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Decay of Be^{11}†

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The β decay of Be^{11}, formed in the $Be^9(t,p)Be^{11}$ reaction, has been investigated using Ge(Li) and NaI(Tl) γ-ray detectors and Si α-particle detectors. Eight γ-ray transitions were measured including three weak γ rays with energies of 1772, 2893, and 5019 keV not observed previously in Be^{11} decay. The relative γ intensities show that the 5020-keV state of B^{11} is populated by a Be^{11} first-forbidden β-ray branch of 0.28% ($\log ft = 7.94 \pm 0.14$), as well as by a cascade γ-ray branch of 4.1% from the B^{11} 6793-keV state. Other previously observed β-ray branches have been confirmed. Accurate energies have been obtained for the B^{11} states, including a value of 7978.1 ±1.9 keV for the seventh excitated state. This is 18 keV lower than in previous reports. Delayed α particles are also found in Be^{11} decay; the experimentally observed α-particle spectrum is a continuum extending from an instrumental lower limit of 0.3 MeV up to about 1.0 MeV, and with a total α-particle intensity of 3.0% per decay. These α particles are not in coincidence with 478-keV γ rays from Li^7. It is suggested that this β-ray branch of Be^{11} proceeds to the 9870-keV $J^\pi = \frac{3}{2}^+$ state of B^{11} ($\log ft = 4.03 \pm 0.15$) followed by α-particle emission to the ground state of Li^7, although an α-decay branch to the 478-keV state of Li^7 cannot be excluded. The new features of Be^{11} decay are discussed. It appears that the analog in B^{11} of the ground state of Be^{11} has no antianalog.

I. INTRODUCTION

Twelve years ago we studied[1] the β decay of Be^{11} using plastic scintillators and NaI(Tl) crystals. Four β-ray branches were observed leading to the ground and 2125-keV states of B^{11}, the 6743-6793-keV doublet, and the 7978-keV state. (Excitation energies of the B^{11} states are from the present work, as described in Sec. IV.) A half-life value of 13.57 ± 0.15 sec was determined for Be^{11} and five γ-ray transitions were detected that were fitted into the proposed decay scheme. It was shown that the ft values for β decay to the ground and first excited states of B^{11} were appropriate to first-forbidden transitions rather than to allowed transitions, and we speculated upon the possibility that the ground state of Be^{11} might be of even parity rather than of the expected $J^\pi = \frac{1}{2}^-$. Later work[2,3] showed that, with very high probability, the 5020-keV level of B^{11} was $J^\pi = \frac{3}{2}^-$ and, since Be^{11} β decay to it had a $\log ft \gtrsim 8$,[1] allowed decay could be excluded with fair certainty and the parity of Be^{11} was therefore, indeed, most probably even. The matter was clinched by Alburger *et al.*,[4] who showed from pair spectrometer measurements that the 7978-keV B^{11} state was of $J^\pi = \frac{3}{2}^+$, and furthermore that the upper member of the B^{11} 6743-6793-keV doublet, known to be of even parity,[2] was the one populated in Be^{11} β decay. Since both of these β branches had allowed $\log ft$ values, it was concluded that Be^{11} has even parity. In the meantime Talmi and Unna[5] had shown, in a manner that we shall detail later, how even parity for the Be^{11} ground state was, in fact, not at all surprising.

Two technical improvements have occasioned our return to this problem: the availability of large Ge(Li) detectors of high resolution and the availability at the Brookhaven research Van de Graaff of a triton beam that enables us, through the reaction $Be^9(t,p)Be^{11}$, to make much stronger sources than before when we had to make the activity via the $B^{11}(n,p)Be^{11}$ reaction. A concomitant benefit of the triton beam is that it enables us to make thin sources of Be^{11} and so permits us, by detecting α particles, to study Be^{11} β decay to states of B^{11} above the $Li^7 + \alpha$ threshold.

In this paper we present improved data on the decay to states already studied in the earlier work and new data relevant to further states. This permits us to extend our discussions of the structure of Be^{11} and of the even-parity states of B^{11}.

II. EXPERIMENTAL METHODS AND RESULTS

A. γ-Ray Spectrum

The Be^{11} activity was produced by bombarding Be with 3.0-MeV tritons from the 3.5-MV Van de Graaff accelerator. After a bombardment with a

1.5-μA beam for 30 sec the target was removed from the chamber and carried to a Ge(Li) detector located in the control room. Absorbers consisting of 1.0-cm-thick bakelite and 1.27-cm-thick lead were located in front of the detector to exclude β rays and to discriminate against a fairly strong component of 511-keV annihilation radiation. Beginning about 15 sec after the end of a bombardment the spectrum was recorded in a multichannel pulse-height analyzer for 50–60 sec while moving the source towards the detector so as to maintain the detector leakage current at a value consistent with optimum statistical accuracy without loss of pulse-height resolution. This procedure was repeated as many as 75 times to accumulate a sufficiently well-defined spectrum.

In the first experiments the targets consisted of either 0.001-in.-thick Be foil or a Be crystal. In addition to the five previously observed[1] Be^{11} γ rays, the spectra from these sources exhibited peaks corresponding to γ rays of 1273, 1772, 1779, 2426, 2893, and 5019 keV. While the 1772-, 2893-, and 5019-keV γ rays could be understood in terms of the known levels of B^{11}, the appearance of the 1273-, 1779-, and 2426-keV lines was at first puzzling. Since their intensities relative to other lines were different in the foil and crystal samples, we concluded that they did not belong to Be^{11} decay. It was then realized that these lines could be understood by a small contamination of aluminum in both of the targets from which Al^{28} and Al^{29} were produced by the (t, d) and (t, p) reactions, respectively. Al^{28} emits γ rays of 1779 keV, and the Al^{29} spectrum contains a strong 1273-keV γ ray and other γ rays of which the strongest is at 2426 keV.

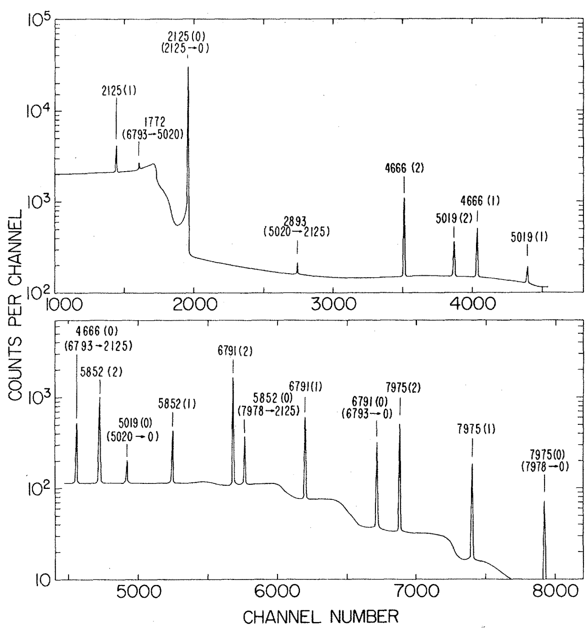

FIG. 1. Spectrum of γ rays from Be^{11} measured with a 30-cc Ge(Li) detector. Data points have been omitted. γ-ray energies are in keV and the symbols (0), (1), and (2) designate full-energy, one-escape, and two-escape peaks. The lines due to 511-keV annihilation radiation and the 2125 two-escape peak occur below channel 1000. Transition assignments, given in parentheses, differ from the γ-ray energies by the nuclear recoil energy. Thus, for the 7978-keV transition the nuclear recoil energy is 3.1 keV.

