The Beta-Decay of B^{12} and Li^8

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The electron spectra of B^{12} and Li^8 have been studied, using a magnetic lens spectrometer. The end point of the B^{12} distribution is 13.43±0.06 Mev, while the Li^8 spectrum tails off gradually with a shape which is consistent with the known broadness of the excited state of Be^8 to which the decay occurs. Neither distribution corresponds to the shape indicated for simple "allowed" transitions, but it seems probable that more than one state of the residual nuclei may be involved in the decay schemes. The discrepancy between the observed end point of the B^{12} spectrum and the mass differences suggests the existence of an excited state at 0.9 Mev either in B^{12} or C^{12}.

INTRODUCTION

RADIOACTIVE Li^8, produced in the bombardment of Li^7 by deuterons, disintegrates by electron emission, with a half-life of 0.89 sec., predominantly to a broad excited state in Be^8 at approximately 3 Mev which in turn decays in $\sim 10^{-21}$ sec. into two alpha-particles. The beta-decay of Li^8 to the ground state of Be^8 is apparently forbidden. The electron spectrum was studied by Crane, Delsasso, Fowler, and Lauritsen[1] and by Bayley and Crane[2] using cloud-chamber methods. The latter investigators found a maximum energy of 12.0±0.6 Mev. The alpha-particle distribution has been investigated most recently by Bonner, Evans, Malich, and Risser[3] who summarize the earlier literature. Radioactive B^{12}, which has a half-life of 0.025 sec., is produced by deuteron bombardment of B^{11} and decays by electron emission, presumably to the ground state of C^{12}. This spectrum was also investigated by Bayley and Crane with a cloud chamber, and was found to have an end point of 12.0±0.6 Mev. More recently Hereford,[4] using an absorption technique, has reported 13.3±0.5 Mev for the end point.

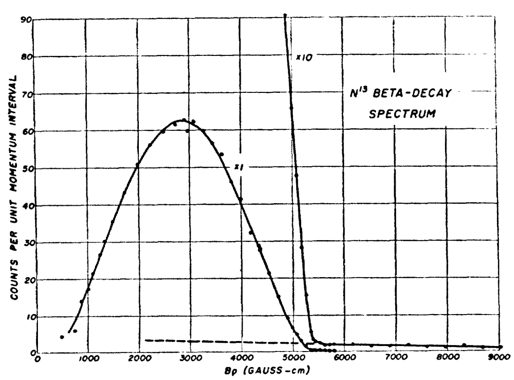

FIG. 1. Momentum spectrum of N^{13} positrons. The ordinate scale is in arbitrary units in this and following figures.

In view of the interest in obtaining more precise information on these spectra, we have studied the electron momentum distributions using a magnetic lens type spectrometer, with considerably better statistics than was possible in the earlier cloud-chamber work. As a check on the performance of the spectrometer, particularly with respect to scattering, the spectrum of N^{13} was also run. A preliminary account of these results has appeared in a Letter to the Editor.[5]

EXPERIMENTAL METHOD

The beta-ray spectrometer used in this investigation was described in an earlier paper.[6] The spectrometer stops were set for ring focusing with a resolution of 2.6 percent. The momentum calibration was obtained from the internal conversion "X" line of Th-D, $B\rho=10{,}000$ gauss-cm. The compensation for the vertical component of the earth's magnetic field and other stray magnetic fields was checked both at the beginning and the end of the experiment and was found to be satisfactory down to the internal conversion "I" line of Th-C, corresponding to a kinetic energy of approximately 200 kev. The deuteron beam from an electrostatic accelerator was brought directly into the vacuum chamber of the spectrometer to bombard suitable targets placed at the source position for the production of the radioactive elements. In order to eliminate the effects of prompt radiation produced during bombardment of the target, observations were made with the beam off. For the N^{13},

TABLE I. Summary of N^{13} β-decay spectrum end-point energies.

