Levels in ^{17}C above the ^{16}C+neutron threshold

G. Raimann,[1] A. Ozawa,[2] R. N. Boyd,[1,3] F. R. Chloupek,[1] M. Fujimaki,[2] K. Kimura,[4] T. Kobayashi,[2] J. J. Kolata,[5] S. Kubono,[6] I. Tanihata,[2] Y. Watanabe,[2] and K. Yoshida[2]
[1]*Department of Physics, The Ohio State University, Columbus, Ohio 43210*
[2]*The Institute of Physical and Chemical Research (RIKEN), Wako-shi, Saitama 351-01, Japan*
[3]*Department of Astronomy, The Ohio State University, Columbus, Ohio 43210*
[4]*Nagasaki Institute of Applied Science, Nagasaki, Nagasaki 851-01, Japan*
[5]*Department of Physics, University of Notre Dame, Notre Dame, Indiana 46556*
[6]*Institute of Nuclear Study, University of Tokyo, Tanashi, Tokyo 188, Japan*
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The β-delayed neutron decay of ^{17}B was studied using a radioactive ion beam. The neutron energies, measured via time of flight, give information on states in ^{17}C above the ^{16}C+neutron threshold. States in ^{17}C were found at excitation energies of 2.25(2), 2.64(2), and 3.82(5) MeV, and possibly at 1.18(1) MeV. These low-lying states are of possible interest for nuclear physics as well as for astrophysics.

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I. INTRODUCTION

The inhomogeneous models (IM's) of primordial nucleosynthesis [1–5] have recently received considerable attention, especially with regard to abundances predicted for the elements ^{7}Li, ^{9}Be, and ^{11}B [6–8]. Because of the spatial variation of both the matter density and the ratio of neutrons to protons, the abundances calculated within the framework of the IM's differ from those obtained within the standard model [4,5]. Comparison of the predicted primordial abundances with the observed ones should clarify the level to which inhomogeneities existed in the early universe. For various reasons, however, the abundance of ^{7}Li may not be a good measure [9]. The primordial abundances of ^{9}Be [10,11] and ^{11}B [12] are somewhat less sensitive to unknown factors, but neither is easy to observe. However [5], the IM's also predict a considerably higher abundance of elements with mass 12 and greater than does the standard model. Thus the heavier nuclides might provide an independent way of testing the predictions of the IM's. Good candidates, at least from the astronomer's perspective, appear to be the elements Na, Mg, Al, and Si [4]. In order to establish accurate predictions of elemental abundances based on the IM's, however, accurate knowledge of nuclear reaction rates between the intervening nuclides is essential.

Most of the nucleosynthesis in the IM's, however, occurs through nuclei that are just beyond the neutron-rich side of stability, and thus involves short-lived nuclides, mostly with half-lives of the order of a second. In addition, the reactions that are most crucial to linking these nuclides tend to be neutron radiative capture reactions, necessitating an indirect mechanism to determine the cross sections.

Recent studies [4,13] on the pathway of nucleosynthesis anticipated in IM's have identified some of the key branch points in that flow. Specifically, masses 16, 17, and 19 are important for synthesizing nuclides heavier than mass 20. In this work we investigated levels in ^{17}C above the neutron threshold, using β-delayed neutron decay of ^{17}B. These levels would play a crucial role for the ^{16}C$(n,\gamma)^{17}$C reaction that would lead on to yet higher masses, although this reaction is not precisely in the main path of the flow.

The nucleus ^{17}B is of interest not only because of its β-delayed multiple neutron emission [14,15], but also for its anomalously large matter radius [16,17]. The properties of this neutron halo have been investigated theoretically in several recent papers (for example, [18] and references therein). The daughter nucleus ^{17}C, in turn, is also a multiple-neutron emitter [14], but with lower probability. Current literature data for ^{17}C show two low-lying levels, with excitation energies of 292 keV and 295 keV, respectively. Three closely spaced low-lying states are expected [19]. Until now, however, no data on higher lying levels in ^{17}C, in particular, any levels close to the neutron threshold at 730 keV [19], have been available. With the present experiment we have attempted to increase appreciably the information available about ^{17}C levels, especially those just above the ^{16}C $+n$ threshold. These would enable the (n,γ) reaction to proceed resonantly. Thus the results are of interest from a purely nuclear physics perspective, but also for that of astrophysics and the study of IM's of primordial nucleosynthesis.

