We conclude, therefore, (1) from reading of shielded and unshielded electroscopes in the lower atmosphere, (2) from the shape and area of curve B, and (3) from the near equality in the number of the high energy positives and negatives, *that incoming penetrating particles are not a significant factor in the near sea-level ionization*, that instead the observed penetrating particles are secondaries produced in the atmosphere.

In a word, they are the same "penetrating links" which we have already introduced to obtain a consistent interpretation of curve A.

The net result of all the considerations advanced thus far in this paper is contained in the statement that *practically all of the cosmic ray effects observed in the lower part of the atmosphere are secondary effects—splashes of various kinds—produced in the upper layers of the atmosphere by the inflow from outside of electrons (+ or −) or of electrons and photons combined, which no matter what their energy, cannot themselves penetrate through the upper layers because of the powerful barrier set by the laws of nuclear absorption.*

Our experiments thus far yield no crucial evidence as to the relative roles played by electrons and photons in producing the ionization due to the non-field-sensitive half, as measured by energies, of the incoming cosmic rays. A minor part of the incoming non-field-sensitive rays must in any case be electrons to account for the equatorial east-west effect. If they are all electrons, then in accordance with the reasoning in §I we may expect the intercept of curve B on the vertical axis to be at 5.5 (half of 11) or less; since the lower limit to the average energy of these hypothetical electrons cannot be placed at less than about 20 billion electron volts. If curve B should actually be found to cross the axis outside this range then something other than electrons or protons or penetrating charged particles of any sort must be a constituent of the incoming rays. We can probably follow the actual course of curve B farther to the left than we have yet done, though this is not a promising prospect for differentiating between incoming electrons and photons. With suitable *ad hoc* and as yet *unverifiable* assumptions, either hypothesis—electrons alone or a mixture of photons and electrons—can be made to work. The answer to this question, if found at all, will probably be found from more fundamental considerations as to the mode of origin of the rays rather than from a further study of curves A and B.

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Neutrons from Lithium Plus Deuterons

W. E. STEPHENS
W. K. Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California

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The energy distribution of the neutrons from the disintegration of lithium by deuterons has been measured by the method of α-recoils in a helium-filled high pressure cloud chamber. The stopping power was calibrated with thorium C′ α-particles in the chamber. Two distinct groups of neutrons were found with disintegration energies of 15.05±0.2 Mev and 11.8±0.4 Mev. The 15.05 Mev group is attributed to the formation of Be^8 in a normal state and the 11.8 Mev group to the formation of Be^8 in an excited state of about 3.3 Mev with a width at half-maximum of about 1.5 Mev. A more or less continuous distribution was observed from 9 Mev to 3 Mev (the limit of observation). These neutrons may come from higher wider states of Be^8.

INTRODUCTION

THE neutrons resulting from bombardment of lithium with deuterons were first observed by Crane, Lauritsen and Soltan.[1] The neutron energy distribution was measured by Bonner and Brubaker[2,3] by the method of proton recoils in a methane filled high pressure cloud chamber[4] with a mica sheet to further

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[1] Crane, Lauritsen and Soltan, Phys. Rev. **44**, 693 (1933).

[2] Bonner and Brubaker, Phys. Rev. **47**, 973 (1935).

[3] Bonner and Brubaker, Phys. Rev. **48**, 742 (1935).

[4] Brubaker and Bonner, Rev. Sci. Inst. **6**, 143 (1935).

increase the stopping power. The stopping power of the gas and mica were calculated and hence somewhat uncertain. In order to obtain a more accurate value of the maximum energy of the neutrons, this experiment was repeated by the method of α-recoils[5] in a helium filled high pressure cloud chamber with the stopping power of the chamber calibrated with thorium C$'$ α-particles.

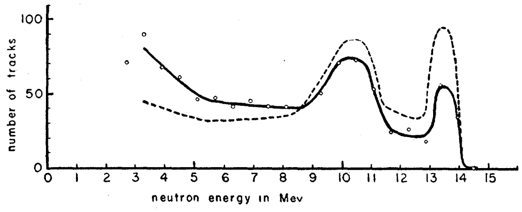

FIG. 1. Energy distribution of neutrons emitted at 90° from lithium bombarded with 0.93 Mev deuterons as inferred from recoils in helium. The points are the observed number of tracks. The dashed curve is the distribution after being corrected for $n-\alpha$ cross section and geometrical conditions.

