Discovery of Two Isotopes, ^{14}Be and ^{17}B, at the Limits of Particle Stability*

J. D. Bowman,† A. M. Poskanzer, R. G. Korteling,‡ and G. W. Butler§
Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720
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We have used ΔE-E and time-of-flight techniques to observe the products of the interaction of 4.8-GeV protons with a uranium target. Two new isotopes, ^{14}Be and ^{17}B, were observed to be particle stable, and two others, ^{12}Li and ^{16}B, were shown to be particle unstable. The new isotope ^{17}B recently had been predicted to be particle stable, but the observation of ^{14}Be was surprising because it was thought to be unstable on the basis of both theoretical predictions and previous experimental results.

A few years ago it was believed that all the particle-stable isotopes of the elements up through boron had been discovered.[1-3] The energy by which the heavier isotopes of each element were predicted to be unbound are listed in Table I.[4-6] In addition, there were experiments showing the particle instability of ^{9}He and ^{10}He,[7] and ^{13}Be[8] and ^{14}Be.[9] The ^{14}Be result was from a heavy-ion-transfer experiment in which the yield was more than a factor of 10 lower than that expected from systematics. A year ago, Thibault and Klapisch[5] recalculated the masses and predicted ^{17}B bound by 0.6 MeV and ^{19}B bound by 0.2 MeV, as shown in column 2 of the table. The present experiment was stimulated by this recalculation which predicted ^{17}B to be the lightest undiscovered isotope.

The method of production used was the interaction of high-energy protons with a uranium target, an approach which had been quite fruitful in the past.[8,10-12] A uranium target 28 mg/cm^2 thick was placed in the 4.8-GeV external proton beam of the Bevatron. Fragments were identified in a ΔE-E telescope in which the two detectors were separated by 25 cm. The time of flight of the fragments between the two detectors was recorded together with the ΔE and E values. The time-of-flight and E signals were used to identify the mass number of the fragments, and the ΔE-E information was used to distinguish the elements. The telescope of silicon detectors was at 90° to the beam and consisted of a 25-μm ΔE detector and a 67-μm E detector, both collimated to 4×6 mm^2. The E detector was at a distance of 42 cm from the target with a veto detector immediately behind it to reject particles which did not stop in the E detector. All the detectors were cooled to -23°C. Most of the electronics, including the preamplifiers, had been used in a previous experiment and have already been described.[13] The timing resolution [full width at half-maximum (FWHM)] in the present experiment for ^{11}B fragments which deposited 20 MeV in the E counter was 290 psec, giving a mass resolution at mass 11 of 4.4%.

A problem encountered in the previous experiment[13] was the background from accidental coincidences which obscured the interesting regions of possible new isotopes. Thus, for the present experiment pulse-width discrimination was introduced to eliminate spurious events caused by two pulses occuring within a time shorter than could be distinguished by a pile-up rejector. The time between the leading edge and crossover of each signal was measured with a resolution (FWHM) of 130 psec for the ΔE detector and 70 psec for the E detector. Signals proportional to the pulse widths were also recorded for each event. They were corrected for walk with pulse height in the off-line data analysis, and then windows at $\frac{1}{4}$ the peak height were set on these signals, which reduced the background a factor of 80.

TABLE I. Neutron or two-neutron binding energies[a] in MeV.

	1966[b]	1972[c]	Now[d]
^{9}He	Unbound	-3.8	No change
^{10}He	-10.0	-4.9	No change
^{12}Li	Unbound	-4.8	-3.9
^{13}Li	Unbound	-6.3	-4.5
^{13}Be	-2.7	-3.3	-2.3
^{14}Be	-2.4	-1.5	$+0.4$
^{16}Be	Unbound	Unbound	-2.4
^{16}B	-1.0	-1.2	No change
^{17}B	-4.0	$+0.6$	No change
^{19}B	Unbound	$+0.2$	No change

[a]Listed are the neutron binding energies for the odd-N isotopes and the two-neutron binding energies for the even-N isotopes.

[b]See Ref. 4.

[c]See Ref. 5.

[d]Changes caused by the recently measured mass of ^{14}B. See Ref. 6.

In a data-taking period of three weeks at an average beam intensity of 6×10^{11} protons per pulse (10 pulses/min), 12-million events of the elements Li through N were recorded. Stability over this long data collection period was achieved by having two separate pulsers feed tagged simulated events to the preamplifiers which allowed two-point stabilization of the data. Events were selected which had E signals between 10 and 60 MeV, time-of-flight signals between 10.6 and 27 nsec, and met the above requirements of the pulse-width discriminators. The wide energy window was achieved by correcting the E signals for the dead layer on the E counter, and by correcting the time-of-flight signals for walk with both E and ΔE. The E and time-of-flight signals were then used to calculate the mass number A of each fragment. The ΔE-E signals were used to calculate a particle identification signal and then the calculated mass number was used to remove the mass dependence in order to calculate the atomic number Z. Thus, a two-parameter display of yield versus Z and A was obtained in which each isotope appeared as a mountain peak. It was observed that there was a small amount of tailing of the yield to low Z. This amounted to 0.1–0.4% at one Z lower and was evaluated at masses 10 and 13 where ^{10}Li and ^{13}Be were known not to exist. Thus, by knowing the form of this tailing and normalizing it at the point one-half Z higher, this small effect could be subtracted out when taking mass yield cuts at constant Z. These final graphs[14] are shown in Fig. 1 for the elements Li, Be, and B.

