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AEC RESEARCH AND DEVELOPMENT REPORT

**THE SPECTRUM OF POLONIUM-
BERYLLIUM NEUTRON SOURCES**

(Information Report)

BY

R. J. BREEN

M. R. HERTZ

D. U. WRIGHT, JR.

MOUND LABORATORY

Operated by

MONSANTO CHEMICAL COMPANY

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Miamisburg, Ohio

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R. J. BREEN, M R HERTZ, AND D U WRIGHT, JR

Date: June 13, 1955

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ABSTRACT

A proton recoil neutron spectrometer usable in the range of 1.3 to 11 Mev was used for the investigation of the neutron radiation from polonium beryllium neutron sources. The spectra of two standard sources were congruous within the resolution of the instrument. Average energy of the neutrons from these sources was 4.5 Mev.

The spectra contained two major groups: the larger, with a relative intensity of 7 and energy peak of 3.2 Mev, resulted from leaving the residual C^{12} nucleus in the 4.45 Mev energy level; and the smaller, with a relative intensity of 3 and energy peak of 6.4 Mev, resulted from leaving the C^{12} nucleus in the ground state. A hypothetical spectrum constructed from thick target excitation curves using the 7:3 ratio was in agreement with the experimental results.

INTRODUCTION

Rather complete information was available on neutron sources prepared at Mound Laboratory, except for the neutron spectra. By making measurements on several sources any variations in spectra with factors varied in the preparation could be detected.

Several investigators obtained the neutron spectra of polonium-beryllium neutron sources ^{1, 2, 3, 4, 5}. In most cases different methods and techniques were used to obtain the spectra. Also the methods of fabricating the neutron sources were not given. Cochran and Henry¹ determined the neutron spectra of two polonium-beryllium sources, and their data indicated a variation with neutron efficiency.

A proton-recoil proportional counter was chosen to minimize the time and labor of the measurements. The theory of this type of counter was developed by Gossick.⁶ Cochran and Henry used a three-section tube because of high background radiation. In the work at Mound Laboratory background was low enough that a three section tube had little advantage over a two-section tube. In addition the two section tube had greater sensitivity.

DESCRIPTION OF THE APPARATUS AND ITS FUNCTIONS

The spectrometer consists of a holder for the interchangeable radiator-absorber, *R-A*, combinations, a two-section proportional counter and associated electronic instruments. The proportional counter shown in Figure 1 is constructed of brass, nickel plated, and has a 1-milligram-per-square-centimeter mica window attached with wax (Apiezon W). The Mound Laboratory tube operated satisfactorily with an electrode potential difference of approximately 800 volts.

Neutrons impinging on the hydrogenous radiator eject protons which pass through the mica window and the two sections of the tube ionizing the gas in those sections. The ionization pulses from each section of the counter are amplified by an A1-A preamplifier and an A1 linear amplifier and are then applied to the pulse height discriminator portion of each amplifier. The output of each discriminator PHS output, is connected to a coincidence circuit, and the PHS output of the rear section amplifier is also connected to a monitor scaler. The output of the coincidence circuit is recorded by a second scaler. A block diagram of the complete instrument is shown in Figure 2. Further descriptions of the circuitry and precautions to be observed in the operation of the equipment are presented in Appendix D.

PROTON RECOIL COINCIDENCE COUNTER

PREAMPLIFIER, A-JA RCL, MARK 15
 LINEAR AMPLIFIER, A-I RCL, MARK 15
 COINCIDENCE CIRCUIT, SEE FIG. 16
 SCALER, ATOMIC, MODEL 1010
 H.V. POWER SUPPLY, ATOMIC, MODEL 326
 H.V. FILTER, SEE FIG. 14
 H.V. MONITOR, SEE FIG. 14

BLOCK DIAGRAM OF NEUTRON SPECTROMETER

THEORY OF THE NEUTRON DETECTOR

THE n - p SCATTERING PROCESS

Charged particles exert electric or magnetic forces capable of ionizing the atoms of the media through which they pass. The neutron is subjected to forces only when it comes within extremely close range of a nucleus and consequently, its presence is not directly detectable. For this reason, known reactions between a neutron and a target material are observed in order to obtain neutron energy information. Hydrogen is a good radiator because its scattering cross section as a function of neutron energy $\sigma_s(E_n)$, shows no resonances and is appreciably larger than that of other light elements. Furthermore, a fact that simplifies calculation and correction, the scattering of neutrons by protons is spherically symmetric (for neutron energies less than 10 Mev) in center of mass⁷ coordinates. The energy of hydrogen recoils is also greater than the recoil energy from any other element.

Proton recoil instruments enable one to obtain information on a given source concerning both E_n and neutron intensity. The fast neutron spectrometer designed and developed by Cochran and Henry¹ and Gossick⁶ is a special case of a proton recoil instrument with a collimator.

THE COUNTING RATE EQUATION⁸

Let $N(E_n/\Omega_1)$ denote the emission rate of neutrons per unit energy per unit solid angle, where Ω_1 denotes the solid angle. The rate at which protons are produced by neutrons or the n - p process rate in a small element within the radiator can be given by

$$df = N(E_n, \Omega_1) S \sigma_s(E_n) t(R, \lambda, \gamma_p) dE_n d\Omega_1 \quad (1)$$

where S is the density of hydrogen atoms in the radiator and $t(R, \lambda, \gamma_p)$ is the effective radiator thickness as a function of proton range R , neutron emission angle λ and proton range obliquity angle γ_p . See Figure 3.

The end result of the analysis and derivation made by Gossick⁹ is the counting rate

$$L = \left[2\pi S \left(\frac{a^2}{b_1 b_2} \right)^2 \right] \left[t_1 t_2 \frac{\sigma_s(\bar{E}_n) \bar{E}_n}{g \bar{R}} \right] N(\bar{E}_n, \bar{\Omega}_1) \quad (2)$$

where t_1 is the radiator thickness, t_2 is the detection width, g is the power factor in Geiger's law and a , b_1 and b_2 are geometric factors as indicated in Figure 3. Protons are produced in t_1 and some of these protons traverse the intervening distance of the tube and are stopped in the detection width t_2 . See Figure 4. The total stopping power of the material between t_1 and t_2 is represented as t_0 . All thicknesses are expressed in centimeter equivalents of radiator material. Using Geiger's law, the range of a recoil proton with collision angle ψ may be expressed in terms of E_n as

$$R = k E_n^{g/2} \cos^g \psi$$

where k is a constant and g is a very slowly varying function of proton energy. Figure 2 of Gossick's report is a plot of g , for paraffin, calculated from the Range - Energy Tables of Hirshfelder and Magee.¹⁰

FIG-3

SOURCE, RADIATOR, AND COLLIMATOR GEOMETRY FOR TYPICAL EXPERIMENT

DIAGRAM OF ABSORBING WIDTH t_0 , RADIATOR
THICKNESS t_1 , AND DETECTOR WIDTH t_2

5866

FIGURE 4

The derivation of Equation 2 from Equation 1 was made on the assumption of "good geometry", which assumes that λ and λ_p may be interchanged with their sines and that b_1 and b_2 are large compared to a . The neutron spectrum is determined from Equation 2.

$$N(\bar{E}_n, \bar{\Omega}_1) = L \left[\frac{1}{2\pi S} \left(\frac{b_1 b_2}{a^2} \right)^2 \right] \left[\frac{g \bar{R}}{t_1 t_2 \sigma_s(\bar{E}_n) \bar{E}_n} \right] \quad (3)$$

The first of the bracketed terms in Equation 3 is a constant, K , for a given counter, which constant is, for this case, 0.52×10^{-24} . The second of the bracketed terms must be calculated for each specific R - A combination and is called the P factor. Equation 3 thus reduces to

$$N(\bar{E}_n, \bar{\Omega}_1) = LKP \quad (4)$$

THE RANGE ERROR OF THE PROTON

The total range error, ρ_{tot} is composed of. (1) energy straggling, ρ_s , (2) angular straggling ρ_a and (3) radiator and detection width error, ρ_t . Energy straggling is independent of the counter, and the value for this error as given by Livingston and Bethe,¹¹ is used. The error of angular straggling due to uncertainties in the neutron emission angle, λ and range obliquity angle γ_p , is an instrument error which depends upon the dimensions a , b_1 , and b_2 . Radiator and detection width errors are due to the uncertainty in the beginning and ending of the range in the radiator and detection width respectively. This error is also instrumental and depends upon the dimensions of t_0 , t_1 , and t_2 .

