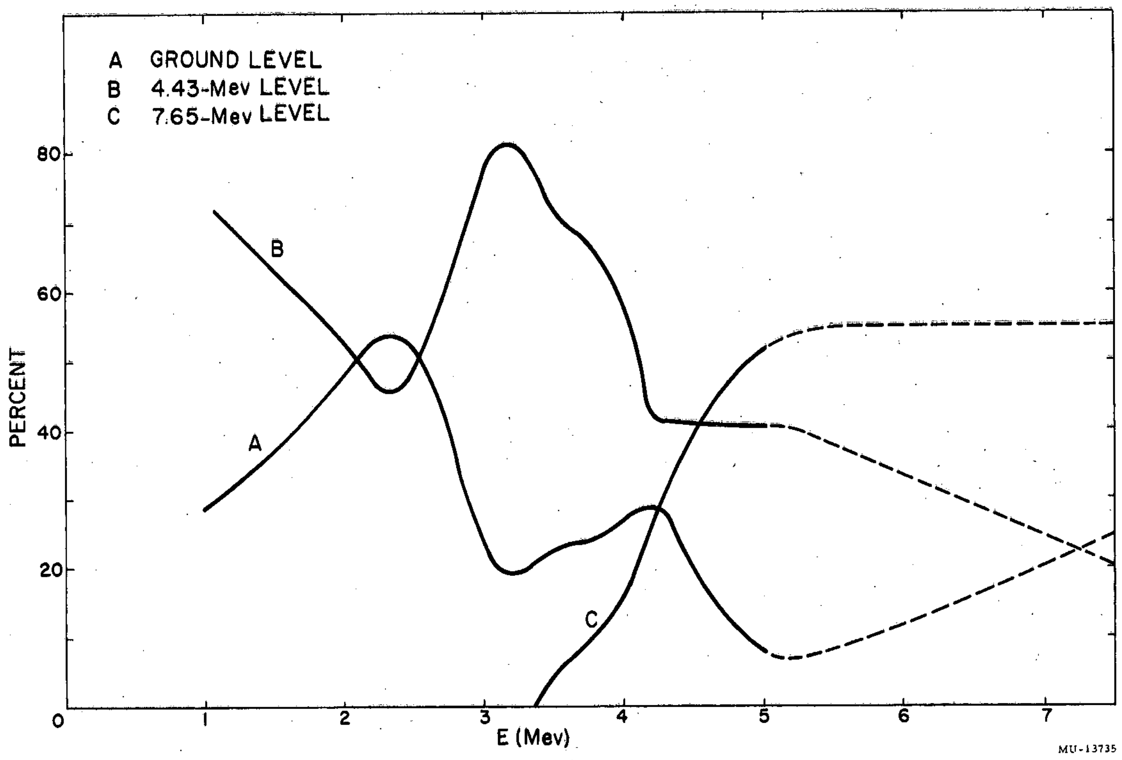

A GROUND LEVEL
B 4.43-Mev LEVEL
C 7.65-Mev LEVEL
PERCENT
80
60
40
20
0
1
2
3
4
5
6
7
E (Mev)
A
B
C
MU-13735

Fig. 9.