End-point energy (Mev)	Date	Observers
1.198±0.006	1939	Lyman[a]
1.218±0.004	1940	Townsend[b]
1.24 ±0.02	1945	Siegbahn and Slatis[c]
1.25 ±0.03	1948	Cook, Langer, Price, and Sampson[d]
1.202±0.005		This experiment

[a] E. R. Lyman, Phys. Rev. 55, 234 (1939).
[b] A. A. Townsend, Proc. Roy. Soc. A177, 357 (1940–41).
[c] K. Siegbahn and H. Slätis, Arkiv. f. Ast. Math. Fys. 32A, No. 9, (1945).
[d] See reference 7.

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[1] Crane, Delsasso, Fowler, and Lauritsen, Phys. Rev. 47, 971 (1935).
[2] D. S. Bayley and H. R. Crane, Phys. Rev. 52, 604 (1937).
[3] Bonner, Evans, Malich, and Risser, Phys. Rev. 73, 885 (1948).
[4] F. L. Hereford, Phys. Rev. 74, 574 (1948).
[5] Hornyak, Dougherty, and Lauritsen, Phys. Rev. 74, 1727 (1948).
[6] Hornyak, Lauritsen, and Rasmussen, Phys. Rev. 76, 731 (1949).

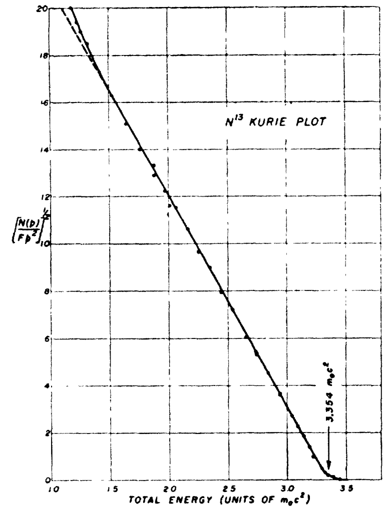

FIG. 2. Kurie plot of N^{13} positron spectrum.

the target was bombarded for fifteen minutes, the accelerator shut down and counting carried out over two or three half-lives. Corrections for decay and normalization for successive runs were ascertained by frequent repetition of certain points in the spectrum. In the cases of Li^8 and B^{12}, because of the short half-lives, the accelerator was run continuously and the deuteron beam periodically intercepted, either mechanically or by means of an electrostatic deflecting plate. In the former method, used in some of the Li^8 experiments, a quartz shutter was interposed in the beam during a one-second counting period and removed for a one-second bombardment. Suitable interlocks cut the counter off during the bombardment period. For the shorter lived B^{12} and for some of the later Li^8 work, an electrostatic deflector was used, operated by a 3000-volt, 60-cycle square wave supply, interlocked with the counting system by means of a simple coincidence circuit. During the counting period, the beam struck a brass target several feet from the spectrometer. Check

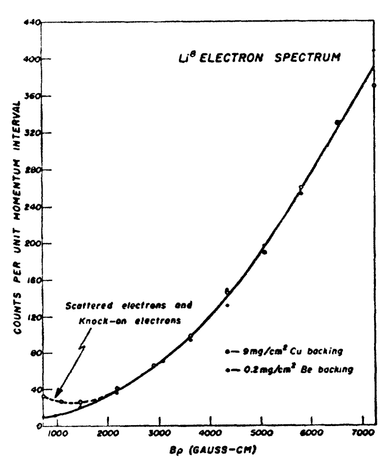

FIG. 3. Low energy end of Li^8 electron momentum spectrum.

runs with the intense prompt radiation of the $Be^9(dn)$ reaction showed that the circuits were working properly and rendered the counters completely insensitive during the bombardment period. The beam was monitored by a separate gamma-ray counter which recorded the prompt radiation.

Primarily to ascertain the extent of scattering in the spectrometer, the spectrum of N^{13} decay positrons was run, using a thin soot target sandwiched between two layers of 0.2 mg/cm² Be foil.* The resulting momentum

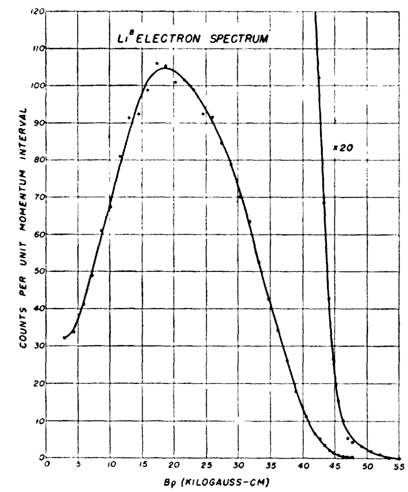

FIG. 4. Momentum spectrum of Li^8 electrons.

