TABLE II. The "upper limit" energies of the low energy neutron spectrum. The neutron angles are in the laboratory system. The proton scattering angles are in the p–p center-of-mass system.

Proton scattering angle	"Upper limit" neutron energies (Mev)		
	0°	90°	180°
40°	0.15±0.07	0.38±0.2	0.07±0.03
67°	0.89±0.3	0.46±0.15	0.37±0.1
90°	3.2 ±1.1	2.6 ±0.6	1.7 ±0.4

The minimum and maximum scattering angles for the two protons have been calculated from the geometry and the limits of the inelastic tangential plateaus. The maximum energy of the neutrons in the forward direction has been calculated from the maximum scattering angles, the maximum energy in the backward direction from the minimum scattering angles. The extension of the radial plateau yields a value for the maximum neutron energy at 90° in the laboratory system. A summary of the results of these calculations is given in Table II.

These neutron energies are the "upper limits" of the low energy neutron peak. A precise definition of "upper limit" cannot be given. However, the number of neutrons emitted with the "upper limit" energy was less than the number emitted at the peak of the distribution by a factor of about five or ten.

There are two features of the neutron energies which are significant. The increase in the neutron energy as the proton scattering angle is increased is real. Also, the ratio of about 2:1 between the neutron energies at 0° and 180° is significant. The accuracy of the measurements does not warrant making a positive statement about the high energy of the neutrons at 90° with a proton scattering angle of 40°. The errors on the neutron energies have been estimated on the basis of the precision of the measurements of the plateaus. Comparison of these results with theoretical calculations is not practical at this time since no detailed calculations on the neutron energy spectrum have been published.

I am indebted to Professor C. L. Oxley for his assistance and advice on this experiment and to the cyclotron crew for their patient cooperation.

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Energy Levels in C^{12} from $Be^9(\alpha,n)C^{12}$*

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A thin polonium source and thin beryllium target have been used to investigate energy states in C^{12}. The neutron spectrum was determined from proton tracks in Eastman NTA emulsions. By investigating the neutrons emitted in the forward and backward directions, neutrons associated with the transition to the ground state of C^{12} were detected, and excited levels in C^{12} were identified at 4.2 and 7.5 Mev above the ground state.

INTRODUCTION

THE neutron spectrum from a mixed Po+Be source has been studied previously.[1] It seemed wise to study the spectrum under improved geometrical conditions so as to resolve better the neutron groups associated with the various energy states in C^{12}. A compromise between good and poor geometry was utilized in the experiment reported in this paper so as to obtain as good resolution as possible compatible with sufficient neutron intensity. Preliminary reports have been given previously.[2]

EXPERIMENTAL PROCEDURE

The experimental arrangement is shown in Fig. 1. The polonium source on a thick nickel foil had a strength of ~100 millicuries and was supplied by the Canadian Radium and Uranium Corporation. It had an area of 4 cm² and was reported to be very thin. The beryllium foil, 0.25 mg/cm² in thickness, was kindly supplied by H. Bradner of the University of California. It was masked by a brass washer so that a circle of area 4.9 cm² was exposed to the alpha-particles. The perpendicular distance from the polonium to the beryllium was 2.2 cm. The angle of incidence of the alpha-particles striking the beryllium ranged from 0° to 47°. 50 micron and 100 micron Eastman NTA nuclear track plates were used to detect the neutrons through observation of the knock-on protons in a forward cone having a half-angle of 12°. The plates were wrapped in aluminum foil and then in paper. The polonium source and beryllium target were placed inside a brass cylinder which was kept evacuated by a Cenco HiVac pump. The entire apparatus was suspended by a wire near the geometrical center of a

* Supported in part by the AEC.
[1] B. G. Whitmore and W. B. Baker, Phys. Rev. **78**, 799 (1950); Perlman, Richards, and Speck, MDDC-39 (1946).
[2] W. H. Guier and J. H. Roberts, Phys. Rev. **79**, 719 (1950); and Phys. Rev. **81**, 317 (1951).

laboratory having dimensions of about 20 ft×20 ft ×20 ft to minimize background resulting from room scattering. The room was air conditioned and kept reasonably dry, which minimized fading of the latent image of the proton tracks during the exposure. The plates, wrapped in aluminum foil surrounded with paper and held in position by strings and wires, were exposed to the protons for about a month and then developed.

DATA AND RESULTS

The proton tracks were measured with Leitz Ortholux and Bausch and Lomb research microscopes. To be acceptable the tracks had to be in a cone such that the angle between the neutron and knock-on proton was 12° or less. Each track length was corrected by the usual method[3] to the length it would have if the proton had gone exactly in the forward direction,[4] taking up essentially all of the neutron energy. The proton range-energy curve as measured for Ilford emulsions[5] was assumed to hold for the Eastman NTA emulsions.

