Beta Decay of Be^{11}

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Be^{11} has been made in the reaction $B^{11}(n,p)Be^{11}$ and its radiations have been studied with plastic and NaI(Tl) scintillation spectrometers both singly and in coincidence. The half-life as determined from measurements on both beta rays and gamma rays is 13.57 ± 0.15 sec. Decay takes place by beta-ray emission to the ground state of B^{11} (61%, $\log ft=6.77$, $\beta_{max}=11.48$ Mev), to the 2.14-Mev first excited state (29%, $\log ft=6.63$), to the 6.76–6.81-Mev doublet (6.5%, $\log ft=5.93$) and to the 7.99-Mev level (4.1%, $\log ft=5.53$). Limits are set on the decay to several other levels, particularly those at 4.46 and 5.03 Mev ($\leqslant 0.2\%$). Gamma rays of 2.121, 4.64, 5.86, 6.76, and 7.97 Mev are observed both singly and in coincidence with beta-ray branches. An energy separation $Be^{11}-B^{11}=11.48\pm0.15$ Mev is derived from the various beta and gamma-ray energy measurements. It is concluded that the assignment $J=\frac{1}{2}-$ for Be^{11}, as expected from the shell model, is possible but cannot be established firmly on the basis of the present evidence.

INTRODUCTION

THE nuclei of the $1p$ shell are of considerable interest because they represent relatively simple systems whose properties we might hope to calculate with some degree of completeness using the individual-particle model in intermediate coupling.[1] Rather few of those whose ground states might be stable against heavy-particle emission remain to be examined in detail. One of these is Be^{11} and we have carried out an investigation of its beta decay to B^{11} in the hope of learning more about both these nuclei.

Ajzenberg and Lauritsen indicated[2] that the energy difference between the ground states of Be^{11} and B^{11} should be about 11.5 Mev. Their suggestion was based on the systematics of the rather scanty evidence available on the $T=\frac{1}{2}$ to $T=\frac{3}{2}$ splittings in light nuclei. Such an estimate might well be in error by several hundred kev but as it stands it implies that Be^{11} might be stable by about 0.5 Mev against breakup into Be^{10} plus a neutron. This made worthwhile a search for this body made by $B^{11}(n,p)Be^{11}$ whose threshold would be at about 12 Mev if the mass defect suggested by Ajzenberg and Lauritsen is correct.

That Be^{11} exists was proposed by Nurmia and Fink[3] who irradiated natural boron with the fast neutrons from the bombardment of tritium with deuterons and found an activity of half-life 14.1 ± 0.3 seconds which appeared to decay chiefly by the emission of energetic beta particles.

APPARATUS

In the present work we used as a neutron source a zirconium-tritium target of thickness 2.06 mg/cm^2 and of atomic composition ratio T/Zr = 1.9. It was usually bombarded by about 18 μA of deuterons of 600 kev from the Van de Graaff accelerator and the boron samples were placed about 5 mm from the tritium target at 0° to the deuteron beam.

We used natural crystalline boron of high purity[4] (99.15%). For measurements involving the detection of beta particles we used samples of diameter 1 in. and superficial density about 150 mg/cm^2 cemented into thin polystyrene holders. For measurements on gamma rays alone we used 6.6 g of loose crystals in a polyethylene bottle. Both the polystyrene and the polyethylene were tested with negative results for induced activity under our normal conditions of irradiation.

The beta particles were detected by a cylinder of Pilot-*B* plastic phosphor of diameter 3 in. and thickness 2 in. coupled to a photomultiplier of type DuMont 6363. The phosphor was separated from the source by an aluminum foil of thickness 2 mils and by one or two millimeters of air. The gamma rays were detected by cylindrical NaI(Tl) crystals. We used a 3-in. right cylinder and a cylinder of diameter $1\frac{3}{4}$ in. and length 2 in. mounted on photomultipliers of type DuMont 6363 and DuMont 6292 respectively at different times. To exclude the beta particles from the gamma-ray detector we usually used 5 mm of copper backed by 5 mm of aluminum in addition to the thin aluminum canning of the crystal itself. For certain investigations where the bremsstrahlung from the beta particles had

* Permanent address: Clarendon Laboratory, Oxford, England. This work was performed while this author was Visiting Physicist at Brookhaven National Laboratory during the summer of 1958.

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1 D. Kurath, Phys. Rev. **101**, 216 (1956); **106**, 975 (1957); *Proceedings of the Rehovoth Conference on Nuclear Structure, 1957*, edited by H. J. Lipkin (North-Holland Publishing Company, Amsterdam, 1958), p. 46.

2 F. Ajzenberg and T. Lauritsen. Revs. Modern Phys. **27**, 77 (1955) and forthcoming review of this series.

3 M. J. Nurmia and R. W. Fink, Phys. Rev. Letters **1**, 23 (1958).

4 We tried a number of samples of boron, of boron nitride, and of boron carbide from several suppliers. Many of these samples were certified to be of 99.5 to 99.7% purity but none in fact contained less than several percent of oxygen which produced N^{16} by the reaction $O^{16}(n,p)N^{16}$. This 7.4-second activity, with beta particles of 10.4 Mev and gamma rays of 6.1 and 7.1 Mev, interfered seriously with the study of Be^{11} which has rather similar properties. The crystalline samples which we finally used contained no oxygen detectable by our measurements. We wish to thank the U. S. Borax and Chemical Corporation for supplying this material.

to be held to a minimum we used as absorber 1 in. of beryllium.

The samples were usually irradiated for about 30 sec after which they were transferred in about 6 sec to the counting system. This delay sufficed for the 0.84-sec Li^8 activity produced in the reaction $B^{11}(n,\alpha)Li^8$ to decay to negligible proportions.

EXPERIMENTS

A major problem was to determine whether in fact the induced activity belongs to Be^{11}. A chemical identification was out of the question but a physical method is open if gamma rays accompany the beta decay. The energy levels of B^{11} are well known.[2] We may therefore hope to make accurate identification of gamma rays following Be^{11} decay with transitions in B^{11}. If this can be done and if it can be shown that the gamma rays are in coincidence with beta particles of appropriate energy and the lifetime of the Be^{11} decay measured by detecting the beta particles themselves is accurately the same as that measured by detecting the various identified gamma rays, then the demonstration is complete.