In the final series of experiments a highly purified sample[6] of Be metal was used as a target, and the spectrum from it contained no evidence for the Al^{28} and Al^{29} lines. Figure 1 shows the Be^{11} γ-ray spectrum from the pure Be target obtained in a run consisting of 65 irradiate-count cycles using a 30-cc Ge(Li) detector. This spectrum was recorded in a 16 384-channel pulse-height analyzer using an 8192-channel analog-to-digital converter. Except for a strong 511-keV annihilation radiation line (not shown in Fig. 1), all of the lines in the spectrum can be uniquely assigned to transitions occurring in Be^{11} decay. The annihilation γ ray is mostly from the β^+ decay of F^{18} produced by the $O^{16}(t, n)F^{18}$ reaction on surface oxygen.

The energies of the Be^{11} γ rays were obtained from the data of Fig. 1 by using computer fitting procedures[7] developed at this Laboratory. Peak positions were first determined for all of the lines including the 511-keV annihilation peak. For the computer input data, γ-ray energies assigned to full-energy-loss peaks were derived from the B^{11} level energies, given in the recent paper by Browne *et al.*,[8] by subtracting the calculated nuclear recoil energy from the corresponding level separation. The energies of one-escape and two-escape peaks were assigned by subtracting 511.0 and 1022.0 keV, respectively, from the γ-ray energy. Fitting of the peak positions was carried out with a polynomial of the form

$$E_{\text{peak}} = \sum_{n=0} \alpha_n x^n , \tag{1}$$

where x is the channel number and the a_n's are coefficients determined by the fit. The initial fit was made omitting the six peaks due to the two γ rays from the seventh excited state of B^{11}, since it became apparent that the energy of this level must differ from the previously reported value of 7996 ± 6 keV[2] by considerably more than the quoted error. In the second fit, the values of these two γ rays obtained in the first fit were included in the input data. Thus, the procedure for obtaining these γ-ray energies can be characterized as a

TABLE I. Be^{11} γ rays and their intensities measured with a 30-cc Ge(Li) detector.

γ energy (keV)	Transition assignment (B^{11} levels in keV)	Intensity in % per β decay[a]
1772.2 ± 0.7	6793 → 5020	0.28 ± 0.06
2124.8 ± 0.7	2125 → 0	33 ± 3
2893.1 ± 0.8	5020 → 2125	0.093 ± 0.028
4666.3 ± 1.8	6793 → 2125	2.00 ± 0.28
5019.3 ± 1.7	5020 → 0	0.47 ± 0.09
5851.8 ± 1.9	7978 → 2125	2.13 ± 0.34
6790.5 ± 1.8	6793 → 0	4.51 ± 0.69
7974.7 ± 1.9	7978 → 0	1.74 ± 0.30

[a]All γ intensities are normalized to a value of 33 ± 3% for the 2125-keV γ intensity, taken from Ref. 1.

"bootstrap" method. The best fit was found for $m = 5$ in Eq. (1), and in this case the quality of fit was indicated by a χ^2 of 0.40. For each of the γ rays (except for 1772- and 2893-keV γ rays) three γ-ray energy values were obtained from the best-fit values of the full-energy, one-escape, and two-escape peaks. A weighted average value for the γ-ray energy was obtained using the three separate values, where the weighting depended on the accuracy with which the corresponding peak position had been determined. The greatest departure of any of the three γ-energy values from the weighted average was only 0.7 keV in the worst case. For the 1772- and 2893-keV γ rays the energy was calculated from the full-energy peak. The γ-ray energies derived in this way are listed in the first column of Table I.

In order to obtain the relative intensities of the γ rays from Be^{11}, the net areas under the various full-energy and two-escape peaks were first derived from the data of Fig. 1. Corrections for absorption of the γ rays in the Pb and bakelite were applied. For the full-energy and two-escape peak efficiencies of the 30-cc Ge(Li) detector the calculations were based on the efficiencies found by Alexander[9] and by Pruys[10] for 25- and 30-cc Ge(Li) detectors, respectively. In both cases, it was noted that in the region from 4 to 8 MeV the two-escape efficiency function is approximately constant, while the full-energy peak efficiency decreases more or less exponentially with increasing energy. The procedure was to find the relative intensities of the γ rays of 4666 keV and higher, using the net areas under the two-escape peaks together with a two-escape efficiency function based on the above-mentioned data, and to use the full-energy peaks and the corresponding efficiencies, similarly derived, for the γ rays from 1772 through 4666 keV. The two groups of relative γ-ray intensities were normalized to the 4666-keV intensity, and the complete set of intensities was renormalized to a value of 33 ± 3% for the intensity[1] per decay of the 2125-keV γ ray. The complete list of intensities is given in the last column of Table I together with errors which include the 9% error in the intensity of the 2125-keV γ ray, the statistical errors in the various net peak areas, and estimates of the errors in the detector efficiency. Earlier experiments on the unpurified Be samples and using a 35-cc Ge(Li) detector gave relative intensities agreeing with those in Table I within the errors.

B. α-Particle Singles Measurements

The search for delayed α particles from Be^{11} was made using a target chamber that had been constructed by Parker[11] for a study of the Be^7+p cross section. This chamber has a pneumatically operated arm which can transfer the target from the bombardment position to a location ~9 mm from the surface of a Si detector.

Targets consisted of either 20- or 50-μg/cm^2-thick layers of Be evaporated onto 0.01-in.-thick Ta. A beam of 3.0-MeV tritons at a current of 1.3 μA was used to bombard the target for 30 sec. While turning down the accelerator voltage, the target was transferred to the detector and a 30-sec count was started 15 sec after the removal of the beam from the target. This delay was sufficient to allow for the nearly complete decay of the very strong delayed α activity from 0.85-sec Li^8 produced in the $Be^9(t, \alpha)Li^8$ reaction.

The first measurements, using a Si detector 50 μ thick, gave a spectrum indicating response not only to the β rays of Be^{11} but to heavy-particle emission as well. In order to decrease the effective energy loss of the β rays in the detector, runs were made using thinner detectors, i.e., of 15-, 9.6-, and 5-μ thickness, all of which were commercial units from ORTEC. The solid points in Fig. 2 comprise the spectrum obtained with the 9.6-μ-thick detector. This was the data accumulation of 40 irradiate-count cycles.