EXPERIMENTAL PROCEDURE

A lithium metal target[6] was bombarded with deuterons accelerated by a peak voltage of 0.93 Mev[7] in a short ion path a.c. tube. The cloud chamber was filled with a mixture of 95 percent helium and 5 percent air to a pressure of 11.9 atmospheres. The stopping power of this gas was determined by finding the mean range of the thorium C$'$ α-particles given off into the chamber from a pin with a deposit of thorium B on the end. After the thorium B had decayed sufficiently, α-recoils from the neutrons were similarly photographed, reprojected and measured. The stopping power was corrected for change in amount of alcohol vapor with temperature and for a slight leakage of the gas during the course of the experiment. The chamber was refilled and recalibrated for the last 1000 pictures to check the calibration.

In a total of 9000 stereoscopic pictures, 1034 α-recoil tracks, which had directions within 8° of a line to the center of the target, were measured. Recoils from neutrons with energies less than 3 or 4 Mev were short enough to be easily missed. Even in the range from 3 Mev to about 6 Mev, the recoils are so short that the resolving power is poor. The distribution in energy of the neutrons inferred from the measured α-recoils is shown in Fig. 1. The dashed curve is the distribution after being corrected for the $n-\alpha$ collision cross section and the probability of observing a track of a given length. The $n-\alpha$ collision cross section used was that given by Bonner.[8] Values above 5 Mev were obtained by extrapolating Bonner's curve to a value of $0.44\cdot 10^{-24}$ at 14 Mev. In using these values we must assume that the angular distribution of the scattering does not change with energy. No measurements have been reported on the angular distribution of the $n-\alpha$-scattering. Indeed, above 2 Mev energy of the neutron the deBroglie wave-length of the neutron is no longer large compared to the radius of interaction between neutron and α-particle and the scattering is no longer expected to be spherically symmetrical in the center of gravity coordinates. Nevertheless, measurements on the energy distribution of neutrons from $B-d-n$ which have been made both with helium recoils and proton recoils[5, 9] give quite similar relative intensities of the groups. Hence for our purposes between 6 Mev and 12 Mev the $n-\alpha$ forward scattering seems to be similar to that for $n-p$, which should not depart appreciably from spherical symmetry in the center of gravity coordinates in this region. The relative probability of measuring tracks of different lengths depends on the area of the chamber in which they can start and still not hit the wall. To correct for this, the observed number of tracks of a length R was multiplied by the graphically determined and approximate factor $7.5/(7.5-R)$.

To determine the maximum energy of the neutrons, the measured tracks were plotted in an integral number range curve as shown in Fig. 2. It is easier to fit a smooth curve to the integral points and extrapolate, and also Livingston and Bethe's[10] corrections are for integral or semi-

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[5] Bonner and Brubaker, Phys. Rev. **50**, 308 (1936).

[6] The lithium targets turn black in air, probably due to the formation of a thin layer of Li$_3$N on the surface, as suggested by Sheperd, Haxby and Hill, Phys. Rev. **52**, 675 (1937).

[7] The voltage on the tube has been calibrated against the sparkless sphere gap voltmeter of Sorenson, Hobson and Ramo, A. I. E. E. **54**, 651 (1935).

[8] T. W. Bonner, Phys. Rev. **45**, 601 (1934).

[9] Stephens and Bonner, Phys. Rev. **52**, 527 (1937).

