Beta Decay of B^{13}†

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The β decay of B^{13} has been studied by means of plastic and NaI(Tl) scintillation detectors. The activity was formed in the $B^{11}(t,p)B^{13}$ reaction using a mechanically chopped beam of 3.0-MeV tritons from a Van de Graaff accelerator. β-γ coincidence measurements have confirmed a previously reported β branch to the 3.68-MeV second excited state of C^{13}. By means of a β-neutron time-of-flight method, β branches to neutron-emitting levels of C^{13} at 7.5 and 8.86 MeV have been observed. The C^{13} levels in MeV, B^{13} β branches to these levels in percent, and the corresponding log*ft* values are ground, 92.1±0.8, 4.02±0.02; 3.68, 7.6±0.8, 4.47±0.05; 7.5, 0.094±0.020, 5.37±0.09; and 8.86, 0.16±0.03, 4.63±0.08. The present results are consistent with recent assignments of $J^\pi=\frac{5}{2}^-$ and $\frac{1}{2}^-$ to the 7.55- and 8.86-MeV C^{13} levels, respectively. It is suggested that the 7.55-MeV member of the 7.50-7.55-7.68 C^{13} triplet is the one populated in B^{13} β decay. The experimental log*ft* values agree well with theoretical calculations by Cohen and Kurath.

I. INTRODUCTION

An early success of the nuclear shell model was the treatment of the $A=13$ system by Lane.[1] Within the framework of the intermediate-coupling model, Kurath[2] calculated the expected excitation energies of the odd-parity states in the $A=13$ nuclei. With a value of 5.5 assigned to the intermediate-coupling parameter a/k, Kurath predicted a $J^\pi=\frac{3}{2}^-$ level at 3.7 MeV above the ground state, a $J^\pi=\frac{5}{2}^-$ level at 5.3 MeV, and a $J^\pi=\frac{1}{2}^-$ level at 10.7 MeV. The known levels at 3.68 MeV in C^{13} and 3.51 MeV in N^{13} have both been experimentally assigned a spin parity $J^\pi=\frac{3}{2}^-$ and they are identified as the $\frac{3}{2}^-$ level predicted by the model. Several early experimental attempts[3] were made to find the $J^\pi=\frac{5}{2}^-$ levels in C^{13} and N^{13}, but without success. It now seems to be well established that there are no excited states in C^{13} between the known levels at 3.85 and 6.87 MeV or in N^{13} between the known levels at 3.56 and 6.38 MeV.

More refined calculations of the levels expected in the $A=13$ nuclei have now been made by Boyarkina,[4] Barker,[5] Halbert *et al.*,[6] and Cohen and Kurath.[7] The calculations of the last three of these authors are reasonably consistent in their predictions of the excitation energies of the first three odd-parity excited states. Cohen and Kurath, for example, find the $J^\pi=\frac{3}{2}^-$ level at 3.7 MeV, the $J^\pi=\frac{5}{2}^-$ level at 7.4 MeV, and the $J^\pi=\frac{1}{2}^-$ level at 9.0 MeV.

Experimental identification of the $J^\pi=\frac{5}{2}^-$ and $\frac{1}{2}^-$ levels now appears to have been made by Fleming *et al.*,[8] who have recently studied the (p,t) and (p,He^3) reactions on C^{13} and N^{15} targets. Their data, in conjunction with previous work, enabled them to make firm spin-parity assignments of $J^\pi=\frac{5}{2}^-$ and $\frac{1}{2}^-$ to the C^{13} levels at 7.55 and 8.86 MeV, respectively. These are presumably the two states predicted by the shell model. Fleming *et al.* also have assigned $J^\pi=\frac{5}{2}^-$ to the 7.42-MeV level in N^{13} which is taken to be the mirror of the C^{13} 7.55-MeV level. A tentative assignment of $J^\pi=\frac{3}{2}^-$ was given to the C^{13} level at 9.52 MeV.