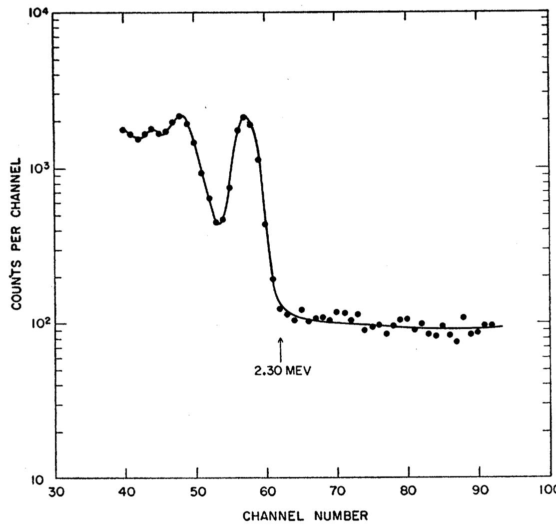

FIG. 2. The 2.12-Mev gamma ray seen in higher dispersion under the same conditions as in Fig. 1. The arrow indicates the expected position of the photopeak of a 2.30-Mev gamma ray.

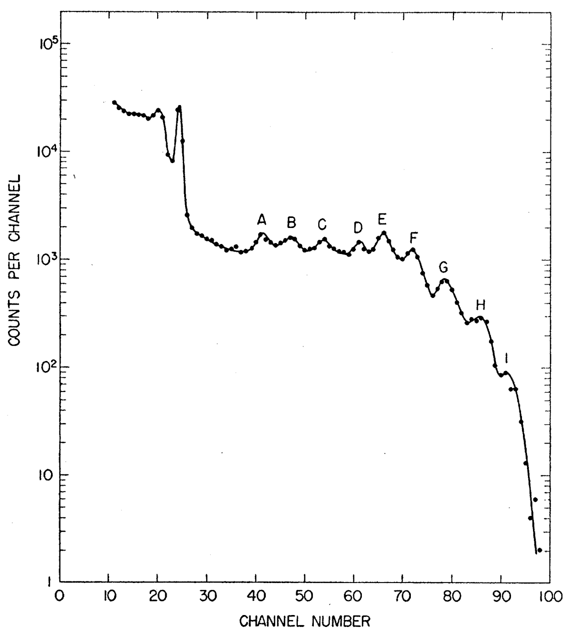

FIG. 1. Simple gamma-ray spectrum from Be^{11} decay observed with an NaI(Tl) crystal $1\frac{3}{4}$ in. in diameter and 2 in. long. Call the peak representing the full energy of the gamma ray the full peak, and call the peaks representing the escape of one and two annihilation quanta from the crystal the one-escape and two-escape peaks, respectively. The peak at channel 24 is the full peak from the 2.1-Mev gamma ray. Peak *A* is the two-escape peak of the 4.6-Mev line; peak *B* is the one-escape peak of the 4.6-Mev line; peak *C* is the superposition of the full peak of the 4.6-Mev line and the two-escape peak of the 5.9-Mev gamma ray; peak *D* is the one-escape peak of the 5.9-Mev line; peak *E* is the superposition of the full peak of the 5.9-Mev line and the two-escape peak of the 6.8-Mev gamma ray; peak *F* is the one-escape peak of the 6.8-Mev line; peak *G* is the superposition of the full peak of the 6.8-Mev line and the two-escape peak of the 8.0-Mev line; peak *H* is the one-escape peak of the 8.0-Mev line; peak *I* is the full peak of the 8.0-Mev line. This labeling of the peaks is adhered to in Figs. 3, 9 and 10.

A. Gamma-Ray Spectra

Figure 1 shows a pulse spectrum from the smaller of the two NaI(Tl) crystals (roughly 2-in. cylinder). No beta-particle coincidence is involved. An intense photopeak at about channel 24 is seen. Figure 2 shows this peak in higher dispersion. The energy of the corresponding gamma ray was determined by several intercomparisons with accurately known standard gamma rays from Bi^{207}, Na^{22}, and Co^{60} (including the 2.505-Mev "addition line" of the 1.1728- and 1.3325-Mev lines from this source). Our final value is $E_{\gamma 1}=2.121\pm0.010$ Mev. This corresponds with the first excited state of B^{11} whose energy is given as 2.138 ± 0.009 Mev by the reaction $B^{10}(d,p)B^{11}$.[5] We note in passing that accurate gamma-ray measurements[6] following inelastic proton scattering in boron have given a gamma-ray energy of 2.134 ± 0.005 Mev. This, however, as the authors noted, must be corrected for the Doppler shift (the measurement was made at 0°) since the level is short-lived.[7] When this is done, a level position of 2.122 ± 0.005 Mev results which is more closely in accord with our present measurements than with the heavy-particle work although the differences cannot be said to be serious.

Returning to Fig. 1, we see many peaks at higher channel numbers. These we have identified in the figure caption. The correctness of these identifications is demonstrated in two ways. Firstly, the composite

[5] Van Patter, Buechner, and Sperduto, Phys. Rev. **82**, 248 (1951).
[6] McCrary, Bonner, and Ranken, Phys. Rev. **108**, 392 (1957).
[7] D. H. Wilkinson, Phys. Rev. **105**, 666 (1957); Metzger, Swann, and Rasmussen, Phys. Rev. **110**, 906 (1958).

spectrum of Fig. 1 may be decomposed very satisfactorily into its underlying pure spectra by using the known response of the crystal to various standard gamma rays of high energy—for example, the 6.14-Mev line from the second excited state of O^{16} and the 4.43-Mev line from the first excited state of C^{12}. Secondly, the similar measurements made with the larger NaI(Tl) crystal (3-in. cylinder) showed the same nine peaks but with changed relative intensity because of the changed probability for the escape of the annihilation quanta. Figure 3 shows the spectrum seen with the bigger crystal; for example the full peak I of the 8.0-Mev line is now more important relative to the one-escape peak H and peak A has decreased in relative intensity.