[10] Livingston and Bethe, Rev. Mod. Phys. **9**, 389 (1937).

integral curves. No correction for "area" error[11] need be applied to the integral curve. In addition to the corrections given by Livingston and Bethe for natural straggling, thick target, obliquity, and angle between neutron and α-recoil,[10] we have included in the total straggling term (called S'' by Livingston and Bethe) a term for the straggling due to error in measuring the tracks. No correction was made for the fact that a.c. was used to accelerate the deuterons.[12] The angle χ_0 in the correction for angle between neutron and α-recoil was taken as 10° since due to the wide target it was possible to measure a few recoils which had angles of 8° to 16° with the neutron direction but still only 8° with a line to the center of the target. Bethe's revised 1937 range energy curve[13] was used. After making these corrections, the observed neutron energy at 90° to 0.93 Mev deuterons is 14.01 Mev. The disintegration energy calculated from the observed neutron energy is then $Q_{10}=15.05\pm0.2$ Mev.

If we treat the second peak in the same way, allowing for the spread due to the natural width of the group by adding 1 Mev to the straggling correction, we find the energy of the neutrons to be 11.1 Mev and the disintegration energy $Q_{11}=11.8\pm0.4$ Mev. This is quite uncertain, because it is not known how such a level width changes the extrapolation. We can fit the high energy group approximately with a Gaussian error curve with its center at about 13.5 and a straggling of about 0.5 Mev. If we assume this to be the experimental neutron distribution from a narrow level then we can spread a dispersion curve out by such a Gaussian error curve and by fitting this to the second group we can get an idea of the real width. The width at half-maximum by this method is $\gamma=1.5$ Mev. We get another value for the energy of the level by taking the difference between the peaks. This comes out 3.5 Mev, slightly larger than the value 3.3 Mev obtained from the extrapolations. The 11.8 Mev group is about twice as intense as the 15.05 Mev group.

DISCUSSION

The high energy peak was found by Bonner and Brubaker and attributed by them, to the reaction

$$\mathrm{Li}^7+\mathrm{H}^2\rightarrow\mathrm{Be}^8+n^1+Q_1,$$

where Be^8 is left in its normal state. The present value of $Q_{10}=15.05$ Mev is somewhat higher than that of Bonner and Brubaker. From the known masses of Li^7, H^2 and n^1, the mass of Be^8 is calculated to be just stable with respect to two α-particles. However, the accuracy of the experiment is not enough to rule out the value of 0.1 Mev unstable which Livingston and Bethe[14] calculate from the corrected energies of the reactions[15, 16]

$$\mathrm{B}^{11}+\mathrm{H}^1\rightarrow\mathrm{Be}^8+\mathrm{He}^4+8.60\pm0.11\text{ Mev}$$

and

$$\mathrm{B}^{11}+\mathrm{H}^1\rightarrow{}^*\mathrm{Be}^8+\mathrm{He}^4 \rightarrow\mathrm{He}^4+2\mathrm{He}^4+8.70\pm0.2\text{ Mev}.$$

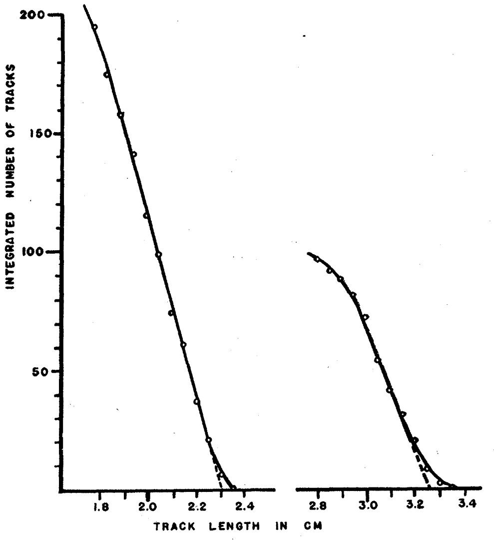

FIG. 2. Integrated number of tracks plotted against track length for the two groups of neutrons. The track length scale should be shifted 0.025 cm to the right.

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[11] King and Rayton, Phys. Rev. **51**, 826 (1937).

[12] The effect of using a.c. voltage to accelerate the deuterons has been investigated by Dr. H. Staub. He has calculated graphically the theoretical curve for the range distribution of measured tracks for a.c. incident energy of the deuteron and finds no appreciable difference between the extrapolated value in this case and the case of d.c. incident energy as treated by Livingston and Bethe, Rev. Mod. Phys. **9**, 385 (1937).

