States of Be^{11}, B^{11}, and C^{11}†

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The gamma-decay of the 4.46- and 5.03-Mev levels of B^{11} has been determined by (p,γ) coincidences using the reaction $Be^9(He^3,p)B^{11}$. The 5.03-Mev level is found to decay with a probability of 0.14 ± 0.03 via the state at 2.13 Mev; the intensity of the branch to the state at 4.46 Mev is less than 3×10^{-3}. The intensity of the branch from the 4.46-Mev level via that at 2.13 Mev is less than 5×10^{-3}. The data on these states are reviewed and it is concluded that the present results strongly favor the choices $J=\frac{1}{2}-$, $\frac{5}{2}-$, $\frac{3}{2}-$ for the states at 2.13, 4.46, and 5.03 Mev, respectively, without appeal to a model. It is, however, emphasized that the body of data as it stands at the moment might admit $J=\frac{1}{2}+$ for the 2.13-Mev state and $J=\frac{1}{2}-$ for the 5.03-Mev state. The previsions of the independent-particle model (IPM) are then examined and it is concluded that best general agreement between theory and experiment is achieved for $a/K\approx4-4.5$. The likely relevance of the collective model is remarked upon. It is demonstrated with the aid of the reaction $B^{10}(p,\gamma)C^{11}$ that the ordering of the first three excited states of C^{11} is the same as in B^{11}. The beta-decay of Be^{11} is reconsidered in the light of the increased firmness of the assignments in B^{11} and of the previsions of the IPM; it is concluded that Be^{11} is most probably of even parity.

INTRODUCTION

THE low-lying $T=\frac{1}{2}$ levels of $A=11$ are of considerable interest for an unusual variety of reasons:

(i) We are here in the middle of the $1p$ shell, the independent-particle model (IPM) is faced with a five-body problem, and it is unlikely that extensive agreement between theory and experiment could be written off as due to chance. In fact, the theoretical level scheme is particularly sensitive to the intermediate coupling parameter a/K for $A=11$, and so reliable level assignments are important in tying down the a/K and K values in this significant region of the shell.[1]

(ii) The first excited state at 2.13 Mev in B^{11} and at 1.99 Mev in C^{11}, reputedly of $J=\frac{1}{2}-$,[2] is nevertheless excited by stripping in the reactions $B^{10}(d,p)B^{11}$ and $B^{10}(d,n)C^{11}$ sometimes displaying an $l=1$ pattern.[3] This is of great interest for our discussion of the mechanism of the stripping process indicating the importance of an exchange,[4] spin-flip,[2,5] or other "irregular" mechanism, and the assignment should be confirmed by every means possible.

(iii) The beta decay of Be^{11} leads to the ground and first excited (2.13-Mev) states of B^{11} with respective $\log ft$ values of 6.77 and 6.63.[6] According to the shell model, Be^{11} should be $J=\frac{1}{2}-$ and so allowed decays are expected to these two states if they are indeed, respectively, $J=\frac{3}{2}-$ and $\frac{1}{2}-$ as is supposed. These rather large $\log ft$ values lead to the supposition that Be^{11} may be $J=\frac{1}{2}+$ rather than $J=\frac{1}{2}-$, i.e., of the "wrong" parity.[6,7] The decay to the 5.03-Mev state has $\log ft\geq8.2$, a value that excludes an allowed transition with fair certainty. A comparison between the experimental level scheme and that calculated in intermediate coupling suggests that the 5.03-Mev level is $J=\frac{7}{2}-$.[1] It is, however, reported[8] that this level branches with a probability of about 0.12 to the first excited state, the chief transition being to the ground state. If then, the 2.13-Mev state is indeed $J=\frac{1}{2}-$ it is difficult to reconcile the low-energy branch with $J=\frac{7}{2}-$ (or $J=\frac{5}{2}-$) for the 5.03-Mev state and $J=\frac{3}{2}-$ would seem to be implied. [The (d,p) stripping pattern is of $l=1$.[3] An anomaly of the type responsible for the $l=1$ pattern for the first excited state would admit $J=\frac{1}{2}-$ but we should naturally favor an interpretation in favor of "regular" stripping, i.e., $J=\frac{3}{2}-$, etc. We should also favor $J=\frac{3}{2}-$ since the intermediate-coupling level scheme[1] provides a nearby $J=\frac{3}{2}-$ state and no nearby $J=\frac{1}{2}-$ state. Furthermore, the theoretical branching ratio[9] from the $J=\frac{3}{2}-$ model state to the $J=\frac{1}{2}-$ (first excited) model state is about 0.10, in good agreement with the experimental report. These

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[1] D. Kurath, Phys. Rev. **101**, 216 (1956).
[2] D. H. Wilkinson, Phys. Rev. **105**, 666 (1957).
[3] N. T. S. Evans and W. C. Parkinson, Proc. Phys. Soc. (London) **A67**, 684 (1954); see also the results for the corresponding state in $B^{10}(d,n)C^{11}$ in E. E. Maslin, J. M. Calvert, and A. A. Jaffe, Proc. Phys. Soc. (London) **69**, 745 (1956); M. Cerineo, Nuclear Phys. **2**, 113 (1956).
[4] N. T. S. Evans and A. P. French, Phys. Rev. **109**, 1271 (1958).
[5] J. E. Bowcock, Phys. Rev. **112**, 923 (1958); see also J. Hensel and W. C. Parkinson, Phys. Rev. **110**, 128 (1958).
[6] D. H. Wilkinson and D. E. Alburger, Phys. Rev. **113**, 563 (1959).
[7] I. Talmi and I. Unna, Phys. Rev. Letters **4**, 469 (1960).
[8] A. J. Ferguson, H. E. Gove, J. A. Kuehner, A. E. Litherland, E. Almqvist, and D. A. Bromley, Phys. Rev. Letters **1**, 414 (1958).
[9] D. Kurath, Phys. Rev. **106**, 975 (1957).