We see that peaks A, B, D, F, H, and I each belong to a single gamma ray while peaks C, E, and G each belong to two. The latter group was therefore discarded for the purpose of energy determination. This determination was accomplished with the aid of several standard gamma rays including the two mentioned above; that from C^{12} was given by a Pu-Be source through the reaction $Be^9(\alpha,n)C^{12}$; that from O^{16} followed the beta decay of N^{16} made by the reaction $O^{16}(n,p)N^{16}$. Both crystals were used in the energy determinations and at least 6 separate sets of measurements were made on each gamma ray under a variety of conditions. The energies resulting from this work are: $E_{\gamma 2}=4.64\pm0.02$ Mev; $E_{\gamma 3}=5.86\pm0.04$ Mev; $E_{\gamma 4}=6.76\pm0.03$ Mev; $E_{\gamma 5}=7.97\pm0.03$ Mev. These gamma rays we identify as being respectively: from the 6.758–6.808-Mev doublet to the first excited state; from the 7.987-Mev state to the first excited state; from the 6.758–6.808 doublet to the ground state; from the 7.987-Mev state to the ground state (see Fig. 13 for the B^{11} states and for our final decay scheme). Our measurements are probably not accurate enough to discriminate with certainty to which member of the 6.758–6.808-Mev doublet the decay leads or if it goes to both. However, both the measurement of the ground state transition and of the cascade energy suggest that the lower member of the doublet is the one more probably involved.

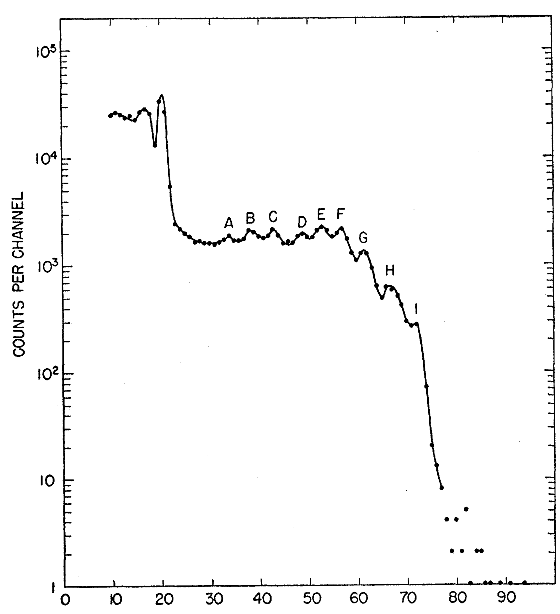

Fig. 3. Same as Fig. 1 but using a 3-in. right cylinder of NaI(Tl).

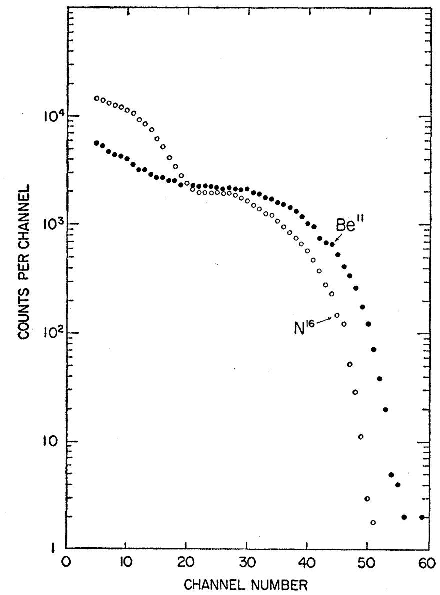

Fig. 4. The simple beta-particle spectra from the decay of Be^{11} and N^{16} (end point 10.39 Mev) observed with a plastic phosphor 3 in. in diameter and 2 in. thick. The Be^{11} points are plotted correctly; the N^{16} points have been displaced downwards slightly to avoid confusion of the figure.

B. Beta-Particle Measurements

We must now determine the decay energy of Be^{11} and confirm and extend these conclusions about the decay scheme by examining the beta particles. The pulse-height distribution of the beta rays detected by the Pilot-B crystal is shown in Fig. 4 where we also show the spectrum of beta particles from N^{16}. This latter body was made by the reaction $O^{16}(n,p)N^{16}$ using as source LiOH of the same dimensions and superficial density as the boron similarly bonded with polystyrene into identical polystyrene holders. From the known mass defect of N^{16}, the end point of its beta-particle spectrum is at 10.39 ± 0.02 Mev.[2] The clear low-energy branch which has an end point at around channel 22 is of 4.25 Mev and leads to the second excited state at 6.14 Mev (the weaker branch to the 7.12-Mev state does not show up here).

It is evident from Fig. 4 that the energy released in the Be^{11} decay is somewhat greater than that from N^{16}. A crude estimate of the beta-ray end point. above 11 Mev, shows that the highest energy component

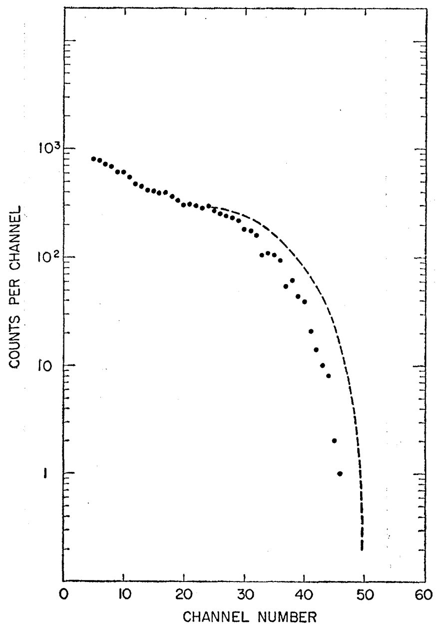

FIG. 5. Beta particles from Be^{11} seen in coincidence with gamma rays falling in a channel around 2.1 Mev. The dashed comparison spectrum is from N^{16} (end point 10.39 Mev). Beta-energy $=9.32\pm0.15$ Mev.

