THE EXCITED STATES OF CARBON TWELVE

by

James Robert Wayland, Jr.

A Thesis Submitted to the Faculty of the

DEPARTMENT OF PHYSICS

In Partial Fulfillment of the Requirements
For the Degree of

MASTER OF SCIENCE

In the Graduate College

THE UNIVERSITY OF ARIZONA

1962

STATEMENT BY AUTHOR

This thesis has been submitted in partial fulfillment of requirements for an advanced degree at the University of Arizona and is deposited in the University Library to be made available to borrowers under rules of the Library.

Brief quotations from this thesis are allowable without special permission, provided that accurate acknowledgment of source is made. Requests for permission for extended quotation from or reproduction of this manuscript in whole or in part may be granted by the head of the major department or the Dean of the Graduate College when in their judgment the proposed use of the material is in the interests of scholarship. In all other instances, however, permission must be obtained from the author.

SIGNED: James Robert Wayland, Jr.

APPROVAL BY THESIS DIRECTOR

This thesis has been approved on the date shown below:

R. M. Kalbach

R. M. KALBACH
Associate Professor of Physics

10-19-62
Date

ABSTRACT

The low energy excited states of C^{12} were studied by bombarding beryllium with alpha particles. The resulting neutron spectrum from the reaction Be^9 (α,n) C^{12} was found from the proton recoil spectrum in nuclear emulsions. The neutron spectrum indicated the existence of a previously unknown state at approximately 2.5 Mev.

ACKNOWLEDGMENTS

The completion of this experiment was greatly accelerated by the aid and assistance of Richard Lehman and the use of facilities of the Health Physics Department of the University of California Lawrence Radiation Laboratory. I also wish to thank my thesis director, Dr. R. M. Kalbach, for his encouragement.

TABLE OF CONTENTS

I. INTRODUCTION

The energy levels of C^{12} have recently attracted attention in the field of stellar evolution and in the study of neutron sources which depend upon the reaction $Be^9(\alpha,n)C^{12}$. The answers to many of the questions in each case depend upon an exact knowledge of the energy states of C^{12}: In the latter case, the energy spectrum of the neutrons has an unexplained peak which could be explained by an excited state of C^{12} at approximately 2.5 Mev. The present knowledge of the excited states of C^{12} indicates states at 4.43 Mev, 7.66 Mev, 9.0 Mev, 9.3 Mev, and higher.[1] However, all previous experiments dealing with the excited states of C^{12} were concerned with the higher energy states. This experiment was designed to study the possibility of an excited state at an energy lower than 4.43 Mev.

---

[1] F. Ajzenberg-Selove and T. Lauritsen, <u>Nuclear Physics</u>, 10, 1 (1959).

II. THEORY OF THE NEUTRON SPECTRUM FROM (α,n) SOURCES

W. N. Hess[2] has calculated the neutron energy spectrum for various neutron sources which use (α,n) reactions. He first assumes that monoenergetic alpha particles hit nuclei, T, producing a neutron and a final nucleus, F.[3] The neutrons will be emitted with angles θ_{cm} relative to the incident alpha direction in the center-of-mass system, and give rise to a distribution of neutron energies in the laboratory system. To obtain the neutron distribution in the laboratory system, one must first find the energy of the assumed monoenergetic neutrons in the center-of-mass system,[4] E_n', which can be shown by proper use of nonrelativistic dynamics, to be

$$E_n' = [M_f/(M_f + M_n)]\ \{E_\alpha[M_T/(M_T + M_\alpha)] + Q\}. \quad (1)$$

In the laboratory system, the neutron energy, E_n, can then be shown to be

$$E_n = [2M_nM_\alpha/(M_T + M_\alpha)]\ [E_\alpha E_n/M_\alpha M_n]^{\frac{1}{2}}\cos\theta_{cm}' + E_n' + [M_\alpha M_n/(M_T + M_\alpha)^2]E_\alpha, \quad (2)$$

---

[2] W. N. Hess, <u>Annals of Physics</u>, <u>6</u>, 115 (1959).

[3] The following discussion of how Hess obtained the neutron spectrum is taken from his paper.

[4] Henceforth, an unprimed quantity refers to the laboratory system, and a primed quantity refers to the center-of-mass system.

where

M_f = mass of the residual nucleus,
M_n = mass of the neutron,
M_α = mass of the alpha particle,
E_n = energy of the neutron in the laboratory system,
E_α = energy of the alpha particle in the laboratory system, and
Q = nuclear disintegration energy.

Equation (2) would allow one to find the resulting energy distribution of the neutrons in the laboratory system. (One must, of course, make the assumption that the neutrons are emitted isotropically in the center-of-mass system, with an energy given by equation (1).)