II. EXPERIMENTAL SETUP

The experiment was done at the projectile-fragmentation-type radioactive beam facility (RIPS) of the Institute of Physical and Chemical Research (RIKEN). A description of the facility is given in [20]. The setup was identical to that used to study the β-delayed neutron decay of ^{19}C [21]. Briefly, a primary beam of ^{22}Ne with an energy of 110 MeV/nucleon impinged on a primary target of ^{9}Be (thickness 5 mm). An ECR ion source produced the initial beam, and the acceleration of the ions was performed by the AVF Cyclotron and the RIKEN Ring Cyclotron. The primary beam intensity at the target was about 55 particles nA, which resulted in a ^{17}B rate of about 120 s^{-1}. A schematic diagram of the setup is given in Fig. 1. The projectile fragments were analyzed by two dipole magnets, which were adjusted to maximize the rate of ^{17}B ions. An Al wedge was included at the primary focus $F1$ to disperse beam contaminants. Particle identification during beam tuning and focusing was done using time of

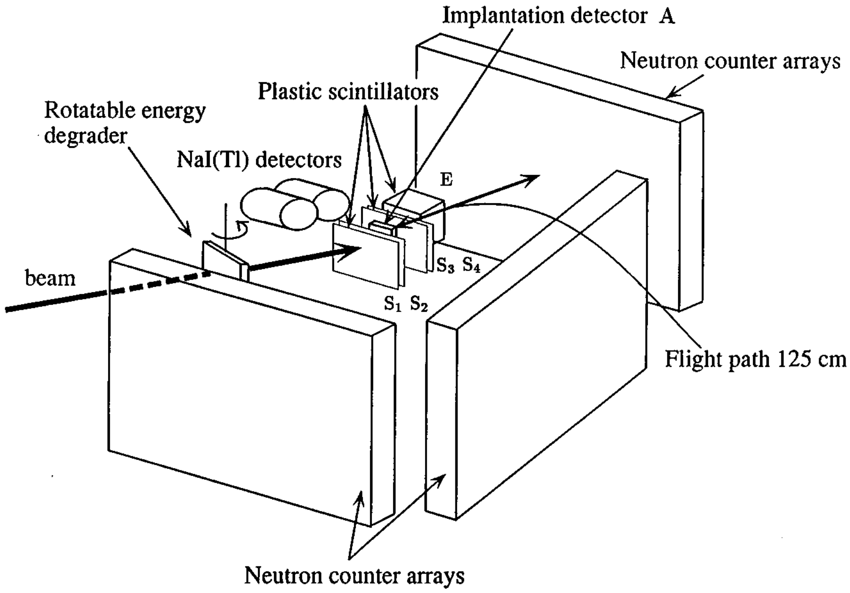

FIG. 1. Schematic diagram of the experimental setup. The ^{17}B beam enters from the left, passes through the rotatable energy degrader, the first two scintillators S_1 and S_2 and is stopped in the implantation β detector A. Also shown in the diagram are the E detector used for measuring the β spectra, the NaI γ-ray detector, and the neutron walls.

flight and ΔE detection. Adjustable slits at the focal points $F1$, $F2$, and $F3$ were used to increase the purity of the beam. The ^{17}B ions passed through a thin Mylar window (25 μm) and through a final rotatable Al absorber (675 mg/cm ^{2}, thickness 2.5 mm) which degraded the energy of the ions sufficiently for them to be stopped in a plastic scintillator. The ^{17}B ions then underwent β decay into ^{17}C (half-life of about 5 ms [19], Q_β value of 22.68(14) MeV [22]). The β decay was followed by a one-neutron decay with a probability of $p_{1n}=63(1)\%$ [15] [the probability for decay into the ^{17}C ground state without emission of a neutron, p_{0n}, is 21(2)%, and $p_{2n}=11(7)\%$]. The energies of the emitted neutrons were determined by time of flight (TOF), with the β decay providing the start signal and large neutron walls yielding the stop signal. In addition, NaI counters were used to detect γ events from decays of excited ^{16}C states in cases in which the neutron decay was not to the ^{16}C ground state. The beam purity was high, the main contaminant being ^{19}C (the ratio ^{17}B/^{19}C was about 10/1). No neutron groups stronger than the background were observed from ^{19}C β-delayed neutron decay. During the experiment the yield at $F3$ was typically 20–40 s^{-1}.