The levels of C^{13} from 8.8 to 11.0 MeV have also been studied recently by Galati *et al.*,[9] through analysis of the resonances in $C^{12}+n$ scattering. Definite assignments of $J^\pi=\frac{1}{2}^-$ and $\frac{3}{2}^-$ have been made to the 8.86- and 9.90-MeV levels, respectively, and a tentative assignment of $J^\pi=\frac{1}{2}^-$ or $\frac{3}{2}^-$ has been given to the narrow level at 9.52 MeV, all consistent with the results of Fleming *et al.*[8]

Cohen and Kurath's theoretical work[7] on the $A=13$ system also included calculations of the log*ft* values for the various β-decay branches of B^{13}. According to the model, B^{13} should have a spin parity $J^\pi=\frac{3}{2}^-$. Values for the log*ft* values of the β branches to the states discussed above were derived, based on two different choices of parameters.

It was suggested to us[10] that a detailed study of the β decay of B^{13} would be of interest as a further test of the model. The decay scheme of B^{13} has been investigated previously by Marques *et al.*[11] They measured the B^{13} half-life as 18.6±0.5 msec and they showed that β decay takes place mainly to the $J^\pi=\frac{1}{2}^-$ ground state of C^{13} ($E_{\beta\max}=13.44$ MeV, 93%), but that there is also a branch of 7% to the 3.68-MeV $J^\pi=\frac{3}{2}^-$ γ-emitting level. It was concluded that B^{13} has a spin parity $J^\pi=\frac{3}{2}^-$, as was expected from the shell model.

Since all states in C^{13} above 4.9 MeV are unstable

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[2] D. Kurath, Phys. Rev. **101**, 216 (1956).

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against neutron emission, Marques *et al.* searched for neutrons that would be associated with β-decay branches of B^{13} to higher excited states of C^{13}. By means of a long counter they showed that less than 1.5% of the B^{13} decays proceed to neutron-emitting levels. However, Chiba *et al.*[12] were able to detect delayed neutrons from B^{13} decay with a BF_3 counter. They reported a yield of $(5.2\pm2.6)\times10^{-3}$ neutrons per β decay, but they did not measure the energies of these neutrons.

We have used the β-neutron time-of-flight method to detect such events, to determine the excitation energies of the C^{13} states being fed, and to find the branching ratios of the β decay. Two distinct β branches of B^{13} to neutron-emitting states in C^{13} were observed.

To our knowledge, there have been only a few previous applications of the β-neutron time-of-flight method. Gilat *et al.*[13] measured the β-ray branching of N^{17} to neutron-emitting states of O^{17}. More recently, two groups[14] have studied the β branching of Li^9 to neutron-emitting states of Be^9 by means of this technique.

II. EXPERIMENTAL METHODS

The experimental arrangement for the study of B^{13} decay is illustrated in Fig. 1. A beam of tritons from the Van de Graaff passes through a mechanical chopper located ~12 ft from the target. The chopper, together with its associated timing and electronic gating system, has been described previously.[15] Since this device operates on a 17-msec irradiate-count cycle, including 3 msec of irradiation and 12 msec of counting, it is quite suitable for the study of B^{13}.

Metallic boron powder enriched to 97% in B^{11} was deposited in a thick layer on a steel backing to form the target. This was placed in a thin-walled glass target chamber. The β rays from the target were detected with a 3-in.-diam ×2-in.-thick Pilot-B plastic scintillator coupled to an RCA 8575 photomultiplier tube through a short light pipe. This was placed approximately 1.5 cm from the target at 90° to the beam.

A 5×5-in. NaI(Tl) detector was used for detecting γ rays. As in earlier work,[15] a special cathode follower unit was used in order to stabilize the gain under the beam-pulsing conditions. Carbon and copper absorbers were placed in front of the γ detector in order to exclude β rays with a minimum of bremsstrahlung production.

The neutron detector consisted of an 8-in.-diam ×1-in.-thick NE102 plastic scintillator coupled with a conical Lucite light pipe to an RCA 8575 photomultiplier tube. The neutron detector was placed opposite the β detector at 90° to the beam and at distances d of 35 to 100 cm from the target, depending on the particular measurement. Pb and Al absorbers were placed in front of the neutron detector in order to exclude β rays.