Let σ be the cross section for the (α,n) reaction and let n be the number of target atoms. Then in a thickness dx at x, there will be $n\sigma dx$ interactions. Each interaction will produce a neutron. If E_α is the energy of the alpha particle, then the total number of neutrons produced as the alpha particle comes to rest is

$$Y = \int_0^{R_\alpha} N(x) n\sigma(E) dx = nN(0) \int_0^{E_\alpha} [\sigma(E)/(dE/dx)] dE, \quad (3)$$

where N(0) is the total number of incoming alpha particles. However, a complication arises because the alpha particles in an extended neutron source are slowed down by ionization from their initial energy E_α to E = 0 (or they sometimes interact before coming to rest). Hess approximated the slowing down process by making a computation for a discrete number of monoenergetic alpha particles of energies from 0 up to E_α. He obtained for the yield per incoming alpha particle:

$$\begin{aligned} Y/N(0) &= n \int_0^{E_\alpha} [\sigma/(dE/dx)]\, dE \\ &\simeq n\{E_1[\sigma(E)/(dE/dx)]_{E_1/2} + \\ &+ (E_2-E_1)[\sigma(E)/(dE/dx)]_{(E_1+E_2)/2} + \cdots \\ &+ (E_{m+1}-E_m)[\sigma(E)/(dE/dx)]_{(E_\alpha+E_m)/2}\}, \end{aligned} \qquad (4)$$

where E_i $(i = 1,2,\ldots,m+1)$ are the chosen alpha energies.

Hess then found the neutron energy spectra for monoenergetic alpha particles of mean energy, E_1, $(E_1+E_2)/2$, ... $(E_\alpha+E_m)/2$. As can be seen from equation (4), each of these must be weighted by the factor W:

$$\begin{aligned} &W[(E_m+E_{m+1})/2] = \\ &(E_{m+1}-E_m)[\sigma(E)/(dE/dx)]_{(E_m+E_{m+1})/2}. \end{aligned} \qquad (5)$$

Thus the total spectrum is obtained by adding in each of the contributions from the various monoenergetic alpha particles.

Using this type of analysis, Hess predicted a dip at 6 Mev in the spectrum for plutonium-beryllium neutron sources. But experimentally, this dip has not been found.[5] Hess suggested that this could be due to an unknown excited state of C^{12} between the ground state and the first known state at 4.43 Mev. To attempt to find out if there is an

[5]R. Lehman recently made a very accurate determination of this spectrum and found no dip at 6 Mev (private communication).

excited state lower than 4.43 Mev, the reaction $Be^9(\alpha,n)C^{12}$ was studied. If one knows the Q-value for the reaction, and the energy of the incoming alpha particles, one can find the excited states of C^{12} by examining the resulting neutron spectrum. This has been done by F. Ajzenberg-Selove and P. H. Stelson[6] but with the purpose of finding the ratio of the number of C^{12} nuclei in the 4.43 Mev state to the number in the 7.66 Mev state. The present experiment was then designed to study the region between the 4.43 Mev state and the ground state.

---

[6]F. Ajzenberg-Selove and P. H. Stelson, Physical Review, 120, 500 (1960).

III. EXPERIMENTAL PROCEDURE

To study the neutrons from the reaction $Be^9(\alpha,n)C^{12}$, nuclear emulsions were chosen as the detection media. The neutrons will interact in the emulsion with protons through the process of elastic collision. The resulting proton recoil spectrum can be analysed by the methods given below to give the neutron spectrum.

The reaction $Be^9(\alpha,n)C^{12*}$ was studied by bombarding a beryllium target with 5.47 Mev alpha particles from a 1.2 millicurie americium (241) source.[7] The target used for this experiment was approximately 300 Kev thick. The source and the target were separated by a lead collimator 0.25 inches thick to reduce the effects of the strong gamma background from the source. This assembly was mounted in an aluminum box and the box was evacuated to a pressure of approximately 100 microns of mercury (see Figures 1 and 1-A). The target was next to a thin Mylar window, which was 0.4 inches from Ilford L-4 nuclear emulsions held as shown in Figure 1. The emulsions were then exposed for three weeks. After the

---

[7]This equipment, the targets, and associated apparatus were used through the kind generosity of R. Lehman and the Health Physics Department of UCLRL.

