Radioactivity of Be^{10}†

J. LEVINGER* AND E. MEINERS**
Metallurgical Laboratory, University of Chicago, Chicago, Illinois
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From the beta-activity induced in beryllium by (1) fast deuteron bombardment, and (2) slow neutron capture, the half-life of Be^{10} is determined. The value is between 10^6 and 10^7 years. The beta-end-point is roughly 650 kev, and no gammas were observed. These results confirm those of McMillan and Ruben. The $B^{10}(n,p)Be^{10}$ cross section for thermal neutrons is computed by comparison with the known value for $B^{10}(n,\alpha)Li^7$, assuming disintegration to the ground state possible for the former reaction.

INTRODUCTION

McMILLAN and Ruben[1] have recently published measurements made in 1940 on the half-life and beta-end-point of a long-lived beryllium activity. A mass-spectroscopic separation by Pierce and Brown[2] has established that the active isotope has mass 10. In 1944 we measured the activity produced by Be^9 (d,p) and (n,γ) reactions; and from these yields estimated the Be^{10} half-life. We have also measured the beta end-point, and studied the gamma-activity. These measurements are not as complete as we would like, owing to our transfers to other sections of the Manhattan Project.

CHEMICAL SEPARATIONS

Our strongest sample of Be^{10} came from the thick beryllium target of the Washington University cyclotron, which had been activated by about 600,000-microampere hours bombardment by 10.45-Mev deuterons.[3] The target was etched to the calculated depth of deuteron penetration, giving us 1.7 grams of beryllium. The beryllium was purified by a chemical procedure similar to that used by McMillan and Ruben. The initial separation consisted of a chloroform extraction of beryllium basic acetate, and purification by precipitation of the copper group of sulphides. Six different samples were then prepared for counting the beta-activity, using different additional purifications in preparing each sample, as follows: (1) five beryllium hydroxide precipitations, and precipitation of the zinc group of sulphides, to remove contaminants; (2) one beryllium hydroxide precipitation; (3) three beryllium hydroxide precipitations; (4) two beryllium hydroxide precipitations, and an incomplete berryllium ammonium phosphate precipitation; (5) a beryllium ammonium phosphate precipitation of the material not precipitated in the previous procedure; and (6) a chloroform extraction of beryllium basic acetate. The average specific activity of these 6 samples was measured on a GM tube as 17.5 ± 1 betas/sec. mg of beryllium. This small difference among the six samples established that the activity was beryllium.

HALF-LIFE OF Be^{10}

Let Y' be the d-p yield for a thick beryllium target activated by 10.45-Mev deuterons. The total deuteron flux was 1.3×10^{22}. From the specific activity given above, the activity produced in the whole target is calculated as 29,000 betas/sec. This figure is certainly low, as we know that much of the beryllium was sputtered off the target during the bombardment.[4] The upper limit on the Be^{10} half-life is then

$$T_{\frac{1}{2}}\leqq\frac{1.3\times10^{22}\times0.693\,Y'}{29{,}000\times3.16\times10^{7}}=1.0\times10^{10}Y'\text{ years.}$$

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* Now at Cornell University, Ithaca, New York.

** Now at Washington University, St. Louis, Missouri.

[1] E. M. McMillan and S. Ruben, Phys. Rev. **70**, 123 (1946).

[2] A. K. Pierce and F. F. Brown, III, Phys. Rev. **70**, 779 (1946).

[3] Based on a recent measurement of the deuteron energy by Kurie.

[4] This spalling off of active material has recently been confirmed by measurements of E. M. McMillan on the other Washington University target (private communication).

McMillan and Ruben measured the Be^{10} activity produced by 12,000-microampere hours bombardment of beryllium by 16-Mev deuterons. They give the half-life as $6.4\times10^{8}Y$ years, where Y is the d-p yield for 16-Mev deuterons. For comparison with their results, we may estimate Y/Y' from the ratio of the deuteron ranges as about 2. Then our measurement gives a half-life eight times the McMillan and Ruben determination; but, as already pointed out, our results can only be considered as an upper limit.

Assuming that the d-p cross section for high energy deuterons is somewhat less than half the geometrical cross section, and that the effective nuclear radius is about 5×10^{-13} cm, we calculate a d-p cross section of 0.3 barn (+0.3 b., −0.15 b.). This agrees in order of magnitude with the cross section as estimated from the thick target d-n yield for 1-Mev deuterons.[5] By use of this cross section, Y' is calculated as one nucleus of Be^{10} formed per 1000 deuterons, and Y as 1/500. The Be^{10} half-life from our results is estimated as less than 10^{7} years; and from McMillan and Ruben's measurements as about 1.3×10^{6} years.

Since the beryllium cross section for capture of slow neutrons is known,[6] the Be^{10} half-life can be determined from the specific activity induced in beryllium by a known neutron activation. Beryllium metal was activated in the Clinton pile for several months. After chemical separations similar to those given above for purification of the Washington University cyclotron target, the beta-activity was only 10 counts/min. We are uncertain whether this low activity is due to contamination, or to Be^{10}. The upper limit for the specific activity due to Be^{10} is taken as 0.02 beta/sec. mg of beryllium; and the Be^{10} half-life is calculated as greater than 10^{6} years. This value is in fortuitously good agreement with our calculation from McMillan and Ruben's measurements; and is consistent with the upper limit on the half-life set by our measurement of the d-p yield.