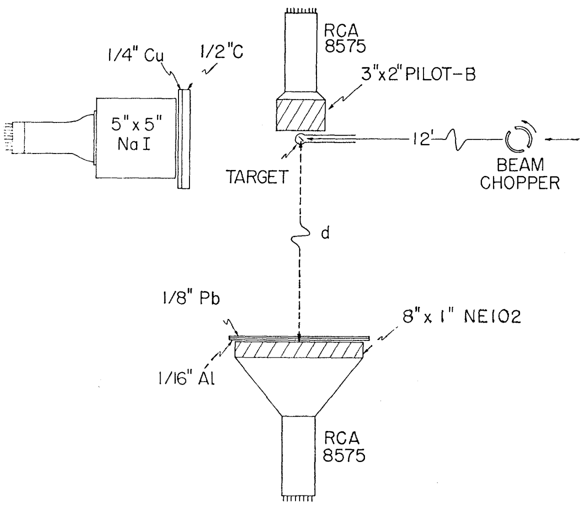

FIG. 1. Experimental arrangement for measurements on B^{13} decay. β rays are detected in the 3×2-in. Pilot-B scintillator, coincident γ rays in the 5×5-in. NaI(Tl) detector, and time-of-flight neutrons in the 8×1-in. NE-102 scintillator. The neutron flight path d was set at 35 to 100 cm in the various experiments.

Electronic units, all of which were of commercial design, included a coincidence circuit for measuring β-γ coincidences, a time-to-pulse-height converter for measuring the β-neutron time spectrum, and multichannel pulse-height analyzers for recording the γ-ray spectrum in coincidence with β rays, the spectrum of β-ray singles, and the time spectrum of events following β-ray emission.

III. EXPERIMENTAL RESULTS

A. β-Neutron Time-of-Flight Measurements

The B^{13} activity was produced with a 3.0-MeV chopped beam of tritons at an average current of 0.0014 μA. In the initial runs to determine the β-neutron time-of-flight spectrum it became evident that there were two neutron groups emitted in B^{13} decay. Two types of experiments were performed, the first of which consisted of determining the energies of the two groups. Most of these runs were made at a distance d (see Fig. 1) of 50 cm. Biases on the outputs of both the neutron and β detectors were set so that there would be good timing resolution. For any given set of conditions the effective timing resolution was determined from the width of the β-prompt γ peak. This yield resulted mostly from the β branch to the C^{13} 3.68-MeV level followed by γ-ray emission, although β-bremsstrahlung coincidences also contributed to the prompt γ peak. The effective time resolution attained during the

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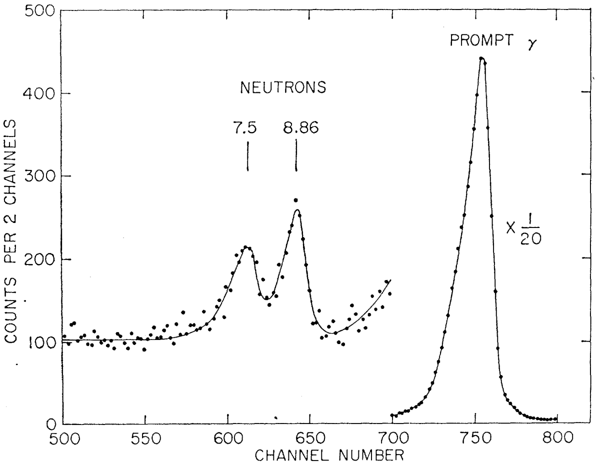

FIG. 2. β-neutron time-of-flight spectrum in the decay of B^{13} for a flight path $d=35$ cm (see Fig. 1). Time increases from right to left and the dispersion is 0.126 nsec per channel. The separation between the β-prompt γ peak and the peaks corresponding to the neutron decay of the C^{13} 8.86- and 7.5-MeV levels are approximately 13 and 16 nsec, respectively.

experiment varied from 1.5 to 2.5 nsec. Because of its relatively high yield, the prompt γ peak could be measured well enough in a few minutes to establish its width. Calibration of the time spectrum was made in terms of standard length delay lines. The spectrum of calibration points was tested for linearity by a χ^2 fit. The standard deviation of this fit was 0.05 nsec.