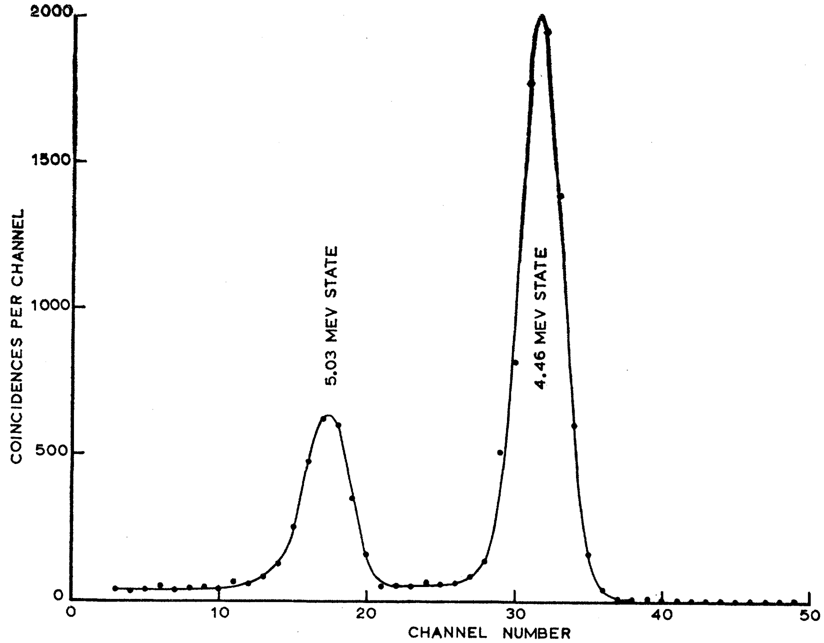

FIG. 1. Proton groups leading to the 4.46-Mev and 5.03-Mev states of B^{11}, observed in the solid-state counter following the reaction $Be^9(He^3,p)B^{11}$. Bombarding energy: 1.7 Mev; angle of observation: 128°.

matters are further discussed later.] But with $J=\frac{3}{2}-$ or the alternative $J=\frac{1}{2}-$ for the 5.03-Mev state, the Be^{11} transition is allowed and the $J=\frac{1}{2}-$ assignment for Be^{11} looks very improbable. The checking of the reported branch from the 5.03-Mev state to the first excited state[8] and the clinching of the $J=\frac{1}{2}-$ assignment for the first excited state by independent data (to exclude the possibility of $J=\frac{5}{2}-$ for the 5.03-Mev state) are therefore crucial to the argument about the parity of Be^{11} based on the $\log ft$ value to the 5.03-Mev state.

(iv) The 4.46-Mev state of B^{11} is reportedly[10] $J=\frac{5}{2}-$ and so should not decay appreciably via the 2.13-Mev state if that is indeed $J=\frac{1}{2}-$. States in C^{11} are found at 4.26 and 4.75 Mev. By charge symmetry we should associate these as mirror states of those in B^{11} at 4.46 and 5.03 Mev, respectively, the shifts of less than 300 kev between the members of the mirror pair being quite acceptable. However, it is reported[11] that it is the 4.26-Mev and not the 4.75-Mev state of C^{11} that branches via the first excited state. This suggests that the states have crossed over in going into C^{11} and that there the 4.26-Mev state corresponds to the 5.03-Mev state of B^{11}. This implied shift of about 800 kev is a serious matter, since we are far from heavy-particle instability and Thomas shifts should be small. It is therefore of importance to check the correspondence between these states of B^{11} and C^{11}.

These several problems may be approached through a careful examination of the gamma-ray decay schemes of the various levels in both nuclei. These measurements will now be described and will be followed by the detailed analysis in terms of the J values.

MEASUREMENTS: RADIATIONS FROM B^{11}

The branching ratios of the 4.46- and 5.03-Mev states of B^{11} were determined by measuring coincidences between the gamma-rays of de-excitation from B^{11} and the protons leading to the state in question from the reaction $Be^9(He^3,p)B^{11}$ ($Q_0=10.33$ Mev).

Thin metallic beryllium targets evaporated onto copper were bombarded with He^3 particles of energy 1.7 Mev. Protons emitted at an angle of 128° to the bombarding beam were detected in a solid-state counter (silicon). The counter was covered with a thin foil of aluminum to exclude the elastically scattered He^3 particles. The gamma rays were detected in a 5 in.×5 in. cylindrical NaI(Tl) crystal whose axis passed through the target at right angles to the plane defined by the He^3 beam and the detected protons and whose front face was 3 cm from the target spot. This very bad geometry for the gamma-ray detector effectively integrated over the $p-\gamma$ angular correlation to a degree quite adequate for our present purposes.

The proton and gamma-ray pulses detected in

[10] G. A. Jones, C. M. P. Johnson, and D. H. Wilkinson, Phil. Mag. 4, 796 (1959). In the original report [G. A. Jones and D. H. Wilkinson, Phys. Rev. **88**, 423 (1952)] of this work on the reaction $Li^7(\alpha,\gamma)B^{11}$, the 4.46-Mev level was given as of $J=\frac{5}{2}+$. The angular distributions and correlations on which this assignment was based are insensitive to the parity but are critically determined by the spin which was always clearly established as $J=\frac{5}{2}$. The change of parity in the assignment followed the stripping results[3] and was easily accommodated in the analysis of the gamma-ray data, leaving the spin unchanged. Certain slight improvements are effected in the gamma-ray analysis by the change of parity, but the present assignment of spin to the state is due to the (α,γ) data, while the parity derives from the stripping.

[11] F. Ajzenberg-Selove and T. Lauritsen, Nuclear Phys. **11**, 1 (1959).

coincidence were displayed on a 64×64 channel two-dimensional pulse-height analyzer constructed at Brookhaven National Laboratory by R. L. Chase. Figure 1 shows the output from the solid-state counter in coincidence with gamma rays in the energy range 3.0−5.5 Mev. The two peaks represent transitions to the two states of interest in B^{11}, at 4.46 and 5.03 Mev. The width of these proton peaks can be understood in terms of the target thickness, straggling of the protons in the aluminum foil placed over the solid-state counter to exclude the elastically-scattered He^3 particles, and the finite angle subtended at the target by the counter. The actual resolution of the solid-state counter was about 0.5% for protons of the energy with which we are concerned here.

