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Deuteron Bombardment of C^{14}

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Bombardment of C^{14} by deuterons produces three nuclear reactions, yielding neutrons, α-particles, and protons, and leads thereby to the formation of N^{15}, B^{12}, and a new radioactive isotope, C^{15}. The half-life of this sixth isotope of carbon is 2.4 sec., and the end point of the β-ray spectrum lies at 8.8 Mev.

Approximate values for relative yields from the various reactions are given, the neutron spectrum is obtained, and the nature of the γ-rays emitted during bombardment is reported.

I. INTRODUCTION

THE radioactive isotope C^{14} can be produced in an atomic pile in quantities sufficient to utilize it as a target material. We have obtained from Oak Ridge several milligrams of $BaCO_3$ which is enriched in C^{14} by about 40 percent.

Thin targets can be prepared from this material by a method previously described.[1] For our purposes, however, targets were prepared by forming a slurry of $BaCO_3$ on a silver disk.[2] Targets usually weighed 200–400 $\mu g/cm^2$, which corresponds to a thickness of 25 to 50 kv for deuterons of energy about 1 Mev. Targets of this type were bombarded with deuterons accelerated in the Van de Graaff generator at the Bartol Foundation[3] or in the larger generator at the Carnegie Institution of Washington[4] (in the case of the $C^{14}(d, p)C^{15}$ reaction). Three different reactions have been observed, yielding neutrons, protons, and α-particles. Only the neutrons have been observed "directly," from proton recoil data; protons and α-particles produced by deuteron bombardment are inferred from the formation of radioactive isotopes.

II. NEUTRON SPECTRUM OF $C^{14}(d, n)N^{15}$

We have used photographic plates to observe the neutrons from the bombardment of C^{14} by deuterons.[3] Ilford C.2 plates with emulsion thickness of 100μ were exposed at 0° and at 90° to a deuteron beam of energy 1.26 Mev. Exposure was made with the edge of the plates about 1 cm from the target and continued for about 6 μa-hr. Development and fixing of the plates were performed by following the procedure of Blau and De Felice,[5] and proton recoils were observed and measured with a microscope. Only recoils which were within 12° of the forward direction and which lay wholly within the emulsion were counted. Our earlier data[3] have been extended by one of us (CPS) and the results are shown in Figs. 1a and 1b.

The residual nucleus N^{15} has excited levels which have been previously established by other reactions. The neutron groups which may be expected from $C^{14}(d, n)$ should correspond to Q-values which leave N^{15} excited to levels[6] of 8.2 Mev (if the bombarding energy is sufficient), 7.2, 6.0(?), 5.39 Mev, and the ground state. At 0° to a deuteron beam of energy 1.26 Mev, we could therefore anticipate groups of neutrons of energies 9.1, 3.8, 3.2, 2.0, and 1.0 Mev; at 90°, the energies become 8.5, 3.4, 2.9, 1.7, and 0.8 Mev. The arrows in Figs. 1a and 1b are placed at abscissas corresponding to these energies. Calculated Q-values from the data of Fig. 1a are 8.15, 2.83, 1.87, and 0.71 Mev; Fig. 1b yields Q-values of 8.18, 2.83, 1.83, and 0.71 Mev. The curves show considerable asymmetry in the groups, and this would indicate fine structure.

The reaction $C^{12}(d, n)$ also takes place during bombardment, but its Q-value (-0.28 Mev) is too near the -0.18 Mev value anticipated for one of the groups from $C^{14}(d, n)$ to make resolution possible. It is obvious, however, that the total yield of neutrons from C^{14} bombardment at 1.26 Mev is considerably greater than the yield of neutrons from bombardment of C^{12}. Correction for track length and emulsion thickness shows that the relative yield from C^{14} bombardment is at least two or three times as great as the yield from C^{12} bombardment.

III. THE REACTION $C^{14}(d, \alpha)B^{12}$

Bombardment of C^{14} with deuterons leads to the production of a β-emitter of very short half-life. Absorption of the β-rays in aluminum showed[3] that their maximum energy was about 13 Mev, and the shape of the absorption curve was identical (Fig. 2) to that which had been previously observed in this laboratory for the β-rays from B^{12}. No attempt was made to measure the half-life of the β-emitter formed in the bombardment of C^{14}, other than to observe visually that the β-emission stopped essentially simultaneously with the cessation

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[†] Assisted by the Joint Program of the ONR and AEC.

