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Upper limit of the lifetime of ^{16}B

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The lifetime of the neutron-unstable nucleus ^{16}B was investigated to search for evidence of delayed neutron emission (neutron radioactivity). The lifetime was inferred to be less than 191 ps (68% C.L.) based upon the lack of ^{16}B fragments observed in the fragmentation of 52 MeV/nucleon ^{17}C nuclei.

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The exact location of the drip lines is one of the most stringent tests of nuclear structure models. The predictions for stability of nuclei along the proton drip line can be tested up to very heavy nuclei. Beyond the proton drip line, the large Coulomb barrier and the angular momentum barrier can lead to very long lifetimes for proton-unbound nuclei (proton radioactivity) [1]. Several of these ground state proton emitters have been observed and they serve as important probes of the drip line since the lifetimes are sensitive to the nuclear potential [2,3]. On the neutron-rich side of stability the search for neutron radioactivity, which arises solely due to the angular momentum barrier, is extremely difficult because of the shorter lifetimes expected and the current inaccessibility of the neutron drip line beyond $Z\sim8$ [4,5].

One interesting candidate for neutron radioactivity is ^{16}B. This nucleus was first reported to be neutron-unstable by Bowman *et al.* who observed the isotopes ^{15,17}B but not ^{16}B [6] from the spallation of uranium by 4.8 GeV protons. This result was later confirmed by Langevin *et al.* who studied the fragmentation of 44 MeV/nucleon Ar on a tantalum target [7]. More recently, Bohlen *et al.* studied ^{16}B produced via the multiparticle transfer reaction ^{14}C(^{14}C,^{12}N)^{16}B [8]. They reported that the ground state of ^{16}B is neutron unbound by only 40 $\pm$ 60 keV and thus is nearly particle stable. Furthermore, the simple shell model picture for the structure of ^{16}B suggests a $d_{5/2}$ orbital for the last neutron. The low neutron binding energy and the $\ell=2$ angular momentum barrier may then yield a quasi-stationary ground state for ^{16}B with a relatively long lifetime.

By reexamining the previous experimental studies of ^{16}B we can estimate limits on its lifetime. In the work of Bowman *et al.* [6] the B fragments were emitted with $\sim$ 2 MeV/nucleon energy over a flight path of $\sim$ 40 cm. From a combination of the ^{16}B flight time with an estimate of the number of ^{16}B that should have been observed relative to the ^{15,17}B in this experiment, we deduce the ^{16}B lifetime to be shorter than $\sim$ 9 ns. In the work of Langevin *et al.*, fragmentation products from reactions of the 44 MeV/nucleon ^{40}Ar beam were separated from the incident beam using a fragment separator and were detected approximately 18 m downstream of the target [7]. Again, assuming we can interpolate the expected ^{16}B yield from the observed ^{15,17}B yields, and estimating the ^{16}B velocity, we deduce a ^{16}B lifetime less than 260 ns from this experiment.

In order to determine an improved limit on the ^{16}B lifetime we have carried out a new investigation of this nucleus, combining several features from the previous experiments. Here we utilize the fragmentation of a radioactive ^{17}C beam as the source of ^{16}B. Because the production of ^{16}B via proton stripping should have a much lower background of other isotopes than in the case of ^{40}Ar fragmentation, a fragment separator is not needed and a compact $\Delta E-E$ Si telescope could be placed directly behind the target to detect and identify boron fragments. This combination of high production rate and detection efficiency, as well as a short flight path, allows an improved lifetime measurement to be made.

The experiment was performed at the National Superconducting Cyclotron Laboratory using a radioactive ^{17}C beam produced from the fragmentation of 80 MeV/nucleon ^{18}O on a 980 mg/cm^2 Be target. The ^{17}C ions were separated using the A1200 projectile fragment separator [9] and focused onto a secondary target of 114 mg/cm^2 C located at the focal plane of the A1200. The energy of the secondary ^{17}C beam was 880 MeV and momentum slits were used in the A1200 device at a dispersive focus to limit the energy spread of the secondary beam to $\pm$ 1%. A thick Cu collimator and a 300 μm Si detector were placed just in front of the secondary target to collimate the beam and to identify the ^{17}C ions on a particle-by-particle basis by measuring energy loss and time of flight through the A1200 device. The purity of this secondary beam was 84% and the incident rate was $\sim$ 500 counts/s. The influence of contaminant particles was removed off line via software cuts.

