nucleus La^{139} has been measured and is 7/2, and the state is characterized as $g_{7/2}$. The log ft value for the 2.38-Mev group implies $\Delta I=0$, 1 yes. Taking the first possibility, the ground state of Ba^{139} is $f_{7/2}$. The fact that the internal conversion line at 0.163 Mev is $M1$ and that the log ft value for the second group is 6.8 definitely established that the first excited state of La^{139} is $d_{5/2}$. The beta-ray group of energy 0.822 Mev appears to be allowed, which would imply that the state at 1.43 Mev is odd and has a spin of 5/2 or 7/2. It is interesting to note that in the region of 57 protons the $g_{7/2}$ and $d_{5/2}$ states have nearly the same energy. In the present case the $d_{5/2}$ state lies above the $g_{7/2}$ by 0.163 Mev.

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Scattering of 14.1-Mev Neutrons in Helium, Hydrogen, and Nitrogen*

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Cloud-chamber studies have been made of the scattering of 14.1-Mev neutrons in helium, hydrogen, and nitrogen. For each of these gases the angular distribution of the elastically scattered neutrons has been obtained. The angular distribution in helium shows a minimum at about 110° in the center-of-mass system, with a large maximum representing forward scattering and a smaller maximum for backscattering. The hydrogen angular distribution is isotropic. Elastic scattering in nitrogen resembles diffraction scattering, showing a strong forward scattering maximum and smaller maxima at 70° and 180°, with minima close to 60° and 130°. Inelastic scattering in nitrogen does not depart from spherical symmetry by more than a factor of two. The elastic scattering cross section for nitrogen is 0.82 barn and the inelastic scattering cross section is 0.48 barn. Cross sections for two- and three-particle disintegrations are 270 and 16 millibarns, respectively.

I. INTRODUCTION

STUDIES of the scattering of neutrons by nuclei are important for the information they yield relative to the nuclear forces involved. Such studies can be made by observing the recoil nuclei. In the scattering of fast neutrons by light nuclei the recoil nucleus can receive an appreciable part of the energy of the incident neutron. The recoil energy is related to the energy of the incident neutron by the equation

$$E_r=E_n\{2\cos^2\phi+(1+1/M)Q/E_n\pm2\cos\phi \times[\cos^2\phi+(1+1/M)Q/E_n]^{\frac{1}{2}}\}M/(M+1)^2, \quad (1)$$

where E_n is the energy of the incident neutron and E_r and M are the energy and mass, respectively, of the recoil nucleus, and ϕ is the angle of the recoil with respect to the incident neutron direction. Q is the energy released in the reaction and is negative for inelastic scattering, zero for elastic scattering.

When the target nuclei are contained in the gas of a cloud chamber, the paths of the recoils are made visible as tracks whose length and direction can be measured directly. If the range-energy relation for the recoil nucleus is known, the length of the track gives the energy of the recoil. The remaining unknown in (1) is Q, which is the negative of the excitation energy of the residual nucleus. Thus a cloud-chamber experiment makes possible a study of the inelastic scattering as well as the elastic scattering.

The present work is a cloud-chamber study of the scattering of 14.1-Mev neutrons in helium and hydrogen, where only elastic scattering is possible, and in nitrogen, where there is considerable inelastic scattering at this energy.

II. EXPERIMENTAL ARRANGEMENT

Monoenergetic 14.1-Mev neutrons were obtained from the $H^3(d,n)He^4$ reaction. The unresolved beam of deuterons from the Rice Institute Cockroft-Walton accelerator was used to bombard a target[1] of tritium absorbed in a 300-μg/cm^2 film of zirconium evaporated onto a tungsten disk. The accelerator was operated at about 160 kev. Molecular ions comprised approximately 80 percent of the beam, so that most of the deuterons incident on the target had energies of 80 kev. An aperture 5 mm in diameter was placed over the target to restrict the diameter of the beam and consequently the size of the neutron source. In each experiment the cloud chamber was placed at 90° to the deuteron beam. The energy spread over the angle subtended by the chamber was less than 0.1 Mev.

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[1] A. B. Lillie and J. P. Conner, Rev. Sci. Instr. 22, 210 (1951).