Figure 1 clearly shows all the known particle-stable isotopes of Li, Be, and B, and in addition, two new isotopes, ^{14}Be and ^{17}B. In the two-parameter display these isotopes appeared as peaks with the yield decreasing in all directions. There are 150 ^{14}Be events and 50 ^{17}B events. As a final confirmation, an examination of all five raw-data parameters for each event of both isotopes showed the raw-data parameters to be distributed in a manner similar to the adjacent isotopes ^{12}Be and ^{15}B.

Although the relative yields cannot be taken as relative cross sections because of the various cutoffs, it is still interesting to compare the yields of isotopes differing by two mass numbers. The yield ratio for ^{14}Be/^{12}Be is 1/225 and for ^{17}B/^{15}B is 1/100. These small ratios can be compared with the corresponding two mass-number ratios leading to isotopes slightly closer to β stability (^{11}Li, ^{12}Be, ^{14}B, and ^{15}B) which are 1/20 to 1/40. Thus it appears that in this light mass region, in contrast to the Na and K region,[12] the mass-yield curve is steeper the further one is from stability. In addition, for ^{14}Be the ratio crosses the $N=8$ neutron shell and one can have an additional decrease in yield similar to that observed[12] at the $N=20$ and 28 shells for the very neutron-excess isotopes of Na and K.

Nuclei known to be particle unstable—^{8}Be, ^{9}B, ^{10}Li, and ^{13}Be—are missing in Fig. 1, and in addition it is clear from the figure that ^{12}Li and ^{16}B are particle unstable. The case of ^{13}Li is less clear. Although there are 1400 ^{11}Li events and no ^{13}Li events in the two-parameter display,

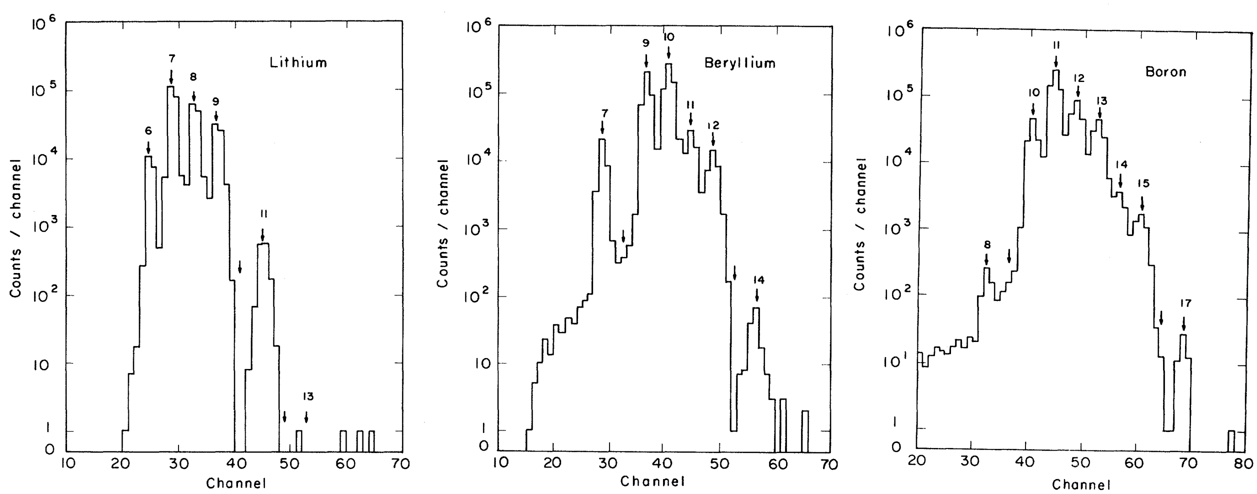

FIG. 1. Mass-number distributions selected on the atomic numbers of Li, Be, and B. Arrows for the new and missing isotopes point to the expected positions of the peaks based on the positions of the main isotopes.

there is a background in this region of about one event per isotope. One expects the $^{13}Li/^{11}Li$ ratio to be smaller than the $^{14}Be/^{12}Be$ ratio because ^{13}Li is further from β stability and also crosses the $N=8$ shell. Thus from these data one cannot conclude that ^{13}Li is particle unstable, although one would not expect it to be stable because it is predicted to be unbound by many MeV.

After the appearance of the clear peak for ^{14}Be in Fig. 1, it was realized that the very recent measurement[6] of the mass of ^{14}B drastically effects the prediction for ^{14}Be. Thibault and Klapisch had assumed ^{14}B to be just bound, but Ball *et al.*[6] found it to be bound by 1.0 MeV. Using this mass and the Garvey-Kelson transverse relation[4,15] one now happily predicts that ^{14}Be is bound by 0.4 MeV as shown in the third column of Table I. All of the other predictions are still consistent with observations. The discrepancy with the heavy-ion-transfer experiment[9] remains unexplained.

The isotope ^{14}Be has $T_z=3$, a spin and parity of 0^+, and a predicted β-decay energy of 17 MeV, while ^{17}B has $T_z=\frac{7}{2}$, a probable spin and parity of $\frac{3}{2}^-$, and a predicted β-decay energy of 23 MeV. Since β decay to low-lying levels is parity forbidden when the neutron is in the s-d shell and the proton in the p shell, both isotopes are probably delayed neutron emitters in 100% of their decays and have half-lives in the range of tens of milliseconds.

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†Present address: Los Alamos Scientific Laboratory, Los Alamos, N. Mex. 87544.

‡Permanent address: Simon Fraser University, Burnaby, B. C., Canada.

§Permanent address: Los Alamos Scientific Laboratory, Los Alamos, N. Mex. 87544.

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