In order to establish the nature of the two main components of this spectrum, a 0.001-in.-thick Al foil was inserted in front of the detector and another run was made. As is clear from the open-circle points in Fig. 2, the portion of the spectrum decreasing rapidly with increasing energy at low pulse heights is due to β rays that are virtually unaffected by the Al foil, while the remainder of the solid-point spectrum is completely removed by the foil and must therefore be assigned to α particles. It was further observed, in a series of runs taken with the detectors of four different thicknesses, that the energy cut off of the β rays decreased with decreasing detector thickness, as

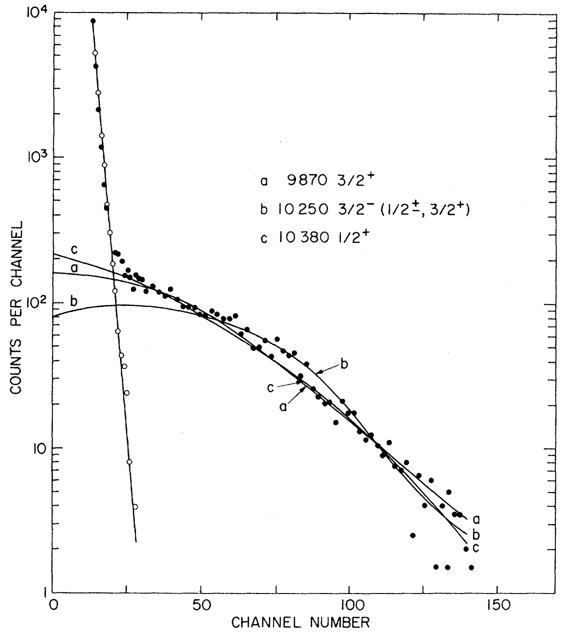

FIG. 2. Solid points represent the spectrum of radiations from a Be^{11} source observed in a 9.6-μ-thick Si detector. Above channel 30 the points are the averages of successive pairs of channels. The activity was formed by a 3.0-MeV triton bombardment of a 50-$\mu g/cm^2$-thick Be layer deposited on a thick Ta backing. Open circles represent the corresponding normalized spectrum observed when a 0.001-in.-thick Al foil was placed between the detector and the Be^{11} source so as to completely absorb α particles. The three curves labeled a, b, and c are the α-particle spectra calculated, as described in the text, under the assumption that the Be^{11} β decay populates the B^{11} states at 9870, 10 250, or 10 380 keV, respectively.

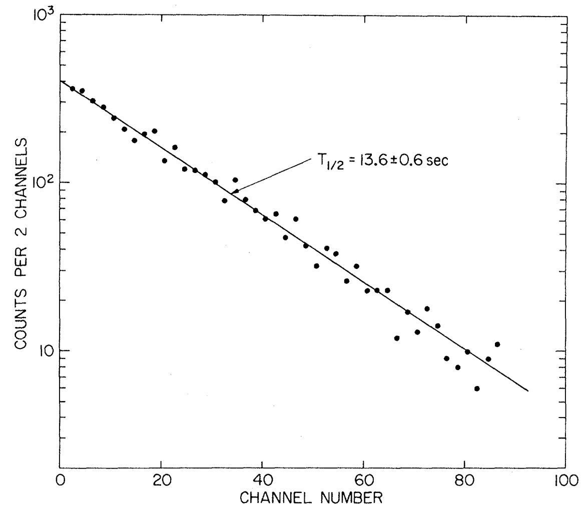

FIG. 3. Decay of pulses in the region above channel 30 in Fig. 2, measured in a multichannel scaler using an advance rate of 0.9 sec per channel. This experiment demonstrates that the delayed α particles from the target decay with the known half-life of Be^{11} (13.81 sec).

expected, whereas the shape and end point of the α spectrum, in the region beyond the β rays, did not change appreciably.

Having observed delayed α particles from the target, it was necessary to establish their assignment to Be^{11} decay. The spectra taken using the 20- and 50-$\mu g/cm^2$-thick targets were of practically the same shape and differed only in the normalized intensity above the β cutoff. The fact that these yields were in proportion to the nominal target thickness indicated that the α activity was associated with the Be layer rather than with a backing contaminant.

The final test to establish the origin of the α particles consisted of measuring the decay rate of all pulses above channel 30 in Fig. 2. This was done by feeding the pulses above that bias level to a multichannel scaler that was recently used[12] to establish a half-life value of 13.81 ± 0.08 sec for the decay of Be^{11}. This measurement, shown in Fig. 3, gives a half-life of 13.6 ± 0.6 sec and is convincing proof that the α particles do indeed arise from the β decay of Be^{11}. The integrated yield of the decay curve in Fig. 3 agrees to within 10% with the sum of counts above channel 30 in Fig. 2 when normalized to the same number of irradiate-count cycles.

Since the 9.6-μ-thick detector used for the spectrum of Fig. 2 was not thick enough to allow a direct energy calibration to be made with an Am^{241} α-particle source ($E_\alpha = 5482$ keV, requiring a detector of >28-μ thickness), a long run on the Be^{11} spectrum was made with a 31-μ-thick detector in order to study the upper energy limit of the Be^{11} α particles. Although the β-ray cutoff energy in this case was considerably higher than in Fig. 2, the upper energy region was unaffected. The pulser was calibrated directly against the Am^{241} α particles and the upper energy limit of the observed Be^{11} α-particle spectrum was found to be 1.0 MeV. It is likely that the true spectrum extends somewhat higher than this, even though there were no pulses observed above the background at energies of >1.0 MeV.

The intensity of α particles per Be^{11} decay was determined by first making a smooth, gently rising extrapolation of the α-particle distribution in Fig. 2 back to zero pulse height. Approximately half of the total α-particle yield was then calculated to fall in the region below the β cutoff energy. The error in the α-particle intensity was estimated to amount to $\frac{1}{3}$ of the area under the extrapolated region, or 15% of the area under the total spectrum. A careful measurement was made of the distance from the source to the detector surface which was 8.7 ± 0.5 mm. The corresponding solid angle derived from this distance and the measured detector area, together with the α-particle total yield from the measured spectrum, was used to calculate the total number of α particles emitted from the source per irradiate-count cycle. By using a target taken from the same sample as for Fig. 2, a separate measurement was made of the γ-ray spectrum. A 5×5-in. NaI(Tl) detector was used for these tests, and the target, after irradiation with a 1.3-μA beam of 3.0-MeV tritons for 30 sec (in a different target chamber), was removed from the chamber and carried to the detector located in the control room. The source was placed at an accurately measured distance from the detector, and the spectrum was recorded for 30 sec, i.e., the irradiate-count cycle was identical to that used in the case of the α-particle measurements. Five irradiate-count cycles were sufficient to accumulate about 800 net counts in the full-energy-loss peak of the 2125-keV γ ray. Well-established curves of absolute photopeak efficiency versus γ energy were used to determine the total number of 2125-keV γ rays emitted from the Be^{11} sample per irradiate-count cycle. This, together, with the α yield discussed above, gives an intensity of $3.0\pm0.7\%$ for the α-particle emission per Be^{11} decay, based on $33\pm3\%$ per decay for the 2125-keV γ ray. The 3.0% value for the branching is actually the average of two sets of γ-ray measurements and two α-particle measurements, the second α measurement using the 5-μ-thick detector mentioned earlier. In the α-particle and the γ-ray measurements, careful target biasing procedures were followed to insure that the indicated beam current was correct and the same in both cases. The final value for the Be^{11} β-ray branch to α-emitting states has an error that includes the separate errors in the α- and γ-ray measurements but does not allow for a possible strong departure of the α-spectrum shape from the smooth extrapolation already described.

C. α-γ Coincidence Measurements

Preliminary analysis of the α-particle spectrum indicated that several states of B^{11} should be considered, and under certain assumptions the α particles in the observed range of energies might decay to the 478-keV first excited state of Li^7 rather than to the ground state. In the former case, one would expect to observe α-γ_{478} coincidences. Experiments were therefore carried out to search for this coincidence effect. The target chamber described above could not be used because of excessive neutron activation of the NaI(Tl) crystal when located in the vicinity of the target.

