CONCLUSION

The division of the variance of the cosmic-ray intensity into 15 percent caused by barometric pressure, 45 percent caused by distribution of air mass as correlated with surface temperature and 10 percent caused by world-wide changes leaving 30 percent unaccounted for is, we believe, new, and if it can be corroborated by the 1940 data when they are available, certainly important.

We wish to thank Professor A. H. Compton for discussing this with us, Dr. John A. Fleming of the Department of Terrestrial Magnetism for making available the Cheltenham and Huancayo data and Mr. D. M. Little of the Aerological Division of the U. S. Weather Bureau for supplying us with the necessary air data.

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A Precise Determination of the Energy of the Neutrons from the Deuteron-Deuterium Reaction*

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A precise determination of the energy of the neutrons from the deuteron-deuterium reaction has been made. The energy of the neutrons emitted in the forward direction to the 0.52-Mev deuterons which produced the disintegrations was found to be 3.58±0.03 Mev. The disintegration Q value of the reaction is 3.31±0.03 Mev. The mass of He^3 calculated from this Q value is 3.01698±0.00006 mass units.

THE neutrons produced when deuterium is bombarded by deuterons are known to come from the reaction

$$H^2+H^2\rightarrow He^3+n^1+Q_1 \quad (1)$$

and those neutrons are now known to be monoenergetic.[1] Such a source of monoenergetic neutrons is most important for neutron scattering experiments as well as for disintegration experiments by neutrons. Furthermore an accurate knowledge of the energy of the neutrons involved in such experiments is essential. For this reason it is important to find their energy accurately at one bombarding energy and angle of observation so that their energies under different bombarding conditions may be accurately calculated.

An accurate knowledge of the energy of the neutrons from reaction (1) also gives one of the best methods of determining the mass of He^3. The value of Q_1 together with the energy liberated in the other deuteron-deuterium reaction

$$H^2+H^2\rightarrow H^3+H^1+Q_2 \quad (2)$$

gives a direct comparison of the binding energy of He^3 and H^3 as well as a means of finding the stability of He^3 and H^3. Several determinations[2] have already been made on the value of Q_1 and it was the purpose of the present experiment to improve on the accuracy of these determinations.

The method of determining neutron energies in this experiment is the same as that previously used.[3] The energy of the neutrons is obtained from the range of recoil-protons in a methane-filled cloud chamber. Because of the near equality of the mass of proton and neutron, a proton recoiling in the forward direction gets

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* A preliminary report of these results was given in Nature **143**, 681 (1939).

† The experimental work was carried out at the Cavendish Laboratory, Cambridge, England, while the writer held a Guggenheim Fellowship.

[1] E. Hudspeth and H. Dunlap, Phys. Rev. **57**, 971 (1940); R. D. Park and J. C. Mouzon, *ibid.* **58**, 43 (1940); H. T. Richards and E. Hudspeth, *ibid.* **58**, 382 (1940); H. H. Barschall and M. H. Kanner, *ibid.* **58**, 590 (1940). All the neutrons produced do not have exactly the same energy. They are monoenergetic only when they are produced in a thin target by deuterons of one energy and are projected at the same angle to the deuteron beam.

[2] P. I. Dee, Proc. Roy. Soc. **148**, 623 (1935); T. W. Bonner and W. M. Brubaker, Phys. Rev. **49**, 19 (1936); E. Baldinger, P. Huber and H. Staub, Helv. Phys. Acta **11**, 245 (1938); T. W. Bonner, Phys. Rev. **53**, 711 (1938).

[3] T. W. Bonner and W. M. Brubaker, Phys. Rev. **47**, 910 (1935); **48**, 742 (1935); **49**, 19 (1936); **50**, 308 (1936).

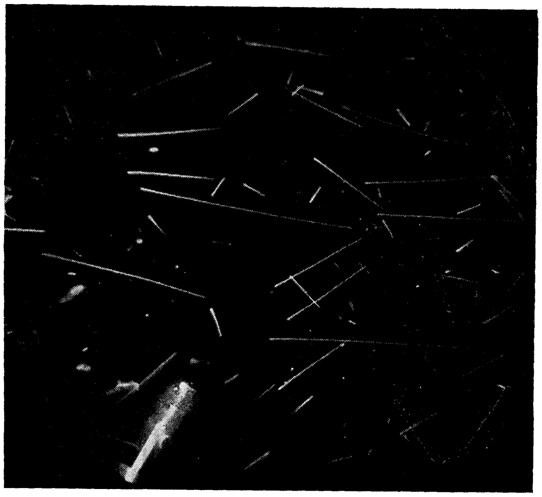

FIG. 1. A cloud-chamber photograph showing numerous recoil-protons. The neutron source was 55 cm to the right of the chamber. The two longest tracks which are nearly horizontal were the only measurable tracks on this picture. The bright object in the lower left-hand side of the chamber is the holder for the Th source.

very nearly the entire energy of the neutron.[4] The problem of measuring the energies of neutrons then becomes one of measuring proton energies in the ordinary way with the well-established range-energy relations.

