The Carbon Isotopes of Mass Ten and Eleven

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(Received August 8, 1940)

C^{11} has been produced by two new reactions; namely, $B^{11}(p,n)C^{11}$ and $N^{14}(p,\alpha)C^{11}$. The upper limit of the positron spectrum of C^{11} has been measured in a cloud chamber and the value 0.95 ± 0.03 Mev obtained. A new isotope, C^{10}, has been produced by the reaction $B^{10}(p,n)C^{10}$. This nucleus has a disintegration period of 8.8 ± 0.8 sec. The upper limit of the positron spectrum was found to be 3.36 ± 0.1 Mev. A discussion is given of the relation which these measurements bear to the isobaric splitting and systematic properties of light nuclei.

INTRODUCTION

THE isotope C^{11} has been produced in several laboratories[1,2] by (p,γ), (d,n) and $(n,2n)$ reactions and is one of the best known of the light positron emitting nuclei. In a preliminary report[3] investigations of two additional processes producing C^{11} were described.

The accepted value[1] for the energy of C^{11}, namely, 1.15 Mev, was obtained under conditions where contamination by N^{13} was probable. This circumstance, together with the fact that the computed disintegration energy of C^{11} suggests a discrepancy, made it important to remeasure this quantity. Recent preliminary observations[4] of the threshold for the $B^{11}(p,n)C^{11}$ reaction likewise indicate that the C^{11} beta-radiation cannot be so energetic as previously supposed.

From the computations of Bethe[5] it appeared quite certain that C^{10} should be stable against disintegration into heavy particles. Because no nucleus of this type was known, and because of the importance of a knowledge of the period and disintegration energy of C^{10} for an understanding of the systematic properties of light nuclear systems, the problem of its production and study seemed to merit attention.

In this paper we report a measurement of the beta-ray energy of C^{11} and describe experiments in which C^{10} was produced and its period and disintegration energy measured.

EXPERIMENTAL

The reactions we have studied were induced by protons of energy up to 6.4 Mev from the Princeton cyclotron. Boron targets were prepared simply by pressing amorphous boron into pieces of clean sheet lead. This method has been found convenient for making targets of many materials which occur in powdered or crystalline form. No appreciable activity is induced in the lead itself.

Bombardments were made in an atmosphere of hydrogen in a chamber open at one end, but through which a sufficient flow of hydrogen was maintained from the other end to prevent air from coming in contact with the target. The beam entered the target chamber through a window of 0.4-mil aluminum. This arrangement permitted the removal of the target without delay, yet avoided contamination by the disintegration products of air. The hydrogen also helped to cool the target. As previously described,[3] bombardment of targets in air always yielded a contamination activity of C^{11} from $N^{14}(p,\alpha)C^{11}$ as well as F^{17} and F^{18} from the bombardment of oxygen. With the present arrangement the amount of contamination is negligible except with certain kinds of target materials which adsorb gases, or with very long bombardments.

Half-life measurements were made with electroscopes of the Lauritsen quartz-fiber type. The short period of C^{10} was determined, after some experimentation, by simultaneously photographing a stop watch dial and the projected

[1] Fowler, Delsasso and Lauritsen, Phys. Rev. **49**, 561 (1936).
[2] Crockcroft, Gilbert and Walton, Proc. Roy. Soc. **A148**, 225 (1935); H. R. Crane and C. C. Lauritsen, Phys. Rev. **45**, 497 (1934); Pool, Cork and Thornton, Phys. Rev. **52**, 239 (1937); Yost, Ridenour and Shinohara, J. Chem. Phys. **3**, 133 (1935).
[3] W. Barkas, Phys. Rev. **56**, 287 (1939).
[4] Haxby, Shoupp, Stephens and Wells, Phys. Rev. **57**, 567 (1940).
[5] H. A. Bethe, Phys. Rev. **54**, 436 (1938).

shadow of the fiber as it passed over a graduated scale. The photographs were taken at intervals of about one second. In the early work[3] on the bombardment of boron by protons the period of C^{11} was the only one which was definitely present. With higher energy protons and short bombardment times the additional short period expected of C^{10} appeared. Under the best conditions we have obtained C^{10} with an initial activity equal to that of C^{11}. It was found possible also to increase considerably the ratio of C^{10} to C^{11} activity by absorbing out much of the softer beta-radiation from C^{11} by interposing aluminum absorbers between the source and the electroscope.