cannot lead to the first excited state of B^{11}, because that would give a mass defect, $M-A$, for Be^{11} of above 25 Mev, whereas the system $Be^{10}+n$ has $M-A=23.94$ Mev. It will further be seen from the coincidence measurements to be reported later that the highest energy beta-ray group does in fact go to the ground state of B^{11} and that this transition is roughly twice as strong as that to the first excited state. We may take this branching ratio as our guide and subtract from the composite Be^{11} spectrum of Fig. 4 the spectrum appropriate to this branch to the excited state, leaving a spectrum that more nearly represents the transition to the ground state alone. This we now compare with the N^{16} spectrum. This was done by matching the spectra in intensity at their maxima and taking the ratios of channel numbers at various ordinates. Over a range of channel number corresponding to about 3 Mev of electron energy this ratio did not change significantly and was therefore taken as a measure of the ratio of the beta-particle energies (the possible importance of the unique forbidden shape of the N^{16} spectrum cannot be great here and was ignored). This analysis was carried out for 5 separate sets of measurements with concordant results and we quote the end point $E_{\beta 1}=11.48\pm0.15$ Mev. We may remark that if the analysis is done without the subtraction of the partial spectrum for transitions to the first excited state of B^{11}, then the Be^{11}-N^{16} channel number ratio is not so constant and the apparent decay energy is lower by 0.21 Mev.

If we are correct in supposing that a beta branch takes place from Be^{11} to the first excited state of B^{11}, we should be able to put it in evidence by displaying only those pulses in the beta counter that are in coincidence with gamma rays of 2.1 Mev. A gamma-ray channel was accordingly set about the 2.1-Mev photopeak and the associated coincident beta spectrum is seen in Fig. 5. The dashed line shows the N^{16} comparison spectrum, and the same type of analysis as before yields $E_{\beta 2}=9.32\pm0.15$ Mev which is in excellent agreement with our expectation of 9.36 ± 0.15 Mev. The next partial spectrum is revealed by biasing the gamma-ray detector above 2.12 Mev so as to exclude the branch just investigated. The range of energy dissipation accepted in the gamma counter was 3.0 to 8.0 Mev and the associated coincident beta spectrum is shown in Fig. 6. The dashed line now indicates the spectrum from Rh^{106} of end point 3.55 ± 0.02 Mev which was used for comparison. After a small correction for the higher beta branch about to be investigated, we find $E_{\beta 3}=4.65\pm0.2$ Mev as against the expected 4.67 ± 0.15 Mev. Finally we raise the bias on the gamma-ray counter above the 6.8 Mev to which belongs the previous branch to measure the partial spectrum of lowest energy. The gamma-ray acceptance range was from 7.0 to 9.0 Mev. The coincident beta spectrum is shown in Fig. 7, again with the Rh^{106} spectrum for comparison. We find $E_{\beta 4}=3.6\pm0.2$ Mev as against the expected 3.49 ± 0.15 Mev.

These beta-particle energy measurements confirm the general decay scheme and together suggest the value $Be^{11}-B^{11}=11.48\pm0.15$ Mev as given by the highest energy transition. This corresponds to $M-A=23.39\pm0.15$ Mev for Be^{11} and shows the excellent success of Ajzenberg and Lauritsen's estimate.

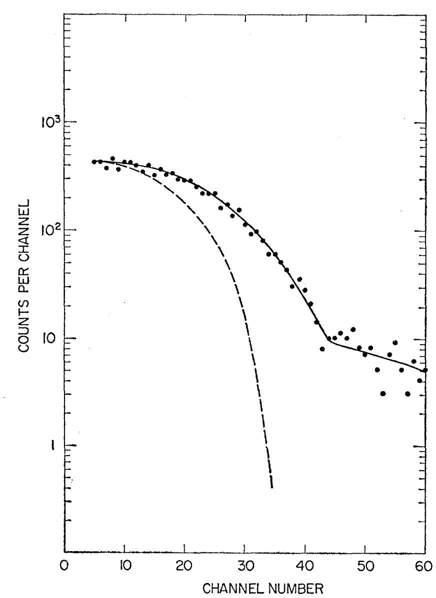

FIG. 6. Beta particles from Be^{11} seen in coincidence with gamma rays of from 3.0 to 8.0 Mev. The dashed comparison spectrum is from Rh^{106} (end point 3.55 Mev). Beta energy $=3.65\pm0.15$ Mev.

C. Half-Life Measurements

It is clear from the foregoing results that B^{11} is the final nucleus of the induced activity. The identification is confirmed by the lifetime measurements. These were made (i) on all beta particles dissipating more than 3.0 Mev in the plastic beta-particle phosphor, (ii) on a narrow channel of width 10% set around the photopeak of the 2.12-Mev line as shown in Fig. 2 such that about 93% of the pulses in the channel are due to that line, and (iii) on all gamma rays dissipating more than 3.0 Mev in the NaI(Tl) crystal. In each case, counting periods of 5 seconds were used and the decay was followed over many half-lives. Typical results are shown in Fig. 8. The background counting rates were, in all cases, very small and corrections have been applied in Fig. 8. In terms of the initial counting rates they were 0.07%, 0.8%, and 1.2% for the beta particles, the 2.12-Mev gamma rays, and the high energy gamma rays, respectively. The half-lives resulting from these measurements were 13.68±0.15 seconds, 13.47±0.20 seconds, and 13.48±0.20 seconds for the beta particles, the 2.12-Mev gamma rays, and the high-energy gamma rays, respectively.[8] It is clear that these several periods refer to the same process, and that the proceeds is the decay of Be^{11} to B^{11}; we quote for the half-life 13.57±0.15 seconds

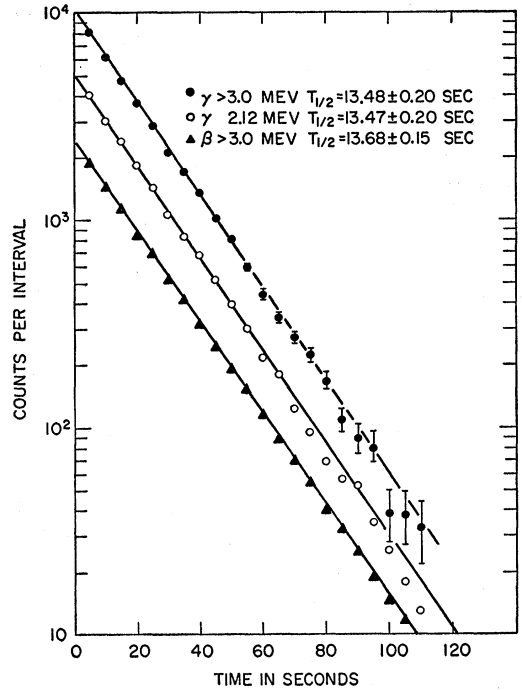

FIG. 8. Decay curves for Be^{11} observed with the different radiations shown. The curve for the high-energy gamma rays is in its correct position with its correct errors (the background has been subtracted). The curve for the lower energy gamma rays has been displaced downwards to avoid confusion of the figure; the initial number of counts per interval was in fact identical with that for the high-energy gamma rays and the errors are similar at similar times. The initial number of counts per interval for the beta-particle curve was about 6×10^4 so the errors are much smaller.