The mean-square deviation in range due to energy straggling, after the proton has traversed a thickness of stopping material, is

$$\overline{\Delta \rho_s^2} = \frac{(R - R_0)^2}{R_0^2}$$

The point at which the intensity is reduced to one-half is defined as the mean range, R_0 . Since the beam of particles is not homogeneous, it is generally preferable to measure the "extrapolated" range, R_{extr} , instead of R . In this case the relative error in straggling is

$$\overline{\Delta \rho_s^2} = \frac{2}{\pi} \frac{(R_{extr} - R_0)^2}{R_0^2} \quad (5)$$

The parameters to consider in angular straggling are a , b_1 , and b_2 (Fig 3). The optimum relation between b_1 and b_2 is that which provides a maximum counting rate for a constant error, $\overline{\Delta \rho_a^2}$. Using a value for g of 3 this optimum relationship is $b_1 = \frac{1}{2} b_2$, for which

$$\overline{\Delta \rho_a^2} = 29.1 \left(\frac{a}{b_2} \right)^2 \quad (6)$$

Since g varies slowly with proton energy the ratio of b_1 to b_2 is somewhat energy dependent. The variation in g was considered negligible and g was replaced by 3 as a first approximation.

The factors t_1 , t_2 and t_0 are indicated in Figure 4. For a proton to be counted it must complete its range in t_2 . On the average the proton will have a range of

$$\bar{r} = t_0 + \frac{t_1 + t_2}{2} \quad (7)$$

It may be shown (Eq. A6.6 of reference 6) that

$$\overline{\Delta \rho_r^2} = \frac{t_1^2 + t_2^2}{12 (R)^2} \quad (8)$$

It was assumed for the present analysis that the instrument discriminates perfectly against background so that the optimum condition of $t_1 = t_2$ holds only for an ideal instrument. In effect, the background intensity may necessitate making the detection width less than the radiator thickness.

The total range error is thus

$$\overline{\Delta \rho_{tot}^2} = \overline{\Delta \rho_s^2} + \overline{\Delta \rho_a^2} + \overline{\Delta \rho_t^2} \quad (9)$$

Applying Geiger's law to these results the corresponding energy error is

$$\epsilon^2 = \left(\frac{2}{g} \right)^2 \overline{\Delta \rho_{tot}^2} \quad (10)$$

OPERATIONAL PROCEDURE

For calibration purposes a thin polonium alpha source is placed directly in front of the counter and the discriminator is set at its approximate mid-position. The gains of the amplifiers are then adjusted until the scaler which records the output of the rear section amplifier starts to register counts. The distance from the source to the counter face is varied until the Bragg ionization peak indicates that the alphas are ending their range within the detection width. Counting rate versus discriminator setting is plotted for each section of the counting tube and the resultant curves are differentiated. The position of the peak in the differentiated curve gives a relative measure of the energy loss of the alpha particle in that section of the tube. The inherent energy resolution can be determined from the differentiated curves. An illustrative calibration plot is shown in Figure 5. This plot presents the best resolution evident during this investigation, the average value being somewhat better than 10 per cent.

The next step in the calibration procedure is the conversion of the instrument settings from alpha particle range values to equivalent proton-range values. The ratio of the maximum energy lost by the alphas to the maximum energy lost by the protons¹² in the last section of the tube is $\frac{0.94}{0.29}$ or 3.2. From an analysis of specific ionization data¹³ for alphas and protons in air and argon the range-energy relations for both the alpha and the proton are not significantly different in either air or argon.

FIGURE 5

To obtain a practical counting rate the discriminator setting was adjusted to allow an interval of pulse heights to be recorded. This distribution in energy is called the "window". Lowering the discriminator setting from a value at which only protons losing 0.29 Mev energy in the last section of the tube were counted to a value at which protons losing as little energy as 0.19 Mev were also counted gave a "window" of 0.32 Mev (See Fig 13.)

The product of 3.2 from the conversion of the alpha-particle-range value to equivalent proton range values and the ratio $\frac{0.29}{0.19}$ from establishment of the 0.32 Mev "window" gives an "advance gain" of 4.9. The gain of the system must therefore be advanced by a factor of 4.9 to record those protons stopping in the last section of the tube. When the gain has been properly established the instrument will record the counting rate L_i for the successive R - A combinations.

The L values were corrected for background and then multiplied by the P factor, in accordance with Equation 4. The resulting product was plotted versus $\bar{E}_n$ (value corresponding to each R - A). The plots which are presented in the next section then represent

$$LP = K' N(\bar{E}_n, \bar{\Omega}_1) \quad (11)$$

where $K' = \frac{1}{K}$

The methods and procedures for determining $\bar{E}_n$, the range error $\sqrt{\epsilon^2}$ and the P value for each R - A combination are outlined in Appendixes A, B and C. The P values are tabulated in Table V.

DATA AND DISCUSSION

The neutron sources used in this investigation consisted of an intimate mixture of polonium-210 alpha emitter and beryllium target material. The polonium was volatilized into an empty nickel container. The beryllium target material was then added after which the container was closed and sealed by coating with nickel. After the sealing was completed the container was heated to distribute the polonium throughout the target material. The source containers were right cylinders having inside dimensions of 0.50 inch by 0.50 inch and outside dimensions after coating 0.70 inch by 0.70 inch.

The two sources used in this investigation were comparable in curie content, neutron intensity and efficiency. The characteristics of these sources are tabulated in Table I.

TABLE I

SOURCE CHARACTERISTICS

SOURCE	CURIES	n/SEC	EFFICIENCY	DATE
PN 47	32.71	8.02×10^7	86.1%	6-2-54
RB 2	34.25	8.65×10^7	88.6%	7-12-54

The instrument was calibrated at frequent intervals to establish that it was functioning consistently.

A spectrum of source PN-47 was measured over the interval of one day the period of time covered by a run with RB-2 was approximately a work week. The data from a typical run on PN-47 are presented in Table II. The results of adjusting these data with the P factor are also listed in Table II and a plot of LP versus $\bar{E}_n$ is shown in Figure 6. Figure 7 is a plot of another run on PN-47. Figures 8 and 9 are plots of LP versus $\bar{E}_n$ for the second source RB-2.

In an effort to minimize the effects of the statistical error twelve runs on PN-47 were normalized and averaged the results are plotted in Figure 10. Four runs on RB-2 were also averaged and the results are also shown in Figure 10.

At the time the neutron spectrum of RB-2 was investigated, the overall counting rate as a function of tube sensitivity was decreasing very slowly. Since the ratio of counting rate to background remained the same and since the decrease in counting rate was small over a long period of time it is felt that this decrease in tube sensitivity does not negate the usefulness of the data in explaining the structure of the spectra.

Figures 6 and 7 are representative of the neutron spectrum curves obtained with PN 47. Two major peaks consistently occur at about 3.2 and 6.4 Mev. The first major peak is composed of three minor peaks which occur at about 3.0, 3.8 and 4.6 Mev. The average curve for PN-47 which is shown in Figure 10 smooths these minor peaks to such an extent that their significance is questionable. These three peaks appeared each time a spectrum was run but they shifted position slightly from one run to another.

Although the peak at 6.4 Mev is considerably smaller than the peak at 3.2 Mev it appears in all the curves obtained from this investigation and its reality is substantiated by a general change in slope in the curve at this point. The curve in Figure 7 has a distinct peak at 7.7 Mev which is not so apparent in Figure 6 or in the average curve of Figure 10 and this peak is probably statistical in nature. Small rises at 7.7 and 8.4 Mev consistently occurred in all spectra obtained from source PN-47 but the statistics at these points prevented any definite conclusions as to their significance.