Spectra similar to Fig. 2, but with somewhat sharper and more symmetric peaks and with a somewhat greater dispersion corresponding to $d=50$ cm, were obtained in the energy measurements. The separation between the β-prompt γ peak and each neutron peak was found by computer-fitting procedures. Allowing for the fact that the γ peak itself is delayed slightly ($\sim$1.7 nsec when $d=50$ cm) the delay time corresponding to each neutron peak was calculated by using the calibration data. From these time delays and the averaged distance from the source to the detector, the neutron velocities were determined. The averaged distance included effects of finite detector angle and neutron absorption in the detector. Based on measurements under several conditions, the final values for the neutron energies are 2.43±0.06 and 3.55±0.10 MeV, corresponding to C^{13} excitation energies of 7.58±0.06 and 8.79±0.10 MeV, respectively, and to B^{13} β-ray end-point energies of 5.9 and 4.6 MeV, respectively.

The second series of measurements on the β-neutron time-of-flight spectrum was for the purpose of determining the β branching ratios. For these runs the biases on the neutron and β detector outputs were set low enough to get good yields and adequate time resolution. Figure 2 illustrates one of the spectra obtained. For purposes of analysis, it was necessary to know the fraction of the total β singles spectrum detected, the relative efficiencies for detecting β rays of various end-point energies, and the absolute efficiencies for detecting neutrons of 2.4 and 3.6 MeV.

Previous work[16] with the same β-detecting scintillator was helpful in obtaining the fraction of β rays detected and the relative efficiencies for β's of various end-point energies since the spectrum shape for high-energy β's had been determined. In this second series of runs, the side-channel bias on the β-detector output was set at about 0.9 MeV, and hence, the differences in the efficiencies for the various high-energy β components were not expected to be large. One slight complication was the presence of a low-energy long-lived β emitter whose pulse-height spectrum extended up to $\sim$3 MeV, and hence was partly above the bias setting. This had an intensity of about 2% of the total yield and required a correction of this amount to the number of β-ray scalar counts. The β singles spectrum, with the aforementioned low-energy component subtracted, served as a calibration for a β of 13.44-MeV end-point energy. The β-ray spectrum in coincidence with the γ-ray detector, when a channel was placed on the full-energy-loss peak of the 3.68-MeV C^{13} γ rays, gave a calibration curve for 9.76-MeV β rays. Based on the observed end points of these two spectra and the calculated end-point energies of 5.9 and 4.6 MeV corresponding to the β rays feeding the 7.5- and 8.86-MeV levels, the appropriate end-points were found and β spectra with the expected shapes were constructed. From these curves, it was calculated that 90±3, 87±3, 79±5, and 74±5% of the β rays feeding the ground, 3.68-, 7.5-, and 8.86-MeV levels, respectively, were detected above the bias level.

The absolute efficiency of the 8×1-in. NE-102 scintillator for detecting the 2.43- and 3.55-MeV neutron groups was calculated by following the procedures described in Refs. 17 and 18. The effective low-energy bias point for the neutron detector was established by calibrating the detector with Na^{22} and Cs^{137} γ-ray sources. By correcting for the difference in light output between proton recoils and electron recoils the low-energy bias for recoil protons was then obtained. A computer program[18] which included the effects of scattering from the carbon and double scattering from hydrogen in the scintillator was then used to obtain the efficiency of the scintillator as a function of neutron energy for a given bias setting. Absolute efficiencies of 0.21±0.02 and 0.18±0.02 were found for the 2.4- and 3.6-MeV neutron groups, respectively. Runs were made at values of the recoil-proton bias ranging from 0.3 to 0.7 MeV. After calculating the solid angle of the detector and correcting (by $\sim$10% total) for the absorption of the neutrons in the Pb and Al, the absolute efficiency times solid angle was found for each neutron group.