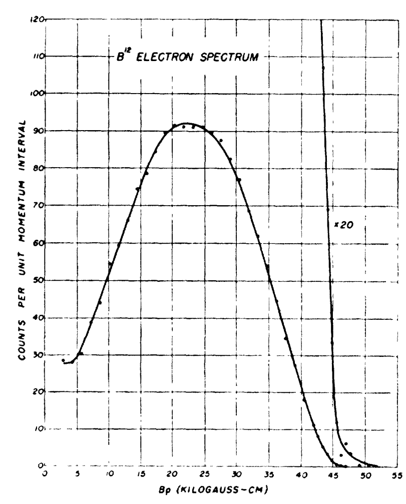

FIG. 5. Momentum spectrum of B^{12} electrons.

spectrum after cosmic-ray and local background have been subtracted is shown in Fig. 1. A background which is slightly field sensitive and of the order of cosmic-ray background is still apparent above the end point of the β-spectrum, indicating a slight diffusion of the radioactive nitrogen from the target and possibly a small degree of scattering in the spectrometer. In connection

* We are indebted to Dr. H. Bradner for the Be foils.

with the former point, it may be mentioned that an appreciable increase in background was observed with non-sandwiched targets when the pumping speed was reduced by turning off the oil diffusion pump on the spectrometer. That no great diffusion of the radioactive nitrogen occurs with sandwiched targets is indicated by the agreement of the half-life of 10.05±0.1 minutes observed here with the values reported in the literature.

When the slight correction for the residual background is made, the Kurie plot of the data, Fig. 2, is linear from about 0.2-Mev kinetic energy to just below the end point. The curvature near the end point can be accounted for by instrumental resolution. The shape of the low energy end of the spectrum is in good agreement with the work of Cook, Langer, Price, and Sampson[7] and indicates that scattering effects in the spectrometer are negligible above 0.2 or 0.3 Mev. The end point observed in this experiment is compared with other determinations in Table I.

For the production of Li^8, thin lithium metal layers were evaporated on various backing foils. Copper foil of 9 mg/cm^2 thickness was found to be most convenient and was used in most of the work. No detectable activity was found from bare foils at the deuteron energies used. Since the decay electrons traversed the copper before being focused in the spectrograph, a check on the effect of scattering in the foil was made by using a target consisting of lithium metal evaporated on a 0.2 mg/cm^2 Be foil. The resulting distributions in the low energy range, shown in Fig. 3, are identical for momenta greater than 2000 gauss-cm. Below this limit, the copper foil gives evidence of some scattering and of knock-on electrons. A subsequent experiment, made with a radically different spectrometer configuration and with a beryllium foil backing yielded satisfactory agreement with the present results in the region re-examined, from 5000 to 35,000 gauss-cm.

In the B^{12} work, thin evaporated films of B_2O_3 on 9 mg/cm^2 copper foil were used throughout.

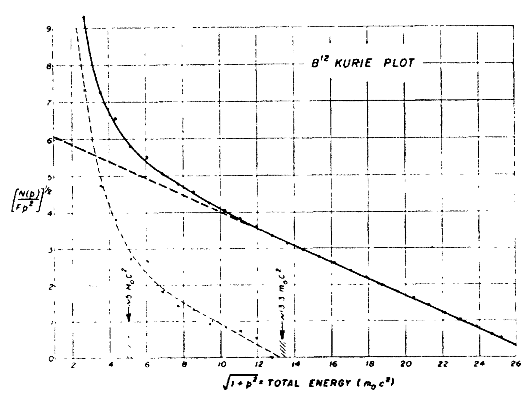

FIG. 6. Kurie plot of B^{12} electron spectrum. The dashed curves indicate a possible decomposition into simple spectra.