The β detector consisted of an assembly of six plastic scintillator components, labeled S_1, S_2, A, S_3, S_4, and E, from left to right in Fig. 1. The detector arrangement was tilted 45° with respect to the beam axis in order to minimize the length of neutron passage through the scintillator. The ^{17}B ions were implanted and stopped in A. The S counters had dimensions of 10 cm $\times$ 10 cm, with a thickness of 2 mm. Counter A was 4 cm $\times$ 6 cm, with 7.2 mm thickness. The E counter was a block of 10 cm $\times$ 10 cm $\times$ 10 cm and was used to observe the β spectra.

Detection of the neutrons was achieved by three large neutron walls, each having an active surface area of about 100 cm $\times$ 100 cm, the centers of which were positioned at a distance of 125 cm from detector A. This translates to a total solid angle of about 1.4 sr. Each wall consisted of 15 or 16 plastic scintillator bars (scintillator type BC-408), with dimensions 6 cm $\times$ 6 cm $\times$ 100 cm, with a Hamamatsu photomultiplier (model R329-02) attached to each end. The time resolution of the neutron walls was about 1.5 ns, and the energy resolution for 1 MeV neutrons was about 4.6% (both resolutions in σ of a Gaussian).

For detection of γ events a 7.6 cm $\Phi\times$ 7.6 cm NaI(Tl) scintillator was mounted at a distance of 16 cm from counter A (corresponding to a solid angle of 1.0 sr).

The beam was operated in a pulsed mode, with beam on for 10 ms (two half-lives of ^{17}B), and beam off (measuring time window) for 20 ms, with data acquisition occurring only in the beam-off mode. After decay of a ^{17}B in the A counter, the energy of each β-delayed neutron was measured by TOF between the A component of the β counter (start) and the neutron walls (stop). A triple β coincidence either between counters A, S_1, and S_2 or between counters A, S_3, and S_4 was required for a valid start signal.

All the photomultipliers in the neutron walls were adjusted roughly to the same gain. The gain was monitored periodically by bringing γ sources close to each wall (^{60}Co and ^{137}Cs) and observing the Compton edges of the pulse-height spectra. The NaI counter was calibrated with ^{60}Co, ^{137}Cs, and ^{22}Na sources.

III. DATA REDUCTION AND RESULTS

The neutron time-of-flight spectra were derived in the standard way. For each scintillator bar, the TOF was determined by averaging the timing signals from the two photomultipliers. The signals were then corrected as a function of their amplitudes, and for different path lengths of neutrons hitting different regions of the walls, as determined from the difference of the timing signals from the two photomultipliers.

The neutron TOF values were measured with an internal clock. In order to get an accurate time calibration, the beam was switched to ^{17}N, and neutrons from the β-delayed decay of ^{17}N into ^{16}O $+n$ were observed (Fig. 2). Three peaks with the known neutron laboratory energies (branchings) [19] of 1.70 MeV (6.9%), 1.17 MeV (50.1%), and 0.38 MeV, (38.0%) were observed. These neutron energies correspond to level energies above threshold [19] of 1.81 MeV, 1.24