The energy measurements of the beta-rays from C^{11} were carried out in a cloud chamber equipped with a well projecting through the glass top into the chamber. In the side of the well was a copper foil window with a surface density of 11.6 mg/cm^2. The chamber was filled with hydrogen and ethyl alcohol vapor. Tracks measured satisfied the following criteria: (a) no visible scattering, (b) at least 10 cm in length, (c) coming apparently from the source. The illumination in the chamber was confined to a region about one centimeter in depth so no correction for the component of momentum parallel to the field was necessary. Photographs were taken with a single Sept camera placed directly above the chamber. The developed photographs were reprojected through the same lens system and curvature of the tracks compared with a set of curves accurately drawn on white paper.

Our magnetic field intensity was determined fairly well by computation from the geometry of the Helmholz coils, and from flip coil measurements. A final accurate value was obtained by placing in the field the chamber of a 180° focusing beta-ray spectrometer and photographing the standard internal conversion lines from the active deposit of thorium. These lines have been carefully measured by Ellis[6] and more recently by Flammersfeld.[7] The field measurement is therefore referred directly to this discrete beta-ray spectrum.

[6] C. D. Ellis, Proc. Roy. Soc. **A138**, 318 (1932).
[7] A. Flammersfeld, Zeits. f. Physik **114**, 227 (1939).

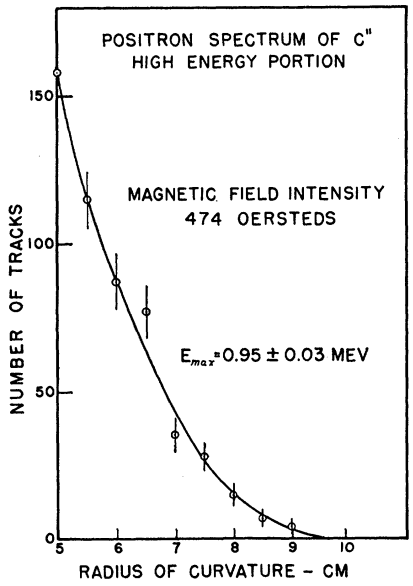

FIG. 1. Momentum distribution of the positrons from C^{11}. A cloud-chamber foil correction of 0.02 Mev has been added to the visually extrapolated upper limit.

The technique for measuring the C^{10} disintegration energy was as follows: The cloud chamber was placed about thirty feet away from the cyclotron at a lower level away from the stray magnetic field and rather well protected by earth from neutrons and gamma-rays. Targets were bombarded in the cyclotron for ten seconds, then placed in a brass capsule which fitted snugly into a pneumatic tube. In this way the target was delivered to the cloud chamber in about two seconds. The total time elapsed between the removal of the target from the beam until the cloud chamber expanded was about four seconds. Using a cycle of ten seconds between cloud-chamber expansions the target was, however, usually strong enough to be used for a second expansion. In spite of the aid of these improved techniques, however, a large amount of labor was required to accumulate the spectrum obtained. This is because only about one-fifth of the boron nuclei are those of B^{10}, and in addition the threshold for the (p,n) reaction in B^{11} is much lower than in B^{10} so that the beta-rays of C^{10} which extend above the energy distribution of those of C^{11} are relatively rare. About half the tracks obtained for C^{10} were photographed with air in the chamber. These electrons showed no essential difference in