Greater accuracy was expected in these measurements than in any previous ones because the neutrons were observed in the forward direction (0°) instead of at 90° to the direction of the bombarding deuterons. Observation of the neutrons in the same direction as the incident deuterons virtually eliminated corrections for angular straggling which are very important at 90°. The effect of deuteron and neutron scattering in the target or target holder was also eliminated. This is because neutrons emitted at 0° have the maximum energy of any produced in the target, and so a few neutrons which have a lower energy because of scattering will not influence the extrapolated range of the recoil-protons. This situation is just the reverse of that at 90° where scattered neutrons or neutrons produced by scattered deuterons could have considerably more energy than those emitted at 90° to the bombarding beam, and hence would increase the value of the extrapolated range.

EXPERIMENTAL ARRANGEMENT AND RESULTS

The cloud chamber which was used in these experiments was 20 cm in diameter and was placed 55 cm from the deuterium target so that neutrons which traversed the chamber were emitted at an angle of $0°\pm 6°$ to the deuteron direction. The path of the resolved deuterons was horizontal so the cloud chamber could be mounted in the usual horizontal position. The chamber was filled with CH_4 and alcohol vapor at a pressure of approximately 2.3 atmos. The deuterium target was a thick one made from "heavy paraffin." A thick target was used instead of a moderately thin one because of the difficulty in obtaining the exact thickness of moderately thin targets. The deuterons were accelerated by the Cavendish high voltage apparatus which was operated at 500 kv. This voltage was measured by a resistance voltmeter which was accurate to $\frac{1}{2}$ percent. The set gave a constant potential except for voltage fluctuations of about 10 kv as observed by the voltmeter. The ripple voltage of the rectifying system was negligibly small. A voltage of 20,000 volts was applied to the ion source so the maximum energy a deuteron could have was 20,000 volts greater than the voltmeter reading. However, the pressure in the discharge was quite high so that usually a positive ion would not get this total voltage drop. A maximum deuteron energy of 520 kev was used in the calculation of the Q value and this is believed to be accurate to within 10 kev.

A shutter was used in the ion path and adjusted so that neutrons entered the cloud chamber only after the chamber was completely expanded. Stereoscopic pictures were taken and reprojected in the usual way through the same camera and lens system.

Five hundred pairs of pictures were taken and on each picture numerous recoil tracks were observed. Figure 1 gives a representative cloud-chamber picture. Only those tracks were measured which were included in the angular cone 0–10° to the neutron direction. A total of 480 tracks were measured which were in the forward

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[4] Because of the slight difference in the mass of the proton and neutron, a neutron with an energy of 4 Mev which makes a head-on collision with a proton retains approximately 1000 volts energy.

direction. The lengths of these tracks, which all began and ended in the chamber, were measured to an accuracy of 0.5 mm.

Figure 2 gives the integral track-length *vs.* number curve for the recoil-protons. The extrapolated track length is 9.23±0.10 cm. The stopping power of the gas mixture was obtained by the use of a weak source of Th C+C′ which was placed inside the chamber before it was filled with methane. The mean range of the 8.53-cm alpha-particles from Th C′ was determined a few hours before determining the neutron energies. The mean track length was found to be 4.08±0.05 cm. This gives a stopping power of 2.09±0.03 for 8.53-cm alpha-particles. The correction for change of stopping power of CH_4 with range was calculated from the curves of Livingston and Bethe.[5] For 19-cm protons the calculated stopping power was 2.04±0.03. From this stopping power the extrapolated range of the recoil protons was calculated to be 18.83±0.34 cm. Such an extrapolated range can probably be as accurately determined for recoil protons as for the protons produced in reaction (2). The length of a recoil track can probably be determined more accurately because the track begins and ends in the chamber while disintegration protons usually enter the apparatus through windows. An accurate measurement of the stopping power of a window is unnecessary when measuring neutron recoils. The limit of accuracy of the neutron energy in the present experiment is principally set by the determination of the stopping power of the gas and not by the error in the extrapolated range of the recoil protons. The same error would have been encountered in measuring the ranges of disintegration protons instead of recoil protons.