The reaction products were detected in a four-element $\Delta E1-\Delta E2-\Delta E3-E$ Si telescope placed immediately behind the secondary target covering laboratory angles forward of 15°. Boron fragments were identified and the total energy was measured using the energy-loss information from the Si telescope detectors. Several ΔE elements were included in the telescope to provide redundant particle identification information in order to reduce background events. The detector thicknesses were 303 μm, 498 μm, 5 mm, and 5 mm, respectively, and the last element of the telescope was 5 cm from the secondary target. The detectors were energy calibrated using $Z=5$ and $Z=6$ ion beams of known energies

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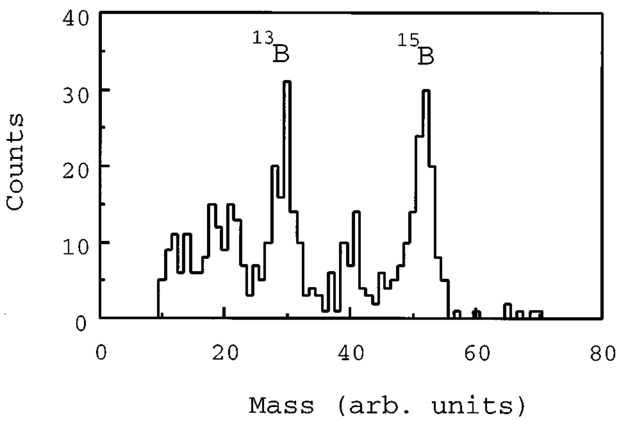

FIG. 1. Particle identification spectrum for boron isotopes seen in the fragmentation of ^{16}C.

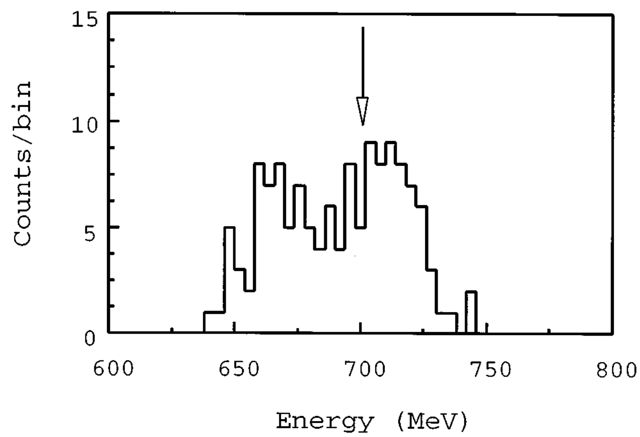

FIG. 2. Total energy spectrum of ^{15}B ions observed from ^{16}C-induced reactions. The arrow indicates the predicted peak energy for ^{15}B ions produced by fragmentation.

produced from the ^{18}O fragmentation reaction and separated with the A1200 separator. A second part of the experiment was carried out using a secondary beam of 815 MeV ^{16}C ions, in place of ^{17}C, to produce particle stable ^{15}B ions via proton stripping. This fragmentation reaction should closely resemble the $^{17}\mathrm{C}\rightarrow^{16}\mathrm{B}$ reaction and provides an estimate of the $1p$ stripping cross section for ^{17}C, as well as a test of the experimental method.

Figure 1 shows the particle identification (PID) spectrum for $Z=5$ isotopes measured in the fragment telescope in the case for the ^{16}C incident beam. These data correspond to events from 4.87×10^{6} incident ^{16}C ions. The PID spectrum was constructed using the $\Delta E1+\Delta E2+\Delta E3$ and E detector energies following the algorithm of Shimoda *et al.* [10]. The data were further restricted to events with the appropriate energy loss in each of the ΔE detectors (to minimize background events) and the fragments were required to stop in the last detector element.