RESULTS

The observed momentum spectrum of Li^8 is shown in Fig. 4 and that of B^{12} in Fig. 5. As compared with the cloud-chamber work of Bayley and Crane, the present Li^8 spectrum is somewhat broader, having a larger number of both low energy and high energy electrons relative to the number at the peak. The present peak occurs at somewhat lower energy. The B^{12} spectrum agrees less well with the earlier work, indicating a considerably higher energy at the peak and relatively many more high energy electrons.

The Kurie plot of the B^{12} spectrum is presented in Figs. 6 and 7, the latter curve indicating the end point on an expanded scale. A straight line fits the higher energy end of the spectrum from a total electron energy of 12 m_0c^2 to the end point of 27.30 m_0c^2. The slight tail just at the high energy end of the spectrum can be accounted for almost entirely by the instrument resolution. The deviation of the experimental curve from a straight line below a total energy of 12 m_0c^2 is very marked. The Kurie plot for the spectrum of Li^8 is shown in Figs. 8 and 9. It will be seen that there is no extensive linear portion in the experimental curve and in particular the deviation from linearity in the neighborhood of the upper energy limit is much more pronounced than for the B^{12} data and cannot be ascribed to the instrumental resolution. Although no sharp end point exists in the usual sense, one may take the extrapolation of the best straight line fit to the spectrum as an effective mean "end point." The "end point" thus obtained is

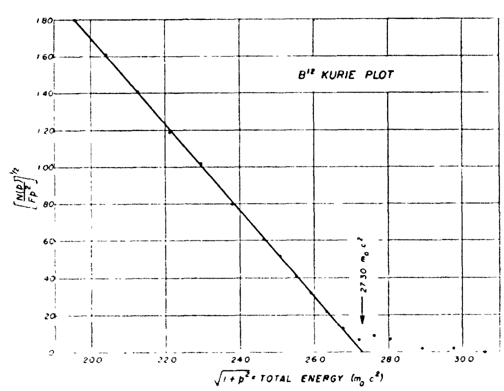

FIG. 7. Kurie plot of B^{12} electron spectrum near end point.

$\sim$26 m_0c^2 ($\sim$13-Mev kinetic energy). Since the Li^8-Be^8 mass difference from Q and mass value calculations is 16.02 Mev,[8] the indication is that the high energy transition in the β-decay of Li^8 is predominantly to an excited state in Be^8 at approximately 3 Mev rather than to the ground state. The curvature of the plot in this region indicates that this level is rather broad. These observations are in good agreement with the existing knowledge from other experiments. The deviation from

[7] Cook, Langer, Price, and Sampson, Phys. Rev. 74, 502 (1948).

[8] Using $Li^7(dp)Li^8=-0.19$ Mev; $Be^8 \rightarrow 2He^4=0.09$ Mev.

linearity of the experimental data below a total energy of 12 m_0c^2 (Fig. 8), as in the case of B^{12}, is quite marked.

DISCUSSION

A proposed disintegration scheme for Li^8 is illustrated in Fig. 10. The α-particle distribution has been observed to extend up to an energy $E_\alpha = 7.75$ Mev[9] and has a maximum intensity at $2E_\alpha = 3.3$ Mev.[3] By analysis of the α-particle spectrum, Bonner *et al.* found that the distribution can best be accounted for by taking the major part of the β-decay to an excited state in Be^8 at 3.1 Mev having a width of 0.8 Mev. There was also some indication that a broad state at 7–9 Mev may be involved in the decay scheme. Their data are reproduced in Fig. 11; the solid curve shown is a reasonable fit to these points at low and intermediate energies and follows approximately the work of Smith and Chang at high energies. As has been pointed out by Bayley and Crane,[2] the electron decay spectrum can be predicted from the α-particle distribution by assuming that the latter, with an appropriate energy-dependent normalization, gives the density of states available in Be^8 for the β-transitions. This assumption is equivalent to stating that the principal mode of decay of the excited states in which Be^8 is left following the Li^8 break-up is by α-particle emission and that γ-radiation can be neglected. The Fermi theory for allowed β-decay then gives the electron distribution:

