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Range of Protons from $N^{14}(n,p)C^{14}$

I. C. CORNOG, W. FRANZEN, AND W. E. STEPHENS
Randal Morgan Laboratory, University of Pennsylvania, Philadelphia, Pennsylvania
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The mean range of protons emitted in the slow neutron disintegration of nitrogen has been measured in a cloud chamber to be 1.00 cm of air, in good agreement with other observers. It is suggested that this range and the energy (561 kev) of the emitted protons as deduced from the $n-H$ mass difference and the extrapolated end point of the C^{14} beta-ray spectrum be used to establish a reliable point on the proton range-energy curve. This point lies on Bethe's original 1937 range-energy curve, but disagrees with Bethe's curve revised to fit the ionization chamber range of artificially accelerated protons.

1. INTRODUCTION

IT has been pointed out[1] that the cycle

$$_0n^1 + _7N^{14} \rightarrow _6C^{14} + _1H^1 + Q$$
$$_6C^{14} \rightarrow _7N^{14} + \beta_- + E$$

leads to

$$n - H = E + Q,$$

and that the best values of these energies known in 1946 were incompatible. Recent work has tended to confirm the suspicion that the proton range-energy curve was at fault.

In order to investigate this cycle in detail, a program was undertaken in this laboratory to measure the carbon 14 beta-ray end point and the range of the protons from the (n,p) reaction. Preliminary values of the C^{14} end point have been published.[2]

Here we wish to describe our measurements on the $N^{14}(n,p)$ protons and to discuss the implications of these data.

[1] W. E. Stephens, Rev. Mod. Phys. **19**, 19 (1947).
[2] W. E. Stephens and Margaret N. Lewis, Phys. Rev. 72, 526A (1947); Margaret N. Lewis and Miriam Paul, Phys. Rev. **73**, 1269 (1948).

2. OBSERVATIONS

An 800 millicurie radium-beryllium neutron source was surrounded by paraffin and placed near a 15-cm horizontal cloud chamber filled with nitrogen plus *n*-propyl alcohol and water vapor to a total pressure of one atmosphere. Approximately 4000 stereoscopic photographs were taken and reprojected through the same camera and mirror. 92 protons which had an angle of less than 30° with the horizontal plane of the chamber and greater than 30° with the normal to the mirror were selected for measurement. Figure 1a shows a histogram obtained by grouping the tracks in 0.07-cm groups, and Fig. 1b shows an integral number range curve.

The most probable location of the peak of the differential straggling curve as obtained from the observed track lengths by the method of least squares and in agreement with the value obtained graphically is 1.005 cm. The straggling as estimated from Fig. 1b is 0.065 cm; this compares with a value of 0.03 cm to be expected theoretically.

The stopping power of the gas was determined

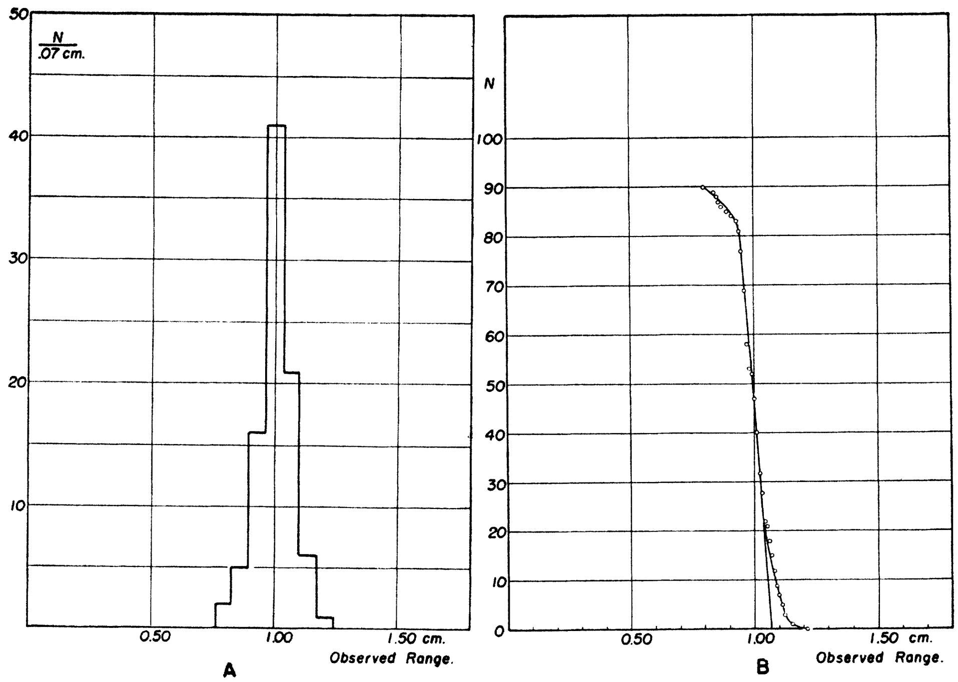

FIG. 1. A. Histogram obtained by grouping $N^{14}(n,p)$ proton tracks in 0.07-cm groups. B. Integral number range curve obtained for $N^{14}(n,p)$ proton tracks.