The data from RB-2 as plotted in Figures 8, 9 and 10 are in agreement with the results from PN-47. The two major peaks occur at approximately the same energies while the minor peaks are somewhat shifted in position.

Other investigators have studied polonium-beryllium neutron spectra with photographic-emulsion techniques. Perlman and co-workers³ observed two peaks at 2.3 and 7.2 Mev. Whitmore and Baker⁵ observed peaks at 3.2, 4.8 and 7.7 Mev with a probable peak at 1.2 Mev they also report the possible existence of two smaller peaks at 5.8 and 9.7 Mev. Richards⁴ reported two peaks at about the same energies as observed by Perlman and co-workers. Using a hydrogen-recoil proportional counter Gossick and Henry² observed two peaks at about 3.2 and 7.2 Mev. Using similar apparatus, Cochran and Henry¹ studied the spectra of two polonium-beryllium neutron sources fabricated at Mound Laboratory and concluded that the two sources had different spectra. Their results indicated peaks at 3.0 and 5.5 Mev for one source, and for the second source a double peak was observed at about 3.5 Mev and another peak at 7.5 Mev.

Most investigations of gamma-ray emission from the polonium-alpha bombardment of beryllium have resulted in the observation of a single gamma-ray energy of about 4.45 Mev. This value was reported by Hertz and Breen¹⁴ who also list the results of other investigators. Excitation of the 7.5 Mev level is indicated by several investigators^{15,16} although most results show that the C^{12} nucleus is left in only one excited state at 4.45 Mev. If this is the only excitation state no more than two major peaks would be observed in the neutron distribution curve. (See Appendixes E and F.)

TABLE I I

EXEMPLARY DATA ON SOURCE PN- 47

<i>R-A NO</i>	<i>L</i> (<i>cts/sec</i>)*	<i>PL</i> (<i>n/sec/Mev/unit solid angle</i>)	<i>E</i> (<i>Mev</i>)
27	0.205 ± 0.0217	0.213 ± 0.0226	1.96 ± 0.467
45	0.175 ± 0.0225	0.168 ± 0.0215	1.99 ± 0.213
28	0.273 ± 0.0250	0.235 ± 0.0215	2.33 ± 0.258
46	0.419 ± 0.0209	0.335 ± 0.0167	2.57 ± 0.300
29	0.450 ± 0.0278	0.367 ± 0.0227	2.84 ± 0.309
47	0.424 ± 0.0288	0.343 ± 0.0233	3.15 ± 0.34
30	0.487 ± 0.0301	0.385 ± 0.0238	3.34 ± 0.356
48	0.435 ± 0.0267	0.343 ± 0.0210	3.63 ± 0.381
31	0.446 ± 0.0278	0.341 ± 0.0212	3.89 ± 0.406
49	0.492 ± 0.0286	0.377 ± 0.0219	4.15 ± 0.427
32	0.430 ± 0.0274	0.315 ± 0.0201	4.38 ± 0.456
50	0.451 ± 0.0264	0.323 ± 0.0190	4.65 ± 0.484
33	0.461 ± 0.0280	0.331 ± 0.0201	4.90 ± 0.505
51	0.401 ± 0.0279	0.268 ± 0.0187	5.15 ± 0.552
34	0.356 ± 0.0258	0.250 ± 0.0181	5.34 ± 0.553
52	0.316 ± 0.0248	0.211 ± 0.0166	5.67 ± 0.592
35	0.278 ± 0.0238	0.185 ± 0.0159	5.94 ± 0.616
53	0.310 ± 0.0247	0.205 ± 0.0164	6.16 ± 0.0636
36	0.280 ± 0.0238	0.187 ± 0.0159	6.42 ± 0.653
54	0.294 ± 0.0247	0.197 ± 0.0166	6.67 ± 0.674
37	0.235 ± 0.0240	0.154 ± 0.0158	6.93 ± 0.702
55	0.240 ± 0.0239	0.155 ± 0.0155	7.18 ± 0.741
38	0.210 ± 0.0226	0.134 ± 0.0148	7.44 ± 0.752
56	0.210 ± 0.0231	0.134 ± 0.0150	7.67 ± 0.786
39	0.168 ± 0.0225	0.109 ± 0.0145	7.92 ± 0.803
40	0.154 ± 0.0210	0.099 ± 0.0135	8.43 ± 0.851
41	0.087 ± 0.0163	0.056 ± 0.0105	8.94 ± 0.903
42	0.073 ± 0.0141	0.047 ± 0.0090	9.44 ± 0.954

*CORRECTED FOR BACKGROUND

INSTRUMENT SETTINGS

FRONT AMPLIFIER (ATOMIC)

REAR AMPLIFIER (RCL)

CHAMBER - 800 VOLTS

COARSE GAIN-64. FINE GAIN-32

COARSE GAIN-8 FINE GAIN-1

0.32 MEV WINDOW

DISCRIMINATOR 47.25

DISCRIMINATOR - 43.95

ADVANCE GAIN - 4 9

RESOLUTION INDICATED BY CALIBRATION, 10%

Po-Be NEUTRON SPECTRUM OF PN-47, DATED 5-13-54

FIGURE 7

21 Fig-8

Po-Be NEUTRON SPECTRUM OF RB-2, DATED 7-26-54

Po-Be NEUTRON SPECTRUM OF
RB-2, DATED 9-13-54

FIGURE 10

Po-Be NEUTRON SPECTRA

On the basis of a single gamma-ray being emitted from the polonium-beryllium neutron source a hypothetical neutron spectrum was constructed for a polonium-beryllium source by the method of Whitmore and Baker⁵ (See also Appendixes E and F) Two neutron-energy distribution curves were constructed one for the transition to the 4.45 Mev state of the residual nucleus, and one for the transition of the residual nucleus to the ground state. These two distributions were normalized and combined to represent the experimental curve as closely as possible. At each point in the ideal spectrum corresponding in energy to an $R-A$ combination, an average was taken over the interval indicated by the standard deviation, or range error, of that $R-A$, (Fig 11). This was done in an attempt to compensate for the difference between the ideal spectrum and what the instrument actually records. Using the ratio of 7 neutrons from the excited state group to 3 neutrons in the ground state group the experimental curve and the hypothetical curve compared very well.

The existence of the minor peaks is not well established. If the peaks do exist their presence may be explained by the two resonances occurring at 1.5 and 4.4 Mev in Halpern's thin target excitation curve¹⁷. This would have the effect of introducing two extra peaks in each of the distributions: e. i. the transition to the ground state and the transition to the 4.45 Mev energy levels.

CONCLUSIONS

A real and reasonably true spectrum of a neutron source may be obtained by using the neutron spectrometer constructed at Mound Laboratory. The bias energy, the lower limit in energy detectable by the instrument is approximately 1.2 Mev while the upper limit in energy is that determined by the $R-A$ combination. Because an instrument of this type is recording data over a pulse height interval it should not be expected to indicate a great deal of structure unless this structure has an energy width at half-maximum greater than $\frac{1}{2}$ Mev. The extended operations reported here indicate that the spectrometer is dependable and stable. It is thus possible to provide the user of a polonium-beryllium neutron source with the spectrum of the source in one run and in supplying this information there is little advantage in increasing the counting time for a datum point beyond $\frac{1}{2}$ hour. The sources used in these investigations emitted between 10^7 and 10^8 neutrons per second, and therefore, longer counting times might be necessary for weaker sources.

The neutron spectrum of a standard polonium-beryllium source indicates a major structure which is consistent from source to source. This structure consists of two groups: one group resulting in the excitation of the 4.45 Mev level of ^{12}C and the other group leaving the residual nucleus of this element in its ground state. The ratio of the number of neutrons in the low energy group to the number of neutrons in the high energy group (ground state) appears to be approximately 7 to 3 for the thick target type of source fabricated at Mound Laboratory. It is therefore expected that 7 gamma rays of approximately 4.45 Mev energy should be observed for every 10 neutrons emitted by a source. This is in accord with the work of others^{15, 16, 3, 4}. The average energy of the neutrons emitted by the polonium-beryllium sources is 4.62 Mev (PN-47) and 4.38 Mev (RB-2).