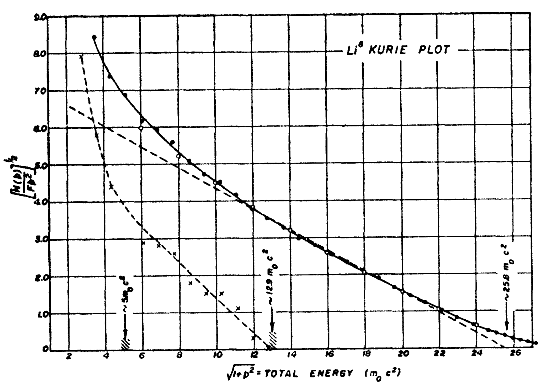

FIG. 8. Kurie plot of Li^8 electron spectrum: Open circles calculated from alpha-particle distribution of Fig. 11. The dashed curves indicate a possible decomposition into simple spectra.

$$N(W)dW = F[W^2-1]^{\frac{1}{2}}WdW \times \int_0^{Q'-W} A(E)[Q'-E-W]^2 dE, \quad (1)$$

where W is the total electron energy in units of m_0c^2, E is the combined kinetic energy of the alpha-particles ($E = 2E_\alpha$), and Q' is the total energy available (atomic mass difference, $Li^8 - 2He^4$, plus m_0c^2). The function

[9] C. L. Smith and W. Y. Chang, Proc. Roy. Soc. **166**, 415 (1938).

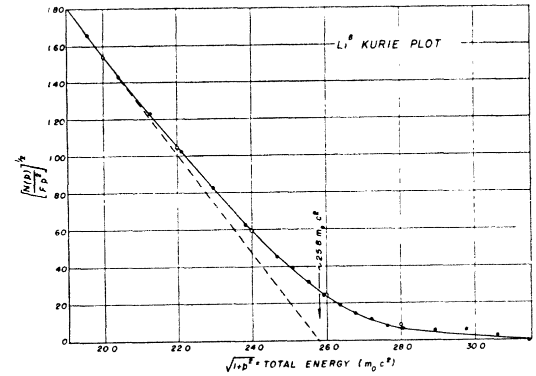

FIG. 9. Kurie plot of Li^8 electron spectrum near end point: Open circles calculated from alpha-particle distribution of Fig. 11.

$A(E)$ is the density of states, given by

$$A(E)dE\int_0^{Q'-E} [Q'-E-W]^2 \times [W^2-1]^{\frac{1}{2}}WdW = N_\alpha(E)dE. \quad (2)$$

The distribution predicted from Eq. (1) using the solid curve of Fig. 11 for the alpha-particle spectrum, is indicated by the open circles of Figs. 8 and 9. The value of Q' which gave the best fit was 32.8 m_0c^2 or 16.75 Mev, which is about 0.13 Mev higher than the value expected from the masses.

The agreement between predicted and observed points is quite satisfactory above a total energy of 12 m_0c^2 and indicates that the electrons observed in this region are adequately accounted for by the observed alpha-particles. The deviations below 12 m_0c^2 appear to require relatively more high energy alpha-particles than have been observed and may suggest that gamma-ray emitting states may be involved in the decay. Delayed gamma-radiation certainly occurs but it is not known to what extent the observed effects may be accounted for by bremsstrahlung. Decomposition of the spectrum of Fig. 8 indicates that about 10 percent of the β-transitions occur to states of Be^8 at $\sim$10 and $\sim$13 Mev and 90 percent to the 3.1-Mev state. From the limit of error associated with the points just at the end point where the spectrum merges with the background, it is estimated that less than 2 percent of the entire β-decay is to the ground state. A less certain estimate is that no more than 5 percent of the β-decay is to the known γ-ray emitting state at 4.8 Mev. If the component

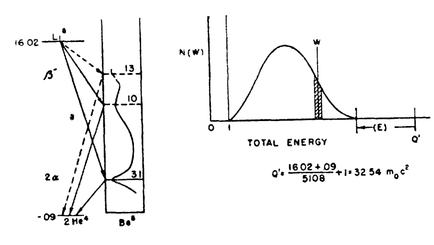

FIG. 10. Suggested disintegration scheme for Li^8 decay.