β AND γ ACTIVITY

Deflection of the particles by a small electromagnet placed between the active beryllium from the cyclotron target and the GM tube showed that the particles were negatrons. Absorption measurements in aluminum from 0.2 to 300 mg/cm² were made for both a thin and a thick source. The thin source gave an inspection end-point of roughly 200 mg/cm²; and an end-point from Feather analysis of 225 mg/cm², or 650 kev. Owing to the low beta-intensity and high gamma-background, the Feather analysis was carried only to 0.6 of the range, and the extrapolated range is therefore inaccurate. The inspection end-point for the thick source was 200±20 mg/cm². These measurements are in fair agreement with the end-point of 180±20 mg/cm², or 550 kev, given by McMillan and Ruben. Both measurements are consistent with the $Be^{10}-B^{10}$ mass difference of 550±110 kev.[7]

Initially a gamma-ray of intensity roughly 4 quanta/beta was observed in the active material, and chemically determined to be a beryllium activity. The half-life from decay measurements, and energy from lead absorption for this gamma-activity were both in good agreement with the known values for Be^{7}. No gamma-activity due to Be^{10} was observed, in agreement with the results of McMillan and Ruben.

PRODUCTION OF Be^{10}

Samples with higher specific activity of Be^{10} might be produced by a $Li^{7}(\alpha,p)Be^{10}$ reaction using cyclotron alphas; by a $C^{13}(n,\alpha)Be^{10}$ reaction with fast neutrons (since this reaction is endothermic by about 3.5 Mev); or by a $B^{10}(n,p)Be^{10}$ reaction in a chain-reacting pile. Bretscher[8] was unable to find Be^{10} activity produced by this last reaction, using deuterons on lithium as a neutron source. He sets the upper limit for the fast neutron cross section for this reaction as $5\times10^{-7}T_{\frac{1}{2}}$ barn, where $T_{\frac{1}{2}}$ is the Be^{10} half-life in years. Using our estimated half-life of 2×10^{6} years, this sets the upper limit on the cross section as 1 barn. Cross sections which are thousands of times smaller than this can be measured using the high neutron fluxes now available. For sufficiently high neutron energies we would expect the $B^{10}(n,p)Be^{10}$ cross section to be of the same

[5] H. A. Bethe and M. S. Livingston, Rev. Mod. Phys. 9, 330 (1937).

[6] M. Goldhaber, Phys. Rev. 70, 85 (1946); and work at the Metallurgical Laboratory, to be published in the Plutonium Project Reports.

[7] B. J. Isaacs, Cornell Thesis, "A Revision of the Isotopic Mass Scale, (1942)"; H. A. Bethe and M. S. Livingston, Rev. Mod. Phys. 9, 245 (1937); and E. Pollard, Phys. Rev. 57, 241 (1941).

[8] E. Bretscher, Nature 146, 94 (1940).

TABLE I. Comparative data on $B^{10}(n,p)Be^{10}$ and $B^{10}(n,\alpha)Li^7$ reactions.

Measurements	$B^{10}(n,p)Be^{10}$ McMillan and Ruben[a]	$B^{10}(n,p)Be^{10}$ This paper	$B^{10}(n,\alpha)Li^7$
beta-end-point Be^{10}	550 kev	650 kev	——
reaction energy	230 kev	130 kev	2500 kev
Coulomb barrier	1850 kev	1850 kev	3700 kev
penetration factor	5×10^{-3}	3×10^{-4}	0.45
cross section (thermal neutrons)	8 barns	0.5 barn	700 barns

[a] Reference 1.

order of magnitude as the $N^{14}(n,p)C^{14}$ cross section, which is about 0.01 barn.[9]

The beta-decay theory[10] predicts a large spin for Be^{10}; while we would expect a spin of zero, since this is an even-even nucleus. Measurements of the ratio of the $B^{10}(n,p)Be^{10}$ and $B^{10}(n,\alpha)Li^7$ cross sections, especially for slow neutrons, might be of interest in establishing selection rules, leading to some knowledge of the spin of the ground state of Be^{10}. Comparison of the (n,p) cross section for thermal neutrons with that for fast neutrons might well be made by comparing the beryllium activity at the surface of a boron lump activated in a pile, with the beryllium activity in the inside of the lump.

[9] H. H. Barschall and M. E. Battat, Phys. Rev. **70**, 245 (1946).
[10] E. J. Konopinski, Rev. Mod. Phys. **15**, 222 (1943).

For thermal neutrons we may estimate the $B^{10}(n,p)Be^{10}$ cross section by comparing the penetration probability for the protons to escape through the Coulomb barrier, with the penetration factor for the much more energetic alpha-particles emitted in the competing $B^{10}(n,\alpha)Li^7$ disintegration, of known cross section.[11] We assume here that the compound nucleus is permitted to disintegrate to the ground state of Be^{10}; while the (n,α) reaction goes to a level of Li^7 about 0.5 Mev above ground.[12] Penetrations are calculated using the Gamow theory.[13]

Table I shows that in the absence of selection rules the $B^{10}(n,p)Be^{10}$ reaction could be observed by the beryllium activity produced by activation of boron by thermal neutrons in a pile; and that the cross section for this reaction is sensitive to the beta-end-point of Be^{10}.

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[11] R. F. Bacher, C. P. Baker, and B. D. McDaniel, Phys. Rev. **69**, 443 (1946); James Rainwater and William W. Havens, Jr., Phys. Rev. **70**, 136 (1946).
[12] H. A. Bethe and M. S. Livingston, Rev. Mod. Phys. **9**, 340 (1937).
[13] H. A. Bethe, Rev. Mod. Phys. **9**, 166 (1937); using nuclear radius of $1.5\times10^{-13}A^{\frac{1}{3}}$ cm.