A hypothetical polonium-beryllium spectrum (shown in Fig 11) calculated on the basis of the results stated here and using the suggested procedures of Whitmore and Baker⁵ correlates well with the experimental spectra of this investigation. On the basis of this comparison and support by the major portion of other available information the spectrum of a normal (fairly efficient) polonium-beryllium neutron source should be similar to Figure 10.

FIGURE 11

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APPENDIXES

APPENDIX A

Stopping Power Analysis of the Counter Tube

The energy loss analysis of the counter tube will yield information as to the minimum energy detectable by the tube. This minimum energy is the bias energy of the instrument excluding any source of protons. The bias energy less the detection width t_2 has been defined as t_0 (Fig 4)

The bias energy is a compromise between the design parameters b_1 and b_2 and the pressure of the filling gas in the tube. The parameters have been previously discussed in the theory of the tube and are indicated in Figure 3. The gas mixture used was 97 per cent Argon - 3 per cent CO_2 at a pressure of 10 centimeters of mercury. Figure 12 shows the dimensions of the tube necessary for calculating the equivalent stopping power of the tube and the detection width.

In order to realize a maximum pulse amplitude the proton must lose maximum energy in the rear section of the tube. A knowledge of this can be attained by plotting the energy lost, ΔE in the last section of the tube as a function of the energy E of the proton entering this section. The distance from D to F in Figure 12 is $1 \frac{9}{32}$ inches or 3.25 centimeters which at 1 atmosphere of pressure is equivalent in stopping power to 0.423 centimeter. Table III was compiled from reported data¹⁸. For this investigation values of proton energy were assumed from which the value of 0.428 centimeter was subtracted. Figure 13 is a plot of the information tabulated in Table III.

The calibration curve Figure 5 indicates an inherent datum-point resolution of less than 10 per cent and the detection of protons whose pulse amplitude interval is approximately this same amount is assumed in this instance. In this case (see Fig 13) the average energy of a proton entering the last section of the tube will be about 0.35 Mev. The distance A to D is $2 \frac{3}{4}$ inches or 6.98 centimeter which at atmospheric pressure is equivalent in stopping power to 0.92 centimeter. The 0.35 Mev proton has a range of 0.60 centimeter. The effective proton range in the detector is the sum of these range values or 1.52 centimeter (0.703 Mev) which is equivalent to a proton range of 1.31 centimeter in air¹⁹. A proton of 0.703 Mev appearing at point A (Fig 13) must have passed through the mica window which is 1.00 milligram per centimeter² thick. Mica of 1.44 milligrams per centimeter² thickness is equivalent in proton stopping power to 1.00 centimeter of air²⁰. Therefore mica of 1.00 milligram per centimeter² thickness is equivalent to 0.694 centimeter of air. The equivalent proton range in the detector and mica window is thus 2.00 centimeters. A correction must be added to the equivalent stopping power of the proton to compensate for the space between the $R-4$ combination and the mica window. This space is about $\frac{1}{4}$ inch, or 0.635 centimeter of air or a total proton range of about 2.64 centimeters. This total range value will dissipate the energy of a 1.10 Mev proton. The difference in energy from 1.10 to 0.35 Mev is equivalent in proton stopping power to a 1.8935 milligrams per centimeter² thickness of polythene²¹, if the equivalence of paraffin and polythene the radiator material used in this investigation is assumed. The energy remaining to a proton of 0.35 Mev energy after having traveled from D to F (Fig 13) is 0.09 Mev. Therefore an equivalent proton range of 0.07506 milligram per centimeter² of polythene remains. Hence t_0 is equivalent to 1.9685 milligrams per centimeter² of polythene. The detection width t_2 is equivalent to 0.493 milligram per centimeter² of polythene. The bias energy determined from the above values is about 1.2 Mev.

DIMENSIONS OF OAK RIDGE TUBE

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FIGURE 12

ENERGY LOST IN LAST SECTION OF THE TUBE AS A FUNCTION OF
ENERGY AT THE ENTRANCE TO THE SECTION

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TABLE III

ENERGY LOST BY A PROTON IN LAST SECTION OF THE TUBE AS A FUNCTION
OF THE ENERGY OF THE PROTON ENTERING THE LAST SECTION

E (MeV)	ΔE (MeV)
0.10	0.10
0.15	0.15
0.20	0.20
0.25	0.25
0.30	0.291
0.40	0.236
0.50	0.192
0.60	0.167
0.70	0.148
0.80	0.135
0.90	0.128
1.00	0.115
1.20	0.101
1.40	0.091

APPENDIX B

Calculations for R - A Fabrication

The fabrication of R - A combinations for a specific energy and range error is facilitated by the reverse process presented in the theory of the Oak Ridge Tube. Let it be assumed that the range error is about the same as the resolution observed in alpha calibration, i.e., 10 per cent. From Equation 10

$$\sqrt{\epsilon^2} = \frac{2}{g} \sqrt{\rho_{to} t^2} = 0.10$$

Since, from Equation 9

$$\overline{\Delta \rho_{to} t^2} = \overline{\Delta \rho_s^2} + \overline{\Delta \rho_a^2} + \overline{\Delta \rho_t^2}$$

and solving for $\overline{\Delta \rho_t^2}$,

$$\overline{\Delta \rho_t^2} = \frac{g^2}{4} \times 10^{-2} - \overline{\Delta \rho_s^2} - \overline{\Delta \rho_a^2} \quad (12)$$

The last two factors can be carried through as constants. From Figure 3, $a = 0.8$ centimeter and $b_2 = 7.8$ centimeters, and inserting these values into Equation 6

$$\overline{\Delta \rho_a^2} = 29.1 \left(\frac{a}{b_2} \right)^4 = 32 \times 10^{-4}$$

Bethe¹⁰ indicates that Equation 5 is

$$\overline{\Delta \rho_s^2} = \frac{2}{\pi} \left(\frac{R_{extr} - R_o}{R_o} \right)^2 \simeq 2 \times 10^{-4}$$

By substitution, Equation 12 is

$$\overline{\Delta \rho_t^2} = \frac{g^2}{4} \times 10^{-2} - 34 \times 10^{-4}$$

If this is set equal to Equation 8

$$\frac{g^2}{4} \times 10^{-2} - 34 \times 10^{-4} = \frac{t_1^2 + t_2^2}{12 (\bar{R})^2}$$

Solving for t_1 ,

$$t_1 = \sqrt{12(\bar{R})^2 \left[\frac{g^2}{4} \times 10^{-2} - 34 \times 10^{-4} - \frac{t_2^2}{12(\bar{R})^2} \right]}$$

From Appendix A, $t_2 = 0.493$ milligram per centimeter² polythene, and

$$t_1 = 3.46 (\bar{R}) \left[25 g^2 - 34 - \frac{203}{(\bar{R})^2} \right]^{\frac{1}{2}} \times 10^{-2} \text{ mg/cm}^2 \text{ polythene}$$

From Equation 7,

$$\bar{R} = t_o + \frac{t_1 + t_2}{2}$$

The stopping power of the absorber is added to t_o . If y is the thickness of aluminum in milligram per centimeter² of polythene equivalent, this correction would be $0.63 y$. Adding the correction

$$t_o = 1.97 + 0.63 y \quad (13)$$

Substituting this into the above equation and solving for y ,

$$y = \frac{1}{0.63} \left[\bar{R} - 2.217 - \frac{t_1}{2} \right] \text{ mg/cm}^2 \text{ Al} \quad (14)$$

For example, to find y for $\bar{E} = 3.0$ Mev: From Table VII of Hirschfelder and Magee²¹, $\bar{R} = 12.65$ milligrams per centimeter². From graph of g versus E of Gossick²², $g = 3.49$. Substituting these values into the equation for t_1

$$t_1 = 3.46 (\bar{R}) \left[25 g^2 - 34 - \frac{203}{(\bar{R})^2} \right]^{\frac{1}{2}} \times 10^{-2} = 7.19 \text{ mg/cm}^2 \text{ polythene}$$

Substituting this value of t_1 , and the value $\bar{R}$ above into the equation for y

$$y = \frac{1}{0.63} \left[\bar{R} - 2.217 - \frac{t_1}{2} \right] = 10.87 \text{ mg/cm}^2 \text{ Al}$$

Table IV shows the results of calculations using this procedure.