Figure 2 shows the gamma-ray spectrum in coincidence with the proton peak corresponding to the 4.46-Mev state. Very small corrections have been made on account of: (i) random coincidences which were estimated from the coincidences corresponding to proton transitions to the B^{11} ground state; (ii) genuine coincidences due to the low-energy tail of the proton group leading to the 2.13-Mev state of B^{11} which extends beneath the proton group to the 4.46-Mev state; these were estimated from true coincidences found for apparent proton energies intermediate between those corresponding to transitions to the first and second excited states (true coincidences which were themselves corrected for the random effect). This low-energy tail, which was of very small proportions, was due to an edge effect in the solid-state counter. The expected positions of the photopeaks for possible cascade gamma rays of 2.13 and 2.33 Mev due to a branch via the first excited state are shown. No such peaks are seen, and we can quote a limit of 5×10^{-3} on the intensity of the cascade relative to the ground-state transition. The excitation energy of the second excited state is determined to be 4.49±0.05 Mev, to be compared with 4.459±0.008 Mev of the literature.[11]

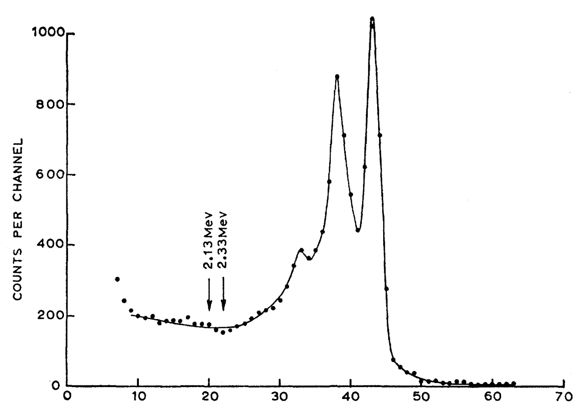

FIG. 2. Gamma-ray spectrum seen in coincidence with protons leading to the 4.46-Mev state of B^{11}. The expected positions of the photopeaks of the gamma rays of the cascade through the first excited state are shown. The peaks in channels 33, 38, and 43 are due to the ground-state transition.

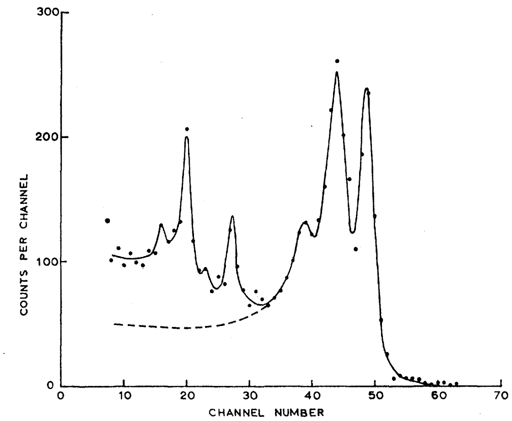

FIG. 3. Gamma-ray spectrum seen in coincidence with protons leading to the 5.03-Mev state of B^{11}. The peaks in channels 39, 44, and 49 are due to the ground-state transition; that in channel 27 is the photopeak from the transition to the first excited state; that in channel 20 is the photopeak from the transition from the first excited state. The dashed curve shows the expected form of the 5.03-Mev spectrum.

Figure 3 shows the gamma-ray spectrum in coincidence with proton transitions to the 5.03-Mev state. Similar small corrections have been applied as for Fig. 2. The cascade is obviously present. The inferred energies of the two transitions are 2.85±0.08 Mev and 2.09±0.05 Mev, to be compared with the expected 2.905±0.010 Mev and 2.127±0.006 Mev.[11] The two transitions are of the same strength to within the accuracy of our measurement and represent a de-excitation probability of 14±3% for the cascade relative to all transitions from the 5.03-Mev level, in good agreement with the earlier report[8] of 12%. The excitation energy of the third excited state inferred from these measurements is 5.05±0.05 Mev, to be compared with the 5.035±0.008 Mev of the literature.[11]

The probability of a cascade from the 5.03-Mev level via that at 4.46 Mev giving gamma rays of expected energy 0.576±0.011 Mev is of importance and was investigated in a separate run. Gamma rays due to annihilation radiation are, of course, found in true coincidence with protons leading to both the 4.46- and 5.03-Mev states. The coincidences for proton transitions to the 5.03-Mev state can be corrected for this effect by reference to those for transitions to the 4.46-Mev state which do not result in any gamma rays of low energy associated with states of B^{11}. When the appropriate subtraction is made, we find the spectrum of Fig. 4. The arrow shows the position of the possible 0.58-Mev peak. No such latter peak is seen, and we set a limit of 3×10^{-3} on the intensity of this cascade de-excitation from the 5.03-Mev state.

These intensities are discussed later.

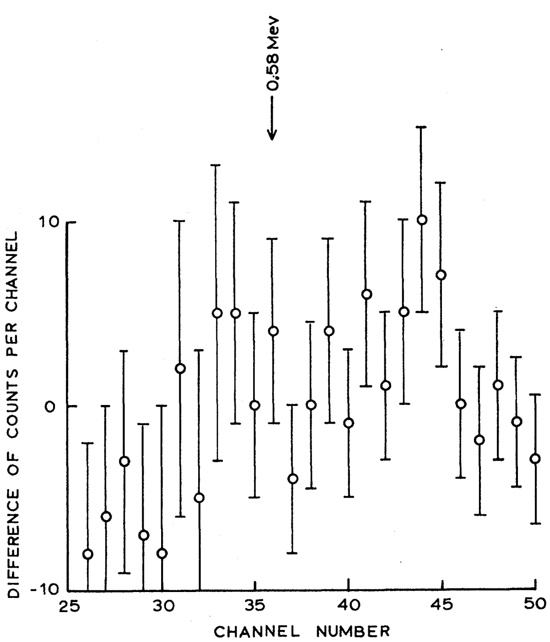

FIG. 4. Low-energy gamma ray difference spectrum seen in coincidence with protons leading to the 5.03-Mev state of B^{11}. The actual spectrum has had subtracted from it the corresponding and appropriately-normalized spectrum associated with proton transitions to the 4.46-Mev state of B^{11} in order to eliminate the effects of the annihilation radiation which is in coincidence with both. The arrow shows the expected position of the photopeak due to a possible transition between the 5.03- and 4.46-Mev states.

MEASUREMENTS: RADIATIONS FROM C^{11}

C^{11} is relatively difficult to handle. We have excited it using $B^{10}(p,\gamma)C^{11}$ and have examined $\gamma-\gamma$ coincidences, again using the 64×64 channel analyzer. Figure 5 shows the level scheme.[11]

A thick elemental target of B^{10} was bombarded with protons of 1.20 Mev and examined by two NaI(Tl) crystals, one of 5 in. diam×4 in. long and the other a cylinder of 3 in.×3 in., in bad geometry at 90° on either side of the target. In this way we excite an unknown number of levels of C^{11} in the effective range of excitation (allowing for the Coulomb barrier) 9.3–9.79 Mev. The excited levels have unknown properties and we do not attempt to determine these properties. We merely hope that the two levels of present interest at 4.26 and 4.75 Mev will be fed appreciably in the ensuing medley of cascades.