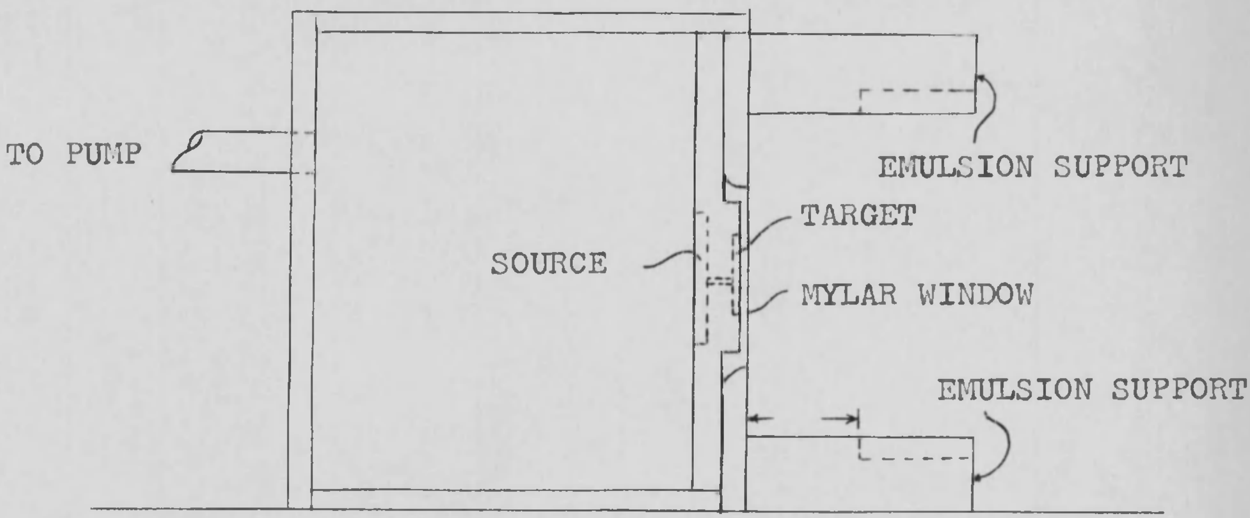


Figure 1. Schematic diagram of the exposure box.

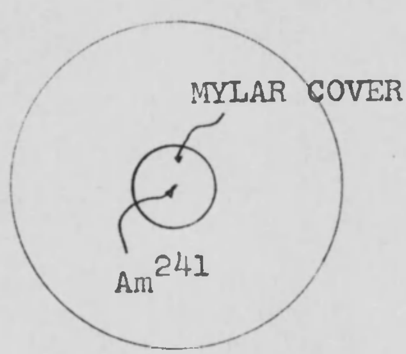


Figure 1-A. The Americium source.

Figures 1 and 1-A

processing, the plates were scanned in the fashion described below.