TABLE IV
CALCULATED VALUES OF RADIATOR AND ABSORBER AS A FUNCTION OF
 E , ASSUMING A RANGE ERROR OF 10 PER CENT

E (Mev)	R or t_1 (mg/cm ² polythene)	A (mg/cm ² Al)
1.5	2.06	0.937
1.75	2.74	0.969
2.00	3.44	3.70
2.25	4.29	5.27
2.50	5.63	6.65
2.75	6.16	8.85
3.00	7.19	10.87
3.25	8.32	13.07
3.50	9.47	15.28
3.75	10.77	17.71
4.00	12.09	20.18
4.25	13.51	22.90
4.50	14.94	25.6
4.75	16.52	28.58
5.00	18.03	31.6
5.25	19.71	34.8
5.50	21.47	37.0
5.75	23.3	41.5
6.00	25.2	45.0
6.25	27.18	48.6
6.50	29.18	52.2
6.75	31.2	56.25
7.00	33.4	60.1
7.25	35.6	64.3
7.50	38.4	68.0
7.75	40.3	72.8
8.00	42.6	77.3
8.50	47.6	86.5
9.00	52.8	96.4
9.50	58.5	106.7
10.00	64.2	117.0
10.50	70.3	128.3
11.00	76.5	139.5

APPENDIX C

Properties of the R - A Combinations

With Table IV being used as a guide, the R - A combinations were assembled in the holder rings and numbered. The actual values of R and A were substituted into Equation 13 and Equation 7, and $\bar{R}$ was thus determined. Table VII of Hirschfelder and Magee²¹ gave $\bar{E}$ (Mev).

The range error, $\sqrt{\bar{E}^2}$, was calculated using Equations 6, 8, 5, 9 and 10. The values of a and b_2 from Figure 3 were substituted into Equation 6 and carried as a constant in the subsequent calculations. The values of t_1 and t_2 used in the above determination of $\bar{E}$ were substituted into Equation 8 along with the value of $\bar{R}$ determined above. The value of Equation 5 for the above $\bar{E}$ was calculated by (1) determining R_0 from Figure 3 of Bethe¹⁹, (2) using this value of R_0 to determine the value, in per cent, of $\frac{R_{extr} - R_0}{R_0}$ from Figure 24 of Bethe¹⁹, and (3) substituting this value into Equation 5. The range error is obtained by adding the results thus far mentioned in this paragraph, as indicated in Equation 9, and substituting this sum into Equation 10 with the value of g from Gossick²².

For example, R - A No. 9

$$\text{Polythene} = 7.15 \text{ mg/cm}^2 \quad \text{Al} = 9.03 \text{ mg/cm}^2$$

$$t_0 = 1.97 + 0.63 \times 9.03 = 7.66 \text{ mg/cm}^2 \quad (13)$$

$$\bar{R} = 7.66 + \frac{7.15 + 0.49}{2} = 11.48 \text{ mg/cm}^2 \quad (7)$$

From Hirschfelder and Magee²¹

$$\text{for } \bar{R} = 11.48 \text{ mg/cm}^2, \bar{E} = 2.837 \text{ Mev}$$

$$\overline{\Delta \rho_a^2} = 32 \times 10^{-4} \quad (6)$$

$$\overline{\Delta \rho_t^2} = \frac{(7.15)^2 + (0.49)^2}{12 (11.48)^2} = 324 \times 10^{-4} \quad (8)$$

From Bethe, (Figure 3)¹⁹

$$\text{for } \bar{E}_3 = 2.837 \text{ Mev}, R_0 = 12.75 \text{ cm Air}$$

From Bethe, (Figure 24)¹⁹

$$\text{for } R_0 = 12.75 \text{ cm Air}, \frac{R_{extr} - R_0}{R_0} = 2.1\%$$

$$\overline{\Delta \rho_s^2} = \frac{2}{\pi} (2.1 \times 10^{-2})^2 = 2.81 \times 10^{-4} \quad (5)$$

$$\overline{\Delta \rho_{tot}^2} = (324 + 32 + 2.81) 10^{-4} = 358.81 \times 10^{-4} \quad (9)$$

$$\overline{\epsilon^2} = \left(\frac{2}{g} \right)^2 358.81 \times 10^{-4} \quad (10)$$

from Gossick²²

$$\text{for } \overline{E_s} = 2.837, \quad g = 3.484$$

$$\overline{\epsilon^2} = \left(\frac{2}{3.484} \right)^2 358.81 \times 10^{-4} \simeq 118.2 \times 10^{-4} \quad (10)$$

$$\therefore \sqrt{\overline{\epsilon^2}} = 10.88\% \text{ Std Dev or } 0.309 \text{ Mev}$$

The actual thicknesses of polythene radiator, R , and absorber, A , used in the specific R - A combination are found in Table V. The representative neutron energy, $\overline{E_s}$, and the range error of each R - A combination are listed in Table V also.

With the information that exists at this point, it is possible to calculate the value of P , Equation 4 and Equation 11. The computational form of P is the factor enclosed with the second set of brackets of Equation 3. For clarity

$$P = \frac{g \overline{R}}{t_1 t_2 \sigma_s (\overline{E}) \overline{E_n}}$$

in which the only factor not referred to in this appendix is $\sigma_s(\overline{E_n})$. Reference 23 can be used as source of this information. The results of the indicated operation are in Table V.

TABLE V
R-A COMBINATIONS WITH CALCULATED RANGE ERROR AND P FACTOR

R-A NO.	R (mg/cm ² poly)	A (mg/cm ² Al)	RANGE ERROR			P
			E_3 (MeV)	$\pm E_3$	(%)	
1	2.47	0	1.44	0.194	13.4	0.940
2	3.58	0	1.54	0.248	16.1	0.710
3	3.70	0	1.55	0.257	16.6	0.689
4	5.42	0	1.73	0.339	19.6	0.551
5	3.38	3.39	1.96	0.467	10.1	1.04
6	3.72	3.37	1.99	0.213	10.7	0.958
7	5.10	5.37	2.33	0.258	11.04	0.861
8	6.38	6.70	2.57	0.300	11.7	0.799
9	7.15	9.03	2.84	0.309	10.88	0.816
10	8.29	11.39	3.15	0.34	10.8	0.808
11	9.46	13.60	3.34	0.356	10.6	0.791
12	10.61	16.18	3.63	0.381	10.5	0.788
13	11.99	18.65	3.89	0.406	10.4	0.764
14	13.32	21.72	4.15	0.427	10.3	0.767
15	14.9	23.8	4.38	0.456	10.4	0.733
16	16.58	26.95	4.65	0.484	10.4	0.718
17	18.0	29.8	4.90	0.505	10.3	0.719
18	20.6	32.33	5.15	0.552	10.7	0.669
19	21.2	36.15	5.39	0.553	10.25	0.701
20	23.9	39.5	5.67	0.592	10.4	0.669
21	25.8	43.1	5.94	0.616	10.4	0.666
22	27.5	46.6	6.16	0.636	10.3	0.662
23	29.0	50.6	6.42	0.653	10.17	0.668
24	30.9	54.8	6.67	0.674	10.1	0.671
25	33.3	58.53	6.93	0.702	10.1	0.657
26	36.2	62.4	7.18	0.741	10.3	0.647
27	37.8	66.9	7.44	0.752	10.1	0.657
28	40.5	70.7	7.67	0.786	10.24	0.651
29	42.7	75.4	7.92	0.803	10.1	0.646
30	47.8	84.5	8.43	0.851	10.1	0.641
31	52.8	94.6	8.94	0.903	10.1	0.643
32	58.5	104.9	9.44	0.954	10.1	0.638
33	64.0	115.3	9.94	1.02	10.1	0.633
34	70.1	126.8	10.44	1.055	10.1	0.636

APPENDIX D

Apparatus, Miscellaneous

The high voltage power supply used was the positive portion of an R. F type manufactured by the Atomic Instrument Company, Cambridge Mass., as Model 326. The operating voltage was filtered Figure 14 and monitored by an electrostatic voltmeter. Small variations were detected by a Speedomax millivolt recorder at approximately the 10-volt level between a voltage dividing network on the supply and a voltage divider across a battery, Figure 14. With the spectrometer in a temperature controlled room and cooled by forced air, regulation in the order of $\frac{1}{10}$ volt per day was attained. Experience indicates that, due to temperature sensitivity the use of this type of power supply would not be feasible without these precautions.