Consider first Fig. 6, which shows the gamma-ray spectrum observed in the smaller crystal in coincidence with pulses corresponding to energies in the range 5.10–5.48 Mev in the other crystal. By imposing this condition, we exclude from our examination the upper members of cascades leading to the 4.26- and 4.75-Mev states. The energy range selected excludes our seeing the decay of the 4.75-Mev state since this will be fed by a gamma ray of maximum energy 5.04 Mev. We shall see, however, the decay of the 4.26-Mev state if it is fed, the maximum gamma-ray energy to it being 5.53 Mev. Figure 6 shows, in fact, a fairly well-defined transition of measured energy 4.32±0.1 Mev. The expected three peaks due to this transition are delineated by the full line. Evidently many other transitions of lower energy are present, associated with unidentified initial transitions to states of C^{11} above 6.5 Mev, but these do not concern us and we have not attempted any decomposition of the spectrum. If, however, there were a branch from the 4.26-Mev state via the first excited state we should expect to see the elements of it at the positions indicated γ_1 and γ_3 in Fig. 6 (in the notation of Fig. 5) and in intensities (based on the known branching ratio in B^{11}) that should make them clearly visible. No such peaks appear to show up identifiably, corresponding to a branching ratio of less than 2% for the 4.26-Mev state.

Consider now Fig. 7. Here the spectrum is displayed in coincidence with pulses representing the energy range 4.35–4.72 Mev. Into this range will fall pulses due to initial transitions to both states at 4.26 and 4.75 Mev. If both these states are fed we shall see their superimposed spectra extending to higher channel numbers than in Fig. 6. This is the case, as can be seen. We make no attempt to unscramble these lines, which also contain transitions leading to the 4.75-Mev state.

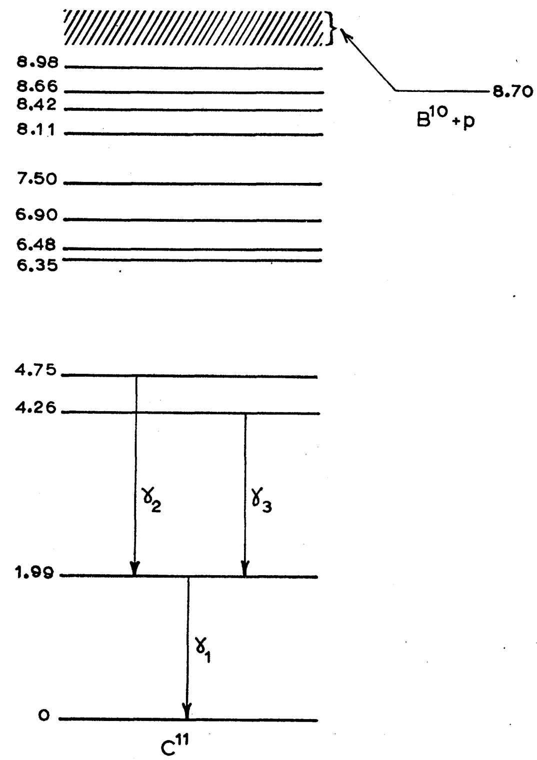

FIG. 5. Level scheme of C^{11}. The energies are in Mev. The cross-hatched region shows the band of excitation achieved in the conditions of the experiment: the bombardment of a thick target with protons of 1.20 Mev. The labeled gamma rays are those discussed in the text; the same notation is used in Figs. 6 and 7.

There are now also clearly seen the two lines indicated γ_1 and γ_2 which have measured energies 2.05 ± 0.08 and 2.72 ± 0.08 Mev, agreeing well with the expected 1.99 and 2.76 Mev of the elements of a cascade from the 4.75-Mev level which is now accessible. The estimated intensity of the cascade from the 4.75-Mev state is $15\pm5\%$.

This establishes clearly that it is the 4.75-Mev level and not that at 4.26 Mev that branches via the first excited state.

STATES OF C^{11}

The situation is already clear concerning the comparison between C^{11} and B^{11}. The fact that it is the 4.75-Mev and not the 4.26-Mev level of C^{11} that branches to the first excited state shows that the second and third excited states have the same order in the two nuclei. The apparent gross discrepancy with the expectation of charge symmetry is removed. Since we are concerned with $M1$ transitions which are not mirror transitions although they link mirror states, the exact comparison between the branching ratios in the two nuclei is not to be made. However, we should expect the reduced speeds to be rather closely the same under these conditions.[12] It is therefore not surprising that the branching ratio of $14\pm2\%$ found in B^{11}, transferred to the energies obtaining in C^{11} and remaining at 14%, agrees with the rather poorly determined $15\pm5\%$ of C^{11} itself.

This conclusion that the states of C^{11} are in the same order as those of B^{11} is supported by the observation that the reduced proton width as seen through stripping, $B^{10}(d,n)C^{11}$, is substantially smaller for the 4.75-Mev state than for the 4.26-Mev state,[13] just as the reduced neutron width for the 5.03-Mev state of B^{11} is substantially smaller than that for the 4.46-Mev state as seen in the mirror reaction $B^{10}(d,p)B^{11}$.[3,14]

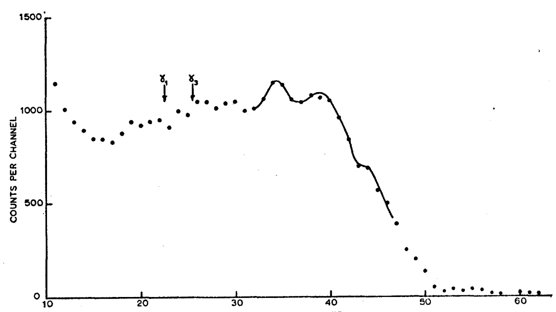

FIG. 6. Gamma-ray spectrum from C^{11} seen in coincidence with pulses in the energy range 5.10–5.48 Mev. The full line indicates the three peaks associated with the ground-state transition from the 4.26-Mev state; the arrows labeled γ_1 and γ_3 indicate the expected positions of the photopeaks associated with a possible cascade from that state through the first excited state (in the notation of Fig. 5).

[12] G. Morpurgo, Phys. Rev. **114**, 1075 (1959).
[13] A. N. James, A. T. G. Ferguson, and C. M. P. Johnson, Nuclear Phys. (in the press).
[14] O. M. Bilaniuk and J. C. Hensel, Phys. Rev. **120**, 211 (1960).

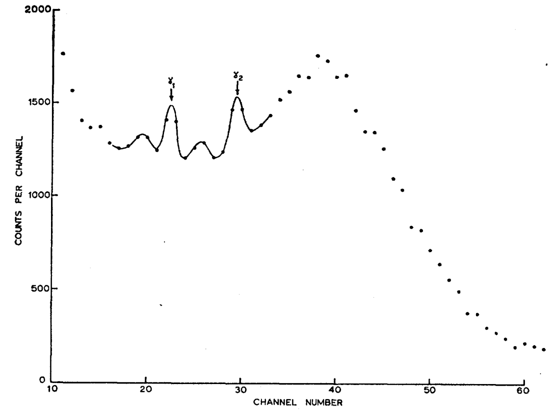

FIG. 7. Gamma-ray spectrum from C^{11} seen in coincidence with pulses in the energy range 4.35–4.72 Mev. The arrows labeled γ_1 and γ_2 indicate the photopeaks of the cascade gamma rays of the transition from the 4.75-Mev state via the first excited state (in the notation of Fig. 5).