D. Relative Intensity Measurements

We may now estimate the relative intensities of the various beta branches. Call these $I_{\beta0}$, etc., and normalize to $\sum I_\beta = 1$. From the gamma-ray spectra such as those of Figs. 1 and 3 we can estimate the relative intensities of the various gamma rays seen in the decay. Call these $I_{\gamma1}$, etc., without any normalization. We find, combining information from both crystals,

$$I_{\gamma1}:I_{\gamma2}:I_{\gamma3}:I_{\gamma4}:I_{\gamma5}=32:2.1:2.4:4.4:1.7;$$

this corresponds to

$$\left(I_{\beta2}+\frac{2.1}{6.5}I_{\beta3}+\frac{2.4}{4.1}I_{\beta4}\right):I_{\beta3}:I_{\beta4}=32:6.5:4.1.$$

We must now make a comparison of beta-particle and gamma-ray intensities. This was done by measuring the probability that a gamma ray of 2.1 Mev is in coincidence with any beta particle. The beta counter was biased at an energy dissipation of 1.0 Mev and the coincident gamma rays were displayed. At so low a bias in the beta counter, all the beta branches are detected with almost the same efficiency and the remaining small correction is easily applied. From the gamma-ray spectrum the number of coincident 2.1-Mev gamma rays was found for the known number of beta counts. The absolute gamma-ray detection efficiency was cal-

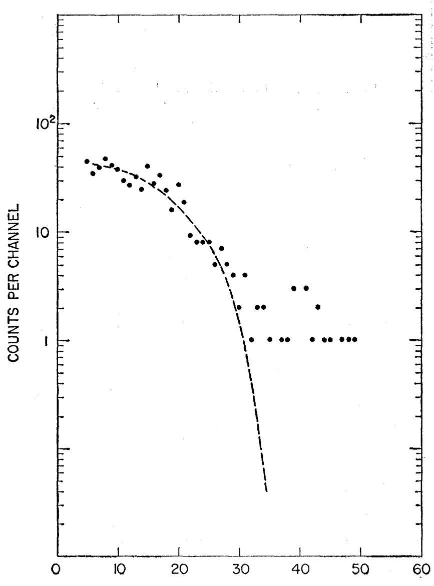

FIG. 7. Beta particles from Be^{11} seen in coincidence with gamma rays of from 7.0 to 9.0 Mev. The dashed comparison spectrum is from Rh^{106} (end point 3.55 Mev). Beta energy=3.6±0.2 Mev.

[8] We may note here that the absolute efficiency of the beta counter for the gamma ray is only about 4% for the geometry used.

culated from the known geometry, the absorption in the aluminum and copper screens, and the intrinsic crystal efficiency taken from the standard tables.[9] The larger NaI(Tl) crystal was used here. This measurement was done twice with care in rather different conditions. The results were identical and we find the probability P that a beta particle is accompanied by a gamma ray:

$$P=I_{\beta 2}+\frac{2.1}{6.5}I_{\beta 3}+\frac{2.4}{4.1}I_{\beta 4}=0.33\pm0.03.$$

This gives

$$I_{\beta 1}=0.61;\quad I_{\beta 2}=0.29;\quad I_{\beta 3}=0.065;\quad I_{\beta 4}=0.041.$$

There are other less accurate ways of measuring P and these were done as a check. Firstly we displayed the beta particles in coincidence with gamma rays of 2.1 Mev and compared the coincidence ratio with the beta counting rate without the coincidence condition. This gave $P=0.45\pm0.15$. Secondly we simply compared, without any coincidence condition, the beta and gamma counting rates. This gave $P=0.32\pm0.07$. These checks were considered satisfactory and were not used further.

It seems, from the work reported so far, that beta branches take place to the ground state and to the levels at 2.138, 6.758–6.808, and 7.987 Mev. There has been no sign of transitions to the states at 4.459 and 5.034 Mev and it is already clear from the simple gamma spectra that such transitions have an intensity of $I_{\beta 4.45}$, $I_{\beta 5.03}\leqslant 0.007$. (We use the work of Ferguson *et al.*[10] from which we learn that these two levels decay chiefly to the ground state.) These branches are of some importance and we investigated the matter further by examining the gamma rays in coincidence with the beta particles as a function of bias on the beta counter. Figure 9 shows the result with the beta counter biased at 1.5 Mev. This spectrum, as it should be, is similar to Fig. 3 (the larger crystal was used for the gamma rays) with some attenuation of the higher energy gamma rays owing to the relatively inefficient detection of their beta branch. (The same notation for labeling the high-energy peaks has been adopted as in Figs. 1 and 3.) When the bias on the beta counter is raised to 3.5 Mev we find the spectrum of Fig. 10. We are now excluding the lowest energy beta branch, and

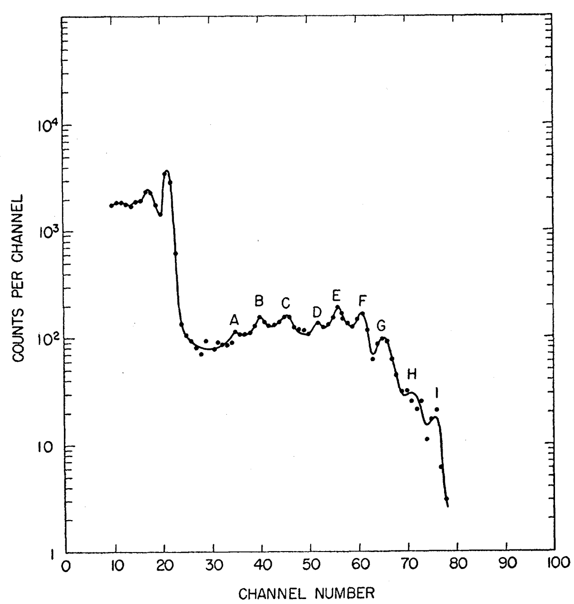

FIG. 9. Gamma-ray spectrum from Be^{11} seen in coincidence with beta particles of energy greater than 1.5 Mev. The 3-in. crystal was used. See Fig. 1 for the labeling.