^{13,15}B are the most prominent boron isotopes; ^{15}B arises from one-proton stripping of the incident ^{16}C beam, while the lighter boron isotopes probably are predominantly produced from excited ^{15}B fragments which deexcite by neutron emission. A few counts, probably corresponding to background events, can be seen in the region of ^{16,17}B in the PID spectrum. Since these fragments are not expected to be strongly produced in the fragmentation of ^{16}C, a likely source of these background events is multiparticle hits in the fragment telescope which can have similar energy-loss signatures as the heavy boron isotopes. The probability of multiparticle hits is enhanced by the large solid angle of the fragment telescope, and represents one limitation of the experimental method.

Figure 2 shows the total energy spectrum of the ^{15}B isotopes from the ^{16}C fragmentation. The cutoff at the lowest energies is due to the requirement that the ^{15}B ions enter the last E detector in the fragment telescope. The arrow in the figure indicates the energy for ^{15}B fragments with the same velocity as the incident beam, after accounting for the energy loss in the secondary target. This is the peak energy we expect from simple fragmentation. Events from the transfer reaction $^{12}\mathrm{C}(^{16}\mathrm{C},^{15}\mathrm{B})^{13}\mathrm{N}$ would peak about 20 MeV higher. The data show a broad peak [full width at half maximum (FWHM) $\sim$ 30 MeV] about 8 MeV above the predicted fragmentation peak energy, suggesting that these events arise from a combination of transfer reactions and fragmentation. The broad width results from a combination of the energy spread of the secondary beam, the large angular acceptance of the fragment telescope, and the intrinsic width associated with the stripping reactions. The events below 700 MeV arise from more dissipative collisions. The total number of identified ^{15}B ions is 133, of which 69 are in the high-energy peak (above 694 MeV) corresponding to the least-dissipative fragmentation transfer one-proton stripping reactions. This yields a cross section of 2.4 ± 0.3 mb which is well within the range of $1-10$ mb expected for one-nucleon-removal cross sections in this energy regime.

The PID spectrum for $Z=5$ fragments from the target bombardment of ^{17}C projectiles is shown in Fig. 3. These data result from 9.05×10^{6} incident projectile ions. It is not surprising that a ^{16}B peak is absent, owing to the known particle instability of ^{16}B, and we find that ^{13,15}B are again the dominant boron isotopes. We expect that the ^{15}B ions arise predominantly from the neutron decay of ^{16}B projectile-like fragments produced via one-proton stripping of the ^{17}C beam. An examination of the ^{15}B total energy spectrum in

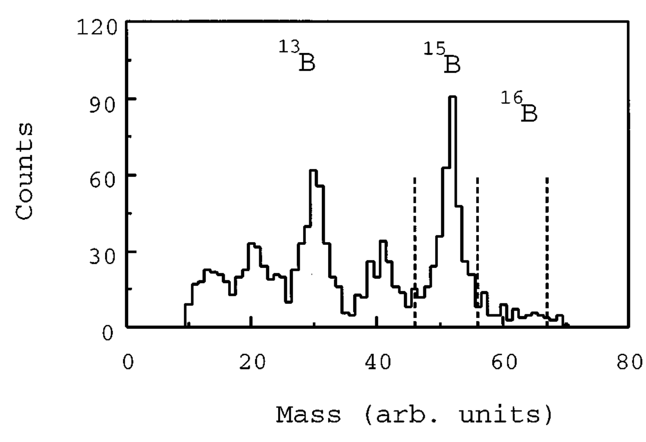

FIG. 3. Particle identification spectrum for boron isotopes seen in the fragmentation of ^{17}C. The PID windows used for ^{15}B and ^{16}B are shown.