STATES OF B^{11}

Consider now the levels of B^{11}. We accept tentatively the evidence of (d,p) stripping[3] that the parities of those levels with which we are concerned are odd and that the spins are $3/2\leqslant J\leqslant 9/2$, with the possible exception of the first excited state about which we have already remarked and whose assignment of $J=\frac{1}{2}-$ we must now examine and test anew. The ground state is assuredly of $J=\frac{3}{2}-$.

The measured lifetime of 4.6×10^{-15} sec[15] for the first excited state, firmly demands (as did the earlier lifetime limit)[2] that the transition to the ground state be dipole. The same conclusion follows for the second excited state from the lifetime of 1.2×10^{-15} sec.[16] We have just determined an upper limit of 5×10^{-3} on the branching ratio of the second to the first excited state; this implies a partial lifetime of greater than 2.4×10^{-13} sec and so, if the branch were an $M1$, we would have $|M|^2<(1\times10^{-2})$ in Weisskopf units. The chance that an $M1$ transition in the $1p$-shell has so small a value of $|M|^2$ is less than about 0.1.[17] It is therefore likely that the second and first excited states are not linked by an $M1$ transition. The only way of arranging things is, therefore, for the first excited state to be $J=\frac{1}{2}-$ and the second excited state to be $J=\frac{5}{2}-$. This conclusion does not, in fact, depend on our exclusion of $J=\frac{1}{2}-$ for the second excited state by the assumption that it is not reached by irregular stripping (although that would be most surprising since the cross section is quite large), since $J=\frac{1}{2}$ is firmly excluded by the anisotropy of the gamma rays from it to the

[15] F. R. Metzger, C. P. Swann, and V. K. Rasmussen, Phys. Rev. **110**, 906 (1958).
[16] V. K. Rasmussen, F. R. Metzger, and C. P. Swann, Phys. Rev. **110**, 154 (1958).
[17] D. H. Wilkinson, *Proceedings of the Rehovoth Conference on Nuclear Structure*, edited by H. J. Lipkin (North-Holland Publishing Company, Amsterdam, 1958), p. 175.

ground state seen in the reaction $Li^7(\alpha,\gamma)B^{11}$.[10] These conclusions, based on gamma-ray systematics, are no more than suggestive; they are, however, identical with those already reached about both states from other and completely independent evidence (reference 2 for the first excited state, reference 10 for the second) and it would now be most surprising if indeed the first and second excited states of B^{11} were other than $J=\frac{1}{2}-$ and $J=\frac{5}{2}-$, respectively. Note that this conclusion about the spin of the second excited state is even stronger if the first excited state should turn out to be $J=\frac{1}{2}+$.

Our present measurements do not bear on the parity of the 2.13-Mev state which we take as odd from the irregular stripping,[3] though we must note that, at least in the (d,p) reaction, the pattern varies greatly as a function of bombarding deuteron energy and has appeared to show up characteristics of $l=2$,[18] and even of $l=4$.[19] No clear-cut evidence is available. However, the double-stripping reaction $Be^9(He^3,p)B^{11}$ observed at bombarding energies of 5.7, 8.8, and 10.2 Mev shows an $l=0$ pattern[20] strongly favoring odd parity and $\frac{1}{2}\leqslant J\leqslant\frac{5}{2}$. The reaction $B^{10}(He^3,d)C^{11}$ to the corresponding state shows $l=1$ at a bombarding energy of 9.84 Mev,[21] again confirming the odd parity. Some caution is perhaps still necessary, however, in accepting the evidence of these still rather novel reactions. Further evidence as to the correctness of $J=\frac{1}{2}-$ rather than $J=\frac{1}{2}+$ comes from the excitation of B^{11} and C^{11} first excited states in the reactions $C^{12}(N,2N)$ using incident nucleons (both neutrons and protons) of energy 100–150 Mev. In these experiments, the first excited state is reached in just the right proportion relative to the ground state to agree with the IPM's prediction on the basis of a pure knock-out mechanism and for the value of the intermediate coupling parameter that gives agreement with the experimental level scheme and other low-energy properties.[22] The most likely configuration for a low-lying $J=\frac{1}{2}+$ state would involve a $2s_{\frac{1}{2}}$ nucleon coupled to states of B^{10} (see the first excited states of C^{13} and N^{13}), and this state could not be reached by a knock-out mechanism from C^{12} if we continue to describe the ground state of that nucleus as $1p$.[8] The experimental evidence, none of it conclusive, is therefore strongly in favor of odd parity and on this we must remain for the time being. An entirely fresh approach to this problem, for example an accurate determination of the internal conversion coefficient, would be most welcome.

[18] K. S. Lee and N. S. Wall, Bull. Am. Phys. Soc. **2**, 208 (1957).
[19] B. Zeidman and J. M. Fowler, Phys. Rev. **112**, 2020 (1958).
[20] S. Hinds and R. Middleton, Proc. Phys. Soc. (London) **75**, 754 (1960).
[21] S. Hinds and R. Middleton, Proc. Phys. Soc. (London) (in the press).
[22] A. B. Clegg, K. J. Foley, G. L. Salmon, and R. E. Segel (to be published).

This conclusion about the parity is fortified by the IPM in intermediate coupling,[1] which predicts a $J=\frac{1}{2}-$ state which furthermore has a theoretical lifetime[9] in good accord with the measured figure[15] at just this region of excitation. Although we cannot firmly exclude $J=\frac{1}{2}+$, we are led to prefer $J=\frac{1}{2}-$, since otherwise we should have to tolerate a state that we do not expect but with the properties of the one that we do expect, while the one that we do expect remains elusive.[23]

Consider now the assignment of the 5.03-Mev level of B^{11}. Consider the $J=\frac{7}{2}-$ assignment suggested for it by the IPM. This can be rejected firmly because: (i) The branch to the first excited state (now taken definitely as $J=\frac{1}{2}-$) would be an $M3$ of strength roughly 0.1 of the $E2$ to the ground state, whereas the corresponding ratio of the Weisskopf units is only about 1.5×10^{-7}. (ii) The branch to the second excited state (now taken definitely as $J=\frac{5}{2}-$) would be an $M1$ of strength less than roughly 0.02 of the $M3$ to the first excited state, whereas the corresponding ratio of Weisskopf units is about 1.3×10^{7}. (According to the IPM[9] this low-energy $M1$ transition should be rather weak, but it cannot be called upon to salvage so great a discrepancy.) The possibility of $J=\frac{1}{2}+$ for the first excited state does not weaken these arguments appreciably. The assignment $J=\frac{7}{2}-$ would be contrary to the conclusion based on the $l=0$ pattern in double stripping,[20] $Be^9(He^3,p)B^{11}$, that $\frac{1}{2}\leqslant J\leqslant\frac{5}{2}$.