The track density obtained was quite low. Essentially four 1 in.×3 in. plates had to be scanned to obtain 513 tracks in the forward direction and 511 in the backward direction. The plates exposed in the 90° position have not been analyzed.

Histograms giving the number of tracks observed in each 20-micron interval after correction to 0° recoil[4] are shown in Fig. 2. The neutron background is seen to be low, and the tracks fall into distinct groups. Figure 3 shows the results when the groups are corrected for the variation in the *n-p* scattering cross section[6] and for the relative probabilities that the tracks will go out of the emulsion.[3]

An attempt was made to calculate the shape of the neutron distribution for each group so that the excitation energy of each level in C^{12} could be determined from the position of the peak. However, the assumption was made in this calculation that the angular distribution for each group is spherically symmetric in the center-of-mass system.[7] Since this assumption cannot be justified and is probably incorrect, it was decided to determine the excitation levels by taking the maximum neutron energy associated with each group, after allowing for "straggling," instrumental and true. The maximum neutron energy was taken at the center of each of the 20-micron intervals indicated by the arrows in Fig. 2; the "straggling" would give rise to a 10- or 20-micron uncertainty in the position of the maximum.

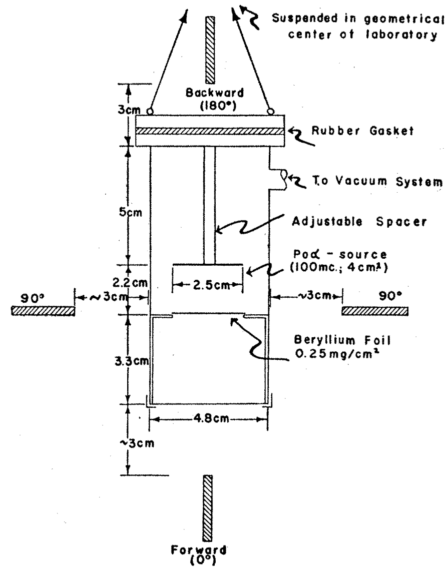

FIG. 1. Schematic of the Po-Be thin target source.

The particle energies and masses, and the Q for each excitation level in C^{12} are related by the equation,

$$E_\alpha\left(1-\frac{M}{M_c}\right)+Q$$
$$=E_n\left(1+\frac{m}{M_c}\right)-\frac{2(mM)^{\frac{1}{2}}}{M_c}(E_nE_\alpha)^{\frac{1}{2}}\cos\theta, \quad (1)$$

where E_α and M are the energy and mass respectively of the incoming alpha-particle, E_n and m are the corresponding energy and mass of the outgoing neutron, M_c is the mass of C^{12}, and θ is the angle between the incoming alpha-particle and outgoing neutron in the laboratory system. Inserting $E_\alpha=5.3$ Mev, $M=4.00390$, $m=1.00893$, and $M_c=12.00382$, this equation simplifies

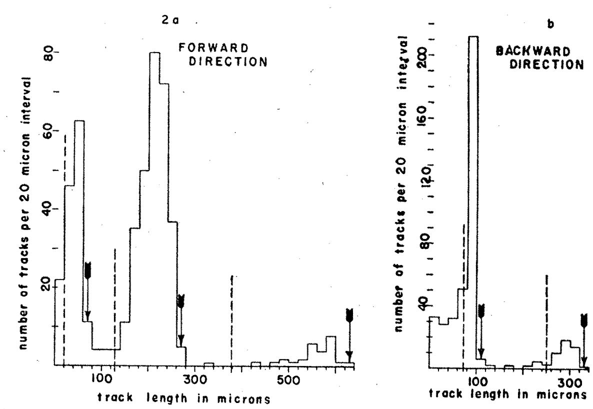

FIG. 2. Proton track distributions corrected to 0° recoil.

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[3] H. T. Richards, Phys. Rev. **59**, 796 (1941).

[4] These corrections are made on the assumption that the neutrons enter the plates with good collimation; actually a few neutrons can enter the forward plate at about 20° from a line joining the center of the plate to the center of the beryllium target, and a few can enter the back plate at a 14° angle with the same line. This gives rise to considerable instrumental straggling and is partly the reason for the choice of intervals as large as 20 microns in the histograms of Figs. 2 and 3; another reason is to obtain better statistics for each point.

[5] Lattes, Fowler, and Cuer, Proc. Phys. Soc. (London) **59**, 883 (1947).

[6] Bailey, Bennett, Bergstralk, Nicholls, Richards, and Williams, Phys. Rev. **70**, 583 (1946).

[7] W. H. Guier, Master's thesis, Northwestern University (1950).