[1] Shoupp, Jennings, and Sun, Phys. Rev. **75**, 1 (1949).

[2] Several of these targets were kindly prepared by Dr. E. Shapiro.

[3] E. L. Hudspeth and C. P. Swann, Phys. Rev. **78**, 337 (1950).

[4] Hudspeth, Swann, and Heydenburg, Phys. Rev. **77**. 736 (1950).

[5] M. Blau and J. A. De Felice, Phys. Rev. **74**, 1198 (1948).

[6] The data are summarized by W. F. Hornyak and T. Lauritsen, Rev. Mod. Phys. **20**, 217 (1948).

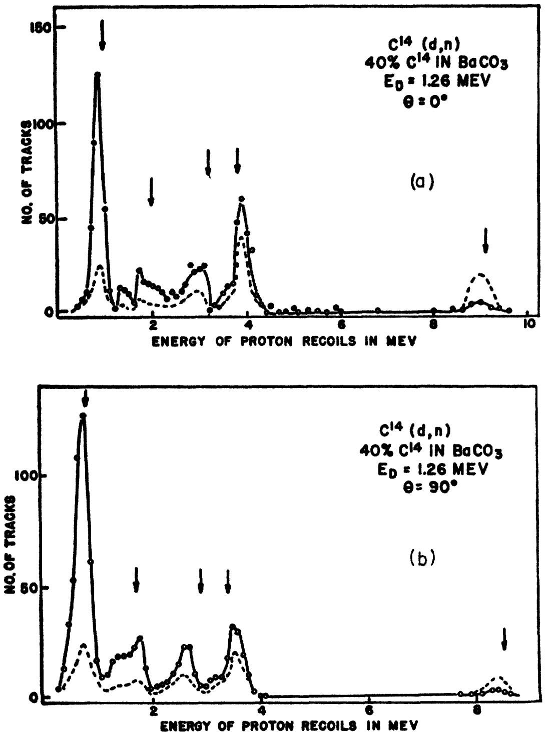

FIG. 1. Neutron spectrum from bombardment of C^{14} by deuterons. The intense group just below 1 Mev comes largely from bombardment of C^{12}. Arrows indicate positions of groups anticipated from known levels of N^{15}. (a) Observations at 0° to the bombarding beam, (b) observations at 90°.

of bombardment. These facts, together with the expected possibility of the reaction, serve to confirm the formation of B^{12} from $C^{14}(d, \alpha)$. B^{12} has a known half-life of 0.02 sec. and emits β-rays of maximum energy 13.4 Mev. The calculated Q-value for the reaction is 0.25 Mev.

The yield of β-rays from the $C^{14}(d, \alpha)B^{12}$ reaction was measured at a bombarding voltage of 750 kev. The cross section was found to be approximately 1.7×10^{-27} cm^2, which is somewhat greater (by a factor of nearly two) than the cross section for the $B^{11}(d, p)B^{12}$ reaction at this same bombarding voltage. The yield was observed to rise rapidly with increased bombarding voltage, indicating a much steeper excitation curve for $C^{14}(d, \alpha)B^{12}$ than for $B^{11}(d, p)B^{12}$ up to about 1.3 Mev.

IV. PRODUCTION OF C^{15}

The $C^{14}(d, p)C^{15}$ was expected to occur in our bombardments when the energy of the deuteron beam was sufficiently great. Assuming the mass of C^{15} to be 15.0165, as estimated by Bethe,[7] the Q-value for this reaction should be about -2 Mev. This estimate of the mass of C^{15} would make it stable against disintegration into C^{14} and a neutron by only 100 kv.