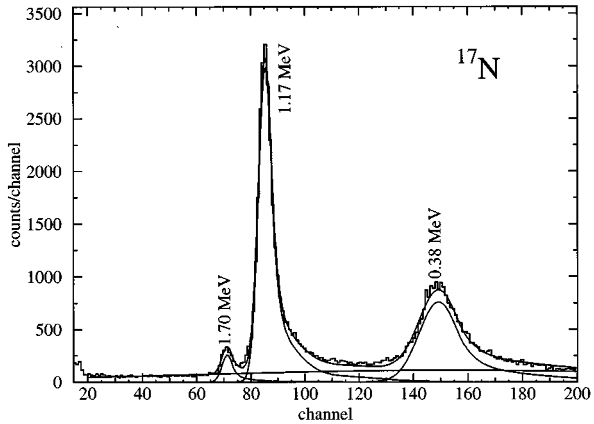

FIG. 2. Fully corrected ^{17}N β-delayed neutron TOF spectrum used for the energy calibration. The channel numbers correspond to the time of flight in ns.

MeV, and 0.41 MeV. A fourth known peak (neutron energy 0.88 MeV, energy above threshold 0.94 MeV, branching 0.6%) was much too weak and too close to the 1.17 MeV peak to be observed. The three peaks were used for the neutron energy calibration. Since the 0.38 MeV peak was quite strong, this indicates that the neutron detection threshold was well below that energy.

Figure 2 shows that the ^{17}N TOF peaks are clearly asymmetric. Although we do not fully understand the cause of the asymmetry, we assumed that all events under the tail of each asymmetric peak belonged to that peak. Thus an asymmetric fit function was used to obtain each integral. The asymmetric function (a combination of a Gaussian plus a tail for the larger TOF side consisting of a polynomial multiplied by an exponential term) was obtained from the prominent, and isolated, 1.17 MeV peak. In subsequent fits, the same asymmetric shape was consistently applied to all peaks (the tail was matched to the Gaussian at the half maximum point, and its width was scaled with the width of the Gaussian); the only free parameters then were the three parameters of the underlying Gaussian. The background was fitted with a broad Gaussian. It should be pointed out that the exact (asymmetric) shape is not crucial for obtaining the integrals, as long as all peaks are fitted *consistently* using the same shape. Indeed, using Gaussians or Lorentzians for fitting gives the same relative intensities within error bars.

In the data analysis, only 31 of the 47 bars in the three neutron walls were used. These were the ones with the lowest noise phototubes, hence, those that allowed the lowest threshold settings. The thresholds of these detectors were verified to be roughly 15 keV electron-equivalent energy. Because this setting is so low, the efficiencies of all the detectors used in the analysis were essentially the same for the neutron energies we observed, as was verified by comparing neutron yields, especially those at low energies, observed in higher and lower threshold groups of detectors. The absolute efficiency of the detectors used (see Fig. 3) was calculated by means of a Monte Carlo simulation using a standard prescription [23]. The accuracy of the calculated efficiencies was then checked by comparing the yields in the peaks from the ^{17}N β-delayed neutron emission with the well-established branching ratios of that decay. As can be seen from Table I, the branching ratios determined from our data, using our calculated efficiencies, are in excellent agreement with the known ratios, thus confirming the accuracy of our efficiencies to within a few percent down to a neutron energy of 0.38 MeV. Figure 4 shows a fully corrected ^{17}B β-delayed neutron TOF spectrum. The peaks in this figure were fitted simultaneously with the asymmetric shape described above. A broad Gaussian was used for the background in order to account for two-neutron breakup.

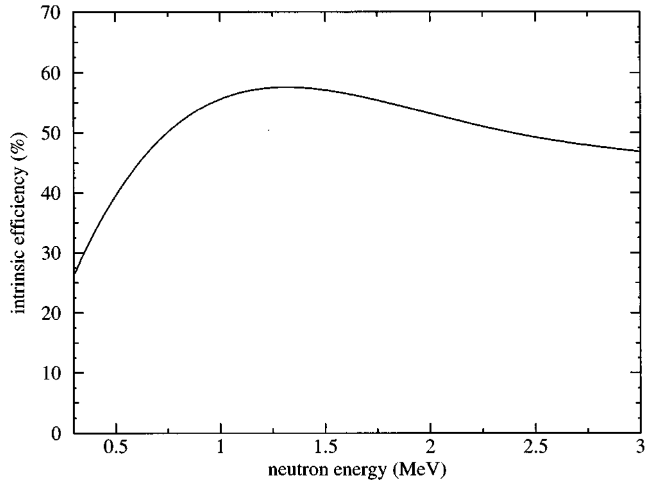

FIG. 3. Neutron efficiency for the detectors used in the data analysis as a function of the neutron energy, calculated for neutron energies above 0.3 MeV.