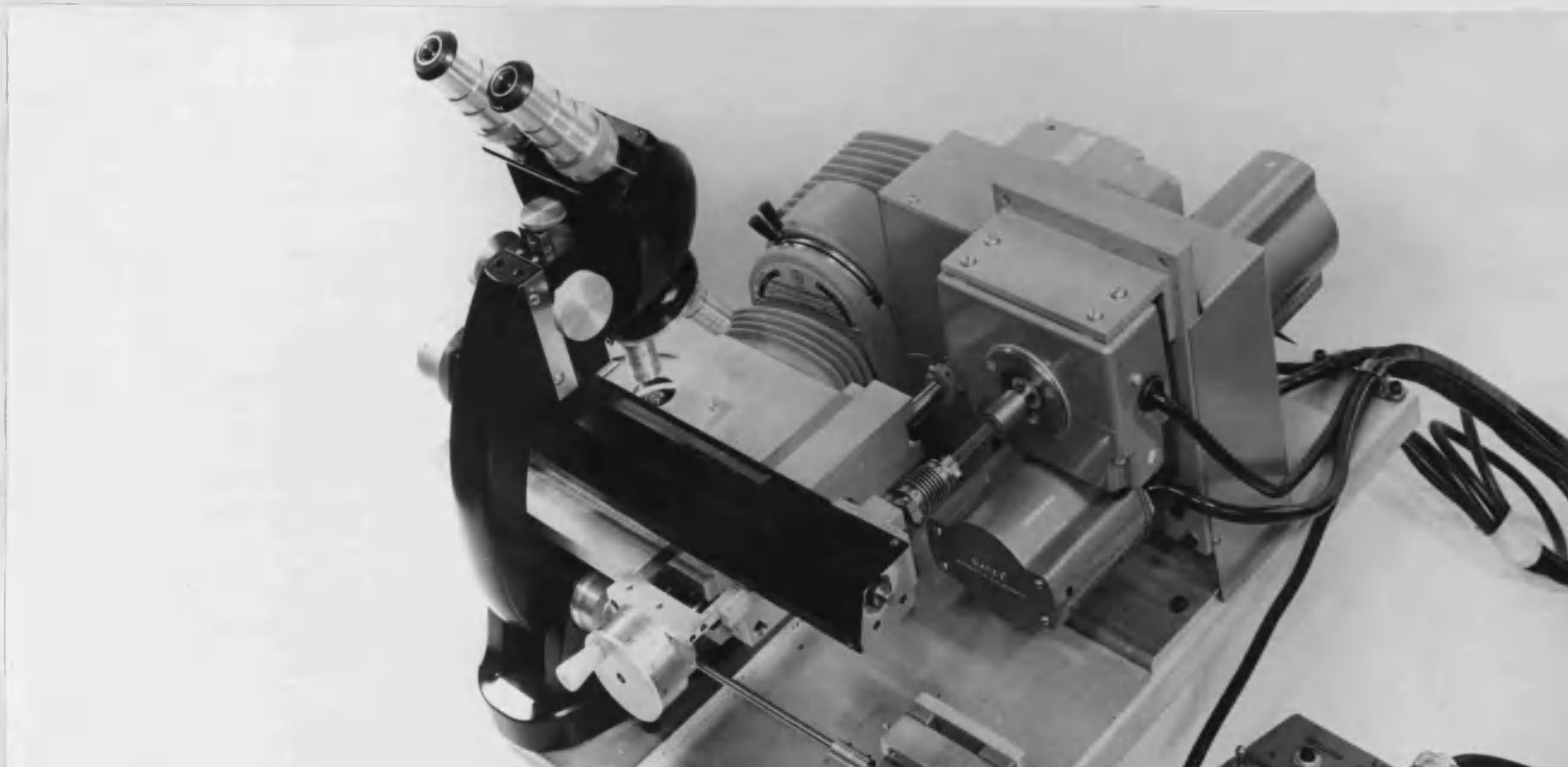
The emulsions were scanned at the University of California Lawrence Radiation Laboratory on the digitized microscope shown in Figures 2 and 3. There is a strong natural background of low energy alpha tracks from thorium in the emulsions. The energy of the alpha particles ranged from 0 to 6 Mev, but with the dominant peak at 1.5 Mev, with few particles above 2 Mev. This background was determined by inspection of a control emulsion with a history identical to the above plates, except for the exposure. The track length of a 2 Mev alpha particle is approximately 50μ. Alpha particles and protons produce tracks in this type of emulsion which are very similar. Only those tracks with lengths greater than 50μ.were scanned. Thus, by ignoring tracks of lengths less than 50μ in the raw data, the major proportion of this background was eliminated (the background above 2 Mev was eliminated in the usual manner). Those tracks which left the emulsion or originated from a star were not measured. Also, equal volumes of emulsions were scanned on each plate to obtain proper normalization.

One must determine the neutron spectrum from the proton recoil spectrum in the emulsions. First one must find the energy distribution of proton recoils N(E) in a hydrogenous media which results from elastic collisions of neutrons

Figure 2. The digitized microscope.


IBM

Figure 3. The digitized microscope
and related apparatus.



with protons. If E_o is the neutron energy in the laboratory system and M_p is the mass of the target proton, then the energy of the recoiling proton is given by

$$E = E_o[4M_pM_n/(M_p+M_n)^2]\cos^2\theta, \tag{6}$$

where θ is the angle between the recoil proton and the original direction of the neutron (see Appendix B).

For N_o incoming neutrons, the number of protons, dN, projected between the angles θ and $\theta + d\theta$ is given by

$$dN = N_o n\sigma_c(\emptyset)d\Omega = 2\pi N_o n\sigma_c(\emptyset) \sin \emptyset \frac{d\emptyset}{d\theta} d\theta, \tag{7}$$

where $\sigma_c(\emptyset)$ is the differential cross section per unit solid angle in the center-of-mass system for the above collision, n is the number of scattering nuclei per unit area, and $\theta = (\pi-\emptyset)/2$. $\emptyset$ is the angle through which the masses are scattered in the center-of-mass system.

Since $M_p \approx M_n$, we can write equation (6) as

$$E = E_o\sin^2(\emptyset/2). \tag{8}$$

Then

$$dE/E_o = \sin(\emptyset/2)\cos(\emptyset/2)d\emptyset = \tfrac{1}{2} \sin \emptyset d\emptyset \tag{9}$$

and

$$dN = 4\pi N_o n\sigma_c(\emptyset)dE/E_o. \tag{10}$$

The neutron spectrum is then given in terms of the proton spectrum by the relation[8]

---

[8]The above discussion was taken from Segre, <u>Experimental Nuclear Physics</u>, <u>I</u>, 131ff. (1952).

$$N_o(E_o) = -(dN/dE_o)[E_o/n\sigma(E_o)]. \qquad (11)$$

The negative sign is introduced to give the resulting spectrum the proper slope and a factor of 4π is dropped.