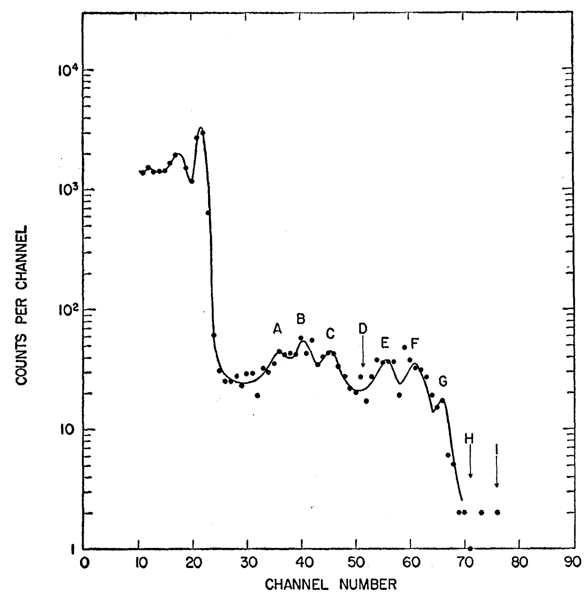

FIG. 10. Same as Fig. 9 but requiring a beta particle of greater than 3.5 Mev.

peaks H and I whose expected positions are shown have accordingly disappeared (also peak D which belongs solely to the 5.86-Mev cascade radiation from the 7.99-Mev state). In Fig. 11 the bias in the beta counter is raised to 4.7 Mev which excludes the branch to the 6.758–6.808-Mev doublet but would still admit beta particles leading to the levels at 4.46 and 5.03 Mev. As expected, all the identified high-energy peaks have disappeared. There are, however, some counts significantly in excess of background (which has been subtracted in all these figures) in the channels above the photopeak of the 2.1-Mev line. We show the expected positions of the usual three peaks for gamma rays of 4.46 and 5.03 Mev and it seems that the excess counts are consistent with the presence of such lines in the

[9] Wolicki, Jastrow, and Brooks, Naval Research Laboratory Report NRL-4833, 1956 (unpublished).

[10] Ferguson, Gove, Litherland, Almqvist, and Bromley, Bull. Am. Phys. Soc. Ser. II, 2, 51 (1957), and private communication.

coincidence spectrum. A similar suggestion is in fact contained in Fig. 10 whose analysis into lines of 4.64 and 6.76 Mev seems to give a bigger intensity ratio of low- to high-energy components than that derived from the simple spectra of Figs. 1 and 3. This would be expected if in fact there were gamma rays of 4.46 or 5.03 Mev in coincidence with beta particles leading directly to those states. These particles would be accepted more efficiently by the beta counter than those leading to the 6.758–6.808-Mev doublet on account of their greater energy. However these indications are not conclusive. We must consider ways in which a similar effect could be generated without the participation of a beta transition to the 4.46- or 5.03-Mev levels. One surely is

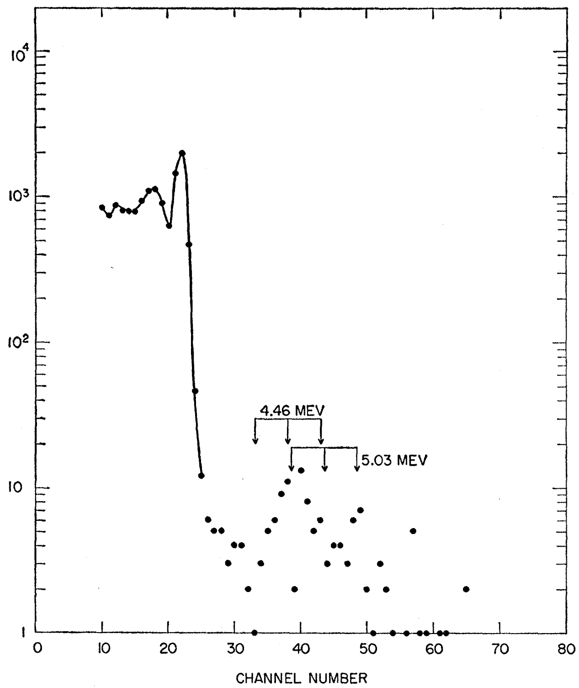

FIG. 11. Same as Fig. 9 but requiring a beta particle of greater than 4.7 Mev. The two tridents indicate the expected positions of the two-escape, one-escape, and full peaks for gamma rays of energy 4.46 and 5.03 Mev.

by the simultaneous detection of a beta particle and of a gamma ray in the beta counter. Suppose that, with the beta counter biased at 4.7 Mev as in Fig. 11 a beta particle leading to the 6.758–6.808-Mev doublet enters the beta counter. It cannot of itself activate the beta-ray side of the coincidence circuit; but if the B^{11} level then branches via the 2.138-Mev state and the lower energy gamma ray is absorbed in the beta counter the bias level can be passed, and if the 4.64-Mev gamma ray is absorbed in the gamma-ray counter the effect produced in Fig. 11 is seen. It is difficult to estimate the chance of this complicated chain of events but the detectors are close together and the geometrical efficiencies are high. It seems quite likely, however, that this effect could