For the experiments on helium and nitrogen the same cloud chamber was used. This chamber was of rather heavy construction, as it was designed to operate at either high or low pressures. The body of the chamber was a Pyrex cylinder 23 cm in diameter and 13 cm high, with a wall thickness of 0.9 cm. The outer surface of the cylinder was painted black, except for a window 7.4 cm high and 13 cm wide for admission of the light beam. Illumination was by a 5000-watt incandescent lamp, the light from which was rendered parallel by a lens and cooled by a water cell before it reached the chamber. The chamber was placed with its center 30 cm from the neutron source.

A small chamber of light construction was used for the experiment on hydrogen in an effort to minimize the number of scattered neutrons inside the chamber. The body of this chamber was a Pyrex cylinder having an inside diameter of 15.4 cm and a height of 8.1 cm, with a wall thickness of 0.3 cm. The illuminated portion was 4.3 cm high and 11.3 cm wide. The source of light was a 1000-watt incandescent lamp, the light from which passed through a lens and water cell before reaching the chamber. The center of this chamber was 14 cm from the neutron source.

Stereoscopic pictures of the tracks formed in the chamber were taken through an optical system utilizing one camera and a front surface mirror. The system used with the large chamber for the nitrogen and helium experiments had a stereoscopic angle of about 20°. The stereoscopic angle for the system used with the small chamber for the hydrogen experiment was 15°.

The processed film was reinserted in the camera and the images were projected through the optical system used in taking the pictures. By proper orientation of a white screen, the two images of a track formed thereon could be made to coincide. From the coincident images were measured the true length and orientation in space of the original track. Only tracks making angles of less than 45° to the horizontal were measured. A geometrical correction was applied to the data to allow for tracks excluded by this limitation.

The true length of a track was taken to be its measured length minus its width. Tracks as short as 0.5 mm were measured, although most tracks less than 1 mm long were probably missed. Tracks greater than 2 mm long are considered to have been observed with 100 percent efficiency. Estimated measurement errors are 0.5 mm for length measurements and 2° for angle measurements. For the short tracks of slow nitrogen recoils the errors in angle are closer to 10°.

III. RESULTS

A. Helium

Neutron scattering in helium has been the subject of several experiments[2–4] using proportional counters or ionization chambers. These experiments cover the energy range 0.4 to 14.3 Mev. The data are in substantial agreement with the calculations of Dodder and Gammel,[5] who made phase shift analyses of proton-alpha scattering at energies up to 9.48 Mev. The results they obtained for Li^5 were applied to the mirror nucleus He^5 and neutron-helium scattering. Phase shifts from the theory of Dodder and Gammel are presented by Seagrave[4] for neutron energies up to 20 Mev.

For the present study of neutron scattering in helium the large cloud chamber was filled to approximately 3 atmospheres with 99.9-percent pure helium. The helium was passed through a liquid air trap before it entered the chamber, to remove any vapor that might have been present. Water was used for the vapor in the chamber. The stopping power of the chamber gas was calculated[6] to be 0.56. The alpha-particle tracks ranged up to 15.9 cm in length. Maximum track length component normal to the direction of the neutron was 5 cm at 30°. It is desirable to define a counting volume sufficiently small that all tracks originating in this region would be certain to stop within the illuminated volume of the chamber. The ranges of the alpha recoils encountered in this experiment were too great to allow this practice. Tracks were measured if they began 1.5 cm within the illuminated volume, 3 cm from the wall of the chamber toward the neutron source, and 5 cm from the opposite wall. If a track left the illuminated portion of the chamber, its visible length was recorded as a minimum value.

One thousand tracks were measured. Of these, approximately 35 percent had lengths less than 1.8 cm and were distributed roughly uniformly in angle. This group was compeletely resolved from the remainder of the tracks for recoil angles less than 60°, corresponding to neutron scattering at angles greater than 60° in the center-of-mass system. These tracks were due to neutrons of energies around 1 Mev which had been scattered from the walls of the chamber or the floor. The neutron-helium cross section has a resonance close to 1 Mev, at which energy it reaches a magnitude of 6.7 barns.[7] This is approximately 7 times the cross section at 14 Mev, which has been measured to be 1.02 barns.[8] The observed low-energy background could be produced by a group of 1-Mev neutrons approximately 10 percent of the intensity of the neutrons coming directly from the tritium target. There were some scattered neutrons of other energies incident on the chamber. The recoils from these neutrons were distributed randomly in length and angle and numbered about 5 percent of the total tracks measured. The total intensity of scattered neutrons was thus about 15 percent of that of the 14-Mev neutrons.