[13] Private communication. In this region the new curve does not differ appreciably from the one given in Livingston and Bethe, Rev. Mod. Phys. **9**, 266 (1937).

[14] Livingston and Bethe, Rev. Mod. Phys. **9**, 310 (1937).

[15] Kirchner and Neuert, Physik. Zeits. **35**, 292 (1934); Oliphant, Kempton and Rutherford, Proc. Roy. Soc. **150**, 241 (1935).

[16] Dee and Gilbert, Proc. Roy. Soc. **154**, 279 (1936).

The fact that Bonner and Brubaker's curve does not show the second group of neutrons may possibly be due to uncertainty in their corrections for the probability of measuring a track of a given length which went through the mica. The correction they applied varies from about +150 percent at 8.4 Mev to 0 percent at 9.9 Mev to +150 percent at 11.2 Mev, and might well have obscured a peak here. It should be pointed out, however, that if there were a strong homogeneous group of neutrons at 1.7 Mev, then recoil protons from the alcohol vapor in the chamber, might, if treated as α-recoils, give the 11.8 Mev peak observed in helium. The low energy part of Bonner and Brubaker's curve gives no evidence of such a group. This second group then probably represents a 3.3 Mev level in Be^8 with a width at half-maximum of about 1.5 Mev. This is presumably the ${}^1D_2$ level which theoretical calculations[17] place at 1.9 Mev. There is quite a lot of evidence for such a level. A 2.8 Mev level with a width of 0.77 Mev has been observed in the $B^{11}-p-\alpha$ reaction[16] and a similar 3 Mev level was found in the $B^{10}-d-\alpha$ reaction.[18, 19] Also the radioactive α-particles from Li^8 indicate such a level with an energy between 4.7 and 2.6 Mev and a width of 1.4 to 1.0 Mev.[20, 21]

The neutrons between 5 and 9 Mev may come from a wide excited state around 6 Mev. Evidence for such a level has been found in the $B^{11}-d-\alpha$ reaction[18, 19] and also perhaps in the $Li^8-e^{-}\alpha$ reaction[20, 21] and in theoretical calculations of the ${}^1G$ level.[17] The ${}^{13}P$ level has been calculated[17] to come at about 12 Mev and would give neutrons around 3 Mev in some agreement with Bonner and Brubaker's corrected low energy maximum. Further evidence for this 12 Mev level is found in Fowler and Lauritsen's[21] radioactive $Li^8-e^{-}\alpha$ energy distribution. When they correct their observed energy distribution for the fact that the probability of the beta-transition should increase at least as $(E_{\beta\,\max})^5$, then a very wide level seems to be present around 10 to 12 Mev.

If these considerations are correct, then it may be possible to account for the disintegration of Li^7 by deuterons by the two primary reactions[22]

$$Li^7+H^2\rightarrow Be^8+n^1+Q_1,$$
$$Li^7+H^2\rightarrow He^5+He^4+Q_2$$

and then

$$Be^8\rightarrow He^4+He^4+Q_3,$$
$$He^5\rightarrow He^4+n^1+Q_4,$$

where Be^8 and possibly He^5 are also formed in excited states. It also seems possible that these higher levels of Be^8 are quite wide and merge into a sort of continuum in accord with the idea of Kempton, Browne and Maasdorp.[23]

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[17] Feenberg and Phillips, Phys. Rev. **51**, 597 (1937).

[18] Cockcroft and Lewis, Proc. Roy. Soc. **154**, 246 (1936).

[19] Wheeler (mentioned in Livingston and Bethe, Rev. Mod. Phys. **9**, 320 (1937)).

[20] Lewis, Burcham and Chang, Nature **139**, 24 (1937).

[21] Fowler and Lauritsen, Phys. Rev. **51**, 1103 (1937).

[22] Evidence for the He^5 reaction has been found by Williams, Shepherd and Haxby, Phys. Rev. **51**, 888 and **52**, 390 (1937).

[23] Kempton, Browne and Maasdorp, Proc. Roy. Soc. **146**, 922 (1934).