To determine the number of neutrons at a given energy E, one must then multiply the slope of the proton recoil distribution at each point by the constant $1/n$, and by the parameters $-E$ and $1/\sigma(E)$.

To find the proton recoil spectrum, one must find the corrected length given by

$$l = [f_1(x_1-x_2)^2 + f_1(y_1-y_2)^2 + f_2(z_1-z_2)^2]^{\frac{1}{2}}, \quad (12)$$

where the rectangular coordinates of the end points of the track are (x_1, y_1, z_1) and (x_2, y_2, z_2), f_1 is the lateral (x,y) and f_2 the vertical (z) emulsion shrinkage factor (the square of the ratio of the original dimension to the same dimension after development). This length is compared with a range-energy table[9] for protons in nuclear emulsions, and the proton tracks are sorted into one of 50 energy intervals of 0.4 Mev.

As only proton tracks which originate and end inside the emulsion are measured, the uncorrected spectrum is incorrect by a geometrical function which gives the probability that a track of a given length which originates in the emulsion will be retained in the emulsion. If T is the thickness

---

[9] W. W. Barkas, UCRL-3769, (unpublished), 1957.

of the emulsion, and if one assumes infinite lateral extent of the emulsion, this function is given by

$$P_i = [T - 0.5R(E_i)]/T \qquad \text{for } R \leq T$$
$$P_i = T/2R(E_i) \qquad \text{for } R \geq T \tag{13}$$

where $R(E_i)$ is the range of a proton of initial energy E_i and P_i is the fraction of the proton recoil tracks which are completely contained in the emulsion. (These correction factors are derived in Appendix A.) Each $(\Delta N/\Delta E_i)$ is multiplied by the corresponding $1/P_i$ to generate correct points

$$(\Delta N/P_i\Delta E_i) = N(E_i) \tag{14}$$

of a proton energy spectrum. The standard deviation of each point $N(E_i)$ is computed by the relation

$$S_i = \sqrt{\Delta N_i}/P_i\Delta E. \tag{15}$$

The very small error in ΔE has been neglected.

The slope of this spectrum, $dN(E_i)/dE$, is obtained by subtracting the ordinates of adjacent points. Then the slope at an average point E_i given by

$$\bar{E}_i = (E_i+E_{i+1})/2 \tag{16}$$

is computed by

$$\frac{dN(E)}{dE} = \frac{N(E_{i+1}) - N(E_i)}{E_{i+1} - E_i}\ . \tag{17}$$

Then, as explained above, one obtains the neutron energy spectrum $N_o(\bar{E}_i)$ by multiplying this slope by $-\bar{E}_i/\sigma(\bar{E}_i)$. The standard deviation of $N_o(\bar{E}_i)$ is computed by the propagation of error to be

$$S = \frac{[S_i{}^2 + S_{i+1}{}^2]^{\frac{1}{2}}}{E_{i+1} - E_i} \quad \frac{E_i}{\sigma(E_i)} \; . \tag{18}$$

IV. EXPERIMENTAL RESULTS AND CONCLUSION

A total of 390 tracks were measured using the method outlined above. The resulting spectrum is shown in Figure 4. Because of the small number of tracks which were measured, the results from the analysis method were combined into 0.4 Mev energy intervals.

The Q-value for the reaction $Be^{9}(a,n)C^{12}$ in which C^{12} is in the ground state, is 5.704 Mev.[10] As the alpha particles lose approximately 0.3 Mev in going through the beryllium target and its Mylar shield, the ground state of C^{12} should correspond to an energy of the emitted neutron of $5.7 + (5.47 - 0.3) = 10.87$ Mev.

The background problem was very serious. Due to a contamination of thorium, there was a peak at 1.5 Mev (with measurable background to 6 Mev) from the alpha decay of thorium. There are other reactions which may have occurred, namely:

	Reaction	Q for the Reaction
1	$Be^{9}(\alpha,n)3He^{4}$	-1.57 Mev
2	$Be^{9}(\alpha,n\alpha)Be^{8}$	-1.67 Mev
3	$Be^{9}(\alpha,n)C^{12*}$ to states 9.0 or 9.33 Mev	5.704 Mev

[10] F. Enerling, L. A. Koenig, J. H. E. Mallauch, and A. H. Wapstra, Nuclear Physics, 15, 342 (1960).