The three main peaks correspond to neutron energies of 2.91(5) MeV, 1.80(2) MeV, and 0.82(1) MeV (Table II). An investigation of possible daughter decays (see Fig. 5 for a level diagram) reveals that the 0.82 MeV peak corresponds to the β-delayed neutron decay of ^{16}C into ^{15}N $+n$. According to published data [19], there are two ^{16}N states above threshold that decay into the neutron channel (level energies in ^{16}N of 3.36 MeV and 4.32 MeV). These states give rise to neutron energies (after recoil correction) of 0.81 MeV (branching ratio of 84%) and 1.72 MeV (branching ratio of 16%). The 1.72 MeV neutron group could not be seen separately in the spectrum because it was under the shoulder of the much stronger peak at 1.80 MeV. The identification of the 0.81 MeV peak is confirmed by the correlation of its intensity in the TOF spectrum with gates of different β energies. The β's from ^{17}B leading to the two observed neutron peaks have maximum energies of about 20 MeV. The β's from the decay of ^{16}C leading to the third observed neutron

TABLE I. Branching ratios obtained from the β-delayed neutron decay of ^{17}N, compared to literature values [19]. The uncertainties of the literature energies are in the 1 keV range. The main contribution to the errors in the branching ratios results from the uncertainty of the β efficiencies caused by uncertainties of the threshold.

E_n (MeV)	Branching (%)	Literature branching (%)
1.70	6.4(10) [a]	6.9(5)
1.17	49.1(46) [a]	50.1(13)
0.38	39.5(46) [a]	38.0(13)

[a]Normalized to 95(1) % [19].

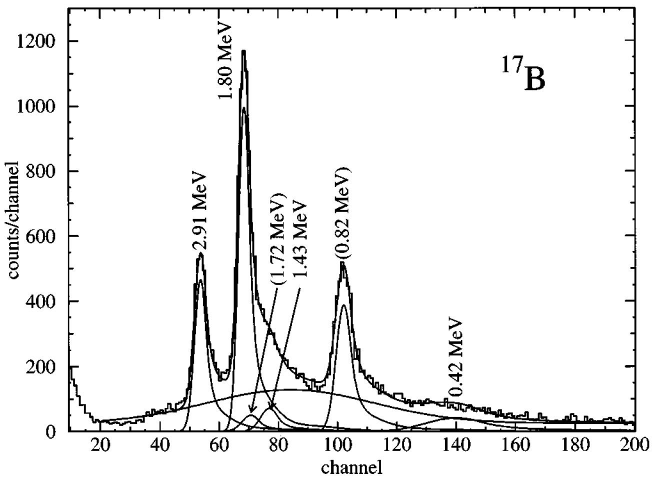

FIG. 4. Fully corrected ^{17}B β-delayed neutron TOF spectrum. The channel numbers correspond to the time of flight in ns. The ^{17}B peaks are observed at neutron laboratory energies of 2.91(5) MeV, 1.80(2) MeV, 1.43(2) MeV, and 0.42(1) MeV. The 1.72 MeV and 0.82 MeV peaks correspond to neutron decays in the β-delayed decay of the daughter nucleus ^{16}C.

peak, on the other hand, have maximum energies of only about 5 MeV (Fig. 5). Hence, gating the neutron TOF spectrum with only the high energy portion of the β spectrum should make the β-delayed ^{16}C peak disappear, as was observed. The remaining two main neutron peaks are consistent with decays of excited ^{17}C states, both from the time scale of associated β decays and from the maximum β energies.