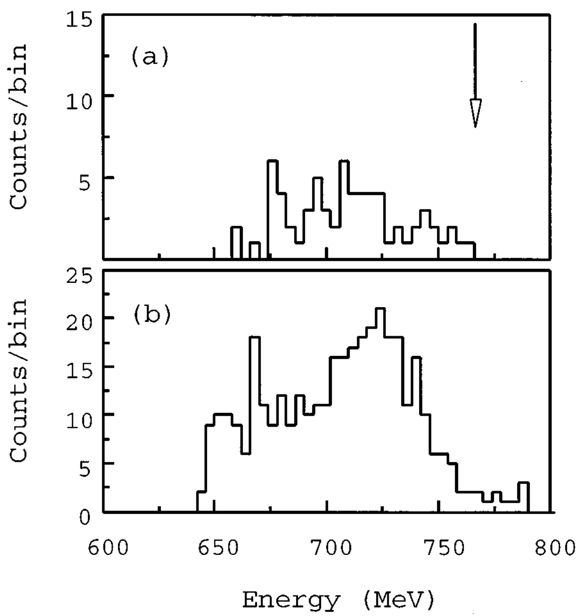

FIG. 4. (a) Total energy spectrum of ^{16}B candidate ions observed from ^{17}C-induced reactions. The arrow indicates the predicted peak energy for ^{16}B ions produced by fragmentation. (b) Total energy of ^{15}B ions seen in the fragmentation of ^{17}C.

Fig. 4(b) shows a similar structure as in Fig. 2 with a high-energy peak containing $\sim$ 230 counts. This yield corresponds to a 4.4$\pm$0.3 mb cross section, similar in magnitude to the one-proton-removal cross section observed for ^{16}C.

On the other hand, if the ^{16}B lifetime was long enough, some ^{16}B ions would survive until detected in the particle telescope and would be identified as ^{16}B in the PID spectrum. In fact, we do see 67 events in the ^{16}B window of the PID spectrum in Fig. 3. Most of these events arise from background events, probably due to multiparticle hits. However, we can significantly reduce this background by looking at the total energy spectrum. Figure 4(a) shows the total energy spectrum for these ^{16}B candidates with the expected energy for fragmentation products shown by the arrow. Clearly, most of the events are well below this energy and we see no analogous high-energy fragmentation-transfer reaction peak as was seen for the one-proton-stripping product of ^{16}C. Estimating that the ^{16}B events would peak at $\sim$8 MeV above the fragmentation prediction with a FWHM of 30 MeV, as seen in the ^{16}C$\rightarrow$^{15}B case, we find four events which continue to satisfy all of the conditions for ^{16}B fragments arising from the least-dissipative fragmentation transfer reactions. Assuming these events are ^{16}B, we can use the calculated stopping time for ^{16}B fragments in the fragment telescope (690$\pm$69 ps), as well as an expected yield of ^{16}B ions of 4.4 mb (from the ^{15}B yield), to calculate a ^{16}B lifetime of 170 $\pm$21 ps. However, under the present experimental conditions it is impossible to positively identify these events as ^{16}B. In all likelihood they result from background processes and our calculated lifetime represents an upper limit on the actual ^{16}B lifetime.

This new limit of the lifetime does not put any constraints on the decay energy of ^{16}B other than that it be unbound. A simple shell model calculation assuming a $d_{5/2}$ orbital for the last neutron yields lifetimes of 3.7×10^{-16} s and 1.1×10^{-13} s for decay energies of 10 keV and 1 keV, respectively.

In summary, we have measured boron isotope fragments from reactions of 51 MeV/nucleon ^{16}C and 52 MeV/nucleon ^{17}C with a ^{12}C target, using a short-flight-path, large-solid-angle target-detector geometry. From the ^{15}B yields we infer one-proton-stripping cross sections of 2.4$\pm$0.3 mb and 4.4 $\pm$0.3 mb for ^{16}C and ^{17}C, respectively. Furthermore, for the case of ^{17}C fragmentation, we have set an upper limit of 0.1 mb for the yield of neutron-unstable ^{16}B ions identified in the fragment telescope (based upon four counts) which corresponds to an upper limit on the lifetime of ^{16}B of 191 ps (68% C.L.). This limit is approximately 50 times lower than the previous experimental limit.

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