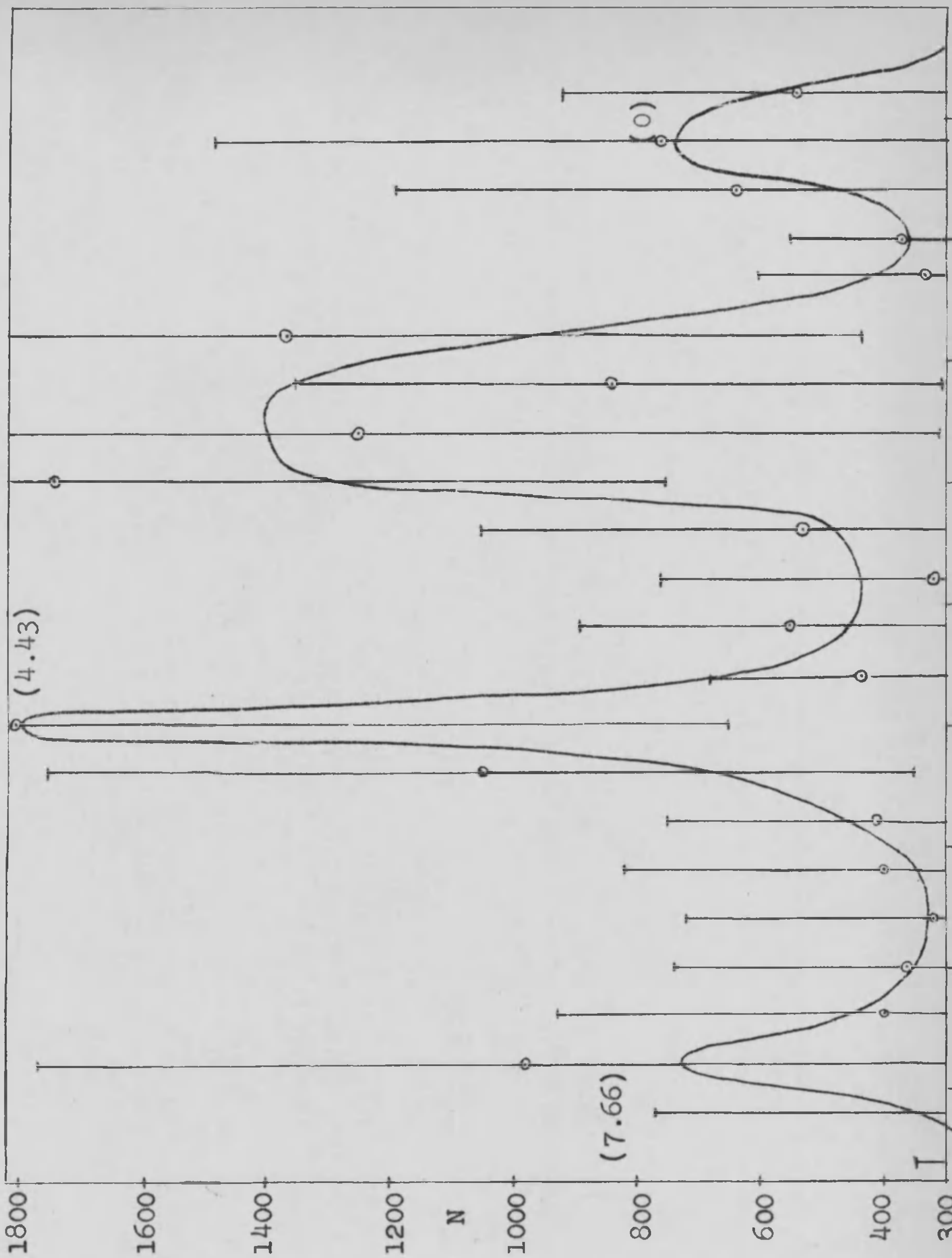


Figure 4. Data for E_α=5.47 Mev in the reaction $Be^9(\alpha,n)C^{12}$. N is the relative number of neutrons per 0.4 Mev interval. E_n is the neutron energy.

	Reaction	Q for the Reaction
4	$C^{12}(\alpha,n)O^{15}$	-8.45 Mev
5	$C^{16}(a,n)Ne^{19}$	-12.16 Mev
6	$C^{13}(\alpha,n)O^{16}$	2.21 Mev

However, as one can see from energy considerations, the emitted neutrons from the reactions 1, 2 and 3 will all be in a region which could not affect the results of the neutron spectrum corresponding to an excited state of C^{12} at 2.5 - 3.0 Mev. The reactions 4 and 5 are so endoergic that the corresponding neutrons would be of such an energy that they would not affect the results. However, neutrons corresponding to the ground state of the reaction 6 would have an energy of 2.21 + (5.47 - 0.3) = 7.38 Mev. But since there is a dip at this point in the spectrum of Figure 4, this reaction apparently did not cause a strong background.