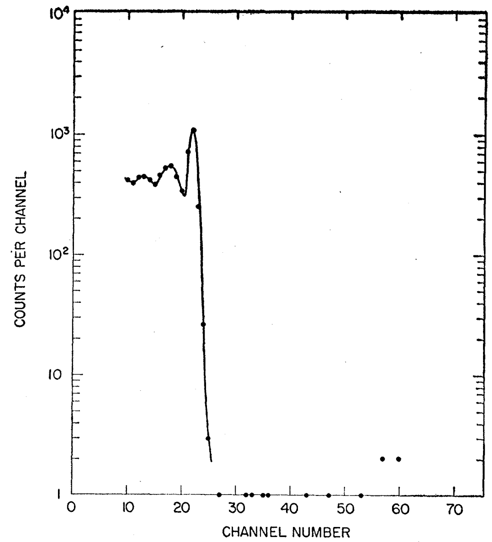

FIG. 12. Same as Fig. 9 but requiring a beta particle of greater than 5.6 Mev.

explain much of the apparent beta-gamma coincidence rate. We accordingly can interpret the data only as representing an upper limit on the beta branching to the 4.46- and 5.03-Mev states. We find that $I_{\beta 4.46}$ and $I_{\beta 5.03}$ are each $\leqslant 0.002$. These limits are sharper than those already reported from an examination of the simple gamma-ray spectra and are sharper than the limits that can be derived from results such as those of Fig. 6 where beta particles in coincidence with gamma rays are displayed.

A further increase of bias on the beta counter to 5.7 Mev, which should still admit the beta branch to the 4.46- and 5.03-Mev states, results in the coincident gamma-ray spectrum shown in Fig. 12 which represents an effectively pure 2.1-Mev line. Owing to the very low efficiency with which the sought beta branches would now be detected, we cannot safely use these results to sharpen the limit but they certainly confirm it.

Limits on the possible branches to other states of B^{11} may be derived from the simple gamma-ray spectra of Figs. 1 and 3. The states at 7.298 and 8.568 Mev decay chiefly to the ground state of B^{11}; that at 8.927 Mev does also but is unstable by 0.26 Mev against alpha-particle emission which competes more-or-less equally with the gamma rays. Higher states do not yield appreciable numbers of gamma rays owing to the alpha-particle competition.[10] From the absence of these higher energy gamma rays we find $I_{\beta 7.30} \leqslant 0.015$, $I_{\beta 8.57} \leqslant 0.003$, and $I_{\beta 8.93} \leqslant 0.0015$.

This leaves a residual problem in that we do not know to which member of the 6.758–6.808-Mev doublet the beta decay leads. The indication of the energy measurement is the lower member but it is not clear-cut. We find the ratio of ground-state transitions to cascade transitions via the 2.138-Mev state to be about 2.1 to 1. For the 6.808-Mev state, this ratio is given[10] as 3.8 to 1;

TABLE I. Summary of the properties of Be^{11} found in the present investigation.

B^{11} state (Mev)	E_β (Mev)	% betas	$\log ft$	E_γ (Mev)	% gammas	Half-life (sec)
0	11.48±0.15	61 (β_1)	6.77	···	···	13.68±0.15
2.138	9.32±0.15	29 (β_2)	6.63	2.121±0.010	32 (γ_1)	13.47±0.20
4.459	···	≤0.2	≥8.2	···	···	
5.034	···	≤0.2	≥8.2	···	···	
6.758 6.808	4.65±0.2	6.5 (β_3)	5.93	(i) 6.76±0.03 (ii) 4.64±0.02	4.4 (γ_4) 2.1 (γ_2)	
7.298	···	≤1.5	≥6.4	···	···	13.48±0.20
7.987	3.6 ±0.2	4.1 (β_4)	5.53	(i) 7.97±0.03 (ii) 5.86±0.04	1.7 (γ_5) 2.4 (γ_3)	
8.568	···	≤0.3	≥6.3	···	···	
8.927	···	≤0.15	≥6.3	···	···	

it might, however, be somewhat modified on account of differing angular distributions of the two components, an uncertainty to which our measurements are not subject. For the 6.758-Mev state, however, there is only a suspicion of a cascade transition via the 2.138-Mev level,[10] which would appear to conflict with our data. A branch from the 6.758-Mev state via the 4.46-Mev state whose intensity is about 20% of the ground state transition is reported.[10] On the basis of this number we should expect to find, in our experiment, a gamma ray of energy 2.30 Mev of intensity about 2.7% of that of the 2.1-Mev line. We accordingly made a careful search on the upper side of the strong 2.1-Mev line. For example, on Fig. 2 we show the expected position of the photopeak of this possible 2.30-Mev line. It seems barely likely that such a 2.30-Mev line is present in the required intensity and so this cannot confirm the involvement of the 6.758-Mev level in the beta transition. Evidence is therefore conflicting and we must leave it as an open question for the moment.

SUMMARY OF RESULTS

For convenience we gather together in Table I the results of this investigation. The energies of the B^{11} states are those given by the reaction $B^{10}(d,p)B^{11}$ already cited. The entry "% gammas" gives the percentage of all Be^{11} disintegrations that result in the gamma ray in question. The three half-lives quoted are those measured on the beta particles, on the 2.12-Mev gamma ray, and on the high-energy gamma rays.

We quote the following values:

Half-life of Be^{11}: 13.57±0.15 seconds.

$Be^{11}-B^{11}$: 11.48±0.15 Mev.

$M-A$ for Be^{11}: 23.39±0.15 Mev.

The situation is summarized in Fig. 13.

DISCUSSION

From its place in the $1p$ shell we should expect Be^{11} to have the property $J=\frac{1}{2}-$. The fact that the $\log ft$ values for the transitions to the ground ($J=\frac{3}{2}-$) and 2.138-Mev ($J=\frac{1}{2}-$) states of B^{11} are approximately the same while that for the transition to the 4.46-Mev ($J=\frac{5}{2}-$) state is considerably greater agrees with this assignment. On the other hand, these first two $\log ft$ values of about 6.8 and 6.6, respectively, are rather large and would be consistent with first forbidden transitions and thus with $J=\frac{1}{2}+$, $\frac{3}{2}+$, or $\frac{5}{2}+$ for Be^{11}. Such even parity would be very unexpected. In this case the transition to the 4.46-Mev, $J=\frac{5}{2}-$ state would also be first forbidden but it is in fact much slower than those to the ground and first excited states. This argues against even parity for Be^{11}. A tendency has been noticed[11] for the $\log ft$ values of first forbidden transitions to be greater for $\Delta J=2$ than for $\Delta J=0, \pm1$. This might seem to suggest that if Be^{11} has even parity its spin is more likely to be $\frac{1}{2}$ and also that we cannot use the present argument against even parity for Be^{11}. However, this tendency is probably due to dominance of the Coulomb energy term in the majority of first forbidden transitions with $\Delta J=0, \pm1$ and its absence from the $\Delta J=2$ transitions. But there is no such dominance here because the nucleus is light and the transition energy is high.