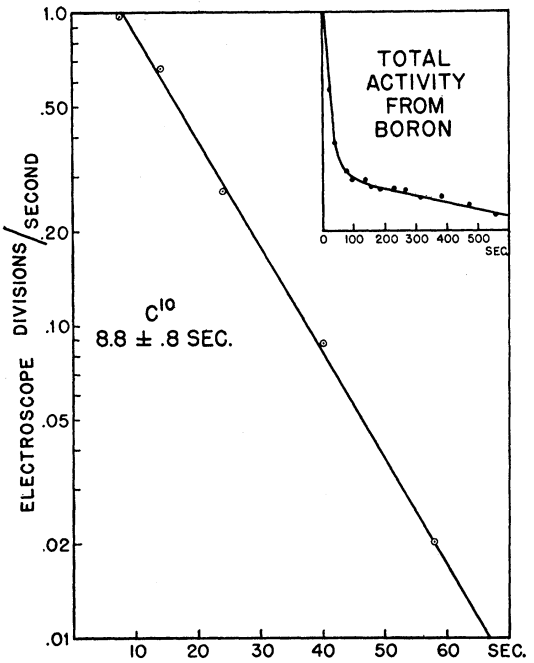

FIG. 2. A typical C^{10} decay curve. The insert curve shows to what extent it was necessary to allow for the C^{11} activity.

distribution from those photographed in hydrogen so the two sets of data were added together. Indeed, for such high energy electrons air is perhaps preferable to hydrogen because of the better definition of the tracks produced by slower diffusion of the droplets and greater ionization.

RESULTS

The accepted value[8] for the period of C^{11} is 21 minutes. We have made many incidental observations of this period, and this figure is near the mean of our experimental values. We cannot claim, however, accuracy to better than about one percent. The older value[9] of 20.5 minutes is, nevertheless, definitely too low.

In Fig. 1 is the observed momentum distribution of the positrons from C^{11}, giving an upper limit of 0.95 ± 0.03 Mev. Because of the lead backing used for our boron targets, and because of the scattering in the target well of the cloud chamber, as well as the indeterminate solid angle into which the lower energy electrons are emitted, we have not included the low energy portion of the spectrum. All targets used for measuring the C^{11} spectrum were aged for at least one minute to permit the C^{10} activity to disappear before observations were made.

The period of C^{10} was found to be 8.8 ± 0.8 sec. In Fig. 2 is shown one of the decay curves observed, and the curve obtained after the C^{11} activity was subtracted.

The momentum distribution of the positrons from C^{10} in the region above the upper limit of the C^{11} spectrum is shown in Fig. 3. From this one obtains an upper limit of 3.36 ± 0.1 Mev.[10]

That the short period is really associated with C^{10} by $B^{10}(p,n)C^{10}$ one concludes from the circumstance that all other energetically possible reactions lead to well-known products, none of which so far has been found to have an isomeric form.

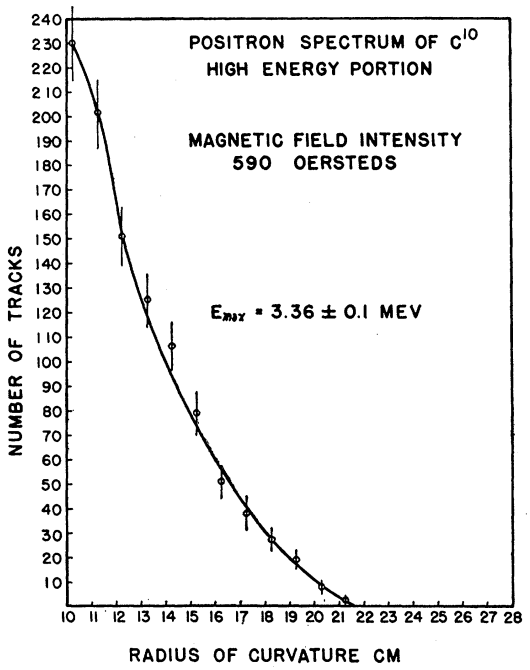

FIG. 3. Momentum distribution of the high energy end of the positron spectrum of C^{10}. Foil correction of 0.03 Mev has been added to the visually extrapolated upper limit.