In order to bombard C^{14} with deuterons of higher energy than we can conveniently produce at the Bartol Foundation, we have utilized the larger generator at the Carnegie Institution of Washington.[4] We had supposed initially that any C^{15} produced might have a short half-life, so that it would yield β-rays which could be confused with the β-rays from the decay of B^{12} formed in the competing $C^{14}(d, \alpha)B^{12}$ reaction. The estimated maximum energy of the β-rays from C^{15} is 10.8 Mev (using a C^{15} mass of 15.0165), which is comparable to the maximum energy of 13.4 Mev for the β-rays from B^{12}. While bombarding C^{14} with deuterons of energy about 2 Mev, however, we found that the activity of the target was quite appreciable for several seconds after the beam was shut off. This activity could not be due to B^{12}, and we therefore ascribed it to the decay of C^{15}. The half-life of this isotope was determined by following the activity of the target; counts were recorded after the bombarding beam had been shut off for varying lengths of time. The mean of three sets of data (using varying thicknesses of absorber between coincidence counters) showed the half-life to be 2.4 sec., with an estimated error of not more than 10 percent.

The nature of the β-ray spectrum of C^{15} was investigated by absorption of the β-rays in aluminum. Coincidence counters were used for detection; varying thicknesses of aluminum absorber were placed between the source and the first counter, with $\frac{1}{8}$ in. of aluminum absorber between the counters (to prevent coincidences from the decay of N^{13} which was built up in activity through bombardment of normal carbon in the target). The absorption curve is shown in Fig. 3. The extrapolated end-point lies at 4.6 g/cm^2 of aluminum absorber (with correction for thickness of counter walls, etc.),

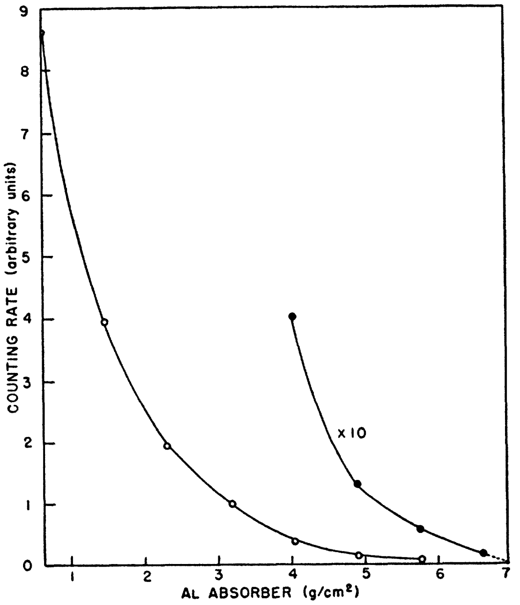

FIG. 2. Absorption of β-rays produced in the reaction $C^{14}(d, \alpha)B^{12}$. The shape of the spectrum and the extrapolated end point are identical with that observed for the β-rays obtained from deuteron bombardment of B^{11}.

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[7] H. A. Bethe, *Elementary Nuclear Theory* (John Wiley and Sons, New York, 1947).

which corresponds to a maximum β-ray energy of 8.8±0.5 Mev. This value of the energy, together with the half-life measurement of 2.4 sec., indicates that the $C^{15}-N^{15}$ decay is a first-forbidden transition. The calculated mass of C^{15}, based on the end-point of the β-ray spectrum and using the mass of N^{15} as[7] 15.00489, is 15.01434, which is about 2 Mev lower than the estimated value. It is not certain, however, that decay of C^{15} is to the ground state of N^{15}; some evidence for delayed emission of γ-rays was found (indicated by "background" in the absorption of β-rays described above).

The Q-value for the $C^{14}(d, p)C^{15}$ reaction is certainly somewhat greater than -1.2 Mev, since a rough excitation curve (Fig. 4) showed that the yield at a bombarding voltage of 1.4 Mev is quite appreciable. The indication of a weak resonance at 1.9 Mev bombarding energy was checked in two independent runs; at the time of these observations we did not have an opportunity to take more extensive data.

The yield from the $C^{14}(d, p)C^{15}$ reaction has been compared approximately with the yield from $C^{14}(d, \alpha)B^{12}$ by observation of the β-rays emitted during bombardment and also by the delayed activity of the bombarded target. With deuterons of 1.4 Mev, the formation of B^{12} is roughly seven times as probable as is the formation of C^{15}; at 2.6 Mev the formation of C^{15} is about seven times as probable as the formation of B^{12}.