The A1-A preamplifier and A1 linear amplifier are of the Jordan-Bell type manufactured by the Radiation Counter Laboratories, Chicago, Ill. Each instrument was modified to provide for feeding high voltage to the tube and the grid circuit of the discriminator section cathode follower output (V-17) was modified as shown in Figure 15, to increase the normal 3 volt output pulse to approximately 15 volts. This increased output triggered the coincidence circuit which required about 10 volts. The coincidence circuit is shown in Figure 16.

The only precaution necessary in connection with the operation of the coincidence circuit is the setting of the sensitivity of the scaler to accept pulses not less than 5 volts in amplitude. Large pulses to one input of the coincidence circuit tend to produce small spurious output pulses. The circuit normally produces negative output pulses of 20-40 volts amplitude when both inputs receive simultaneous pulses.

At the start of the experiments, an elaborate calibration was carried out for relative gains at various settings of the discriminators and gain controls of the front and rear amplifiers. Later developments proved this to be an unnecessary precaution since the gains were nominally in accord with the values as indicated on the instruments.

FIGURE 14

HIGH VOLTAGE FILTER AND MONITOR CIRCUITS

MODIFICATIONS TO THE A-1 AMPLIFIER
PULSE HEIGHT SELECTOR SECTION

FIGURE 15

MLM-1054

41 Fig-16

FIGURE 16

COINCIDENCE CIRCUIT

APPENDIX E

Energetics of the $Be^9 (\alpha, n) C^{12}$ Reaction

In a polonium-beryllium neutron source, the polonium alphas bombard the Be^9 target nucleus forming a compound nucleus which emits a neutron, leaving C^{12} as the product nucleus. The reaction is expressed as

or merely $Be^9 (\alpha, n) C^{12}$

Q is the internal energy evolved in mass conservation. A reaction is exothermic or endothermic on the basis of whether

$$Q = (M_1 + M_2) - (M_3 + M_4) > 0$$

or

$$Q = (M_1 + M_2) - (M_3 + M_4) < 0$$

where M is the mass and the subscript 1 represents the incident alpha, 2 the target nucleus 3 the emitted neutron and 4 the residual nucleus.

If Q is positive, there is no minimum energy the incident alpha must have before the reaction is energetically possible. A negative Q means there is a threshold below which the reaction is not at all likely.

The only part of the kinetic energy that can enter into the reaction is the kinetic energy relative to the center of mass

$$E_{rel} = \frac{1}{2} \mu v_{rel}^2$$

where $\mu = \frac{M_1 M_2}{M_1 + M_2}$, the reduced mass of the system. Since the target nucleus is stationary the kinetic energy of the system must be that due to the incident alpha. In this case

$$E_{rel} = \frac{M_2}{M_1 + M_2} E_1$$

The remainder of the incident alpha energy must go into the kinetic energy of the center of mass.

$$E_{c.m.} = E_1 - E_{rel} = \frac{M_1}{M_1 + M_2} E_1$$

Hence, the energy available, E_a , for reaction must be

$$E_a = E_{rel} + Q$$

In emission of the neutron, momenta must be conserved so that in the center of mass system

$$\bar{P}_3' + \bar{P}_4' = 0$$

where P is the momenta and the prime denotes the center of mass system, or

$$E_4' = \frac{M_3'}{M_4} E_3'$$

Since $E_a = E_3' + E_4' = E_{rel} + Q$

$$\frac{M_2}{M_1 + M_2} E_1 + Q = E_3' \frac{M_3 + M_4}{M_4}$$

and

$$E_3' = \frac{M_4}{M_3 + M_4} \left(\frac{M_2}{M_1 + M_2} E_1 + Q \right)$$

The velocity of the neutron in the center of mass system is related to the velocity of the center of mass and the velocity of the neutron in laboratory coordinates.

$\bar{V}_{c.m.} + \bar{V}_3' = \bar{V}_3$, the bar denoting a vector, and

$$(V_3')^2 = V_{c.m.}^2 + V_3^2 - 2V_{c.m.} V_3 \cos \theta_3$$

In terms of E , since $V^2 = \frac{2E}{M}$,

$$\frac{E_3'}{M_3} = \frac{E_{c.m.}}{M_{c.m.}} + \frac{E_3}{M_3} - \sqrt{\frac{2E_{c.m.}}{M_{c.m.}}} \sqrt{\frac{2E_3}{M_3}} \cos \theta_3$$

Setting these two expressions for E_3' equal and collecting terms in E_3 ,

$$\sqrt{\frac{E_3}{M_3}} = \sqrt{\frac{E_c}{M_c} \frac{m}{m}} \cos \theta_3 \pm \sqrt{\frac{E_c}{M_c} \frac{m}{m} \cos^2 \theta_3 - \frac{1}{M_3} \left[\frac{E_c}{M_c} \frac{m}{m} - \frac{M_4}{M_3 + M_4} \left(\frac{M_2 E_1}{M_1 + M_2} + Q \right) \right]}$$

finally

$$E_3 = M_3 \left(\sqrt{\frac{M_1 E_1}{(M_1 + M_2)^2} \cos^2 \theta_3} \pm \sqrt{\frac{M_1 E_1}{(M_1 + M_2)^2} \cos^2 \theta_3 - \frac{1}{M_3} \left[\frac{M_1 E_1}{(M_1 + M_2)^2} - \frac{M_4}{(M_3 + M_4)} \left(\frac{M_2 E_1}{M_1 + M_2} + Q \right) \right]} \right)^2$$

When θ_3 equals zero the positive sign indicates E_3 maximum and the negative sign indicates E_3 minimum, then

$$E_3 = M_3 \left(\sqrt{\frac{M_1 E_1}{(M_1 + M_2)^2}} \pm \sqrt{\frac{M_1 E_1}{(M_1 + M_2)^2} - \frac{1}{M_3} \left[\frac{M_1 E_1}{(M_1 + M_2)^2} - \frac{M_4}{(M_3 + M_4)} \left(\frac{M_2 E_1}{M_1 + M_2} + Q \right) \right]} \right)^2$$

The known elements from the specific $Be^9(\alpha n)C^{12}$ reaction are

$$M_1 = 4 \quad M_2 = 9 \quad M_3 = 1, \quad M_4 = 12$$

$$(M_1 + M_2) = (M_3 + M_4) = 13$$

Therefore the expression for E_3 at $\theta_3 = 0$ reduces to

$$E_3 = \left\{ \sqrt{\frac{4E_1}{13^2}} \pm \sqrt{\frac{12}{13} \left(\frac{9}{13} E_1 + Q \right)} \right\}^2 \quad (16)$$

The maximum energy of the alpha is 5.30 Mev and the Q of Equation 12 computed using the mass values given by Staub et al²⁴, is 5.71 Mev. This latter value of Q corresponds to the group of neutrons leaving C^{12} in the ground state. The Q^* value corresponding to the group of neutrons leaving C^{12} in the 4.45 Mev level is merely $5.71 - 4.45 = 1.26$ Mev. Substituting these values into Equation 16

$$E_3 = \left[0.154 \sqrt{E_1} \pm \sqrt{0.645 E_1 + 5.268} \right]^2 \quad (17)$$

$$E_3^* = \left[0.154 \sqrt{E_1} \pm \sqrt{0.645 E_1 + 1.163} \right]^2 \quad (18)$$

APPENDIX F

Hypothetical Neutron Spectrum

In a study of the reaction $Be^9 (\alpha, n) C^{12}$ Whitmore and Baker⁵ calculated neutron spectra for various given energy levels of C^{12} . In the presentation here a refinement is added to their suggestions by summing the contributions of the neutron groups in a ratio which is apparent from the experimental spectra of this investigation.