Figure 4 indicates that there are excited states of C^{12} which correspond to the 4.43 Mev and the 7.66 Mev states. These are marked on the graph. However, there is also a strong peak at approximately 8.3 Mev, as can be seen from the zeros (within statistical error) on either side of a peak well above zero. This would correspond to an excited states of C^{12} at 2.5 Mev.

Because of poor statistics, the experimenter hopes to repeat this experiment with a high intensity beam of an accelerator. This would give a large enough total number of tracks to enable one to locate the peak more precisely. The relative abundance of C^{12} in the 2.5 Mev state to the 4.43 Mev state, etc., could thus be obtained.

APPENDIX A

A CALCULATION OF THE FRACTION OF PROTON RECOILS WHICH ORIGINATE IN A NUCLEAR EMULSION AND ARE RETAINED IN THE EMULSION

Let the emulsion be of thickness T.

Case I. If the range of the proton recoil, R(E), is less than or equal to T, then the fraction retained in the emulsion is given by the expression (see Figure 5):

$$\text{Fraction retained} = [T-2R(E)+R(E) + \int_0^{R(E)} \cos\theta dx]/T$$

$$= \{T-R(E) + \int_0^{R(E)} [x/R(E)]\, dx\}/T$$

$$= [T-0.5R(E)]/T.$$

Case II. If the range of the proton recoil is greater than or equal to T, then (see Figure 6):

$$\text{Fraction retained} = \int_{-\theta_1}^{0} d\Omega/4\pi + \int_0^{\phi} d\Omega/4\pi$$

$$= \int_0^{\cos^{-1} x/R(E)} 2\pi\sin\theta' d\theta'/4$$

$$+ \int_0^{\cos^{-1}(T-x)/R(E)} 2\pi\sin\theta' d\theta'$$

$$= \tfrac{1}{2}[\cos\theta']_0^{\cos^{-1}x/R(E)}$$

$$+ \tfrac{1}{2}[\cos\theta']_0^{\cos^{-1}(T-x)/R(E)}$$

$$= T/2R(E).$$

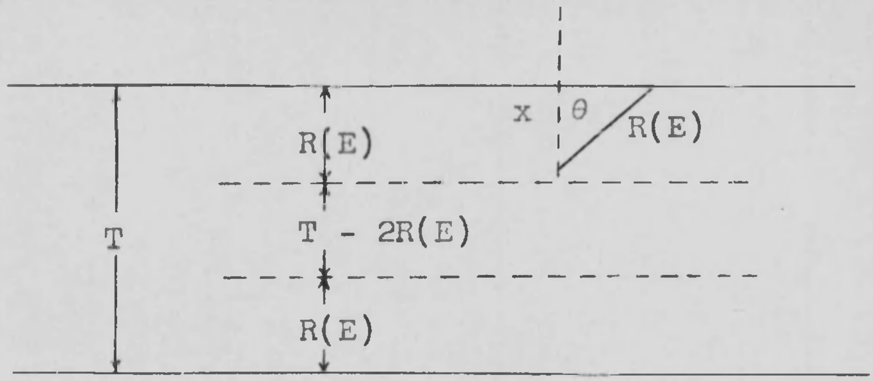


Figure 5. The nuclear emulsion considered with respect to the retention of a proton in the case R(E) T.

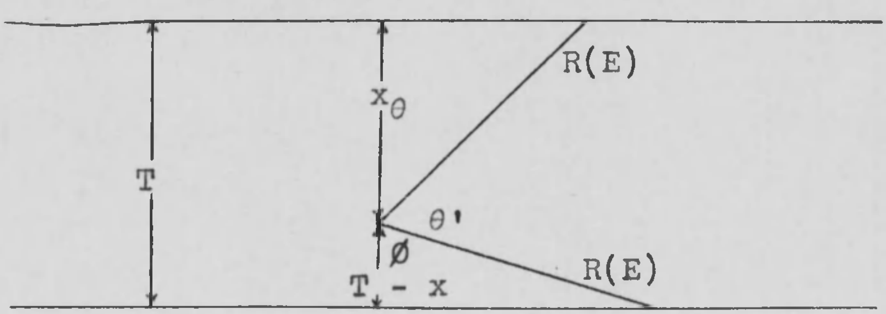


Figure 6. The nuclear emulsion considered with respect to the retention of a proton in the case R(E) T.