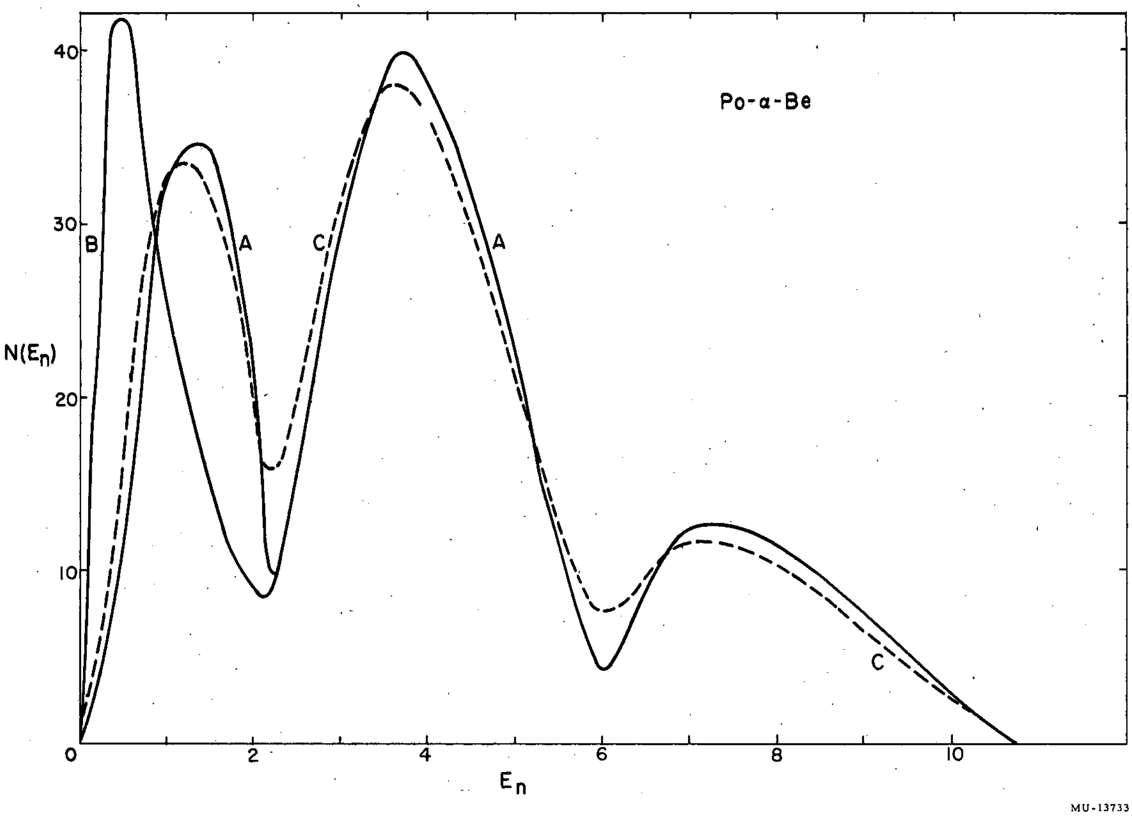


Fig. 10.

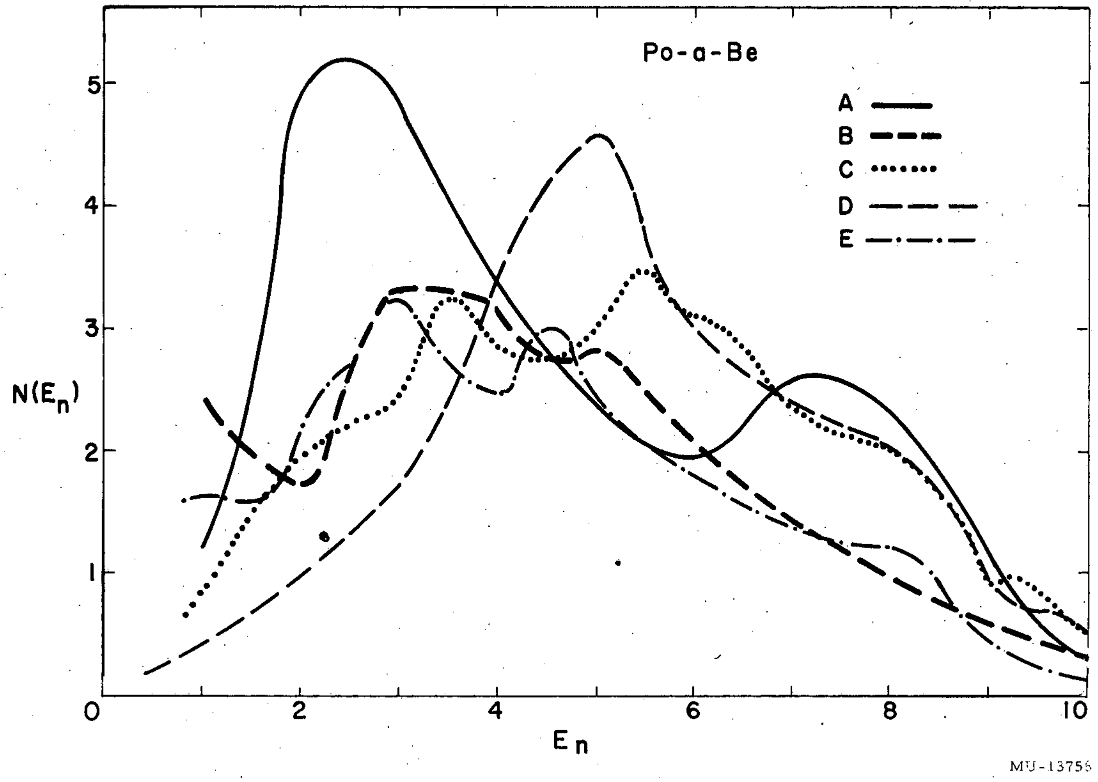


Fig. 11.