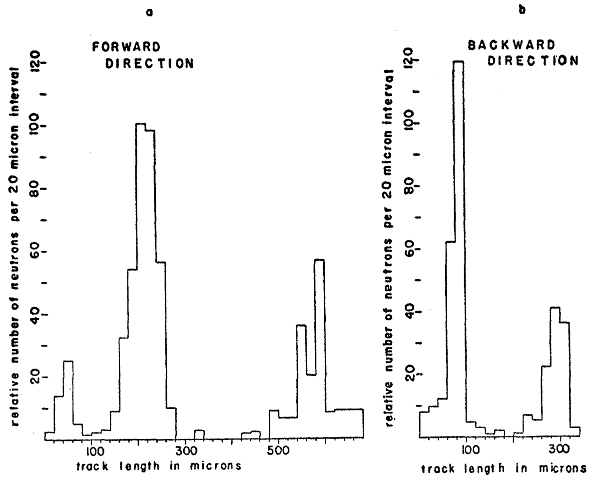

FIG. 3. The relative number of neutrons associated with proton tracks in each 20 micron internal after correction for the n-p scattering cross section and for plate geometry.

to

$$3.53+Q=1.084E_n-0.771(E_n)^{\frac{1}{2}}\cos\theta. \qquad (2)$$

The maximum neutron energy for each group in the forward direction is obtained by setting $\theta=0°$. These energies for the groups associated with the ground state and the first and second excited states of C^{12} as obtained from Fig. 2 are 10.7, 6.4, and 2.9 Mev respectively. Putting these values into the above equation gives Q values of 5.68, 1.47, and -1.79 Mev, respectively. These correspond to the energy levels of C^{12} at 0, 4.1, and 7.5 Mev. The accepted Q for $Be^9(\alpha,n)C^{12}$ for the ground state of C^{12} is 5.75,[8] predicting a neutron energy of 10.8 Mev for $\theta=0°$. The statistics are so bad for the group associated with the ground state that the precision in our measurement is very poor; the good agreement is fortuitous.

The maximum neutron energy for each group in the backward direction is obtained by setting $\theta=139°$. This is approximately the minimum θ which can give rise to neutrons hitting the photographic plate in the backward direction, as can be seen from a study of the geometry in Fig. 1. The maximum neutron energies in the two groups in the backward direction are chosen in the same manner as for the forward direction. These are 7.2 and 3.7 Mev, respectively. Putting these values of E_n and $\theta=139°$ into Eq. (2), we have Q values of 5.68 and 1.48 Mev, respectively. These correspond to the ground-state transition and the transition to the first excited state in C^{12}. This level is calculated to be at 4.2 Mev.

[8] Hornyak, Lauritsen, Morrison, and Fowler, Revs. Modern Phys. **22**, 291 (1950).

TABLE I. Q-values for the neutron groups, and energy levels in C^{12}.

Q's (Mev)			Energy levels in C^{12} (Mev)		
Forward	Backward	Hornyak *et al.*	Forward	Backward	Hornyak *et al.*
(5.68)	5.68	5.75	0	0	0
1.47	1.48	1.28	4.2	4.2	4.47
−1.79	—	−1.25	7.5	—	7.

The results for the plates in both forward and backward directions are summarized in Table I and compared with the Q values given by Hornyak *et al.*[8] The agreement is well within the limits of our experimental error which is of the order of a few tenths of one Mev. In earlier reports of this work there appeared to be an additional level at 7.8 Mev.[2] Better statistics and an investigation of sources of error fail to confirm this.

In order to investigate the possibility of other levels so close to those given that they would be unresolved in this experiment, the minimum track length to be expected for each group was calculated, using the Q value in Table I obtained for each group. In the forward direction these would result from neutrons emitted at $\theta=70°$ and from α-particles reacting near the bottom of the beryllium layer, having an energy $\sim$4.85 Mev. There will also be some "instrumental straggling" due to lack of perfect collimation of the neutrons entering the photographic plate. These combined effects predict minimum track lengths of 370, 128, and 20 microns for the three groups in the forward direction. These would fall at the vertical dashed lines shown in Fig. 2. A similar analysis for the plates in the backward direction predict minimum track lengths of 250 and 78 microns for the two groups. Making allowances for "straggling," the results indicate that there are probably no unresolved levels unless they are very close to those indicated or of low intensity.[9]

An estimate of the relative intensities of the neutrons in the different groups was made by determining the areas under the histograms of Fig. 3. In the forward direction the ratio of the intensity associated with the transition to the first excited level in C^{12} to that associated with the transition to the second appears to be 8:1. In the backward direction the corresponding ratio for the ground-state transition to that of the first excited level appears to be 1:2.

The authors wish to express their gratitude to Betty Guier, Shirley Fisher, and Barbara Kraus for considerable assistance in the proton track measurements.

[9] The long tail below the lower peak in Fig. 2(b) is probably the result of short tracks $\sim$15 microns long from the group associated with the 7.5-Mev level and from some background of low energy scattered neutrons. The statistics are so poor for the upper peak in Fig. 2(a) that nothing can be said about it.