The solid angle in the center-of-mass system was

[2] R. K. Adair, Phys. Rev. **86**, 155 (1952).
[3] P. Huber and E. Baldinger, Helv. Phys. Acta **25**, 435 (1952).
[4] J. D. Seagrave, Phys. Rev. **92**, 1222 (1953).
[5] D. C. Dodder and J. L. Gammel, Phys. Rev. **88**, 520 (1952).
[6] C. M. Crenshaw, Phys. Rev. **62**, 54 (1942).
[7] Bashkin, Mooring, and Petree, Phys. Rev. **82**, 378 (1951).
[8] Coon, Graves, and Barschall, Phys. Rev. **88**, 562 (1952).

divided into ten equal parts and the number of neutrons scattered into each interval was plotted at the angle representing the midpoint of the interval. These data include those tracks which left the light beam, and hence had no true length measurements. Accordingly, rather large tolerances were allowed for tracks upon which complete length and angle measurements were made. Tracks were admitted if their length and angle measurements fell within 2 mm and 4° of the calculated values. In the small-angle region, where confusion with the low-energy background exists, an approximate background correction was made by subtracting from the total number of recoils counted the average of the number of low-energy tracks seen in the angular intervals where resolution was complete. This correction was of the order of 20 percent.

The plot of the neutron-helium data is shown in Fig. 1, along with a theoretical curve using phase shifts calculated by Dodder and Gammel for 14 Mev.[4,5] The agreement is good within the limits of the experiment. The discrepancy at small angles can be attributed to the uncertainty in the background corrections for these intervals. The similarity between the scattering of neutrons and protons by helium supports the idea of equivalance of the mirror nuclei He^5 and Li^5.

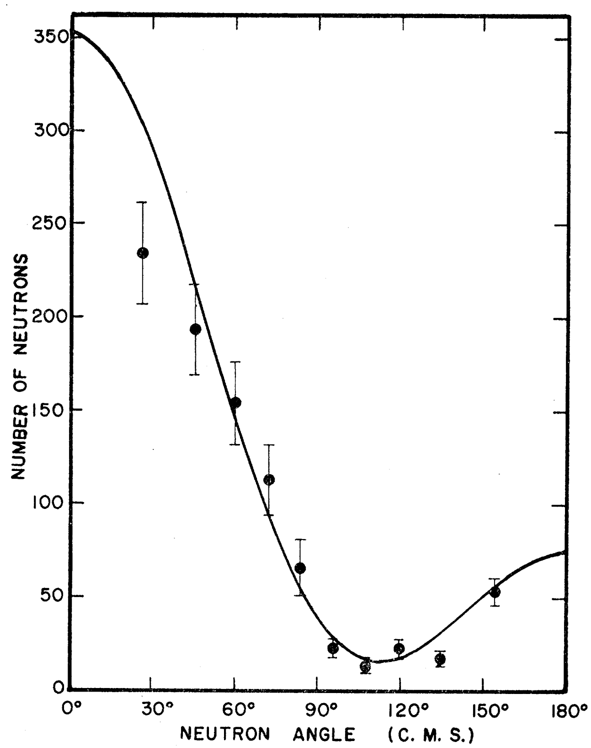

FIG. 1. Angular distribution in the center-of-mass system of 14.1-Mev neutrons scattered in helium. The solid curve is the theoretical distribution according to Dodder and Gammel.

B. Hydrogen

Previous experiments[9–13] on the neutron-proton angular distribution at 14 Mev have indicated isotropy in the center-of-mass system. However, if there were a large peak, such as might be due to diffraction scattering it would probably lie at smaller angles than those covered by the existing data. The small-angle intervals were the principal regions of interest in this cloud-chamber investigation.

Because of the decrease in the total neutron-proton cross section from about 4.5 barns at 1 Mev[14] to 0.689 barn at 14 Mev,[15] one could expect the same type of low-energy background problem as was encountered in the helium experiment. In order to minimize the effect of this low-energy background the chamber of light construction was used. The background appeared roughly isotropic; any very strong anisotropy in the neutron-proton angular distribution could be expected to be evident above the uniform background.