The general equation Equation 15 of the preceding section indicates the fact that a reaction with a given Q will give rise to neutrons of varying energy. The energy of the polonium alpha is 5.3 Mev but with a thick target as is the case here it seems best to assume a uniform distribution in alpha energy. The number of alphas having energies in any range dE_1 is proportional to dE_1 . The variation in neutron energy due to variation in emission angle is also evident from the same equation.

It is assumed here that an alpha of energy E_1 liberates $f(E_1)$ neutrons which are spread uniformly over a range of energies from E_3 to $(E_3 + dE_3)$ proportional to

$$f(E_1)dE_1 \frac{dE_3}{R(E_1)}$$

The total number of neutrons of this energy is therefore proportional to

$$dE_3 \int_x^y \frac{f(E_1)dE_1}{R(E_1)} = F(E_3)dE_3 \quad (19)$$

The distribution of neutrons $F(E_3)$ was calculated on the basis of these assumptions using the excitation curve of Segre and Wiegand²⁵ for $f(E_1)$. The distribution functions for $Q = 5.71$ and 1.26 were normalized and summed in a ratio of 3 to 7 respectively.

Figure 17 is a plot of $(E_3)_{max}$ and $(E_3)_{min}$ versus E_1 resulting from the calculations using Equations 17 and 18.

Table VI contains steps in the computation of the ground state neutron group up to the integration indicated in Equation 19. Table VII shows the results of the integration indicated in Equation 19 for the ground state neutron group.

Table VIII concerns the neutron group leaving C^{12} in its 4.45 Mev level from which it decays to ground state via gamma emission. Table IX concerns the neutron group which is accompanied by gamma emission.

Column 3 of Table X is the result of summing the contributions from both the low and high energy group after normalization in a ratio of 7 to 3 respectively. The adjustment factor for the high energy group is 0.4336. The dashed curve in Figure 11 is a plot of this same information. This is the ideal spectrum with no allowance for window or range error. Column 4 of the same table is the average over the interval indicated in Column 2. The latter information are circled datum points in Figure 11 which are connected by a solid curve.

MAXIMUM AND MINIMUM NEUTRON ENERGIES FROM
 $\text{Be}^9 (\alpha, n) \text{C}^{12}$ REACTION (EQ.17 AND EQ.18)

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FIGURE 17

TABLE VI
GROUND STATE NEUTRON GROUP
COMPUTATIONAL STEPS IN EQ 19 UP TO THE INTEGRATION INDICATED

E_1 (MeV)	$(n/10^8 \text{ } \alpha \text{ s})^a$	$f(E_1)$	$R(E_1)^b$ (MeV)	$f(E_1)/R(E_1)$ $\times 10^8$
1.0	0.0	0	1.51	0
1.1	-	0	1.58	0
1.2	0.5	0	1.66	0
1.3	0.7	0.2	1.73	116
1.4	1.0	0.3	1.82	165
1.5	1.4	0.4	1.89	212
1.6	1.8	0.4	1.95	205
1.7	2.2	0.4	2.03	197
1.8	2.6	0.4	2.09	191
1.9	3.2	0.6	2.17	276
2.0	3.8	0.6	2.24	268
2.1	4.4	0.6	2.32	259
2.2	5.1	0.7	2.36	296
2.3	5.9	0.8	2.42	331
2.4	6.6	0.7	2.49	281
2.5	7.5	0.9	2.56	352
2.6	8.4	0.9	2.63	342
2.7	9.3	0.9	2.69	335
2.8	10.1	0.8	2.76	290
2.9	11.0	0.9	2.81	320
3.0	11.7	0.7	2.87	244
3.1	12.6	0.9	2.94	306
3.2	13.4	0.8	3.00	267
3.3	14.4	1.0	3.06	327
3.4	15.4	1.0	3.12	321
3.5	16.6	1.2	3.19	376
3.6	17.8	1.2	3.24	371
3.7	19.5	1.7	3.29	517
3.8	21.3	1.8	3.35	538
3.9	23.2	1.9	3.41	557
4.0	25.4	2.2	3.47	634
4.1	27.8	2.4	3.52	682
4.2	30.5	2.3	3.59	641
4.3	33.6	3.1	3.64	852
4.4	37.0	3.4	3.69	922
4.5	40.5	3.5	3.75	934
4.6	44.3	3.8	3.80	1000
4.7	48.0	3.7	3.85	962
4.8	52.0	4.0	3.91	1023
4.9	56.3	4.3	3.96	1087
5.0	60.8	4.5	4.01	1120
5.1	65.5	4.7	4.07	1154
5.2	70.5	5.0	4.11	1218
5.3	76.0	5.5	4.17	1318

a. SEGRE AND WIEGAND²⁵

b $R(E_1) = (E_s)_{max} - (E_s)_{min}$

TABLE VII
GROUND STATE NEUTRON GROUP
INTEGRATION INDICATED IN EQ 19

E_3 (MeV)	α - RANGE ^a (MeV)	$F(E_3)$ $\times 10^8$	E_3 (MeV)	α - RANGE ^a (MeV)	$F(E_3)$ $\times 10^8$
5.3	1.2 - 1.4	281	8.2	2.5 - 5.3	19010
5.4	1.2 - 1.7	895	8.3	2.6 - 5.3	18658
5.5	1.2 - 2.0	1630	8.4	2.7 - 5.3	18316
5.6	1.2 - 2.3	2516	8.5	2.8 - 5.3	17981
5.7	1.2 - 2.6	3491	8.6	2.9 - 5.3	17691
5.8	1.2 - 2.9	4436	8.7	3.0 - 5.3	17371
5.9	1.2 - 3.2	5253	8.8	3.1 - 5.3	17127
6.0	1.2 - 3.5	6277	8.9	3.2 - 5.3	16821
6.1	1.2 - 3.7	7165	9.0	3.3 - 5.3	16554
6.2	1.2 - 4.0	8894	9.1	3.4 - 5.3	16227
6.3	1.2 - 4.2	10217	9.2	3.5 - 5.3	15906
6.4	1.2 - 4.5	12925	9.3	3.6 - 5.3	15530
6.5	1.2 - 4.7	14887	9.4	3.7 - 5.3	15159
6.6	1.2 - 5.0	18117	9.5	3.8 - 5.3	14642
6.7	1.2 - 5.2	20489	9.6	3.9 - 5.3	14104
6.8	1.2 - 5.3	21807	9.7	4.0 - 5.3	13547
6.9	1.2 - 5.3	21807	9.8	4.1 - 5.3	12913
7.0	1.3 - 5.3	21807	9.9	4.2 - 5.3	12231
7.1	1.4 - 5.3	21691	10.0	4.3 - 5.3	11590
7.2	1.5 - 5.3	21526	10.1	4.4 - 5.3	10738
7.3	1.6 - 5.3	21314	10.2	4.5 - 5.3	9816
7.4	1.7 - 5.3	21109	10.3	4.6 - 5.3	8882
7.5	1.8 - 5.3	20912	10.4	4.7 - 5.3	7882
7.6	1.9 - 5.3	20721	10.5	4.9 - 5.3	5897
7.7	2.0 - 5.3	20445	10.6	5.0 - 5.3	4810
7.8	2.1 - 5.3	20177	10.7	5.1 - 5.3	3690
7.9	2.2 - 5.3	19918	10.8	5.2 - 5.3	2536
8.0	2.3 - 5.3	19622	10.9	5.3 - 5.3	1318
8.1	2.4 - 5.3	19291	TOTAL Σ		766567