[8] J. J. Livingood and G. T. Seaborg, Rev. Mod. Phys. 12, 30 (1940).

[9] M. S. Livingston and H. A. Bethe, Rev. Mod. Phys. 9, 359 (1937).

[10] The error placed on the upper limit neglects the possibility of recoil Si nuclei from the aluminum window. However, from a consideration of the difference in the upper limits of C^{10} and Si^{27} and the range of heavy particles, it is believed that this would not increase the value by more than 0.05 Mev.

Discussion

Beta-disintegration energies arise from mass differences between isobars, which for light elements show the influence of four terms, each of which by various means[11,12] may be isolated for study. These are as follows: (a) the mass difference between a neutron and a proton, (b) the electrostatic energy difference between a charge Ze and a charge $Z'e$ confined to the nuclear volume, (c) the effect of "spin dependent" forces, (d) the effect of the Pauli principle on the symmetry properties of the nuclei.

In the mass difference between C^{11} and B^{11} only the terms (a) and (b) are expected to appear. Using the simple formula[11,13]

$$\Delta E = 0.594(A-1)A^{-\frac{1}{3}} \text{ Mev},$$

where A is the mass number, which gives the binding energy difference for two such isobars, one computes a value of 0.91 Mev for the upper limit of the positron spectrum. The agreement with the observed limit of 0.95 ± 0.03 Mev is satisfactory especially in view of the rather detailed, though reasonable, assumptions involved in the calculation. A similar good agreement has been found[13,14] for other light isobaric pairs of this type.

C^{10} is unique in that it has the greatest excess of protons of any known nucleus. The triplet of isobars C^{10}, B^{10} and Be^{10} provides data from which one may draw quantitative conclusions regarding the terms contributing to the isobaric splitting. C^{10} and Be^{10} are believed to be homologs since one may be obtained from the other merely by exchanging the protons and neutrons. That the interaction between two neutrons is essentially the same as that between two protons except for the electrostatic force is verified by the agreement between computed and observed disintegration energies of the odd nuclei (e.g., C^{11} in this paper). Therefore, one should expect C^{10} and Be^{10} to differ in mass only by terms (a) and (b), both of which are known fairly accurately. Taking the mass of B^{10} to be 10.01578 we obtain from our measurement of the beta-radiation a mass of 10.02048 for C^{10}. One may compute[12] the Coulomb energy difference between C^{10} and Be^{10} to be 5.33 mMU, while the mass difference between two neutrons and hydrogen atoms is 1.6 mMU. Our mass of C^{10} together with these estimates for the terms (a) and (b) imply a mass of 10.01675 for Be^{10}. Pollard[15] has measured the energy of protons, presumably from the reaction $Be^9(D,p)Be^{10}$, indicating an energy release of 4.52 Mev. With 9.01482 for the mass[16] of Be^9 the value of 10.01656 is then implied for Be^{10}. The agreement between these values for Be^{10} to within less than 0.2 Mev is as good as could reasonably be expected considering that the probable error in each of the intermediate masses is about this order of magnitude. We may take this as another numerical example to illustrate to what extent two useful and simplifying assumptions of current nuclear theory are justified. These are (1) that the protons have a uniform distribution throughout a nuclear volume which is proportional to the mass number, and (2) that, except for the electrostatic force, the interaction between two protons is the same as between two neutrons.

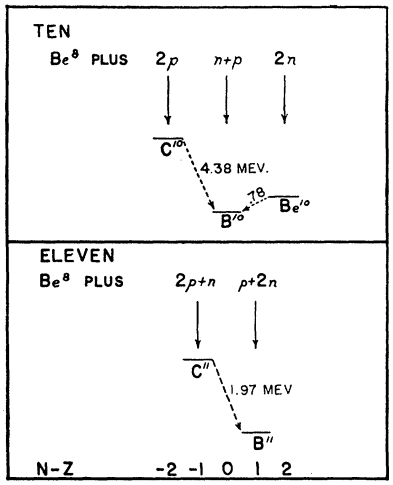

FIG. 4. Diagrammatic representation of the isobaric splittings at mass numbers ten and eleven.