Figures 5 and 6

APPENDIX B

A DERIVATION OF EQUATION (6)

Consider the elastic collision shown in Figure 7. If we let the unprimed symbols represent the quantities before the collision and the primed symbols represent the quantities after collision, the application of the laws of conservation of momentum and energy gives

$$\vec{P}_1 = \vec{P}_1' + \vec{P}_2',$$

and

$$P_{\circ}^2/m_1 = (P_1')^2/m_1 + P_2')^2/m_2$$

where

P_1 = momentum of particle 1
P_2 = momentum of particle 2
m_1 = mass of particle 1
m_2 = mass of particle 2
E_1 = energy of particle 1
E_2 = energy of particle 2
E_o = energy of particle 1 before the collision
v_1 = original velocity of particle 1 in the laboratory system
v_1' = velocity of particle 1 after collision in the laboratory system
v_2' = velocity of particle 2 after collision in the laboratory system
θ_2' = angle between v_1 and v_2'.

We now eliminate P_1' by

$$P_1^2/m_1 = (\vec{P}_1 - \vec{P}_2')^2/m_1 + (P_2')^2/m_2$$

$$= [P_1^2 + (P_2')^2 - 2P_1P_2'\cos\theta_2']/m_1 + (P_2')^2/m_2$$

$$0 = (P_2')^2(1/m_1 + 1/m_2) - 2P_2'P_1\cos\theta_2'/m_1.$$

If P_2' is not zero, we find

$$P_2' = (2P_1 \cos\theta_2'/m_1)[m_1 m_2/(m_1 + m_2)]$$
$$= [2m_1 v_1 m_2/(m_1 + m_2)] \cos\theta_2'.$$

Therefore, we have

$$E_2' = (P_2')^2/2m_2 = 2m_1^{\,2} m_2 v_1^{\,2} \cos^2\theta_2'/(m_1 + m_2)^2$$
$$= 4m_1 m_2/(m_1 + m_2)^2 E_o \cos^2\theta_2'.$$

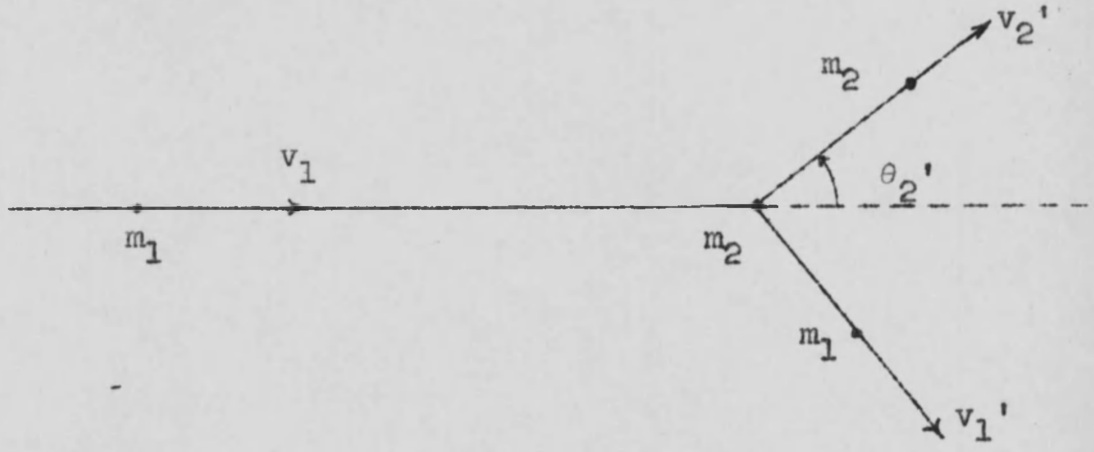


Figure 7. The elastic collision of m_1 and m_2.

Figure 7

BIBLIOGRAPHY

Ajzenberg-Selove, F., and Lauritsen, T., Nuclear Physics, 10, 1 (1959).

Ajzenberg-Selove, F., and Stelson, P. H., Physical Review, 120, 500 (1959).

Barkas, W. W., UCRL-3769, (unpublished, 1957).

Enerling, F., Koenig, L. A., Mallauch, J. H. E., and Wapstra, A. H., Nuclear Physics, 15, 342 (1960).

Hess, W. N., Annals of Physics, 6, 115 (1959).

Lehman, R. L., private communication.

Segre, E., Ed., Experimental Nuclear Physics, 1, 131ff (1952).