Nine hundred recoil tracks were measured. Measurements of angle only were made, as the stopping power of the chamber gas was not great enough to allow measurements of length. Of the tracks measured, 800 were from pictures taken with the cloud chamber filled to 20 pounds pressure with 99.5 percent pure hydrogen. The other 100 tracks were from pictures taken with the chamber filled to 22 pounds pressure with a mixture of 50 percent hydrogen and 50 percent argon. In each case water was used for the vapor.

The angular distribution obtained is shown in Fig. 2. The points represent the number of neutrons scattered into certain polar angle intervals, divided by the solid angle represented by the interval. The angular intervals were 20° wide for angles greater than 90°, and 10° wide for angles less than 90°. Within statistics the distribution appears to be isotropic. Because of the considerable background present in the experiment it was not thought worth while to improve the statistics by measuring more tracks.

C. Nitrogen

The angular distribution for neutrons scattered in nitrogen has been studied by the counter method at energies between about 1 and 3 Mev.[16,17] At those energies marked anisotropies were found whose form varied as the neutron energy increased across a resonance. The disintegrations produced by 14-Mev neutrons have been studied by Lillie,[18] who used a

[9] C. F. Powell and G. P. S. Occhialini, Rept. Int. Conf. "Fundamental Particles," 1946.
[10] J. S. Laughlin and P. G. Kruger, Phys. Rev. **73**, 197 (1948).
[11] H. H. Barschall and R. F. Taschek, Phys. Rev. **75**, 1819 (1949).
[12] Remley, Jentschke, and Kruger, Phys. Rev. **89**, 1194 (1953).
[13] Allred, Armstrong, and Rosen, Phys. Rev. **91**, 90 (1953).
[14] *Neutron Cross Sections*, Atomic Energy Commission Report AECU-2040 (Technical Information Service, Department of Commerce, Washington, D. C., 1952).
[15] Poss, Salant, Snow, and Yuan, Phys. Rev. **87**, 11 (1952).
[16] Baldinger, Huber, Ricamo, and Zünti, Helv. Phys. Acta **23**, 503 (1950).
[17] Fowler, Johnson, and Risser, Phys. Rev. **91**, 441 (1953).
[18] A. B. Lillie, Phys. Rev. **87**, 716 (1952).

cloud chamber. Lillie also measured the recoil tracks occurring at angles less than 15° to the neutron direction. Those tracks were so short at the pressure of one atmosphere at which he operated his cloud chamber that he was able to conclude only that inelastic scattering is considerably more likely than elastic scattering for recoils projected at small angles.

For the present study the large cloud chamber was filled to approximately 1/5 atmosphere of nitrogen, with water as the vapor. This chamber was the same one used in the helium experiment, so that one could again expect a background due to scattered neutrons having an intensity of about 15 percent of that of the 14-Mev neutrons. While not insignificant, this background does not pose quite so serious a problem in nitrogen as it does in helium and hydrogen. The neutron cross section for nitrogen decreases by about a factor of two from 1 Mev to 14 Mev,[14] compared to the factor of close to seven for the lighter nuclei.

The chamber was flushed and filled with nitrogen of 99.5-percent purity. To determine the stopping power, a polonium alpha-particle source was placed in the chamber. The source was covered with a shield which could be moved aside by means of a magnet from outside the chamber. Five frames of the alpha-particle tracks were photographed at the beginning, middle, and end of each 250-picture roll of film. The stopping power was determined to be 0.187 for the alpha particles, taking the range of plonium alpha particles to be 3.82 cm.[19] For the slower nitrogen recoils the stopping power was somewhat larger than this because of the variation with particle velocity of the stopping power of hydrogen in the water vapor. Values of the stopping power of hydrogen were taken to be 0.35 for the nitrogen nuclei and 0.20 for the alpha particles.[6] The corrected value of the stopping power of the chamber gas for the nitrogen nuclei was 0.191.

The expected track lengths of the recoils were calculated using the range-velocity data of Blackett and Lees[20] for nitrogen nuclei. It was found that a further correction of 1.6 percent in the stopping power was needed to make the calculated track length agree with the observed value for the group of recoils projected in the forward direction by elastically scattered neutrons. The final stopping power used was 0.194.