The disintegration Q value of the reaction was found by the method of Livingston and Bethe.[5] In their symbols, the pure range straggling s for particles of this range is 2.03 percent. Since the neutrons were observed at 0°, the angular straggling is vanishingly small. The change in neutron energy between 0° and 6° is somewhat less than 6 kev and the angular straggling can, therefore, be neglected. The total straggling s'' was 2.04 percent. The thick target correction β was calculated to be 0.996 and hence $X_{\mathrm{extr}}=0.52$. Consequently the difference between extrapolated and mean range is $0.52\times 0.0204\times 18.8=0.20$ cm. It follows that the mean range is 18.63±0.34 cm. This corresponds to a proton energy of 3.53 Mev. The correction in the case of recoils which made angles of 0–10° to the direction of the neutron is $\frac{1}{2}E_2\chi_0^2=0.05$ Mev. Therefore the energy of the neutrons coming from the top layer of the target in the direction of the deuteron is 3.58±0.03 Mev. The disintegration energy is then calculated from the relation $Q_1=(4/3)E_n-(1/3)E_H-(2/3)(2E_nE_H)^{\frac{1}{2}}$. The value of Q_1 is 3.31±0.03 Mev.

This Q value is very close to the value 3.29 ±0.08 which was previously reported by the writer.[6] However the probable error has been considerably reduced in these new measurements.

Mass of He^3 and the Instability of H^3

The difference between the mass of H^3 and He^3 can be found from reactions (1) and (2). By subtracting (1) from (2) we get

$$H^3-He^3=(n-H)+Q_1-Q_2.$$

Since all three of the terms are accurately known, the mass difference between H^3-He^3 can be accurately determined. The value $(n-H)$ is 0.00080 mass unit or 0.74 Mev[7] with a probable

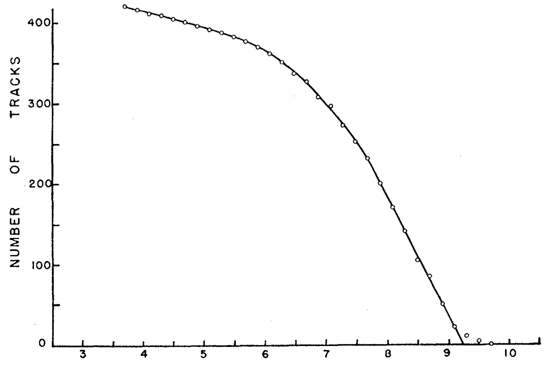

Fig. 2. The integral track-length *vs.* number curve for the recoil protons. The extrapolated track-length is 9.23±0.10 cm. The corresponding extrapolated range is 18.83±0.34 cm.

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[5] M. S. Livingston and H. A. Bethe, Rev. Mod. Phys. **9**, 276 (1937).

[6] T. W. Bonner, Phys. Rev. **53**, 711 (1938).

[7] H. A. Bethe, Phys. Rev. **53**, 313 (1938); J. Chadwick, N. Feather and E. Bretscher, Proc. Roy. Soc. **163**, 366 (1937); F. T. Rogers and M. M. Rogers, Phys. Rev. **55**, 263 (1939).

error of 0.04 Mev. Q_2 is 3.98±0.02 Mev.[8] The mass difference H^3-He^3 so computed is 0.07 ±0.05 Mev. This indicates that H^3 should be unstable. The instability of H^3 was predicted by the writer[6] by this argument using the older value of $Q_1=3.29$ Mev.

Rumbaugh, Roberts and Hafstad[9] have pointed out the discrepancy between the value of Q_1-Q_2 and the value of Q_4-Q_3 as found in the following reactions

$$\begin{gathered} Li^6+n\rightarrow He^4+H^3+Q_3 \\ Li^6+H\rightarrow He^4+He^3+Q_4. \end{gathered}$$