Secondly, consider the possible assignment $J=\frac{5}{2}-$ for the 5.03-Mev state. The $E2$ branch to the first excited state relative to the $M1$ ground state transition would be about 1×10^{-4} using Weisskopf units, against the experimental 0.1. If we make the $E2$ transition improbably strong—10 Weisskopf units—and the $M1$ transition improbably weak—10^{-2} Weisskopf units—the experimental ratio could barely be met. This makes the assignment look rather unlikely. The $M1$ branch to the second excited state would be, using Weisskopf units, of strength about 20 relative to the $E2$ to the first excited state, against the experimental less than 0.02. To meet this limit we must, as before, assume that the $E2$ is improbably strong and assume that also this $M1$ transition is improbably weak. The assignment $J=\frac{5}{2}-$ requires three unlikely assumptions and is therefore regarded as very unlikely. The argument would be slightly strengthened if the first excited state were $J=\frac{1}{2}+$.

[23] At this stage in the development of our understanding of the light nuclei, we are still testing the various models that present themselves. This can only be done by reaching as sure an assignment as possible by the usual systematic and model-independent methods and then comparing the result with the prediction of the several models. It is clearly hazardous to invoke a particular model in pretending to the assignment, choosing that one of the states of that particular model that most nearly fits the incomplete experimental data, and claiming to have made an experimental assignment as a result. Any considerations concerning the expectation of the IPM in arriving at an assignment must therefore be put forward with reservation.

The assignment $J=\frac{3}{2}-$ for the 5.03-Mev level accords with all the facts. The strength of the observed low-energy branch is very reasonable as the result of two competing $M1$ transitions. On the basis of energy alone we should expect the missing branch to the second excited state, also an $M1$, to have a strength of about 1.5×10^{-3}, which is a little less than our experimental upper limit.

This assignment, so far experimental only, now invites association, as has already been made,[8,14] with the second $J=\frac{3}{2}-$ state of the IPM. The theoretical branching ratio does not depend very rapidly on the intermediate coupling parameter in the region of interest ($a/K\approx4-6$) and we are led to expect about 0.10 for the relative strength of the branch to the first excited state, to be compared with the experimental 0.13 (the mean of the present and earlier[8] figures), and about 3×10^{-3} for the strength of the branch to the second excited state, to be compared with the experimental limit of just this amount. We conclude that the behavior of the 5.03-Mev state accords well with the expectation of the IPM if we adopt the assignment $J=\frac{3}{2}-$ to which we are led by the experimental data themselves.[23] The value of a/K giving agreement for this branching ratio is about 3. A further comparison with the expectation of the IPM may be made for the stripping results[14] from the reaction $B^{10}(d,p)B^{11}$. No interpretation of these results using distorted waves has yet been published, but the qualitative comparison with the prediction of the IPM is clear at least as regards the distinction between $J=\frac{7}{2}-$ and $J=\frac{3}{2}-$ for the 5.03-Mev state. Stripping to the former is predicted to be strong and to the latter, weak (for all values of a/K that need to be seriously considered). In fact, the 5.03-Mev state is rather weakly excited, and so the stripping results, if we may now associate them with the prediction of a specific model, also favor $J=\frac{3}{2}-$. In a naive interpretation of the situation, the comparison of the experimental results with the IPM would suggest $a/K\approx2$.

A final caution is necessary about the 5.03-Mev level. No data so far presented exclude $J=\frac{1}{2}-$ for this state. The gamma decay discussed here is consistent with this assignment. The stripping pattern in $B^{10}(d,p)B^{11}$ is closely similar to that for the first excited state at $E_d=7.7$ Mev,[3,14] and the intensity is only a factor of two greater. The stripping pattern in $B^{10}(He^3,d)C^{11}$ leading to the 4.75-Mev state (now known from the present work to be the analog of the 5.03-Mev state of B^{11}) is also very similar to that leading to the first excited state,[21] which may suggest a similar mechanism and $J=\frac{1}{2}-$. Only by invoking the theoretical IPM expectation[23] do we rule out $J=\frac{1}{2}-$ (no $J=\frac{1}{2}-$ state is forecast, other than that identified at 2.13 Mev, within many Mev of 5 Mev). Angular correlation measurements on the transitions from the 5.03-Mev level (or those from the 4.75-Mev state of C^{11}) would be extremely welcome, but none has so far been reported.

COUPLING SCHEME OF THE IPM DESCRIPTION: THE COLLECTIVE MODEL

We may now compare the experimental data with the expectation of the IPM on the assumptions: (i) that the sequence of states from the ground state up is $J=\frac{3}{2}, \frac{1}{2}, \frac{5}{2}, \frac{3}{2}$, all of odd parity; (ii) that we should seek to identify all these with states of the model.

A few years ago, when it was thought that the 5.03-Mev state might well be the first $J=\frac{7}{2}-$ state of the IPM, the best accord between theory and experiment was found for[1,24] $a/K\approx6$ (using $L/K=6.8$, to which value the predictions are not very sensitive). This was the highest a/K value found necessary in the $1p$ shell[25] and placed $A=11$ somewhat out of line with the systematics of neighboring nuclei, suggesting an unexpected peak in the curve of a/K vs A. With the present assignments, taking into account the dynamical properties, (namely, the gamma-ray branching from the 5.03-Mev level and the reduced nucleon widths seen through stripping), we are forced to considerably lower values of a/K to get best fit and something like $a/K\approx4-4.5$ is indicated, as has already been noted.[14] This makes the a/K vs A plot considerably smoother and makes more likely a simple monotonic increase through the shell.