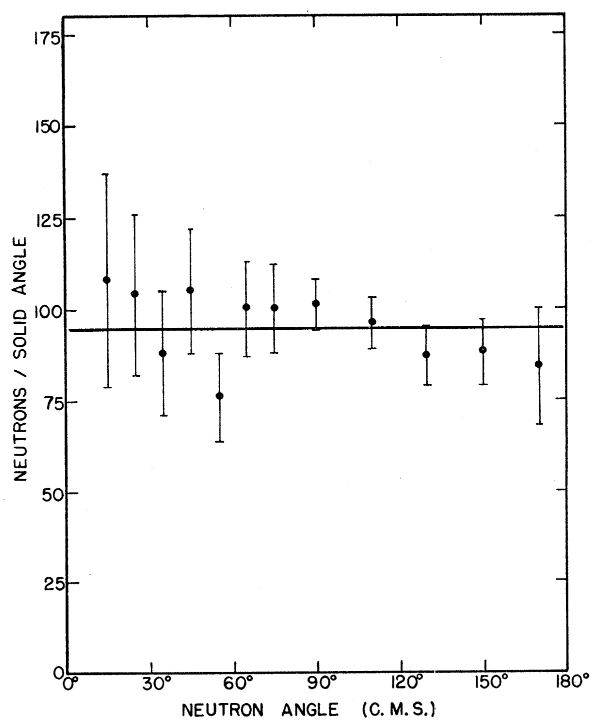

FIG. 2. Angular distribution in the center-of-mass system of 14.1-Mev neutrons scattered in hydrogen. The straight line represents isotropy in the center-of-mass system.

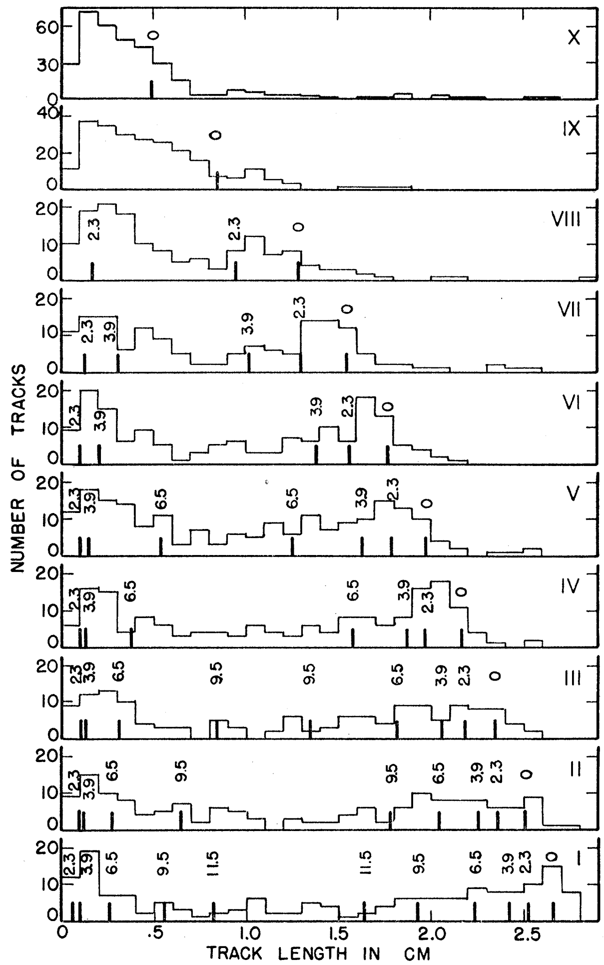

FIG. 3. Plot of number of nitrogen recoil tracks as a function of track length. The ten groups represent equal increments for the cosine of the angle of projection of the recoil nucleus. For the elastically scattered neutrons these groups also represent equal energy intervals. The short, heavy lines represent excitation of the nitrogen nucleus to the energies with which the lines are labeled.

[19] H. A. Bethe, Revs. Modern Phys. **22**, 213 (1950).

[20] P. M. S. Blackett and D. S. Lees, Proc. Roy. Soc. (London) **A134**, 658 (1932).

Figure 3 is a plot of the measurements of 1900 recoil tracks. The ten groups illustrated represent equal energy intervals for the recoils due to elastically scattered neutrons. Within each group are plotted the number of tracks in each 1-mm increment of track length, as a function of track length. It should be noted that the ordinates of Groups IX and X are drawn to scales different from those of the other groups. The broad vertical lines on the diagram indicate the calculated track lengths for recoils representing excitation of the N^{14} nucleus to the energies with which the broad lines are labeled. Only a few representative levels are indicated on the histogram. N^{14} has over 30 levels that can be excited in a collision with a 14-Mev neutron.[21] The $(n,2n)$ reaction is not taken into consideration here. It has a cross section of only 5.67 millibarns at 14 Mev[22] and can be neglected in the present experiment.