Below 9.38 MeV in C^{13}, the only particle decay possible is neutron emission to the ground state of C^{12}.

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[18] T. B. Grandy, Ph.D. thesis, University of Alberta, 1967 (unpublished).

Therefore, the β-branching ratios can be found from the ratio of delayed neutron yields (net areas under the neutron peaks) to the number of β counts, corrected for the efficiency times solid angle of the neutron detector and for the relative β efficiencies. Final values for the β-ray branches are $(0.094\pm0.020\%)$ to the 7.5-MeV level and $(0.16\pm0.03)\%$ to the 8.86-MeV level.

B. β-γ Coincidence Spectrum

The β branching to the 3.68-MeV C^{13} level can be found from the number of 3.68-MeV γ rays in coincidence with the total β spectrum. Corrections to the recorded β's for the presence of a low-energy β emitter of long half-life and for the fraction of B^{13} β's above the bias were made as discussed above. The area under the 3.68-MeV full-energy-loss peak was corrected for analyzer dead time, for full-energy peak efficiency times solid angle at the distance used, and for the absorption of the γ rays in the carbon and copper absorbers. The number of 3.68-MeV γ rays per β ray was found by simple calculation.

The weighted average of three different runs leads to a value of $(7.6\pm0.8)\%$ for the B^{13} β branch to the 3.68-MeV C^{13} level.

C. Test for a Possible B^{12} Contribution

Implicit in the above analyses is the assumption that, aside from the low-energy β-ray component already corrected for, all of the high-energy β rays in fact originate from B^{13}. It is possible that other short-lived activities could be present.

One test for contaminant activities consisted of setting the energy bias on the β detector at 4 MeV and observing the β count where the beam was removed from the target. The drop in the β-counting rate from ~20 000/sec to a level of only a few counts/sec appeared to be instantaneous. In any case, activities with $T_{1/2}>0.5$ sec and $E_{\beta\max}>4$ MeV were of negligible intensity.

The most likely activity with $T_{1/2}<0.5$ sec and $E_{\beta\max}>4$ MeV is B^{12} which can be produced by the $B^{10}(t,p)B^{12}$ reaction in the B^{10} (~3%) in the target. Since the end-point energies and half-lives of B^{13} and B^{12} are nearly the same it would not be possible to distinguish between these two activities in the β spectrum. A significant B^{12} β contribution would evidently lead to erroneous values for the B^{13} β-branching ratios, unless proper corrections were made.

The γ-ray spectrum in coincidence with β rays can serve as a test for the presence of B^{12}, since B^{12} decays with a branch[19] of 1.3% to the first excited state of C^{12} at 4.44 MeV. Even though this branch is a factor of 6 smaller than the 7.6% B^{13} branch to the C^{13} 3.68-MeV level, the higher energy of the 4.44-MeV γ ray places its full-energy-loss peak just above the 3.68-MeV pulse-height spectrum in a region of low background.

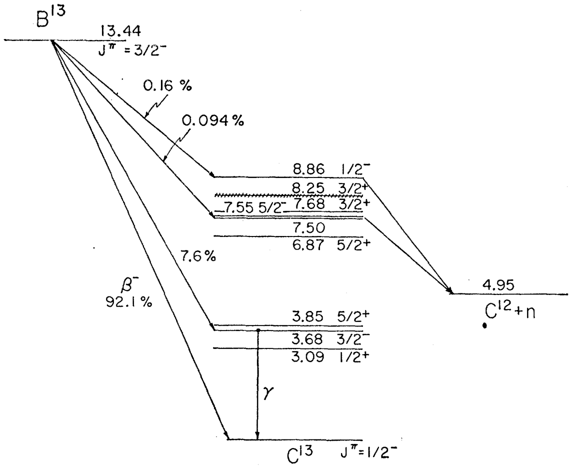

FIG. 3. Proposed decay scheme of B^{13} showing the present results on the β-ray branching. The energies, spins, and parities of the C^{13} levels are taken from previous work. As explained in the text, the B^{13} β-ray branch to the "7.5-MeV" level probably takes place to the $J^\pi=\frac{5}{2}^-$ 7.55-MeV member of the 7.50-, 7.55-, 7.68-MeV triplet.