It is interesting to note that this change in a/K brings better agreement between the experimental and calculated magnetic moments for the ground state of B^{11}: The theoretical value always lies above the experimental, but they approach most nearly to the theoretical curve in a rather sharp minimum at $a/K\approx4$.[1] The experimental radiative width for the second excited state [16] is somewhat greater than the theoretical for all reasonable values of a/K. A reduction of a/K from 6 to 4 lowers the theoretical value by about 20% and so is not serious. Below $a/K\approx4$, however, the theoretical value begins to fall rapidly, passing through zero ($M1$ component) at $a/K\approx1-1.5$. This suggests that we might regard $a/K=4$ as approaching the lower limit for good fit to the over-all body of data. Another feature of the decay of the 4.46-Mev state that accords surprisingly well with the expectation of the IPM is the $E2$ component. This is about 5% (by intensity)[10] which corresponds, using the measured lifetime,[16] to a partial $E2$ width of about 2.7×10^{-2} ev. This is a very large width and is roughly 8 Weisskopf units on a radius constant of 1.35×10^{-13} cm. The $E2$ width given by the IPM[9] is about 1.6×10^{-2} ev at $a/K\approx4.5$, also considerably greater than a Weisskopf unit. The IPM figure is very insensitive to a/K. This experimental value for the $E2$ component has been confirmed in a radically different way from that in which it was first

[24] D. H. Wilkinson, Proceedings of the First Robert A. Welch Foundation Conferences on Chemical Research, 1957 (unpublished), p. 13.

[25] D. H. Wilkinson, *Proceedings of the International Conference on Nuclear Structure, Kingston*, edited by D. A. Bromley and E. W. Vogt (University of Toronto Press, Toronto, Canada, 1960), p. 20.

obtained (angular correlations),[10] namely, by the inelastic scattering of protons of 185 Mev, by B^{11},[26] a process controlled by a matrix element of structure closely similar to that for the electric radiative transition.[27] (The experimental figure of 2% for the relative intensity of the $E2$ component quoted elsewhere[8] does not agree so well with the inelastic proton scattering data. On the other hand, it agrees equally well with the IPM prediction on the lower rather than the upper side. The mean of the experimental figures would give very close agreement.) The model thus agrees with experiment that this is an unusually strong $E2$ transition.

The total experimental radiative width of the first excited state[15] agrees with the IPM calculation[9] of the $M1$ component at $a/K\approx 7$, but the theoretical figure is not very strongly dependent on a/K. At $a/K=4$ the discrepancy is by a factor of about 1.5, which we must still regard as quite good agreement. The $E2$ component of this transition cannot be obtained by angular correlation measurements since $J=\frac{1}{2}$. However, it can be inferred from the scattering of protons of medium energy in the manner referred to above. Clegg finds[26] $\Gamma_\gamma < 2\times 10^{-4}$ ev, which is to be compared with the IPM prediction $\Gamma_\gamma \approx 7\times 10^{-5}$ ev (at $a/K\approx 4.5$). In other words, according to the IPM the reduced $E2$ transition strength from the first excited state is about 5 times less than that from the second excited state, while experimentally it is at least 3 times less. The IPM prediction is not strongly dependent on a/K.

In summary, our present information about the states now in question accords quite well in all respects with the previsions of the IPM for $a/K\approx 4$ or a little larger, and this value itself fits in well with the systematics of neighboring nuclei.[24,25] There is, unfortunately, a snag in the form of the $J=\frac{7}{2}-$ state which the model predicts in the same region of excitation as the $J=\frac{5}{2}-$ and second $J=\frac{3}{2}-$ states that we have just discussed. The lowering of the a/K value tends to raise the $J=\frac{7}{2}-$ state relative to the $J=\frac{5}{2}-$ and $\frac{3}{2}-$ states, but the effect is a weak one. In fact, the state of B^{11} at 6.76 Mev seems likely to be this $J=\frac{7}{2}-$ state.[8,10,14,28] Perhaps we should not regard this displacement of the $J=\frac{7}{2}-$ state (by about 2 Mev) as in itself too severe a failure of the IPM. It seems likely, however, that the model also fails in another way on this state, namely its radiative properties. Its $E2$ transition to the ground state is observed[8] to be about 5 times as strong as its $M1$ transition to the $J=\frac{5}{2}-$ state at 4.46 Mev. The weakness of the $M1$ transition is in qualitative accord with the IPM prediction which gives a vanishing matrix element at $a/K\approx 4$. The $E2$ to the ground state has an IPM strength of $\Gamma_\gamma\approx 1.4\times 10^{-2}$ ev at $a/K=4.5$ (and about two-thirds of this figure at $a/K=6$). The

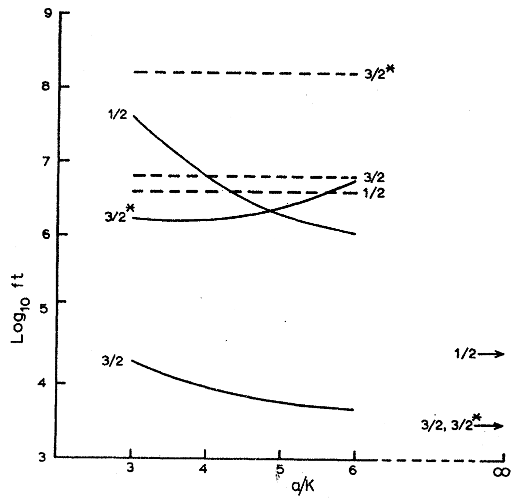

FIG. 8. The prediction of the IPM for the beta decay of the $J=\frac{1}{2}-$ ground state of Be^{11} shown by the full lines as a function of the intermediate-coupling parameter a/K. The spins of the B^{11} states to which the transitions are made are shown on the left of the lines. The second state of $J=\frac{3}{2}-$ is shown as $\frac{3}{2}$*. The experimental values are shown by the horizontal dashed lines.

strength inferred from the inelastic proton scattering[26] is $\Gamma_\gamma\approx 0.1$ ev, which is considerably greater than the IPM figure. This in turn implies for the $M1$ transition to the second excited state $\Gamma_\gamma\approx 2\times 10^{-2}$ ev. The IPM figure, zero near $a/K=4$, rises only to about 2×10^{-3} ev at $a/K\approx 6$. It seems likely, therefore, that the IPM is rather poor at both the $M1$ and the $E2$ transitions from this state.

An alternative view of the whole situation has been proposed by Clegg in terms of the collective model.[29] In its simplest form it describes B^{11} with the ground, second excited, and $J=\frac{7}{2}-$ states as belonging to a rotational band based on $K=\frac{3}{2}$. This explains satisfactorily the separation of the $J=\frac{7}{2}-$ from the $J=\frac{5}{2}-$ state; in fact the former is a little too high on the simple model but can be depressed by suitable refinements. This model also explains the fact that both $E2$ transitions between the ground state and the $J=\frac{5}{2}-$ and $\frac{7}{2}-$ states are very strong (comparable reduced speed). The first excited state belongs to a $K=\frac{1}{2}$ band and so the weak $E2$ from it to the ground state is understood. The second $J=\frac{3}{2}-$ state, that at 5.03 Mev, now becomes the second member of the $K=\frac{1}{2}$ band, and in consequence we expect its $E2$ transition to the ground state to be much weaker than that of the $J=\frac{5}{2}-$ state at 4.46 Mev. This appears to be so from the evidence of the inelastic proton scattering.[26] (The IPM also predicts a much weaker transition.)