1. *Elastic Scattering*

As can be seen from Fig. 3, resolution was not effected for recoils representing any single level of excitation. However, an angular distribution for elastically scattered neutrons was obtained by considering all tracks whose length and angle measurements represented excitation of the recoil nucleus to less than the first excited level of N^{14} at 2.3 Mev. The solid angle in the center-of-mass system was divided into ten equal parts and the expected track lengths for the limits of each division were calculated. The number of tracks in each solid angle division was taken to be the number within the elastically scattered group having track lengths between the values calculated for the limits of the angular interval. Track length was taken to be a more accurate criterion than angle because of large errors present in the angle measurements. These large errors were due to multiple scattering of the slow nuclei as well as to the difficulty of measuring the angles for short tracks.

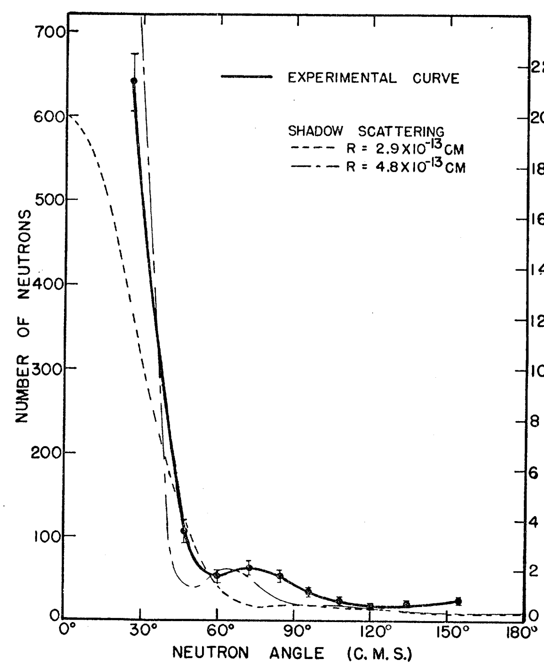

FIG. 4. Angular distribution in the center-of-mass system of 14.1-Mev neutrons elastically scattered in nitrogen. The solid curve is the experimental curve while the dashed curves represent two theoretical curves from the diffraction scattering calculations of Feld *et al.* The ordinate on the right refers to the calculated curves.

The angular distribution of the elastically scattered neutrons thus obtained is shown in Fig. 4. It shows very strong small-angle scattering of the neutrons, with smaller maxima at about 70° and 180° and minima close to 60° and 130°. The latter minimum is very broad, and examination of the data in smaller angular intervals indicates that the curve is essentially flat between 110° and 150°.

The shape of the angular distribution curve is quite similar to that which might be expected from the theory of diffraction scattering. This theory is not intended to apply to such light nuclei, but its characteristic scattering pattern has been observed in the scattering of 14.1-Mev neutrons in oxygen[23] as well as in nitrogen. Feld *et al.*[24] have calculated the angular distributions to be expected of neutrons diffracted by nuclei. They present a series of curves representing the differential scattering cross section as a function of the parameters $x=kR$ and $X_0=K_0R$, where k is the wave number of the neutron outside the nucleus of radius R. K_0 is a number such that the wave number of the neutron inside the nucleus is given by $(K_0^2+k^2)^{\frac{1}{2}}$. Curves for $x=2.2$ and $x=3.7$ are shown in Fig. 4 along with the experimental curve. For both curves $X_0=5$, which is the smallest value of X_0 for which Feld *et al.* present a theoretical curve. The wave number of 14.1-Mev neutrons incident upon N^{14} is 0.77×10^{13} cm^{-1}. For this value of k the theoretical curves shown in Fig. 4 represent scattering from spheres of radii 2.9 $\times10^{-13}$ and 4.8×10^{-13} cm, respectively. The radius of N^{14} lies between these values. It does not seem unreasonable to consider that the experimental curve represents scattering conditions intermediate between those corresponding to the two theoretical curves.