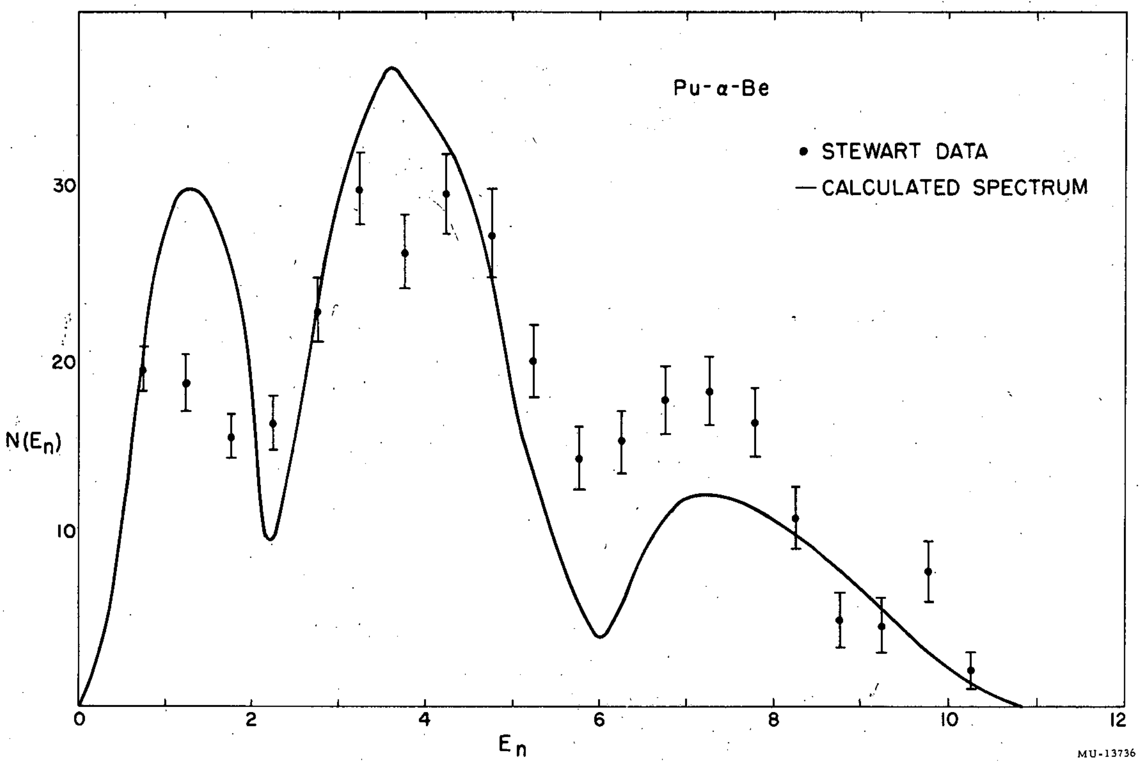

Pu-α-Be
● STEWART DATA
— CALCULATED SPECTRUM
N(E_n)
30
20
10
E_n
0
2
4
6
8
10
12
MU-13736

Fig. 12.