Because of the very low energy of the α particles from Be^{11} a reasonably good vacuum is required to avoid energy loss of the α particles in passing from the source to the detector. A small cylindrical vacuum chamber was therefore constructed having inside dimensions of 4.4-cm diam and 1.5-cm height. Inside the chamber there was a copper frame that held a standard ORTEC 50-mm^2-type Si detector. The frame was also designed to receive a 1×2-cm^2 target, supporting it just above the detector such that the target's 3-mm-diam irradiated spot was centered on the axis of the detector and at about 5 mm from the surface of the Si. By means of a mechanical vacuum pump and a ball valve the chamber could be pumped down rapidly, reaching a pressure of a few hundred microns about 5 sec after setting a circular lid on the O-ring on top of the chamber. The vacuum chamber was placed immediately above, and on the axis of, a 5×6-in. NaI(Tl) detector that had been mounted vertically. The entire apparatus was located in the accelerator control room. Standard electronic circuitry was used to measure coincidences between the two detectors. A pulse-height analyzer recorded the α-particle singles spectrum above a selected pulse-height bias in one section, and the coincident γ-ray spectrum in another section. γ-ray energy calibration and coincidence timing adjustments were made by using a thin source of Bi^{207} together with ORTEC Si detectors of 50-mm^2 area and 400-, 1000-, and 2000-μ thickness. These detectors absorb all or part of the energy of the 976-keV conversion electrons from the Bi^{207}. The 976-keV electrons are in coincidence with 570-keV γ rays, and thus the amplitudes of pulses produced by the two Bi^{207} radiations are close to those of the Bi^{11} experiment. Only small differences in the coincidence timing settings were found using the various thick Si detectors; it was assumed that the same timing adjustments were valid for the very thin Si detectors used in the Be^{11} measurements. But as a precaution the coincidence resolving time was increased to its maximum setting ($\tau\sim100$ nsec) and runs on Be^{11} were made using both leading-edge and trailing-edge timing, each set of conditions having been determined with the thick detectors and with the resolving time sharpened to ~20 nsec.

The procedure was to irradiate a 50-$\mu g/cm^2$-thick Be target on a Ta backing with a 1.5-μA beam of 3.0-MeV tritons for 30 sec, remove the target and carry it to the small vacuum chamber, place it inside, cover the chamber and pump out the air, and start recording the data. All of this was done in 20–25 sec after turning off the beam. The data were stored for about 45 sec.

Runs on Be^{11} were made with the 9.6- and 15-μ-thick Si detectors and with the detector output biased at an α-particle energy of 0.3 MeV. The α-particle singles spectra above the bias level were similar in shape to that in Fig. 2. In each irradiate-count cycle about 150 α particles were recorded, and the various runs consisted of 10–20 such cycles.

The efficiency for detecting 478-keV γ rays in the NaI(Tl) detector, at the source-to-crystal distance of 2.4 cm used in this experiment, was found from standard tables. Corrections were made for absorption of the γ rays in the $\frac{1}{8}$-in.-thick bottom wall of the brass vacuum chamber and an additional $\frac{1}{8}$-in.-thick Al absorber. The over-all photopeak efficiency for 478-keV γ rays was calculated to be 0.11.

In the three main Be^{11} runs, 6200 α particles were detected. If all of these particles were to decay to the first excited state of Li^7 there would have been 680 counts in the 478-keV photopeak. Only 33 counts were actually observed in this region, and the distribution of counts did not suggest the presence of a 478-keV peak. The yield of the entire coincidence spectrum amounted to ~2% of the number of detected α particles and could probably be attributed to random coincidences, mainly due to the strong 511-keV annihilation line. We place an upper limit of <5% on the number of α particles of energies >0.3 MeV that are accompanied by 478-keV γ rays.

III. ANALYSIS OF THE Be^{11} α-PARTICLE SPECTRUM

Analysis of the experimental α-particle spectrum is complicated by several factors. The chief among these are:

(i) In its production through the reaction $Be^9(t,p)Be^{11}$, the Be^{11} is driven into the Ta backing to a depth such that the α particles subsequently emitted from the excited B^{11} lose a significant fraction of their energy in emerging from the Ta; furthermore, the Be^{11} distribution within the Ta covers a considerable range of depth so that the primitive α-particle spectrum, i.e., that arising directly from the β decay, is severely distorted by the absorption on its emergence from the Ta.

(ii) There are several candidate states in B^{11} that might be excited in the β decay; all are broad and, since the region of excitation in question is such that the α-particle penetrability is changing rapidly as a function of energy, the profile of the states is not simple and they tend to display significant asymmetry and tails towards higher excitation.

(iii) As already pointed out in the preceding section, Li^7 has a low-lying excited state at 478 keV, and one must consider α decay of the B^{11} to it as well as to the ground state.

(iv) The region of excitation of B^{11} in question is one over which the W^5 factor in the β decay is changing rapidly; this factor, rather than the profile of the B^{11} states, dominates the situation for the higher regions of excitation, corresponding to the higher α-particles energies.

(v) The properties of the B^{11} states in the region of excitation of importance are not uniquely established and in some cases their existence is unsure.

The relevant region of B^{11} has been best studied by Cusson[13] and by Paul *et al.*[14] A well-established state of $J^\pi = \frac{3}{2}^+$ at a nominal excitation of 9870 keV is revealed by both sets of experiments although a considerable range of parameters is allowed by the experimental data within a gross width for the state of about 200 keV. This state is nominally unstable by 1220 keV against breakup into $Li^7_{g.s.}$ plus an α particle so that the α particles would have a nominal energy of 780 keV. Having regard to the width of the state [and its high-energy tail as mentioned in (ii) above], it does not seem unreasonable that it should be responsible for the experimental distribution of Fig. 2. This expectation is born out by the detailed computations to be described. Unfortunately, there does not exist any set of parameters that fully describes all the measured properties of this state as seen in $Li^7(\alpha,\alpha)Li^7$ and $Li^7(\alpha,\alpha')$-Li^7_{478}; in particular, the state may be very inelastic in its deexcitation, preferring decay to the first excited state of Li^7 by a factor of as much as 4 over decay to the ground state.[13] The α particles leading to the excited state would scarcely be detected in our experiment so that a major uncertainty in the *ft* value would result.

We must also consider the state at a nominal energy of 10 250 keV and of width similar to that of the 9870-keV state. The preferred J^π is $\frac{3}{2}^-$, but $\frac{1}{2}^\pm$ and $\frac{3}{2}^+$ cannot be excluded.[14] If the chief decay of this state were to be to the excited state of Li^7, it could not be distinguished from the 9870-keV state; however, it is reported[13,14] to decay predominantly to the ground state of Li^7.

The final possibility that we seriously entertain is the very broad $J^\pi = \frac{1}{2}^+$ state at a nominal energy of 10 380 keV proposed by Cusson[13] but on arguments not deemed to be compelling by Paul *et al.*[14] (In Cusson's paper the state is the one labeled 5′ in Table II, p. 496.) This state is proposed by Cusson to decay predominantly to the first excited state of Li^7, which would make the nominal energy of its α particles 790 keV; it is therefore as good a *prima facie* candidate as the 9870-keV state.

The first step in the computation of the α-particle spectrum as seen by the silicon detector was to determine the energy and angular distribution of the Be^{11} coming from the (t, p) reaction. This was done on the assumptions that only the ground state of Be^{11} is involved in the production process (the first excited state at 319 keV is also energetically available) and that the protons are isotropic in the center-of-mass frame. Since the proton momentum is only about a third of the triton momentum, neither of these assumptions is very critical.