by observation of the range of Po alpha-particles emitted by a thick source placed in the chamber. The mean range of the alpha-particles was found by extrapolating an integral straggling curve for the particles and equating the extrapolated range thus obtained to the mean range on the assumption that the source was thick.[3] Figure 2 shows the experimental points obtained. The value of the stopping power calculated from the mean range given by this method (3.773 cm) and the known air range of the alpha-particles[4] (3.842 cm) is 1.018. This value must be increased by 0.3 percent to account for the difference in stopping power of the vapor for polonium alpha-particles and 1.00-cm protons as estimated from Bethe's table[5] of stopping powers and particle velocities. We thus obtain a stopping power of 1.022. This value is in good agreement with a value of 1.03 calculated independently from the known temperature and pressure of the gas before expansion, the expansion ratio, and the estimated composition of the vapor mixture.

[3] Livingston and Bethe, Rev. Phys. 9, 287 (1937).
[4] Holloway and Livingston, Phys. Rev. 54, 18 (1938).
[5] Livingston and Bethe, Rev. Mod. Phys. 9, 274 (1937).

From this range in normal air of 1.026 cm we must subtract the range of the recoiling C^{14} nucleus. This range can be estimated to be 0.035 cm by use of Blackett's relation[6]

$$R = kmZ^{-\frac{1}{2}}f(v)$$

and Wrenshall's[7] ranges of C^{12} nuclei. A more reliable value of the range of the C^{14} recoil is obtained from the works of Boggild[8] and Hughes and Eggler[9] who observed 0.03 cm and 0.025 cm, respectively. Assuming 0.03 cm for C^{14}, we obtain a range of 0.996 cm for the range of the proton. The uncertainty in this value can be estimated to be 1 percent for measurement and 1 percent for calibration.

3. DISCUSSION

The proton range observed in these measurements agrees well with results obtained by other

[6] P. M. S. Blackett, Proc. Roy. Soc. **A107**, 349 (1925).
[7] G. A. Wrenshall, Phys. Rev. **57**, 1095 (1940).
[8] J. K. Boggild, D. Kgl. Danske Vid. Selskab, mat-fys. Medd. **23**, 22 (1945).
[9] Hughes and Eggler, Phys. Rev. **73**, 809 (1948). We are indebted to Dr. D. J. Hughes for measuring his C^{14} recoils and informing us of his results.

observers. Bonner and Brubaker[10] reported a range of 1.06 cm but did not take the C^{14} recoil into account; if a correction for this recoil is applied, one obtains 1.03 cm. Boggild[8] who studied the $N^{14}(n,p)$ reaction incidental to his beautiful and extensive investigation of the slow neutron disintegration of B^{10}, obtained a range of 1.00 cm for the protons emitted in the nitrogen reaction. His cloud chamber was filled with air and methyl-alcohol vapor to a pressure of 18-cm Hg. The resulting low stopping power enabled Boggild to see the C^{14} recoil track and to subtract its observed range (0.03 cm) from the observed total track length. The straggling in track lengths (0.03 cm) in his case is just equal to the theoretical value, or approximately one-half of the value observed in our experiment. (This is presumably due to the greater accuracy of measurement attainable at lower pressures with resulting longer track lengths.) Recent work, also done with low pressure air, reported by Hughes and Eggler[9] gives a value of 0.991 cm for the proton range. In this case, the proton ranges were measured by disregarding the portion of the track identified as due to the recoiling C^{14} by its denser ionization. All these results are consistent with a range of 1.00 cm for the proton produced in the slow neutron disintegration of nitrogen.*

Several measurements have been made with ionization chambers of the disintegration energy Q of the $N^{14}(n,p)C^{14}$ reaction with slow neutrons. Huber reports two values, 0.57 ± 0.04 Mev[11] and 0.63 ± 0.01 Mev.[12] However, it appears probable that a more reliable value of Q can be obtained by means of the transmutation cycle mentioned previously. For this it is necessary to know the $n-H$ mass difference and the C^{14} beta-ray spectrum end point.

A value of 755 ± 16 kev is derived in reference 1 for the $n-H$ mass difference by averaging the results of three reliable experiments in which the threshold for the photo-disintegration of the deuteron was determined with different methods of detection. (This value is slightly higher than the value of 751 ± 6 kev sometimes quoted.[13] The lower value is based on a measurement of the $D(e,n)$ threshold,[14] the accuracy of which depends on the calibration of the electron energy used. In the absence of details relating to this calibration, it is not possible to estimate the reliability of the quoted error.)