The transitions to the 6.758–6.808-Mev doublet and to the 7.987-Mev level appear to be allowed ($\log ft=5.93$ and 5.53, respectively). Neither the parity of the 7.987-Mev level nor of the higher of the doublet states is known. The parity of the 6.758-Mev state is odd,[12] and if our energy measurement alone were adequate to fix this as the state involved in the beta decay, the parity of Be^{11} would also be fixed as odd and so most likely $J=\frac{1}{2}-$ because of the relative $\log ft$ values for the transition to the three lowest states of B^{11}. However, the evidence as to which doublet member is involved in the beta decay is conflicting and we cannot safely make this deduction. Furthermore, from a study of the $B^{10}(d,p\gamma)B^{11}$ angular correlation, $J=\frac{3}{2}-$ is not indicated for the 6.758-Mev level and $\frac{5}{2}-$ or $\frac{7}{2}-$ are preferred.[12] However, these spin preferences are perhaps not firm, since the spin assignment for the 6.758-Mev level is based on the use of simple stripping theory to analyze the p-γ angular correlation and this must be rather unsure at the low deuteron energy used. An argument in favor of the beta-ray tran-

[11] See, e.g., M. G. Mayer in *Beta- and Gamma-Ray Spectroscopy*, edited by K. Siegbahn (North-Holland Publishing Company, Amsterdam, 1955), Chap. 16, p. 433.

[12] S. A. Cox and R. M. Williamson, Phys. Rev. **105**, 1799 (1957).

sition to the 6.758-Mev state and hence of odd parity for Be^{11} is that the lower member of the doublet is strongly excited in the stripping reactions while the upper one is not. Furthermore, the upper member gives no clear stripping pattern at all so its parity is unknown. This shows that the lower member of the doublet is closely related to B^{10} while the upper member is not. Since B^{10} and Be^{11} should also be closely related, we might expect a typical allowed $\log ft$ value to the lower member of the doublet if Be^{11} is of odd parity and the spins are suitable but not to the upper member (if it is of odd parity). Similarly, if both Be^{11} and the upper member of the doublet are of even parity, a typical allowed $\log ft$ value is a little surprising since the ground state of Be^{11}, if of even parity, would probably be a rather complicated state.

A further slight argument for odd parity for Be^{11} is the limit on the transition to the 8.927-Mev level which is $\frac{5}{2}+$ or $\frac{7}{2}+$ and which is closely related to B^{10} as is evidenced by the large associated stripping cross section.[13] This limit is not, of course, strong enough to indicate a forbidden transition but its indication is in that direction.

Possible alternative approaches to the parity of Be^{11} are (i) a measurement of the parity of the 7.987-Mev state to which an allowed transition is also seen, presumably best done by $B^{10}(d,p)B^{11}$; (ii) a relative-polarization measurement on the gamma rays in the cascade from the doublet state through that at 2.138 Mev; and (iii) a direct approach through the angular distribution of the reaction $B^{11}(n,p)Be^{11}$ itself.

At present it seems at least possible that Be^{11} may be $J=\frac{1}{2}-$ as expected by the shell model and also by the full individual-particle model in intermediate coupling[1] which further predicts $Be^{11}-B^{11}\sim 11$–12 Mev in accord with our observation. In this case the transitions to the two lowest states of B^{11} are allowed but strongly discouraged and it would be most interesting to know the prediction of the individual-particle model on this point.[1]

We may note another difficulty. The 5.034-Mev level is of odd parity[2] and in its gamma decay, which is chiefly to the ground state, shows a 12% branch via the first excited state.[10] This strongly suggests $J=\frac{3}{2}-$ for the 5.034-Mev level. If this is so and if Be^{11} is $J=\frac{1}{2}-$, then we have an allowed transition with $\log ft \geqslant 8.2$, which is an unhappy situation. Were the spin assignment of this state sure, it would of course be a strong argument for even parity for Be^{11}. But it is not.

We have considered the possibility that the 13.5-second period does not belong with the beta-decay of Be^{11} but to an isomer of that nucleus. We therefore examined with care the gamma-ray spectrum from a few kev to 2 Mev but found no evidence for such a transition.

[13] O. M. Bilaniuk and J. C. Hensel, Bull. Am. Phys. Soc. Ser. II, 3, 188 (1958).

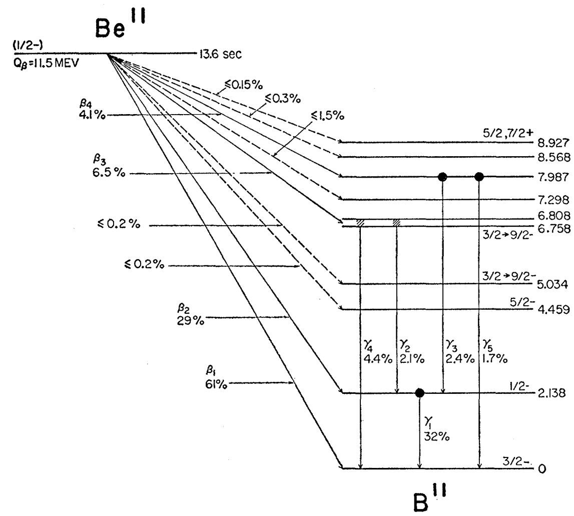

FIG. 13. Decay scheme of Be^{11}. The energies are in Mev. The B^{11} level energies are taken from the $B^{10}(d,p)B^{11}$ measurements cited in the text. That for Be^{11} is the result of the present measurements. The percentages for the gamma rays represent their abundance per Be^{11} decay. The assignments for the B^{11} levels are as cited in the text. All B^{11} levels not shown are unstable against alpha-particle emission.

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