The second step was to calculate the distribution in depth in the Ta of the stopped Be^{11}. This was done using the range-energy data given by Northcliffe and Schilling.[15]

The third step was the most difficult one and was the computation of the primitive α-particle spectrum coming from the breakup of B^{11} following β decay of the Be^{11}. For the three possible B^{11} states discussed above, the parameters of Cusson were used to determine the profiles of the states and their relative breakup probabilities to the ground and first excited states of Li^7. The state profiles were weighted as a function of the excitation in B^{11} by the f value of the β decay to that excitation in order to supply the W^5 factor. As mentioned above, this is a critically important factor.

The final step was to calculate the emergent α-particle spectrum from the primitive spectrum of the third step and the depth distribution of the second step. For this final step, the range-energy data of Northcliffe and Schilling were again used.

Figure 2, curves a, b, and c, show the way in which the three calculated distributions fit the experimental data. Each curve has been adjusted in ordinate position for the best over-all fit to the experimental points. The general quality of the fit is good but it must be remarked that the dominating influence of the W^5 factor together with the

TABLE II. B^{11} level energies and Be^{11} β-ray branches and logft values.

B^{11} level (keV) Present results	Previous results	J^{π}	β branch in %	logft [d]
0	0	$\frac{3}{2}^-$	57 ± 3	6.81 ± 0.02
2125.0 ± 0.7	2124.8 ± 0.7 [b]	$\frac{1}{2}^-$	29 ± 3	6.68 ± 0.04
	4445.3 ± 1.3 [b]	$\frac{5}{2}^-$	<0.06	>10.9
5020.1 ± 1.7	5019.7 ± 1.7 [b]	$\frac{3}{2}^-$	0.28 ± 0.11	7.94 ± 0.14
6742.7 ± 1.8 [a]	6743.8 ± 1.8 [b]	$\frac{7}{2}^-$	<0.08	...
6792.6 ± 1.8	6793.7 ± 1.8 [b]	$\frac{1}{2}^+$	6.8 ± 0.8	5.91 ± 0.05
	7296 ± 4 [c]	$\frac{5}{2}^+$	<0.16	...
7978.1 ± 1.9	7996 ± 6 [c]	$\frac{3}{2}^+$	3.9 ± 0.5	5.58 ± 0.05
	8566 ± 4 [c]	$\frac{3}{2}^-$	<0.06	>7.0
	8925 ± 4 [c]	$\frac{5}{2}^-$	<0.02	>8.5
	9870 ± 20 [c]	$\frac{3}{2}^+$	3.0 ± 0.7	4.03 ± 0.15
			[15 ± 3.5]	[3.33 ± 0.15]

[a] Derived from the present value of the fifth excited state and the (5th–4th) separation of 49.9 keV from the second column (Ref. 8).

[b] See Ref. 8.

[c] See Ref. 2.

[d] The values quoted refer to logf_0t except for the 4445- and 8925-keV states where we quoted logf_1t. The adopted definition of f_1 is that given by E. K. Warburton, G. T. Garvey, and I. S. Towner, Ann. Phys. (N.Y.) 57, 174 (1970), which results in ft values 12 times greater than the older definition [see, for example, J. P. Davidson, Phys. Rev. 82, 48 (1951)]. The limits on the β-decay branches to the 6743- and 7296-keV states are consistent with the established J^{π} values of those states but are not otherwise informative in view of the high degree of forbiddenness of the transitions. The figures without brackets for the 9870-keV state assume that its breakup is solely to the ground state of Li^7; the square-bracketed figures assume the inelasticity given by Cusson (Ref. 13), and if this inelasticity should be correct, the β-ray branch to the ground state would require a decrease of 12% and its logft value a corresponding increase of 0.08. The logft values quoted for the 9870-keV state result from appropriate integration of the f function across the profile of the state. Some uncertainty attaches to this operation on account of the range of parameters allowed by the $Li^7 + \alpha$ scattering data (Refs. 13 and 14); the errors on the logft values have therefore been appropriately increased above those deriving from the ratios.

great distortion of the spectra by the depth distribution of the Be^{11} in the Ta tend to outweigh the differences between the states under consideration. It seems rather likely that the 10 250-keV state should be excluded from chief responsibility on account of its poor fit in the lower energy region, but no discrimination may be made between the other two candidates on the basis of the α-particle spectra alone. However, the absence of α-γ coincidences enables us to say that the possible 10 380-keV state cannot be responsible for more than, at the most, 5% of the α-particle spectrum seen in Fig. 2. It is more difficult to quantify the possible extent of the participation of the 10 250-keV state, but it is unlikely to be responsible for more than 30% of the α-particle spectrum of Fig. 2, and we shall use this figure in discussion.

In Table II we assume that the 9870-keV state is solely responsible for the α particles. It is important to note, however, that the limits that we have just stated for the possible involvement of the 10 250- and 10 380-keV states imply, for the β transitions to them, $\log ft > 4.3$ and > 5.1, respectively.

IV. DECAY SCHEME OF Be^{11}

The γ-ray energies given in the first column of Table I were used to derive the energies of the corresponding states of B^{11}. Corrections for nuclear recoil, ranging from 0.15 keV for the 1772-keV γ ray to 3.1 keV for the 7975-keV γ ray, were added to obtain the level separations. For the 6793- and 7978-keV states, the energy of the state was taken to be the average of the values derived from the ground-state transition and the sum of the two cascade transitions. The difference between the separate values was 0.6 keV for the 7978-keV state and 0.3 keV for the 6793-keV state. The values for the B^{11} states derived from the present work are given in the first column of Table II. The energy of the 6743-keV state given in the first column of Table II is based on our value for the 6793-keV state and the 6793-6743 energy difference of 49.9 keV from the work of