A run of several hours on the β-γ coincidence spectrum failed to reveal any sign of the 4.44-MeV γ ray from B^{12} decay. Based on an upper limit of 0.5% on the intensity of the 4.44-MeV full-energy-loss peak relative to that of the 3.68-MeV peak the upper limit on the total B^{12} β activity is <4% relative to the B^{13} under investigation. Hence, no corrections were made for high-energy contaminant β activities.

IV. DISCUSSION

The results of the present work on B^{13} decay are summarized in Fig. 3 and in the fourth and fifth columns of Table I. Our β-branching intensities to the ground and 3.68-MeV levels of C^{13} are in excellent agreement with Marques *et al.*,[11] who obtained values of 93 and $(7\pm1.5)\%$ for these two β transitions, respectively. The sum of our β-branching intensities to the 7.55- and 8.86-MeV levels agrees with the neutron intensity results of Chiba *et al.*,[12] just within the errors.

The experimental values for the excitation energies corresponding to the two neutron groups from B^{13} are to be compared with the known levels[19] of C^{13}. There seems to be no ambiguity in assigning the more energetic neutron group to the 8.86-MeV C^{13} level since the experimental value of 8.79 ± 0.10 MeV for the excitation energy clearly excludes the nearest-neighboring levels at 8.25 and 9.52 MeV. On the other hand, the experimentally determined excitation energy of 7.58 ± 0.06 MeV, corresponding to the other neutron group, is not sufficiently accurate to allow it to be assigned with certainty to any given member of the 7.50-7.55-7.68-MeV triplet in C^{13}. From energy considerations alone, there is only the weak suggestion that the 7.55-MeV level is favored since the experimental value, while agreeing with the 7.55-MeV level within the errors, differs from the 7.50-MeV level by 1.3 probable

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

TABLE I. β-ray branches in the decay of B^{13}.

Level in C^{13} (MeV)	J^π	β branch (%) previous work	β branch (%) present work	log*ft* (expt) present work	log*ft* (theoret)[a]	
					(8–16)POT	(8–16) 2BME
0	$\frac{1}{2}^-$	93[b]	92.1 ± 0.8	4.02 ± 0.02	3.93	3.89
3.68	$\frac{3}{2}^-$	7 ± 1.5[b]	7.6 ± 0.8	4.47 ± 0.05	4.68	4.59
7.55	$\frac{5}{2}^-$	0.52 ± 0.26 to all neutron-emitting levels[c]	0.094 ± 0.020	5.37 ± 0.09	5.18	5.98
8.86	$\frac{1}{2}^-$		0.16 ± 0.03	4.63 ± 0.08	4.88	4.41

[a] Reference 7.
[b] Reference 11.
[c] Reference 12.

errors and differs from the 7.68-MeV level by 1.7 probable errors. In Fig. 2, peaks corresponding to levels at 7.68 and 7.50 MeV would occur at positions differing by only 4.5 channels.

As is evident from the experimental log*ft* values given in the fifth column of Table I, all four of the B^{13} β transitions are allowed. Since B^{13} has $J^\pi=\frac{3}{2}^-$, then the final states to which these decays occur have odd parity and $J=\frac{1}{2}$, $\frac{3}{2}$, or $\frac{5}{2}$. The log*ft* values of the β decays to the ground and 3.68-MeV levels are consistent with the known spin parities of $J^\pi=\frac{1}{2}^-$ and $\frac{3}{2}^-$, respectively, as had been shown by Marques *et al.*[11]