[11] E. Wigner, Phys. Rev. **51**, 947 (1937).
[12] W. Barkas, Phys. Rev. **55**, 691 (1939).
[13] White, Delsasso, Fox and Creutz, Phys. Rev. **56**, 512 (1939).
[14] W. Barkas, E. C. Creutz, L. A. Delsasso, R. B. Sutton, and M. G. White, Phys. Rev. **58**, 383 (1940).
[15] E. Pollard, Phys. Rev. **57**, 241 (1940).
[16] Allison, Skaggs and Smith, Phys. Rev. **57**, 550 (1940).

One may also evaluate the term (c), the effect of which is apparent in nuclei containing an odd neutron and an odd proton such as B^{10}. The disintegration energy of C^{10} we observed to be 4.38 Mev. The terms (a) and (b) account, however, for only 2.01 Mev. One deduces therefore, that the extra binding energy in B^{10} due to a term of type (c) amounts to 2.37 Mev.

In Fig. 4 is shown graphically the relative masses of the isobars at mass numbers 10 and 11.

The half-life and beta-ray energy found for C^{10} may be interpreted[11] to mean that transitions between the even-even and odd-odd isobars are of the "allowed" type. In some other cases (e.g., for Na^{22} and P^{30}) this does not, however, seem to be true.

OCTOBER 1, 1940 PHYSICAL REVIEW VOLUME 58

On the Angular Distribution of Fast Neutrons Scattered by Hydrogen, Deuterium and Helium

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(Received July 8, 1940)

The angular distribution of d–d neutrons scattered by hydrogen, deuterium and helium was measured by observing the distribution in energy of the recoil particles in an ionization chamber. The scattering in hydrogen and deuterium was found to be essentially isotropic in the angular interval investigated. In helium, collisions with small energy transfer were more frequent than large angle scattering. The absolute differential scattering cross section of helium was measured.

I. INTRODUCTION

MEASUREMENTS of the energy of fast neutrons or the angular distribution of scattered neutrons have in the past been carried out principally in the cloud chamber. This method is the most direct and accurate; however, the evaluation of the experiments is tedious if good statistical accuracy is required.

In the present experiments an attempt is made to measure distributions both in angle and in energy in an ionization chamber by recording the energy of the recoil particles produced in the chamber. The use of an ionization chamber for energy measurements was first proposed by Baldinger, Huber and Staub.[1] These authors derived a simple formula which enables one to obtain the distribution in energy, $S(E)$, of the primary neutrons from the energy distribution $H(E)$ of the recoil particles. For the case in which the scattering is isotropic in the center of mass system and the whole range of the recoil particles is contained in the chamber they show that

$$S(E) = -\frac{1}{n \cdot \sigma(E) \cdot d} E \frac{dH}{dE}, \qquad (1)$$

where $\sigma(E)$ is the scattering cross section of the gas in the chamber, n the number of gas atoms/cm^3, d the depth of the chamber. Their experiments were carried out in a chamber filled with He. After the experiments of Staub and Stephens[2] had shown that $\sigma(E)$ for He is strongly dependent on energy around 1 Mev it seemed preferable to use hydrogen for such experiments.

With hydrogen, one is confronted with the difficulty that the recoil protons from fast neutrons have very long ranges. Since the experiments have to be carried out in such a way that the range of the recoils is small compared with all dimensions of the chamber, it is necessary to use very high pressures for measurements in hydrogen in order to reduce the range. Energy measurements in an ionization chamber filled

[1] E. Baldinger, P. Huber and H. Staub, Helv. Phys. Acta **11**, 245 (1938).

[2] H. Staub and W. E. Stephens, Phys. Rev. **55**, 131 (1939).