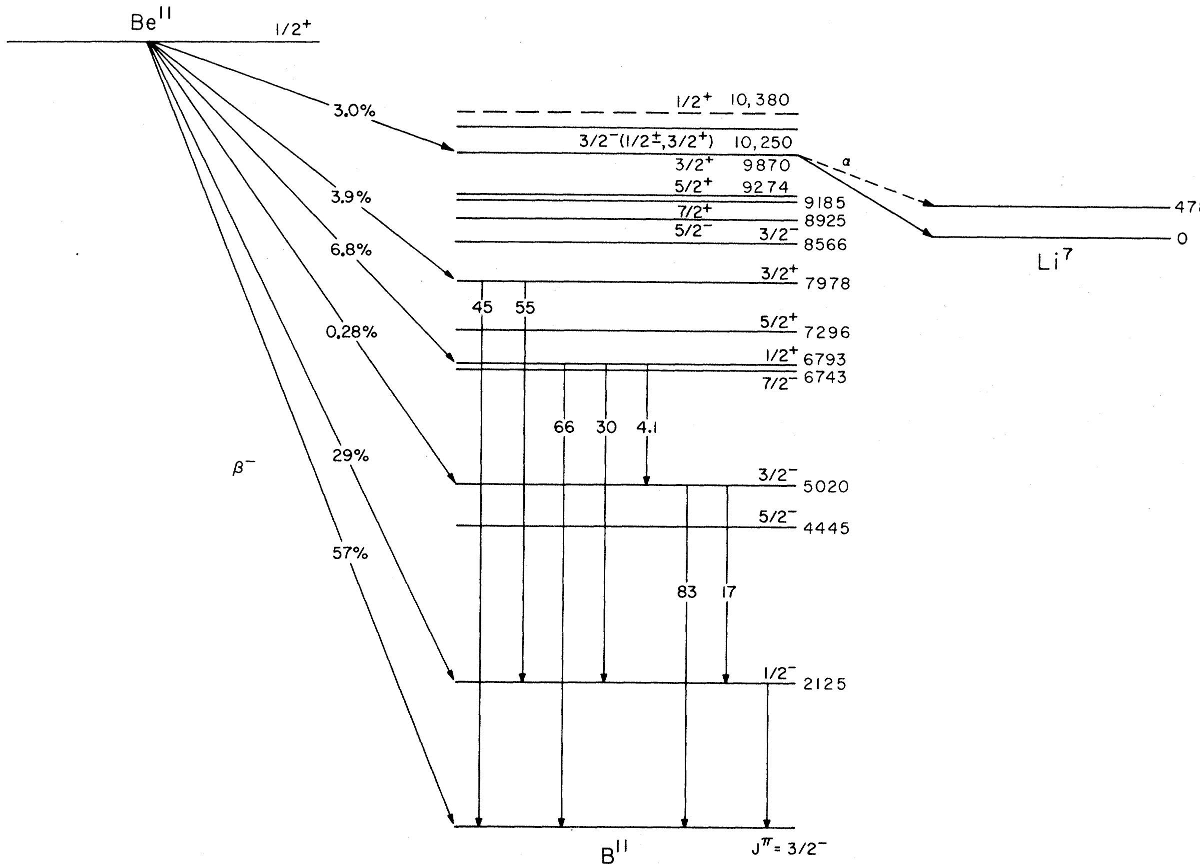

FIG. 4. Proposed decay scheme of Be^{11}. New results from the present work include: β branches to the 5020-keV level and to the α-particle-emitting state at 9870 keV; the 6793 → 5020 γ-ray branch; and considerably sharper upper limits on certain other β- and γ-ray branches.

Browne *et al.*[8] Our inferred excitation energies for the 2125-, 5020-, and 6793-keV states of B^{11} are in agreement with those of Browne *et al.*[8] given in the second column of Table II; our values are assigned the same uncertainties and they can be considered as adjustments to the level energies given by Browne *et al.* The energy of the seventh excited state at 7978 keV is based on the lower states and has an uncertainty derived almost wholly from the lower calibration lines. In this case, our value differs from the previously reported value[2] by three times the standard deviation of the earlier value.

The intensities of the γ rays given in Table I were used to derive the β-ray branching intensities of Be^{11} to the various γ-emitting states of B^{11}, as well as the γ branches of the B^{11} states themselves. The results are summarized in Tables II and III and Fig. 4. The β branches to the 6793- and 7978-keV states given in Table II are 6.8 $\pm$0.8% and 3.9$\pm$0.5%, respectively, in good agreement with the earlier results of 6.5% and 4.1%, respectively. Table III shows that the γ-ray branching from the 7978-keV state is also in good agreement with earlier work.[2] For the 6793-keV state, the two main γ-ray branches listed in Table III are consistent with the previous measurements[1,2] and the new 4.1% γ-ray branch leading to the 5020-keV state is within the previous upper limit[1] of 8%, as is the limit on the γ branch to the 4445-keV state. The 1772-keV transition between the 6793- and 5020-keV states has an intensity of 0.28$\pm$0.06% per decay (Table I) which is insufficient to account for the total population of the 5020-keV state; i.e., the combined intensity of the 5019- and 2893-keV γ rays is 0.56$\pm$0.10% per decay or just twice as great as the intensity of the 1772-keV γ ray. It is therefore necessary to postulate a new β branch from Be^{11} to the 5020-keV state of B^{11} having an intensity of 0.28$\pm$0.11% per decay as given in Table II. The γ branches from the 5020-keV state given in Table III are in good agreement with previous results,[2] although less accurate. A simple calculation shows that the β branch to the 2125-keV first excited state is 29$\pm$3%, as given in Table II.

TABLE III. γ-ray branching ratios from B^{11} levels measured in the β decay of Be^{11}.

Initial state (keV)	J^{π}	Final state (keV)	Branch in % (Ref. a)	(Ref. b)
5020	$\frac{3}{2}^-$	0	83 $\pm$5	85$\pm$2
		2125	17 $\pm$5	15$\pm$2
6793	$\frac{1}{2}^+$	0	66.0$\pm$1.5	71$\pm$5
		2125	30.0$\pm$1.5	29$\pm$5
		4445	<0.5	<8
		5020	4.1$\pm$0.9	<8
7978	$\frac{3}{2}^+$	0	45 $\pm$2	47$\pm$2
		2125	55 $\pm$2	53$\pm$2
		4445	<1.6	<1
		5020	<1.6	<1
		6743	<1.5	...
		6793	<1.4	...

[a]Present results. [b]Ref. 2, Table 11.9

Having determined the Be^{11} β branches to all γ-emitting states, and the 3.0% β branch to the 9870-keV α-emitting state of B^{11} derived in the preceding section, the remaining 57$\pm$3% of the decays proceed to the ground state of B^{11}. This result, also given in Table II, is in agreement with the earlier β branch of 61%. A dashed line in Fig. 4 indicates the possible α-particle decay of the 9870-keV state of B^{11} to the 478-keV first excited state of Li^7. In neither the α singles nor the α-γ coincidence experiments would it have been possible to detect this branch. Should it exist, then the Be^{11} β-ray branch to the 9870-keV state would be considerably greater than 3.0% as discussed in the footnote of Table II.

The $\log ft$ values for all of the observed β branches of Be^{11} are given in the last column of Table II. The values were calculated using the Be^{11} mass excess of 20.174$\pm$0.007 MeV reported recently by Goosman and Kavanagh.[16] Also included in Table II are limits on the β branches to other B^{11} states together with some of the corresponding limits on $\log ft$ values. These branching limits were obtained by searching the γ spectrum of Fig. 1 for the corresponding γ-ray lines, placing upper limits on their intensities, and making the appropriate efficiency and γ-branching corrections. The limits on the β branches to the 8566- and 8925-keV states were derived from an earlier experiment at lower gain which covered the complete γ-energy range up to 10 MeV. Certain other γ transitions between states were also searched for and the corresponding branching limits are included in Table III.

V. DISCUSSION

We discuss the findings of this paper by referring to the decay scheme of Be^{11} shown in Fig. 4. The data for the discussion are summarized in Tables II and III. It is likely that all states in B^{11} below 10 MeV have now been found and all the assignments are certain, or almost so. In giving the assignments of Fig. 4 we have followed the standard compilation[2] for B^{11} with the following additions. In the cases of the 5020-, 6793-, and 7296-keV states, we have used the uniquely established assignments for the analogs in C^{11}, these assignments being consistent with the possibilities established in B^{11}. For the 8566-keV state we have used the recently established assignment[17] for the analog in C^{11}. For the 10 250- and 10 380-keV states we followed the references cited earlier in the present text. The $J^\pi = \frac{1}{2}^+$ assignment for Be^{11} follows from the $l=0$ stripping pattern observed[18] in the $Be^{10}(d,p)Be^{11}$ reaction. This assignment for Be^{11} accords with the theoretical expectation of Talmi and Unna[5] and with the earlier certain demonstration of even parity[4] which, however, left open a range of spin possibilities.