2. *Inelastic Scattering*

The measurements of tracks due to inelastic scattering were examined in three energy groups bounded by the 3.9-, 6.45-, 9.49-, and 12.8-Mev levels. The angular distributions obtained for the three groups are shown in Fig. 5. The large errors in angle for the short tracks made it impractical to attempt to extend these distribu-

[21] F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. **24**, 321 (1952).

[22] E. B. Paul and R. L. Clarke, Can. J. Phys. **31**, 267 (1953).

[23] J. P. Conner, Phys. Rev. **89**, 712 (1953).

[24] Feld, Feshbach, Goldberger, Goldstein, and Weisskopf, Atomic Energy Commission Report NYO-636 (unpublished).

tions below 60° in the center-of-mass system. For angles greater than 60° there appears to be no anisotropy greater than a factor of two for any of the three groups. There is some indication of possible anisotropy for the two groups representing lower excitation, but this could be due to statistics and overlapping of measurements of tracks from one group to the next.

From the number of tracks counted in each of the three inelastic scattering groups the relative probability per unit energy interval for excitation to the levels involved can be estimated. This probability appears to be approximately equal for levels around 5 Mev and levels around 8 Mev. However, the probability per unit energy interval for excitation to levels around 11 Mev is less than that for the lower intervals by a factor of three. This is a rather surprising result inasmuch as there are many more levels at higher than at lower energies. Similar results were observed by Conner[23] for the inelastic scattering of 14-Mev neutrons in oxygen. Analyses of the energy distribution of 14-Mev neutrons scattered by several elements[25] indicate that in general the most probable energies for the inelastically scattered neutrons lie below 3 Mev. This corresponds to a greater probability for excitation of the residual nucleus to higher than to lower levels. These analyses did not include oxygen or nitrogen, and it could be that these two elements are exceptions.

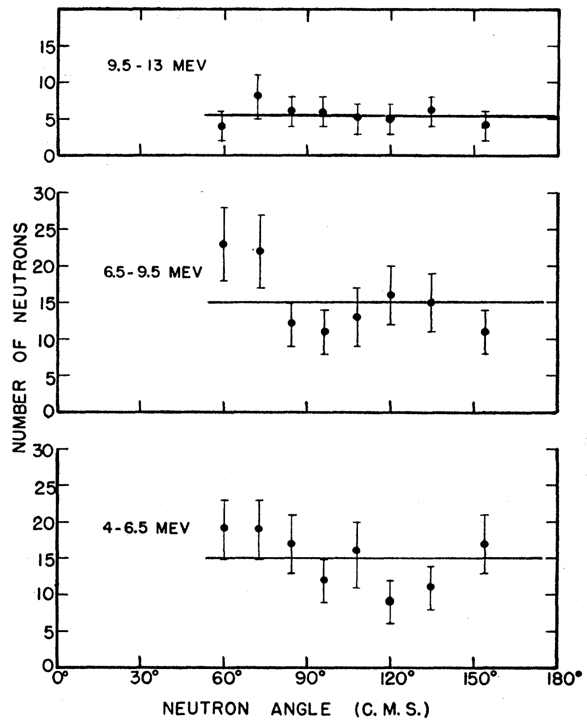

FIG. 5. Angular distribution in the center-of-mass system of neutrons inelastically scattered in nitrogen at 14.1 Mev. The three groups represent three energy intervals for excitation of the nitrogen nucleus. The straight lines represent isotropy in the center-of-mass system.

3. *Cross Sections*

In addition to the recoil tracks measured, a count was made of all disintegration forks and of recoils too short for measurement. In the pictures on which the count was made, there were observed 1822 recoils, 385 two-particle disintegrations, and 23 three-particle disintegrations. Analysis of the measured recoil tracks yielded a ratio for elastic to inelastic scattering of 1.7:1. Assuming the measured value of 1.59 barns[8] for the total cross section of nitrogen for 14-Mev neutrons, one obtains 270 mb as the cross section for two-particle disintegrations, and 16 mb for the three-particle disintegrations. The elastic scattering cross section is 0.82 barn and the cross section for inelastic scattering exclusive of disintegrations is 0.48 barn.

The author wishes to thank Dr. T. W. Bonner for his interest and counsel throughout the course of this work.

[25] E. R. Graves, and L. Rosen, Phys. Rev. 89, 343 (1953).