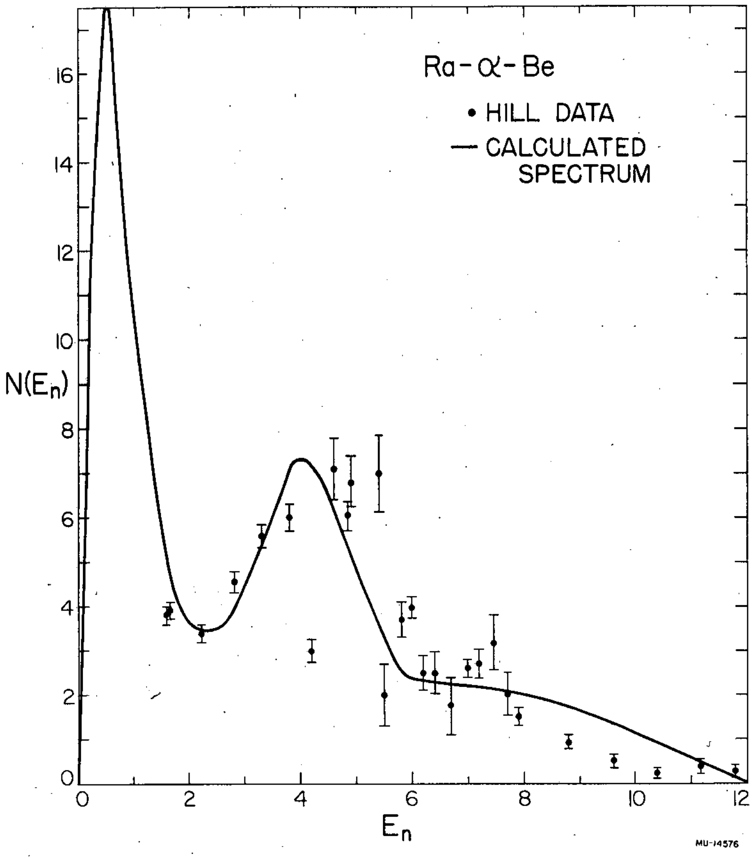

Ra-α-Be
• HILL DATA
— CALCULATED SPECTRUM
N(E_n)
E_n
0
2
4
6
8
10
12
14
16
MU-14576

Fig. 13.

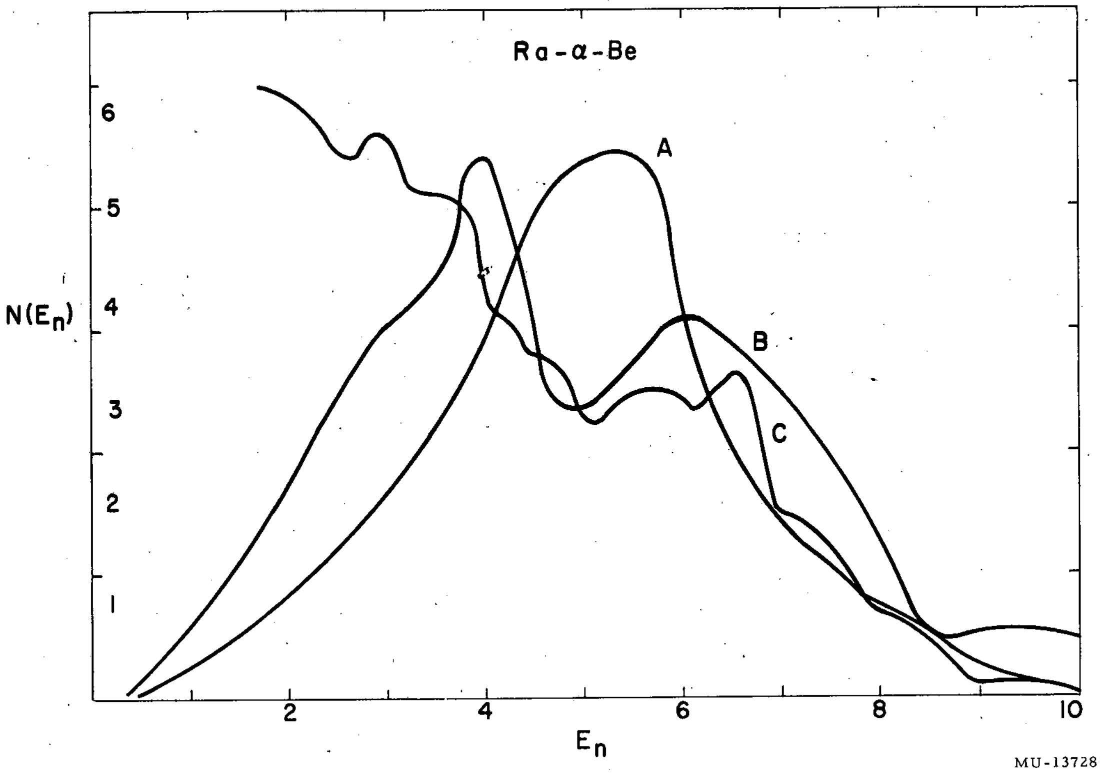


Fig. 14.