We may discuss our results in the light of the Talmi-Unna model[5] for Be^{11}. The model regards Be^{11} as having the ground state of Be^{10} as its unique parent coupled to a $2s_{1/2}$ neutron. The same very simple model was proposed by Lane[19] for the low-lying $J^\pi = \frac{1}{2}^+$ states of C^{13} (3.09 MeV) and N^{13} (2.37 MeV) where the ground state of C^{12} is the similar unique parent for the attachment of a $2s_{1/2}$ nucleon. In the case of $A=13$, direct support for the model comes from the fact that the $J^\pi = \frac{1}{2}^+$ levels in question both display essentially single-particle reduced widths: N^{13} as seen through the directly measured width for the proton-unstable state,[18] and C^{13} as seen through $C^{12}(d,p)$-C^{13} stripping.[20] The model then extends to B^{12} by the removal of a $1p_{3/2}$ proton from the C^{12} core of the C^{13} $J^\pi = \frac{1}{2}^+$ state, thereby generating a $J^\pi = 1^-, 2^-$ doublet with the ground state of B^{11} as the unique parent. These expected states are identified with the $J^\pi = 1^-, 2^-$ states found experimentally in B^{12} at 2.62 and 1.67 MeV, respectively, and these two states indeed display reduced widths for the ground state of B^{11} of single-particle order as seen through $B^{11}(d,p)B^{12}$ stripping.[21] Further removal of a second $1p_{3/2}$ proton from the B^{11} core of the B^{12} states than generates the associated $J^\pi = \frac{1}{2}^+$ state of Be^{11} with the ground state of Be^{10} as unique parent as already remarked. The reduced width of the ground state of Be^{11} for s-wave neutron attachment to the ground state of Be^{10} is indeed essentially one single-particle unit as seen through the $Be^{10}(d,p)Be^{11}$ stripping.[18] Talmi and Unna commented that, within this model, the change in the interaction energy of the $2s_{1/2}$ neutron with the core particles is twice as great, on the removal of the two $1p_{3/2}$ protons (to make Be^{11}), as on the removal of the one (to make B^{12}), so that the competition between the $2s_{1/2}$ neutron level and the $1p_{1/2}$ level should be progressively more favorable to the former as one moves from C^{13} through B^{12} to B^{11}. In C^{13} the $2s_{1/2}$ level is 3.09 MeV above the $1p_{1/2}$ ground state. In B^{12} the center of gravity of the $J^\pi = 1^-, 2^-$ doublet due to the coupling of the $2s_{1/2}$ neutron to the B^{11} core is 1.44 MeV above the center of gravity of the $J^\pi = 1^+, 2^+$ doublet that finds itself as the ground state and that at 0.95 MeV, and that represents the coupling of the $1p_{1/2}$ neutron to the same core. The linear extrapolation into Be^{11} then predicts that the $2s_{1/2}$ state has become the ground state and that the $1p_{1/2}$ state should find itself at about 210 keV. As we have seen, the ground state of Be^{11} is indeed of $J^\pi = \frac{1}{2}^+$. The first excited state is at 319 keV and is indeed of $J^\pi = \frac{1}{2}^-$. This follows from evidence summarized in Ref. 2 and from the $B^{11}(\mu^-, \nu)Be^{11}$ data of Deutsch *et al.*[22] The remarkable success of this simple model leaves little doubt as to its essential correctness and permits us to use it as a realistic basis for discussing the β decay of Be^{11}.

As is seen from Table II, we have determined the strengths of three nonunique first-forbidden β decays of Be^{11} to the ground, first, and third excited states of B^{11}, and have placed a limit on the strength of the unique first forbidden decay to the second excited state. The ft values of the three nonunique transitions are of a quite usual magnitude, but the limit on the f_1t value for the unique first-forbidden transition is interestingly large. The recent complication of unique first-forbidden β decays by Towner *et al.*[23] shows a rather tight clustering of $\log f_1t$ values with all 11 examples for $A \leq 40$ being contained in the range 9.6 ± 0.5. The Be^{11} case studied here is at least 20 times slower than the average. This is probably to be understood as reflecting the accuracy of the simple model for Be^{11}, which has the $J=0$ ground state of Be^{10} as its unique parent; this state is not a parent of the $J^\pi = \frac{5}{2}^-$ state of B^{11} in question within the p^7 description that seems to work rather well.[24] Within these schemes we therefore expect the transition rate in question to be zero. A finite rate for the transition would probably reflect a component in the Be^{11} ground-state wave function in which a $J^\pi = 2^+$ parent in Be^{10} (presumably the lowest) couples to a $1d_{5/2}$ neutron. Experience in the $A=13$ system suggests that such a component is probably rather small.[19] The fractional parentage coefficient within the p^7 scheme of the $J^\pi = \frac{5}{2}^-$ state of B^{11} in question for the lowest $J^\pi = 2^+$ state of Be^{10} is indeed large[25] so that only a few percent admixture by intensity of $Be^{10}(J^\pi = 2^+) \times 1d_{5/2}$ into the ground state of Be^{11} would be needed to explain the observed decay rate. The p^7 description also provides a nice qualitative understanding of the relative strengths of the three nonunique first-forbidden transitions. The theoretical fractional-parentage coefficients of the ground, first excited, and third excited state of B^{11}, C^{11} for the lowest $T=1$ state of the $A=10$ system; i.e., the isobaric triplet including the ground state of Be^{10} are, respectively, -0.30, 0.35, and 0.07.[25] This leads us to expect approximate equality of the first-forbidden decay strengths to the two lowest of the three states with that to the third an order of magnitude weaker, as we observe from Table II.

Before leaving the first-forbidden decays we may comment on the two limits that we have established for decay to the $J^\pi=\frac{3}{2}^-$ state at 8566 keV and to the $J^\pi=\frac{5}{2}^-$ state at 8925 keV. The latter decay is unique first forbidden and our limit of $\log f_1 t > 8.5$ is therefore not an interesting one. The $J^\pi=\frac{3}{2}^-$ state, if we identify it with the third such state of the p^7 scheme, has a theoretical fractional-parentage coefficient for the Be^{10} ground-state isobaric triplet of 0.08; we may therefore expect the Be^{11} decay strength to it to be similar to that to the 5020-keV state where the fractional-parentage coefficient is 0.07. The limit $\log ft > 7.0$ seen in Table II is therefore not surprising.