It may also be, of course, that the IPM can do better with suitable adjustments of its variables, for example, the force mixture. (It is unlikely that reasonable

[26] See reference 22, and see also H. Tyren and T. A. J. Maris, Nuclear Phys. **6**, 82 (1958).
[27] See, for example, reference 25, p. 53.
[28] S. A. Cox and R. M. Williamson, Phys. Rev. **105**, 1799 (1957).
[29] S. G. Nilsson, Kgl. Danske Videnskab. Selskab, mat.-fys. Medd. **29**, No. 16 (1955). D. Kurath and L. Picman, Nuclear Phys. **10**, 313 (1959).

changes of L/K will have an adequate effect but this should be investigated.) However, the displacement of the $J=\frac{7}{2}-$ state from the immediate region of the $J=\frac{3}{2}-$ and $\frac{5}{2}-$ states, taken together with the enhancement of its $E2$ transition, seems to find its most immediate explanation in terms of the collective description.

BETA-DECAY OF Be^{11}

The identification of the 5.03-Mev level of B^{11} with the second $J=\frac{3}{2}-$ level of the IPM, which is most probably correct, enables us to return to the problem of Be^{11}: Is the ground state of that nucleus of $J=\frac{1}{2}-$, as predicted by the simple shell model and also by the IPM, in intermediate coupling? If Be^{11} is $J=\frac{1}{2}-$, we shall have allowed transitions to the ground, first excited, and third excited states of B^{11} but with respective $\log ft$ values of 6.8, 6.6, and $\geqslant 8.2$.[6] While the first two values make it unlikely that $J=\frac{1}{2}-$ for Be^{11} is correct, the third makes it very improbable indeed. The combined evidence is strong enough to reject the assignment with good certainty and to lead us to even parity for Be^{11}.

The detailed IPM calculation confirms this. The theoretical $\log ft$ values are shown in Fig. 8 as functions of a/K. As can be seen, the theoretical transition to the first excited state is slow and indeed agrees with experiment, but that to the ground state is fast—10^3 times faster than experiment. The theoretical transition to the second $J=\frac{3}{2}-$ state is also slow, but is faster by a factor of 10^2 than the experimental upper limit to the speed. It seems that this evidence is good enough to reject $J=\frac{1}{2}-$ for Be^{11}. (We may note that this conclusion is not changed should the 5.03-Mev state turn out, after all, to be the second $J=\frac{1}{2}-$ of the IPM, since the theoretical IPM $\log ft$ value of the Be^{11} transition to that state is about 3.9.)

Although IPM calculations for other possible ground states of Be^{11} belonging to $(1p)^7$ are not available, we can extend the argument based on systematics to reject any state of odd parity. In order to understand the large $\log ft$ value to the 5.03-Mev state, we should have to choose $J\geqslant\frac{7}{2}-$ for Be^{11}. But this would then be totally inconsistent with the $\log ft$ value for the decay to the first excited state.

This conclusion of even parity for Be^{11} is strengthened by consideration of the two transitions that it shows with smaller $\log ft$ values: $\log ft=5.9$ to a member of the 6.76−6.81 Mev doublet and $\log ft=5.5$ to the state at 7.99 Mev.[6] These values are sufficiently small to make it more likely than not that the decays are allowed. The former transition can be identified as being to the 6.81-Mev state, since the subsequent gamma decay leads quite strongly to the first excited state of B^{11} as well as to the ground state.[6] This is the known behavior of the 6.81-Mev level,[8] but not that of the 6.76-Mev state which shows no appreciable branch to the first excited state (as befits its likely assignment of $J=\frac{7}{2}-$). The best evidence as to the parity of the 6.81-Mev state is that it is even. This comes from a study of $Be^9(He^3,p)B^{11}$,[20] which gives $J=\frac{1}{2}$ to $\frac{7}{2}+$. The evidence on the 7.99-Mev state comes only from $Be^9(He^3,p)B^{11}$ and is murky.[20] Work at $E_{He^3}=5.70$ Mev indicated even parity, but the angular distribution depends markedly on the bombarding energy and at $E_{He^3}=8.82$ and 10.23 Mev cannot at present be interpreted. The balance of evidence is therefore that these probably allowed transitions take place to states of even parity and that Be^{11} is therefore of even parity.

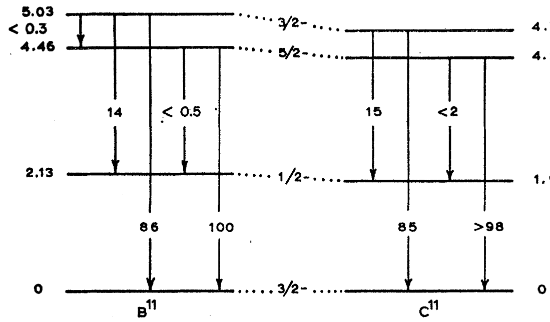

FIG. 9. Level schemes and decay modes of B^{11} and C^{11}.

It has recently been pointed out[7] that the systematics of even-parity states in nuclei of odd mass in the $1p$ shell suggest that the ground state of Be^{11} may well be $J=\frac{1}{2}+$. This would be consistent with the present data. Recent experiments on the production of Be^{11} in the reaction $Be^9(t,p)Be^{11}$ directly suggest even parity for the ground state of Be^{11} although the interpretation is not certain.[30] To be sure, all evidence points away from $J=\frac{1}{2}-$ and towards even parity for Be^{11}.

CONCLUSION

We conclude: (i) It is now improbable that the spins and parities of the low-lying $T=\frac{1}{2}$ states of $A=11$ are not as summarized in Fig. 9. (ii) It is very probable that Be^{11} is of even parity.

ACKNOWLEDGMENTS

We should like to thank Dr. Dieter Kurath for his kindness in making available the theoretical $\log ft$ values for the Be^{11} beta decay according to the IPM. We are also grateful to Dr. A. B. Clegg for the information concerning the $C^{12}(N,2N)$ and $B^{11}(p,p')B^{11}$ reactions and for discussions of the collective model.

[30] S. Hinds, R. Middleton, A. E. Litherland, and D. Pullen (in the press).