The broad shoulder under the 1.81 MeV peak requires special attention, since the asymmetry of this peak is greater than that of the (isolated) 1.17 MeV peak in ^{17}N. This is a clear indication that the broad shoulder is actually caused by one or more smaller unresolved peaks. From the known branching ratios of the ^{16}C peaks at 0.81 MeV and 1.72 MeV, the known relative intensity of the 0.81 MeV peak in the TOF spectrum, and the known efficiency of the detectors, the 1.72 MeV peak (assuming it has a comparable Gaussian width) is fully determined and can be included in the fit. This new fit still does not fully account for the asymmetry of the 1.81 MeV peak. The remaining shoulder of the 1.81 MeV peak is apparently due to another neutron group at 1.43 MeV

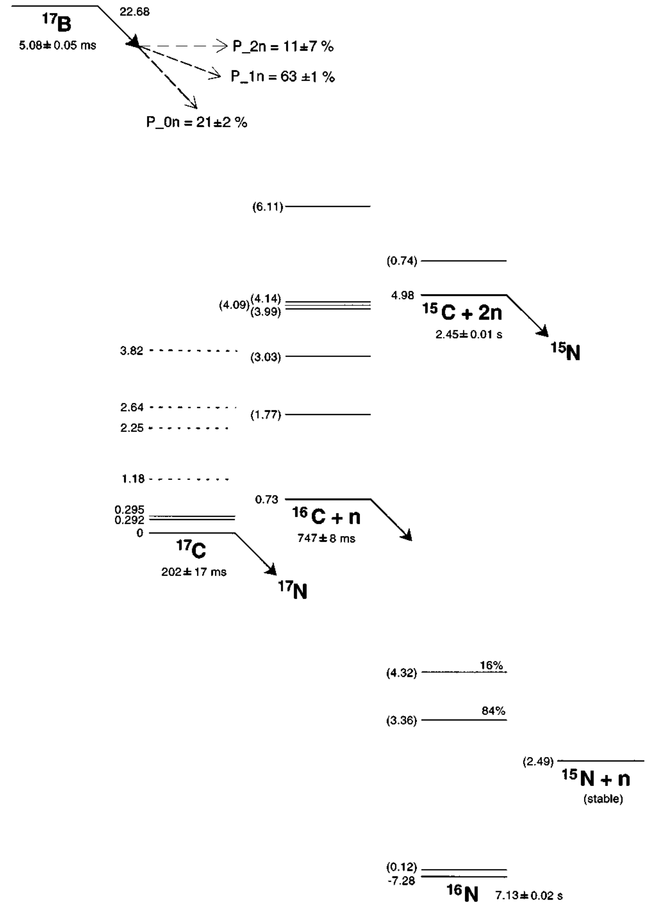

FIG. 5. Level and decay scheme of ^{17}B [15,19,22,28]. The dashed lines are the new levels.

from β-delayed ^{17}B decay (Table II).

Another possible neutron peak, at 0.42 MeV, can be observed only with difficulty in the TOF spectrum, since it is very broad there and cannot easily be distinguished from the background. However, it becomes more apparent when the TOF spectrum is transformed into an energy spectrum (Fig. 6). Note that the peak seen in Fig. 6 cannot be a manifestation of a background subtraction; the energy spectrum in Fig. 6 is the transformation of the raw TOF spectrum. The centroid for this peak was first determined from a fit on the

TABLE II. Energy assignments, branching ratios (normalized to the known probability for $1n$ decay), and log ft values for observed β-delayed neutrons from ^{17}B.

E_n (MeV)	E_x (MeV)	In	Decay to	Branching (%)	log ft
2.91(5)	3.82(5)	^{17}C	g.s.	17.8(14) [a]	4.91(15)
1.80(2)	2.64(2)	^{17}C	g.s.	29.6(25) [a]	4.82(14)
1.72	4.32	^{16}N [b]	g.s.		
[1.43(2)] [d]	[2.25(2)]	[^{17}C]	[g.s.]	[4.7(15)] [a]	[5.66(19)]
0.82(1)	3.37(1) [c]	^{16}N	g.s.		
[0.42(1)] [e]	[1.18(1)]	[^{17}C]	[g.s.]	[10.8(30)] [a]	[5.41(18)]]

[a]Normalized to 63(1) % [15].
[b]Known peak with known branching [19] included in fit.
[c]$E_x = 3.36$ [19].
[d]Peak is under broad shoulder, assignment suggested by peak fitting.
[e]Suggested by energy spectrum.