We turn now to the allowed decays. Consider the analog in B^{11} of the Be^{11} ground state. This state is identified as that at 12.57 MeV[2]. It will have components both from $Be^{10}_{g.s.}$ coupled to a $2s_{1/2}$ proton and also from the B^{10} member of the $Be^{10}_{g.s.}$ isobaric triplet coupled to a $2s_{1/2}$ neutron. The question is now: Does there exist a $T=\frac{1}{2}$ antianalog to this $T=\frac{3}{2}$ analog of the Be^{11} ground state? If such a $J^\pi=\frac{1}{2}^+$, $T=\frac{1}{2}$ state exists its composition will be, by intensity, two parts $Be^{10}+p$ to 1 part $B^{10}+n$. We need only consider the composition by intensity because we are concerned with the β decay to this state which goes solely by the conversion of the $2s_{1/2}$ neutron of Be^{11} into the $2s_{1/2}$ proton of the hypothetical antianalog in B^{11}. The speed of the β decay would therefore simply be $\frac{2}{3}$ of the Gamow-Teller part of the β decay of the free neutron, and this gives the expectation $\log ft = 3.44$. If this antianalog exists, we should expect it several (perhaps 4 to 8) MeV below the analog on the basis of the (poorly established) strength of the $\vec{t}\cdot\vec{T}$ term in the $1p$-shell optical-model potential. The $J^\pi=\frac{1}{2}^+$ state at 6793 keV then becomes the obvious candidate for the antianalog but is not acceptable because the β decay to it is some 300 times too weak. As we have seen in the previous section the possible $J^\pi=\frac{1}{2}^+$ state nominally at 10 380 keV, if it exists, has $\log ft > 5.1$, so β decay to it is at least 50 times too weak and it cannot be a candidate for the antianalog; in addition, its separation from the analog – only a little over 2 MeV – would be surprisingly small. It seems rather sure, therefore, that the antianalog does not exist in B^{11}. The $J^\pi=\frac{1}{2}^+$, $T=\frac{1}{2}$ states must have mixed parentage involving $J^\pi=1^+$, $T=0$ parents as well as the $J^\pi=0^+$, $T=1$ parent responsible for the ground state of Be^{11} and its analog in B^{11}. β decay to such states would involve, coherently, the β decay of the $2s_{1/2}$ neutron of Be^{11} leaving the $T=1$ core unchanged (i.e., the antianalog transition that we have failed to find), and the β decay of the $T=1$ core of Be^{11} leaving the $2s_{1/2}$ neutron unchanged. The latter (core) transitions are well known, from C^{10} to the possible $J^\pi=1^+$ parent states in B^{10} at 717 and 2154 keV which have $\log ft = 3.0$[26] and 4.8,[27] respectively. The states in B^{11} made from the weak coupling of a $2s_{1/2}$ neutron to these low $J^\pi=1^+$ states might not unreasonably be at comparable excitation to that expected for the missing antianalog, and so mixing could be strong resulting in one low-lying $J^\pi=\frac{1}{2}^+$ state, namely, that at 6793 keV and higher states perhaps beyond the reach of Be^{11} β decay. Since one of the $J^\pi=1^+$ parents has a $\log ft$ value of 3.0, comparable with the 3.4 expected for the antianalog decay, the combination involving the two in the appropriate relative amplitude and phase could certainly produce the $\log ft = 5.9$ seen for the 6793-keV level.

It will, however, be noticed that decay to the $J^\pi=\frac{3}{2}^+$ state at 7978 keV is just about twice as strong as that to the $J^\pi=\frac{1}{2}^+$ state at 6793 keV. This might be taken to suggest a common parentage for those two states built only out of the 717- and 2154-keV states of B^{10} that we have just been discussing, without strong participation of the antianalog in the $J^\pi=\frac{1}{2}^+$ state. This would leave us without a resolution of the missing antianalog problem, unless we further supposed that the $J^\pi=\frac{1}{2}^+$ state involving the combination of the $J^\pi=1^+$ parents orthogonal to that lying behind the 6793- and 7978-keV states mixes with the antianalog and displaces it to higher energies. If we mix the $J^\pi=1^+$ parents in such a way that they give the observed strength for β decay to the 6793-keV state (and so also for the 7978-keV state) then their orthogonal combination is expected to give a $J^\pi=\frac{1}{2}^+$ β-decay strength of $\log ft \approx 3.5$ which is powerful enough to cancel the β decay to the antianalog on mixing with it and so permit identification with the 10 380-keV state if that exists. We must, however, then inquire into the strength of β decay to the associated orthogonal $J^\pi=\frac{3}{2}^+$ state; we should expect $\log ft \approx 3.2$. This, as we see from Table II, indeed permits identification with the 9870-keV state if it has the inelasticity reported by Cusson.[13] The fact that the $J^\pi=\frac{3}{2}^+$ state involving the orthogonal combination of the $J^\pi=1^+$, $T=0$ parents lies below the states that involve mixing of the $J^\pi=\frac{1}{2}^+$ orthogonal combination with the antianalog is not pleasing for this model but probably merely reflects the role, that we have neglected here, of the antianalog in the lower-lying $J^\pi=\frac{1}{2}^+$ state.

The situation is, of course, too complex to be resolved with the meager data at hand. We conclude that the antianalog does not exist but that this is not necessarily surprising and presents no major difficulty.

The γ branches displayed in Table III for the most part confirm previously established ratios. The low limit that we place on the branch between the 6793- and 4445-keV states of B^{11} is, however, useful in further strengthening the $J=\frac{1}{2}$ assignment for the former state.

Further studies of Be^{11} decay would be useful if ways could be found to produce very thin sources and to suppress the effects due to the β rays. It would be desirable to reveal the complete structure of the α-particle spectrum, including the region of very low energies. Alternatively, a reinvestigation of the α-scattering properties of the 9870-keV state of B^{11} would help to resolve a major uncertainty in the Be^{11} decay scheme.

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[1]D. H. Wilkinson and D. E. Alburger, Phys. Rev. 113, 563 (1959).

[2]F. Ajzenberg-Selove and T. Lauritsen, Nucl. Phys. A114, 1 (1968).

[3]P. F. Donovan, J. V. Kane, R. E. Pixley, and D. H. Wilkinson, Phys. Rev. 123, 589 (1961).

[4]D. E. Alburger, C. Chasman, K. W. Jones, J. W. Olness, and R. A. Ristinen, Phys. Rev. 136, B916 (1964).

[5]I. Talmi and I. Unna, Phys. Rev. Letters 4, 469 (1960).

[6]The Be sample was obtained from Leico Industries, Inc., New York, and was kindly placed at our disposal by Dr. J. E. Crow.

[7]K. A. Snover, D. B. Fossan, J. McDonald, and E. K. Warburton, to be published; See also R. C. Greenwood, R. G. Helmer, and R. J. Gehrke, Nucl. Instr. Methods 77, 141 (1970).

[8]C. P. Browne, G. Maille, R. Tarara, and J. R. Duray, Nucl. Phys. A153, 289 (1970).

[9]T. A. Alexander, private communication.

[10]H. S. Pruys, private communication to G. A. P. Engelbertink.

[11]P. D. Parker, Phys. Rev. 150, 851 (1966).

[12]D. E. Alburger and G. A. P. Engelbertink, Phys. Rev. C 2, 1594 (1970).

[13]R. Y. Cusson, Nucl. Phys. 86, 481 (1966).

[14]P. Paul, N. G. Puttaswamy, and D. Kohler, Phys. Rev. 164, 1332 (1967).

[15]L. C. Northcliffe and R. F. Schilling, Nucl. Data A7, 233 (1970).

[16]D. R. Goosman and R. W. Kavanagh, Phys. Rev. C 1, 1939 (1970).

[17]H. T. Fortune, J. R. Comfort, J. V. Maher, and B. Zeidman, Phys. Rev. C 2, 425 (1970).

[18]D. L. Auton, Nucl. Phys. A157, 305 (1970).

[19]A. M. Lane, Rev. Mod. Phys. 32, 519 (1960).

[20]R. N. Glover and A. D. W. Jones, Nucl. Phys. 84, 673 (1966).

[21]A. Gallmann, F. Hibou, P. Fintz, P. E. Hodgson, and E. K. Warburton, Phys. Rev. 138, B560 (1965).

[22]J. P. Deutsch, L. Grenacs, J. Lehmann, P. Lipnik, and P. C. Macq, Phys. Letters 28B, 178 (1968).

[23]I. Towner, G. T. Garvey, and E. K. Warburton, to be published.

[24]S. Cohen and D. Kurath, Nucl. Phys. 73, 1 (1965).

[25]S. Cohen and D. Kurath, Nucl. Phys. A101, 1 (1967); and private communication.

[26]T. Lauritsen and F. Ajzenberg-Selove, Nucl. Phys. 78, 1 (1966).

[27]D. R. Brown, S. M. Ferguson, and D. H. Wilkinson, Nucl. Phys. A135, 159 (1969).