Several experiments on the end point of the C^{14} beta-ray spectrum now allow an estimate of E. Assuming the validity of the Fermi theory of beta-decay, we can define E as the extrapolated end point on a Kurie plot; this end point is independent of the neutrino mass.[15] The extrapolated end point of the C^{14} beta-ray spectrum has been determined in a beta-ray spectrograph as

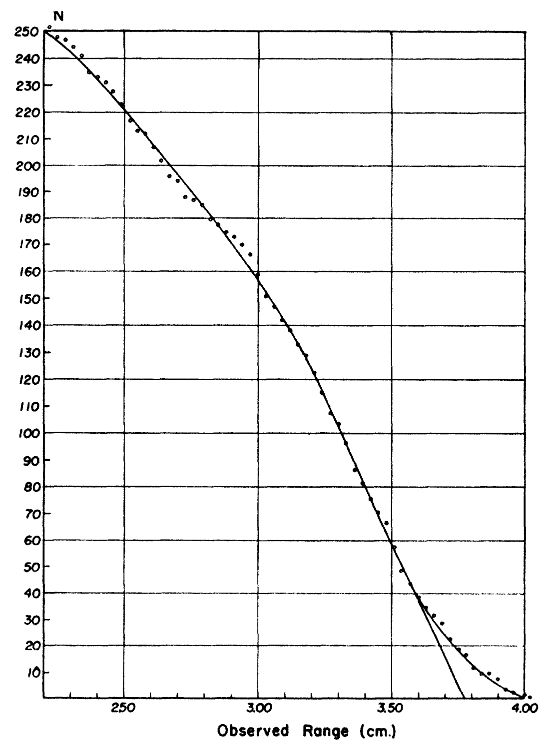

FIG. 2. Integral number range curve obtained for polonium alpha-particles emitted by thick source placed in chamber.

[10] Bonner and Brubaker, Phys. Rev. **49**, 778 (1936).

* *Note added in proof:*—Another determination of the range of the N^{14} (n,p) protons was reported by Cüer (J. de Phys. et Rad. VIII-8, 83 (1947)), who exposed a photographic emulsion impregnated with NaN_3 to slow neutrons and observed the transmutation tracks in the emulsion. He observed a range of 0.985 cm with an estimated uncertainty of 5 percent due to grain straggling and stopping power calibration. This is consistant with our conclusions.

[11] Huber, Huber, and Scherrer, Helv. Phys. Acta **13**, 209 (1940).

[12] Huber and Stebler, Phys. Rev. **73**, 85 (1948).

[13] D. J. Hughes, Phys. Rev. **70**, 219 (1946).

[14] Wiedenbeck and Marhoefer, Phys. Rev. **67**, 54 (1945).

[15] O. Kofoed-Hansen, Phys. Rev. **71**, 451 (1947).

153 ± 5 kev (photographic detection)[16] and 154 kev (counter detection).[17] These values agree with an absorption curve end point of 154 kev.[18] A value of 154 ± 5 kev seems reasonable from these data.

Using $n-H=755 \pm 16$ kev and $E=154 \pm 5$ kev, gives $Q=601 \pm 17$ kev. The proton gets 14/15 of the energy or 561 ± 16 kev. These data seem now to be reliable and consistent enough to establish a point on the proton range-energy curve such that a proton of 561 kev has a range of 1.00 cm with an accuracy of probably better than 3 percent.

Such a point disagrees with the unpublished but blue-printed curve set up by Bethe[19] from the work of Parkinson, Herb, Bellamy, and Hudson[20] on the range of protons accelerated in a statitron. Parkinson's data give ionization extrapolated ranges at 0°C and 76-cm Hg and have to be corrected to compare with the mean ranges at 15°C and 76-cm Hg used here. Bethe applied these corrections as described in reference 19. A 560-kev proton has a range of 0.83 cm on this corrected curve, in serious disagreement with our data. An explanation for this discrepancy is lacking at present. A possible source of error in Parkinson's experiment already mentioned by him is the actual temperature of the gas in the beam which may have been higher than measured due to heating by the beam; the correction that this requires would, however, increase rather than decrease the disagreement.

The 561-kev $-$ 1.00-cm point agrees very closely with Bethe's original curve[21] which was computed from Blackett and Lees' experiments[22] on the ranges of low energy alpha-particles. In these computations the rule $R_H(v)=1.0072R_\alpha(v) - 0.20$ cm was used. If the revised 1938 alpha-particle range-energy curve[23] is used instead of Blackett and Lees' results, only an inappreciable change results.

Consequently the part of Bethe's original curve near 1 cm may be regarded as more nearly correct than the curve revised by use of Parkinson's data. However, the very close agreement at this point may be fortuitous as indicated by the fact that the revised curve fits data on the disintegration of the deuteron[19] by Th C″ gamma-rays considerably better than the original curve. The desirability of new experiments to establish a reliable proton range-energy curve in the low energy region is evident from these observations.

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[16] Unpublished estimate of the extrapolated end point from the work of Lewis and Paul; see reference 2.

[17] P. W. Levy, Phys. Rev. **72**, 248 (1947).

[18] Solomon, Gould, and Anfinsen, Phys. Rev. **72**, 1097 (1947).

[19] H. A. Bethe, Phys. Rev. **53**, 313 (1938).

[20] Parkinson, Herb, Bellamy and Hudson, Phys. Rev. **52**, 79 (1937).

[21] Livingston and Bethe, Rev. Mod. Phys. **9**, 268 (1937).

[22] Blackett and Lees, Proc. Roy. Soc. **A134**, 658 (1932).

[23] Holloway and Livingston, Phys. Rev. **54**, 30 (1938).