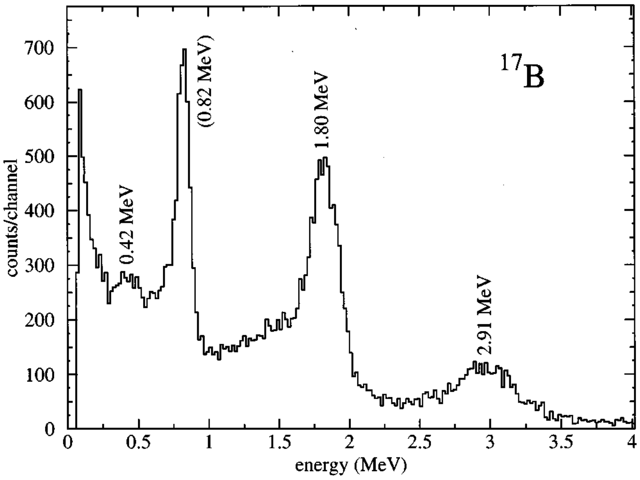

FIG. 6. ^{17}B β delayed neutron TOF spectrum, transformed to an energy scale. Each channel corresponds to 20 keV. The peak at 0.42 MeV is clearly visible.

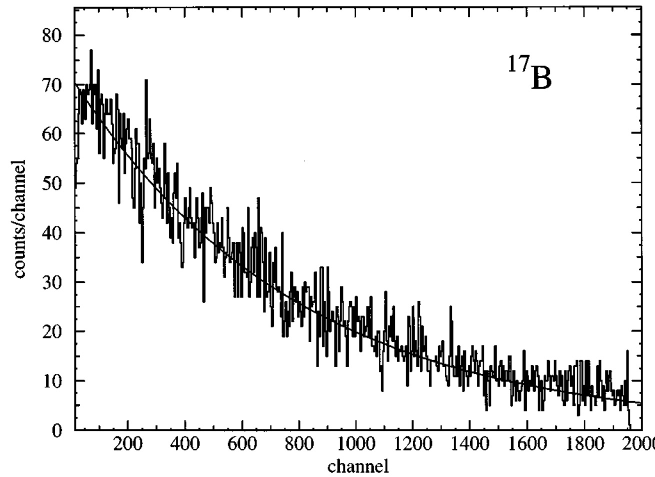

FIG. 7. Time spectrum of ^{17}B β decay, gated to the 1.80 MeV neutron peak. The channel numbers correspond to the time in 0.01 ms. The solid line is an exponential fit.

energy scale and was then included in the fit of the TOF spectrum. Because of the poor peak-to-background ratio even in the energy spectrum, not much can be said about this peak. Since it is so broad, it may well be a doublet. Its width might also imply it results from a more highly excited state in ^{17}C that decays to an excited state in ^{16}C. However, the data obtained for this state do not allow such a determination.

Both the 1.43 MeV peak and the 0.42 MeV peak are consistent with decays of excited ^{17}C states, both from the time scale of associated β decays and from the maximum β energies.

Other neutrons could possibly come from decays of the daughters ^{15}C and ^{17}C. The ^{15}C ground state is above the neutron threshold of ^{15}N. In the ^{17}C case, the β-delayed neutron emission probability p_n has been reported [14,24], and very recently also the β-branchings to excited states in ^{17}N [25]. The subsequent β decay and neutron decays of ^{17}N, in turn, were studied in the energy calibration run with ^{17}N. No indication of ^{17}C or ^{17}N peaks is apparent in the ^{17}B neutron TOF spectrum.