a. SEE FIG 17

TABLE VIII

NEUTRON GROUP LEAVING C^{12} IN ITS 4.45 MEV LEVEL
 COMPUTATIONAL STEPS IN EQ 19 UP TO THE INTEGRATION INDICATED

E_1 (Mev)	$(n/10^3 \text{ a's})^a$	$f(E_1)$	$R(E_1)^b$ (Mev)	$F(E_1)/R(E_1)$ $\times 10^8$
1.0	0.0	0	0.35	0
1.1	-	0	0.89	0
1.2	0.5	0	0.96	0
1.3	0.7	0.2	0.99	202
1.4	1.0	0.3	1.04	288
1.5	1.4	0.4	1.10	364
1.6	1.8	0.4	1.15	348
1.7	2.2	0.4	1.21	331
1.8	2.6	0.4	1.26	318
1.9	3.2	0.6	1.32	455
2.0	3.8	0.6	1.37	438
2.1	4.4	0.6	1.42	423
2.2	5.1	0.7	1.47	476
2.3	5.9	0.8	1.51	530
2.4	6.6	0.7	1.58	443
2.5	7.5	0.9	1.64	549
2.6	8.4	0.9	1.69	533
2.7	9.3	0.9	1.74	517
2.8	10.1	0.8	1.79	447
2.9	11.0	0.9	1.84	489
3.0	11.7	0.7	1.89	370
3.1	12.6	0.9	1.95	461
3.2	13.4	0.8	2.00	400
3.3	14.4	1.0	2.04	490
3.4	15.4	1.0	2.09	478
3.5	16.6	1.2	2.15	558
3.6	17.8	1.2	2.20	546
3.7	19.5	1.7	2.25	755
3.8	21.3	1.8	2.30	783
3.9	23.2	1.9	2.35	808
4.0	25.4	2.2	2.39	921
4.1	27.8	2.4	2.45	980
4.2	30.5	2.3	2.50	921
4.3	33.6	3.1	2.55	1217
4.4	37.0	3.4	2.59	1311
4.5	40.5	3.5	2.64	1326
4.6	44.3	3.8	2.69	1410
4.7	48.0	3.7	2.74	1350
4.8	52.0	4.0	2.79	1434
4.9	56.3	4.3	2.85	1510
5.0	60.8	4.5	2.90	1552
5.1	65.5	4.7	2.94	1599
5.2	70.5	5.0	2.99	1672
5.3	76.0	5.5	3.04	1810

a. SEGRE AND WIEGAND²⁵

b. $R(E_1) = (E_3)_{max} - (E_3)_{min}$

TABLE IX
NEUTRON GROUP LEAVING C^{12} IN ITS 4.45 MEV LEVEL
INTEGRATION INDICATED IN EQ 24

E_g (MeV)	α - RANGE ^a (MeV)	$F(E_g)$ $\times 10^3$	E_g (MeV)	α - RANGE ^a (MeV)	$F(E_g)$ $\times 10^3$
1.5	1.2	0	3.9	2.8 - 5.3	25598
1.6	1.2 - 1.5	854	4.0	2.9 - 5.3	25151
1.7	1.2 - 1.7	1533	4.1	3.0 - 5.3	24662
1.8	1.2 - 2.0	2744	4.2	3.1 - 5.3	24292
1.9 ^d	1.2 - 2.2	3643	4.3	3.2 - 5.3	23831
2.0	1.2 - 2.5	5165	4.4	3.3 - 5.3	23431
2.1	1.2 - 2.7	6215	4.5	3.4 - 5.3	22941
2.2	1.2 - 2.9	7151	4.6	3.5 - 5.3	22463
2.3	1.2 - 3.2	8382	4.7	3.6 - 5.3	21905
2.4	1.2 - 3.4	9350	4.8	3.7 - 5.3	21359
2.5	1.3 - 3.7	11209	4.9	3.9 - 5.3	19821
2.6	1.4 - 3.9	12598	5.0	4.0 - 5.3	19031
2.7	1.5 - 4.1	14211	5.1	4.1 - 5.3	18092
2.8	1.6 - 4.4	17296	5.2	4.2 - 5.3	17112
2.9	1.7 - 4.6	19684	5.3	4.3 - 5.3	16191
3.0	1.8 - 4.8	22137	5.4	4.4 - 5.3	14974
3.1	1.9 - 5.1	26480	5.5	4.5 - 5.3	13663
3.2	2.0 - 5.3	29507	5.6	4.6 - 5.3	12337
3.3	2.1 - 5.3	29069	5.7	4.7 - 5.3	10927
3.4	2.2 - 5.3	28646	5.8	4.8 - 5.3	9577
3.5	2.3 - 5.3	28170	5.9	4.9 - 5.3	8143
3.6	2.4 - 5.3	27640	6.0	5.0 - 5.3	6633
3.7	2.5 - 5.3	27197	6.1	5.1 - 5.3	5081
3.8	2.6 - 5.3	26648	6.2	5.3	1810
			TOTAL	Σ	775536

a. SEE FIG 17

TABLE X
SUMMATION OF THE NORMALIZED LOW AND HIGH ENERGY
NEUTRON GROUPS IN A 7 TO 3 RATIO

E_3 (MeV)	$\pm E$ (MeV)	$F(E_3)$ $\times 10^3$	$\overline{F(E_3)}^a$ $\times 10^3$	E_3 (MeV)	$\pm E$ (MeV)	$F(E_3)$ $\times 10^3$	$\overline{F(E_3)}^a$ $\times 10^3$
1 5		0		6 3		4430	
1 6		854		6 4	0 7	5604	857 2
1 7		1533		6 5		6455	
1 8		2744		6 6		7856	
1 9		3643		6 7	0 7	8884	8129
2 0	0 2	5165	4984	6 8		9456	
2 1		6215		6 9	0 7	9456	8163
2 2		7151		7 0		9456	
2 3	0 3	8382	8581	7 1		9405	
2 4		9350		7 2	0 7	9334	8867
2 5	0 3	11209	11457	7 3		9242	
2 6		12598		7 4	0 8	9153	8921
2 7		14211		7 5		9067	
2 8	0 3	17296	17659	7 6		8985	
2 9		19684		7 7	0 8	8865	8782
3 0		22137		7 8		8749	
3 1	0 3	26480	24688	7 9	0 8	8636	8564
3 2		29507		8 0		8508	
3 3		29069		8 1		8365	
3 4	0 4	28646	27277	8 2		8243	
3 5		28170		8 3		8090	
3 6	0 4	27640	27514	8 4	0 9	7942	7948
3 7		27197		8 5		7797	
3 8		26648		8 6		7671	
3 9	0 4	25598	26021	8 7		7532	
4 0		25151		8 8		7426	
4 1		24662		8 9	0 9	7294	7217
4 2	0 4	24292	24335	9 0		7178	
4 3		23831		9 1		7036	
4 4	0 5	23431	23223	9 2		6897	
4 5		22941		9 3		6734	
4 6		22463		9 4	1 0	6573	6216
4 7	0 5	21905	21298	9 5		6349	
4 8		21359		9 6		6115	
4 9	0 5	19821	19792	9 7		5874	
5 0		19031		9 8		5599	
5 1		18092		9 9	1 0	5303	4765
5 2	0 6	17112	17070	10 0		5025	
5 3		16313		10 1		4656	
5 4	0 6	15362	15277	10 2		4256	
5 5		14370		10 3		3851	
5 6		13428		10 4	1 1	3418	3116
5 7	0 6	12441	12129	10 5		2557	
5 8		11500		10 6		2086	
5 9	0 6	10421	10272	10 7		1600	
6 0		9355		10 8		1100	
6 1		8188		10 9		571	
6 2	0 6	5666	8745				

a. AVERAGE OVER THE INTERVAL $\pm E$ INDICATED IN COLUMN 2