The present result on the log*ft* value of the β to the 8.86-MeV level is consistent with the assignment[8,9] of $J^\pi=\frac{1}{2}^-$ to that level. For the β decay to the C^{13} triplet in the vicinity of 7.5-MeV excitation energy we make use of the assignment[8] $J^\pi=\frac{5}{2}^-$ to the 7.55-MeV level, with which our experimental log *ft* value is consistent. In all probability, it is this member of the triplet that is fed in the β decay of B^{13}. The 7.68-MeV level has $J^\pi=\frac{3}{2}^+$ and would require a first-forbidden transition from B^{13}. Although we still cannot definitely exclude an allowed β decay to the 7.50-MeV level in C^{13}, whose spin and parity are not known at present, consideration of the corresponding region in N^{13}, the mirror nucleus of C^{13}, rules strongly against it. The 6.91-7.18-7.42-MeV triplet in N^{13} evidently corresponds to the 7.50-7.55-7.68-MeV triplet in C^{13}. The $J^\pi=\frac{3}{2}^+$ 6.91-MeV and $\frac{5}{2}^-$ 7.42-MeV levels in N^{13} have been identified[8] as analogs of the 7.68-MeV and 7.55-MeV levels of C^{13}. Charge symmetry implies that the 7.50-MeV level in C^{13} is the analog of the 7.18-MeV level in N^{13}. Since the 7.18-MeV level in N^{13} has been assigned a spin parity of $\frac{7}{2}^+$,[20] charge symmetry predicts a spin parity of $\frac{7}{2}^+$ for the 7.50-MeV level in C^{13} which would rule out an allowed β decay to this level.

Other levels in C^{13} to which allowed β decays might occur are those at 9.52 and 9.90 MeV. The former has been tentatively assigned[8] $J^\pi=\frac{3}{2}^-$, whereas a firm assignment[9] of $J^\pi=\frac{5}{2}^-$ has been made to the latter. The various experimental time-of-flight spectra were examined for possible neutron groups corresponding to these levels. In Fig. 2, a neutron peak corresponding to the 9.52-MeV level would occur at channel 651. An upper limit of 20% relative to the 8.86 peak may be placed on the intensity of such a peak. The upper limit on the corresponding B^{13} β branch is $<0.03\%$, and hence the lower limit on the log*ft* value is >5.0. Similarly, a neutron peak corresponding to the 9.90-MeV level would occur at channel 655. The upper limit on its intensity corresponds to a β branch of $<0.02\%$ and to a limit of log*ft* >5.0. For both of these levels neutron emission is mainly to the C^{12} ground state,[9] and the weak decay mode to the C^{12} 4.44-MeV level does not modify the limits quoted above. If the 8.86-MeV peak in Fig. 2 were to contain a 20% admixture of neutrons from either the 9.52- or 9.90-MeV levels, the correspondingly smaller branch calculated for the β decay to the 8.86-MeV level itself would still lie within our quoted uncertainty for that branch. The limits on the log*ft* values for B^{13} β decay to the 9.52- or 9.90-MeV levels do not appear to contribute any useful information on the spin parities of these C^{13} states.

We now compare our results with the shell-model calculations by Cohen and Kurath.[7] They have used two approximations for the effective two-body interaction. For each of these the parameters were adjusted for a best fit to 35 sets of data in $A=8$–16 nuclei. These fits were designated (8–16)POT and (8–16)-2BME. The log*ft* values for the B^{13} β transitions calculated by Cohen and Kurath are given in the last two columns of Table I. The agreement between experiment and theory is quite good in all four cases. For the two new B^{13} β transitions that have been measured in the present work the log*ft* values are both about midway between the two calculations.

In summary, the decay scheme of B^{13} given in Fig. 3 is consistent with the known information on the levels of C^{13} below 9 MeV, and the β transition rates are in excellent agreement with theory. However, the data cannot make a clear choice between the two versions of the theory.

It is of interest to compare the present results on the β^- decay of B^{13} with the β^+ decay of O^{13}, since O^{13} and B^{13} are mirror nuclei. Assuming charge symmetry, the log*ft* values for β decay of B^{13} to the various C^{13} levels measured in this experiment should be equal to the log*ft* values for the positron decay of O^{13} to the corres-

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ponding N^{13} mirror levels. By using the value of the mass excess of O^{13} measured by Butler,[21] 23.11±0.07 MeV, we can equate the B^{13} and O^{13} $\log ft$ values in order to predict the half-life of O^{13} as well as the intensities of the positron branches of O^{13} to the N^{13} mirror levels. In doing so, we assume that the lower-energy neutron group observed in the present experiment is from the $\frac{5}{2}^-$ 7.55-MeV level in C^{13}. Our predicted value of the O^{13} half-life is 7.7±0.8 msec and the various predicted β^+ branching ratios are given in the third column of Table II.