The γ spectrum is weak and exhibits no clear peaks. Coincidences between γ rays and each of the neutron peaks resulting from neutron decay of ^{17}C also do not produce peaks. Unfortunately, the gain for the γ spectrum was set so that the 1.77 MeV γ rays from the ^{16}C first excited state would have occurred at the high energy edge of the γ spectrum. However, that spectrum was flat near its high energy end, suggesting that all ^{17}C neutron decays were to the ^{16}C ground state. Fortunately, Kurie plots can also be used to determine the ^{17}C states to which the ^{17}B β decays, and hence whether the energies of the resulting neutrons are consistent with decays to the ^{16}C ground state or first excited state. This technique, however, works only for strong well-separated peaks in the neutron TOF spectrum, since the neutron peaks are used as gates for the β spectrum. Since the neutron and β-spectrum end point energies from ^{17}N and ^{16}C decays are known and those from the β-delayed ^{19}C decays could be determined unambiguously (see [21]), the calibration between channels and maximum β energies can be used to calibrate the β spectra from ^{17}B decays to ^{17}C states. If it is assumed that the two well-separated neutron peaks result from decays to the ^{16}C ground state, a good fit to the seven data points is achieved, whereas assumption of decay to the first excited state, or any other excited state, produces a much worse fit. This together with the fact that the γ spectrum is flat near the threshold at 1.77 MeV indicates that all neutron decays of ^{17}C populate only the ^{16}C ground state.

Table II lists the assigned energies of all neutron peaks, as well as the branching ratios and $\log(ft)$ values. The branching ratios were obtained by normalizing to the p_{1n} value given in [15]. More recent experimenters [14,26] have measured only the β-delayed neutron emission probability p_n summed over one- and multiple-neutron decay. These literature values all agree within their error bars. A new investigation [24], however, results in a somewhat higher value for p_n.

Figure 7 shows one of the measured β-time spectra for ^{17}B, gated with the 1.80 MeV neutron group from the decay of ^{17}C into ^{16}C + n. It was fitted with one exponential component. The β-time spectrum gated with β-delayed neutrons from the decay of ^{16}C could not be fitted to give the half-life of ^{16}C, since this half-life, 747 ms [19], is so much longer than our time window (20 ms). The calculated half-life for ^{17}B, averaged over several different fits, is 4.93(19) ms, in reasonable agreement with a weighted average half-life of 5.10(5) ms based on literature values [5.3(6) ms, 5.08(5), ms and 5.9(3) ms given in [19], and 5.20(45) ms given in [24]].

An attempt was made to identify resonant two-neutron decay. To do so, we first rejected events in which the second neutron signal out of a pair was detected in an adjacent neutron bar. In such cases, the second neutron event was most likely initiated by the same (scattered) neutron as the first event. Since the remaining two-neutron events had very poor statistics, the results were not conclusive.

From systematic studies of β decay, all the observed log (ft) values appear to be consistent with allowed transitions (although first forbidden transitions cannot be totally ruled out). With a ^{17}B ground state spin/parity of $J^{\pi}=3/2^{-}$ [19], the spin/parities of the observed ^{17}C states, assuming allowed transitions, are restricted to $(1/2,3/2,5/2)^{-}$. Because of the selection rules for allowed β decay ($\Delta J=0,\pm 1$, no change of parity), only negative parity states were observed. Positive parity states could be populated by (first order) forbidden transitions, which would generally be expected to have lifetimes at least an order of magnitude longer. With the present setup (assuming the correctness of the assumption of allowed transitions), we would not have detected such forbidden transitions, and we therefore cannot exclude the presence of possible low-lying positive parity states in ^{17}C. Theoretical $\log(ft)$ values and spin assignments based on the shell model are in preparation [27].

Within the limits of resolution and detection threshold, this experiment provides no evidence for negative parity states close to the neutron threshold. The observed states in ^{17}C have too high excitation energies to be of astrophysical relevance in IM scenarios. Any $^{16}\mathrm{C}(n,\gamma)^{17}\mathrm{C}$ capture reaction at low energies would therefore have to proceed as a direct capture, as has been assumed in previous IM calculations. Experiments sensitive to positive parity states would clearly be required to provide a final answer.

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