An analogous relation between H^3 and He^3 is found from these reactions:

$$H^3-He^3=(n-H)+Q_4-Q_3.$$

Obviously Q_4-Q_3 should be equal to Q_1-Q_2. Rumbaugh, Roberts and Hafstad measured Q_3 as 4.97 Mev. From this value of Q_3 and Neuert's value[10] of $Q_4=3.72\pm0.08$ Mev they got a value of $Q_4-Q_3=-1.25$ Mev. This differs by 0.58 Mev from the value $Q_1-Q_2=-0.67$ Mev. Recently Perlow[11] has accurately redetermined Q_4. His value of Q_4 is 3.95±0.06 Mev. This new measurement taken with the value of Q_3 of Rumbaugh, Roberts and Hafstad gives $Q_4-Q_3=-1.02$ Mev. This agrees better with the value Q_1-Q_2 than the previous value of Neuert. Still better agreement is obtained if we use the value of $Q_3=4.86$ Mev which was obtained by Livingston and Hoffman.[12] If we again use Perlow's value of Q_4 we find that $Q_4-Q_3=-0.91$ Mev and $H^3-He^3=-0.17$ Mev. This predicts a stable H^3. However, a radioactive H^3 and a stable He^3 have been discovered by Alvarez and Cornog.[13] Consequently it appears that there is still considerable error in the determination of Q_3 or Q_4.[14]

From the value of Q_1 and Q_2, H^3 is calculated to be unstable by 0.07±0.05 Mev. The experimental value of the maximum energy of the β-rays from H^3 is 0.015 Mev.[13] This value of the instability of H^3 could hardly be in error by more than 10 kev and so this indicates a combined error in Q_1, Q_2, and $(n-H)$ of at least 0.04 Mev. This is not a serious discrepancy in view of the estimated probable errors of 0.02 in Q_2, 0.03 in Q_1 and 0.04 in $(n-H)$.

The mass of He^3 can be determined from a combination of the mass-spectroscopic mass of H^2, Q_1 and the mass difference $(n-H)$. This calculated mass of He^3 is 3.01698±0.00006 mass units. An alternate and slightly more accurate method[15] to get the mass of He^3 is from the combination of Q_2, the mass-spectroscopic masses of H^2 and H^1 and the maximum energy of the β-rays from H^3. This gives the mass of He^3 $=3.01703\pm0.00004$ mass units.

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[8] M. L. Oliphant, A. R. Kempton and Lord Rutherford, Proc. Roy. Soc. **149**, 406 (1935).

[9] L. H. Rumbaugh, R. B. Roberts and L. R. Hafstad, Phys. Rev. **54**, 675 (1938).

[10] H. Neuert, Physik. Zeits. **36**, 629 (1935).

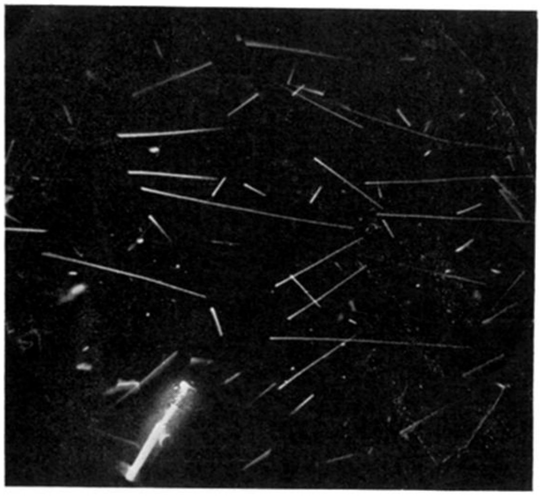
[11] G. J. Perlow, Phys. Rev. **58**, 218 (1940).

[12] M. S. Livingston and J. G. Hoffman, Phys. Rev. **53**, 227 (1938). A preliminary account of these experiments, Livingston and Hoffman, Phys. Rev. **50**, 401A (1936), gave a value of $Q_3=4.67$ Mev. Perlow has pointed out that if this value of Q_3 is used the discrepancy disappears.

[13] L. W. Alvarez and R. Cornog, Phys. Rev. **56**, 613 (1939); R. D. O'Neal and M. Goldhaber, *ibid.* **58**, 574 (1940).

[14] Another chain of reactions involving reaction (2) and the reactions $L^6+H^2\rightarrow 2He+22.20$ Mev and $H^2\rightarrow n+H$ -2.17 Mev together with the mass-spectrographic mass difference $(2H^2-He^4)$ gives a value of $Q_3=4.51$ Mev, if Bainbridge's masses are used. This indicates that it is probably Q_3 that is in error and not Q_4.

[15] In the calculation of the mass of He^3 from the energy of the β-rays from H^3, we have assumed that the rest mass of the neutrino is zero. If the rest mass of the neutrino is not exactly zero, the mass of He^3 so calculated will be in error by the amount of this rest mass.



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