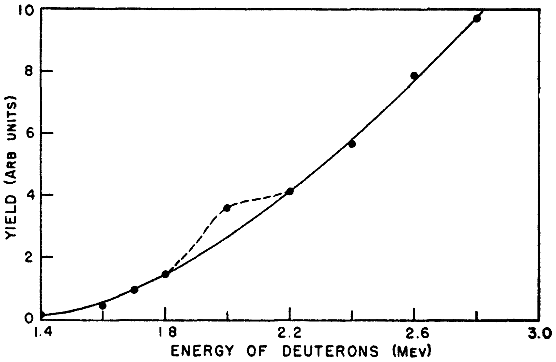

FIG. 4. Rough excitation curve for $C^{14}(d, p)C^{15}$. The point at 2.0 Mev lies off the smooth curve by about four times the statistical probable error.

V. γ-RAYS FROM $C^{14}(d, -)$

The bombardment of C^{14} with deuterons would lead to γ-ray emission through the excitation of states in N^{15}, formed in the reaction $C^{14}(d, n)$. The calculated Q-value for $C^{14}(d, \alpha)B^{12}$ is 0.25 Mev, while the Q-value for $C^{14}(d, p)C^{15}$ is negative. We should therefore expect γ-rays to be associated primarily with the excited states of N^{15} only; the neutron spectra (Fig. 1) indicate that a known excited state at 5.39 Mev is produced in our bombardments, and that transitions from this state to the ground state should yield an intense γ-ray. Of course γ-rays from higher excited states are expected, but our data on the neutron spectrum show that the 5-Mev γ-ray should be the most intense.

We have analyzed the γ-radiation from a target of normal $BaCO_3$ and of a target of this same substance enriched in C^{14}; the bombarding voltage was 1 Mev. The relative abundance of normal carbon in the two targets was determined by following the decay of N^{13} in both cases. Varying thicknesses of aluminum absorber were placed between coincidence counters (with sufficient absorber before the first counter to stop all β-rays), and the results shown in Fig. 5 were obtained. Curves A and B were normalized by utilizing the comparative data on N^{13} decay, and curve C therefore represents an absorption curve of the γ-rays emitted when C^{14} is bombarded by deuterons. The absorption

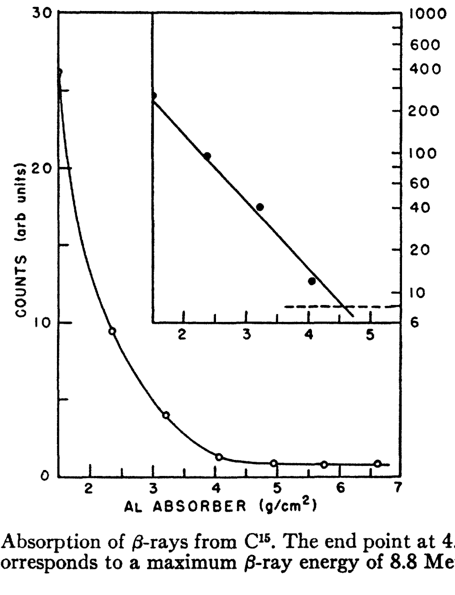

FIG. 3. Absorption of β-rays from C^{15}. The end point at 4.7 g/cm² corresponds to a maximum β-ray energy of 8.8 Mev.

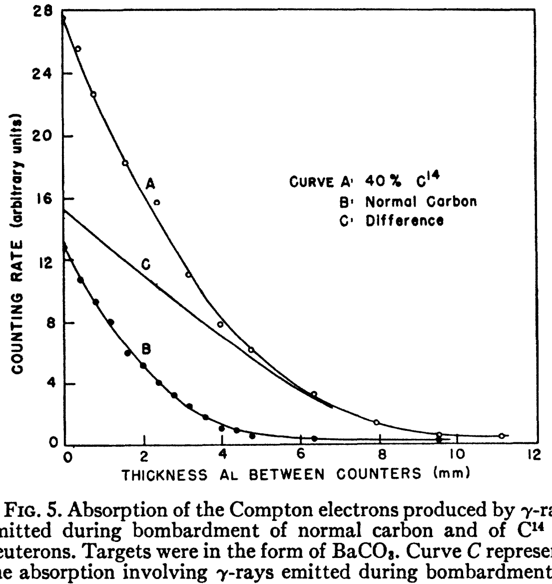

FIG. 5. Absorption of the Compton electrons produced by γ-rays emitted during bombardment of normal carbon and of C^{14} by deuterons. Targets were in the form of $BaCO_3$. Curve C represents the absorption involving γ-rays emitted during bombardment of C^{14} only.