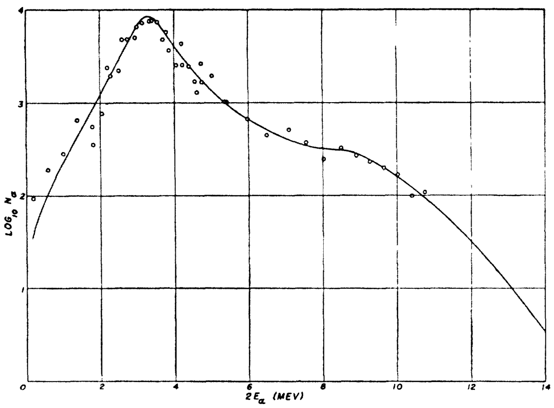

FIG. 11. Alpha-particle distribution from decay of Li^8. Circles represent data of Bonner *et al.* (see reference 3); high energy extrapolation follows approximately work of Smith and Chang (see reference 12).

spectra are of "forbidden" or "unfavored" types, as might be expected from the relatively long half-life, these relative intensity estimates may be considerably modified.

The extrapolated end point of the Kurie plot for B^{12} (Fig. 7) gives 27.30 ± 0.10 m_0c^2 for the total energy or 13.43 ± 0.06-Mev kinetic energy, in agreement with the value 13.3 ± 0.5 Mev obtained by Hereford. If the high energy end of the β-spectrum corresponds to a decay to the ground state of C^{12} then the observed end point, combined with the mass[10] of C^{12} gives 12.01827 ±0.00009 a.m.u. for the mass of B^{12}. From an analysis of the nuclear binding energies Barkas[11] predicts a mass of 12.0188 a.m.u. for B^{12}. Using the observed end point as the decay energy to the ground state of C^{12} and the mass tables of Mattauch and Flammersfeld,[12] the Q of the reaction $B^{11}(dp)B^{12}$ is found to be $+1.07$ Mev. The early work of Cockroft and Lewis[13,14] indicated that the bombardment of boron targets with deuterons of 0.55 Mev yielded no group with range greater than 2.7 cm, implying that the Q of the reaction is probably less than $\sim$0.8 Mev. Recently Hudspeth and Swann[15] have made a direct determination, yielding $Q=0.15$ Mev, based on the analysis of the yield curve for B^{12} and on the measurement of the range in photographic emulsion of a particle group ascribed to this reaction. The discrepancy of 0.92 Mev is too large to be accounted for by the mass uncertainties and appears to indicate either that the decay of B^{12} proceeds mainly to a level in C^{12} at $\sim$0.9 Mev excitation, the transition to the ground state being forbidden, or that the B^{12} is initially formed in an excited state, emitting a gamma-ray before the β-decay. The observation by Hudspeth and Swann of $\beta-\gamma$-coincidences would favor the first hypothesis, although the evidence is not entirely clear.

Note added in proof.—In a more recent paper, E. L. Hudspeth and C. P. Swann, Phys. Rev. **76**, 1150 (1949), report the discovery of a weak, higher energy proton group (corresponding to $Q=1.25$ Mev). It thus appears that the second hypothesis is the correct one.

If 5 percent of the β-decay is assumed to go to a level in C^{12} at $\sim$7.1 Mev and possibly to a broad or composite level at $\sim$11 Mev (Fig. 6), the observed nonlinearity of the Kurie plot below 12 m_0c^2 total energy can be accounted for. A decay of 5 percent or less to the 4.3-Mev level in C^{12} cannot be excluded. It should be pointed out that if the primary decay of B^{12} occurs to an excited state in C^{12} then the estimated energy of the excited states in C^{12} involved in the possible complex decay of B^{12} must be raised from 7.1 to 8.0 Mev and from 11 to 12 Mev.

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[10] R. Cohen and W. F. Hornyak, Phys. Rev. **72**, 1127 (1947).
[11] W. H. Barkas, Phys. Rev. **55**, 691 (1939).
[12] Mattauch and Flammersfeld, Isotopic Report, Special Issue, Zeits. f. Naturforschung (1949).
[13] J. D. Crockroft and W. B. Lewis, Proc. Roy. Soc. **A154**, 246 (1936).
[14] M. S. Livingston and H. A. Bethe, Rev. Mod. Phys. **9**, 326 (1937).
[15] E. L. Hudspeth and C. P. Swann, Phys. Rev. **74**, 1722 (1948).