McPherson *et al.*[22] have observed delayed protons following the production of O^{13} by the $N^{14}(p,2n)O^{13}$ reaction. They measured the O^{13} half-life to be 8.7±0.4 msec. Within the uncertainties our predicted value of 7.7±0.8 msec agrees with the measured half-life. McPherson *et al.* also measured the relative intensities of protons, leaving C^{12} in its ground state, from the 8.93- and 9.48-MeV levels of N^{13} and established an upper limit for the relative intensity of such protons from the 7.42-MeV level of N^{13}. These relative proton intensities do not necessarily reflect the relative positron branches of O^{13} to the 7.42-, 8.93-, and 9.48-MeV levels of N^{13} since the proton branch to the C^{12} first excited state is energetically possible, and it can compete with the proton decay to the ground state in all three cases. We have estimated the relative O^{13} positron branches to these three N^{13} levels, based on the measurements of McPherson *et al.*, by dividing their relative proton intensities by the ratio of the partial elastic proton width to the total width for each level. The widths used were based on the results of inelastic[20] and elastic[23] proton scattering by C^{12}. The resulting estimates of the relative O^{13} positron branches are given in the fourth column of Table II, where these values have been normalized to our predicted % branches by equating the two values of the branch to the 8.93-MeV level. The upper limit of <0.84% for the branch to the 7.42-MeV level estimated from Refs. 20, 22, and 23 is consistent with our predicted branch of 0.24%. Evidently McPherson *et al.* did not observe protons corresponding to the O^{13} positron branch to the 7.42-MeV level of N^{13} since it decays[20] predominantly to the 4.44-MeV first excited state of C^{12}. The protons resulting from such partial branches must, of course, be present but their energies would be much lower than the region of proton energies studied by McPherson *et al.* Our upper limit on the positron branch to the 9.48-MeV level is somewhat lower than the branch estimated from Refs. 20, 22, and 23. Because of the 20% relative uncertainty in our predicted branch to the 8.93-MeV level and the uncertainties in the branch estimated from the Refs. 20, 22, and 23, we cannot place any significance in this quantitative difference. It would be of interest to observe the complete spectrum of delayed protons from O^{13} including branches to the C^{12} 4.44-MeV state. Information could then be obtained on both the β^+-branching ratios of O^{13} and on the partial proton widths of the N^{13} levels to which the β^+ decay takes place.

TABLE II. Comparison of positron branches in the decay of O^{13} predicted by the present work in conjunction with Ref. a to those estimated from Ref. b.

Level in N^{13} (MeV)	J^π	% β^+ branch predicted by present work	Relative β^+ branch in % estimated from Ref. b [c]
0	$\frac{1}{2}^-$	89±11	···
3.51	$\frac{3}{2}^-$	10±2	···
7.42	$\frac{5}{2}^-$	0.24±0.06	<0.84
8.93	$\frac{1}{2}^-$	0.57±0.12	0.57
9.48	$\frac{3}{2}^-$	<0.2	0.33

[a] Reference 21.

[b] References 20, 22, and 23.

[c] These relative branches have been normalized to our predicted values by equating the two values of the branch to the 8.93-MeV level.

It appears that the 9.90-MeV level[9] in C^{13}, rather than the 9.52-MeV level,[8] is the analog of the 9.48-MeV level in N^{13}. Since the present experiment leads to a lower limit of $\log ft > 5.0$ for B^{13} β decay to either the 9.52- or 9.90-MeV levels in C^{13}, either identification of analog pairs leads to the same prediction for the relative positron branch of O^{13} to the 9.48-MeV level in N^{13}.

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