curve drops to half-value at about 3.7-mm absorber; this corresponds to a γ-ray of nearly 6-Mev energy. The quarter-value thickness is nearly 6.0 mm; this would indicate a γ-ray of energy slightly over 7 Mev. It is reasonable therefore[8] to assume that most of the γ-radiation lies in the vicinity of 6 Mev, while more energetic lines are also present but of somewhat weaker intensity. This interpretation is of course quite consistent with the nature of the neutron spectrum, which in turn shows the existence of anticipated levels in N^{15}.

ACKNOWLEDGMENTS

The writers wish to acknowledge the technical assistance of Mr. J. T. Peoples and the continued interest of Dr. W. F. G. Swann, Director of the Bartol Research Foundation.

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[8] Fowler, Lauritsen, and Lauritsen, Rev. Mod. Phys. 20, 256 (1948).

* Note added in proof: L. Yaffe and W. H. Stevens, Phys. Rev. 79, 893 (1950), have attempted to observe the reaction $C^{14}(n, \ )C^{15}$. The reaction was not observed, and it was concluded that the cross-section must be less than 1 microbarn.

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Radioactive Isotopes of Rubidium*

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Neutron deficient isotopes of rubidium have been prepared from bromine by bombardment with helium ions in the Berkeley 184-inch and 60-inch cyclotrons. The properties of these isotopes are as follows:

Isotope	Half-life	Type of radiation	Energy in Mev Particles	Energy in Mev Gamma-rays	Produced by
Rb^{84}	34 days	β^+, K, e^-	1.53(β^+) 0.37(e^-)	0.85	Br-α-n
Rb^{83}	107 days	K	—	—	Br-α-2n
Rb^{82}	6.3 hr.	β^+, K	0.670	1.2, 0.7	Br-α-n Br-α-3n
Rb^{81}	4.7 hr.	β^+, K	0.990	0.95	Br-α-2n Br-α-4n

The mass numbers were determined with a mass spectrograph. Rb^{81} has been shown to decay to the 13-sec. krypton, thereby assigning it to Kr^{81}. Electrons from the conversion of a 190-kev gamma-ray caused by this krypton are observed with the Rb^{81} radiations.

I. INTRODUCTION

As part of a general program in this laboratory of investigation of the properties and mass assignments of radioactive isotopes, we have studied four neutron deficient isotopes of rubidium by mass-spectrographic and counting methods. The results of this work will be a basis for the assignment of some new strontium radioactivities now being studied, and perhaps ultimately of light yttrium and zirconium isotopes.

Barber[1] has assigned a 40-day positron-emitter to Rb^{84}; we have confirmed this assignment, but observe 34 days as the half-life. A 6.5-hour rubidium has been reported by Hancock and Butler.[2] Our mass-spectrographic results showing that there are actually two isotopes of about this half-life, at masses 81 and 82, have already been described.[3] However, subsequent experiments with a beta-spectrometer have yielded more accurate values for their properties than were reported there. A new 107-day activity assigned to Rb^{83} is also described in this paper.

II. CHEMICAL SEPARATIONS

Rubidium activities were produced by bombardment of bromine (as ammonium or cuprous bromide) with helium ions in the Berkeley 60-inch and 184-inch cyclotrons. Two principal procedures were used to separate the rubidium from the target material. In the case of ammonium bromide targets, 20 to 30 μg of inactive rubidium was added to the dissolved target material, the solution was evaporated to dryness and the ammonium bromide target material sublimed off by strong heating. The rubidium activities remained behind and were dissolved in a small volume of water. This solution was divided into two portions. The major portion was used without further purification for mass spectrographic determination of the mass numbers. The remainder was purified further by scavenging with precipitates of silver chloride, strontium carbonate, ferric

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* This work was performed under the auspices of the AEC.

[1] W. C. Barber, Phys. Rev. 72, 1156 (1947).

[2] J. O. Hancock and J. C. Butler, Phys. Rev. 57, 1088 (1940).

[3] Reynolds, Karraker, and Templeton, Phys. Rev. 75, 313 (1949).