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First search for ^{16}Be

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In order to determine the position of the neutron dripline for $Z=4$, a primary beam of ^{40}Ar was accelerated to 140 MeV/nucleon using the newly completed Coupled Cyclotron Facility at the National Superconducting Cyclotron Laboratory at Michigan State University. Neutron-rich fragmentation products emerging from a beryllium production target were separated with the A1900 fragment separator. The isotopes ^{6,8}He, ^{9,11}Li, ^{12,14}Be, ^{17,19}B, and ^{20}C were identified using time-of-flight and energy-loss information, but no events of ^{16}Be were recorded.

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The recently reported emergence of new shell structures in very neutron rich nuclei initiated the reevaluation of the binding energies of nuclei along the neutron dripline [1]. The new shells might be responsible for the fact that ^{26}O is unbound while ^{31}F is still bound. Revisiting even lighter nuclei, it could be possible that ^{16}Be is bound.

The last Be isotope known to be bound is ^{14}Be. The next heavier Be isotope, ^{15}Be, is unbound with respect to one-neutron emission. ^{16}Be is predicted to be bound regarding one-neutron emission, with a one-neutron separation energy of 1.828 MeV [see Fig. 1(a)]. However, ^{16}Be might be unbound regarding two-neutron decay. Early predictions placed the two-neutron separation energy at -2.98 MeV [5].

So far there have been no experiments that searched for ^{16}Be and its particle instability has not been confirmed experimentally. Previous measurements of light neutron-rich nuclei that were able to detect ^{31}F, ^{19}B, and searched for ^{26,28}O [1,6–8] were not aimed at detecting ^{16}Be.

According to a mean-field and shell-model configuration mixing calculation that has recently been undertaken by Brown [3], the two-neutron separation energy of ^{16}Be is only about -628 keV [4].

The same calculation predicts ^{19}B and ^{22}C to be unbound as well [see Fig. 1(b)]. These nuclei, however, already have been measured and are confirmed to be bound [6,8,1]. This comparison opens the question if ^{16}Be could be bound as well, despite having been predicted to be unbound.

The experiment was performed using the Coupled Cyclotron Facility [9] at the National Superconducting Cyclotron Laboratory at Michigan State University. A schematic view of the facility is shown in Fig. 2. The superconducting ECR ion source delivered a beam of $^{40}Ar^{7+}$ with an intensity of 4.4×10^{11} particles per second, which was accelerated to an energy of 12.3 MeV/nucleon in the K500 cyclotron. The beam was then transported through the coupling line to the K1200 cyclotron, where it was radially injected with an intensity of 4.2×10^{10} s^{-1}. A 0.2 mg/cm^2 carbon foil in the K1200 injection line completely stripped the ^{40}Ar ions which could finally be accelerated to the full beam energy of 140 MeV/nucleon. The beam was extracted from the K1200 with an intensity of 9.7×10^{9} s^{-1} and directed onto a 1455 mg/cm^2 beryllium target at the entrance of the A1900 fragment separator [10]. The thickness of the production target was chosen in order to produce ^{16}Be at the maximum magnetic rigidity of the A1900 fragment separator.

The first half of the separator up to image 2 was set to the maximum rigidity of 6.00 Tm. At the second intermediate image, the dispersive plane, a thin (327 mg/cm^2) plastic start detector as well as an achromatic wedge-shaped plastic degrader (971 mg/cm^2) were installed. The momentum acceptance was $\pm2.5\%$. The magnetic rigidity of the dipole stages after the intermediate image was set to 5.6719 Tm, according to energy loss calculations for ^{16}Be using LISE++ [11–13]. The magnetic rigidities of the fragment separator were verified by measuring the magnetic fields with NMR probes.

The detector set at the focal plane comprised a 5×5 cm^2 500-μm-thick silicon detector for the energy loss measurement and a 10-cm-thick plastic scintillation detector for the total particle energy.

A complete and independent particle identification was achieved at the intermediate image and at the focal plane by determining the mass-to-charge ratio with measurements of the particle velocity and the particle charge with energy-loss measurements.

For the identification at the intermediate image, we used the cyclotron's RF time signal and the thin plastic scintillator time to deduce the particle velocity. The energy-loss signal of the scintillator was used to deduce the particle charge. The particle velocity at the focal plane was calculated from the time of flight between the image 2 plastic scintillator and the thick plastic scintillator at the focal plane. The charge was deduced from the energy loss signal in the silicon detector.

The events in the image 2 identification plot are highly correlated with those in the focal plane identification plot.

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RAPID COMMUNICATIONS

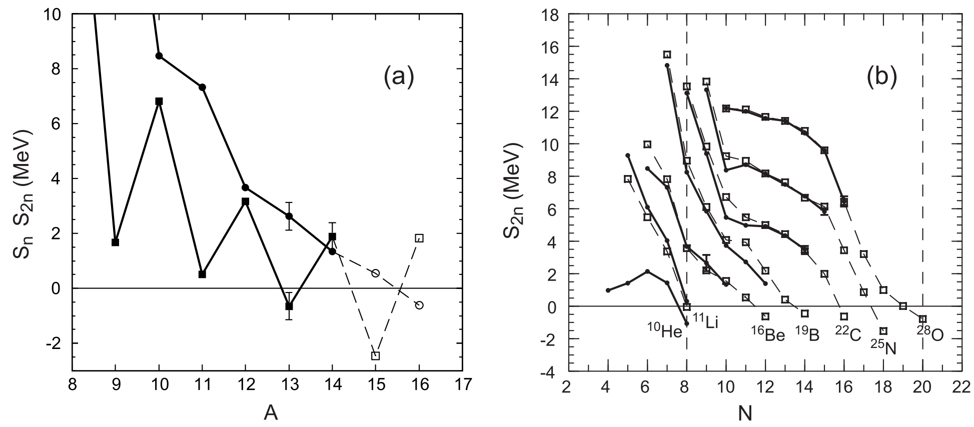

FIG. 1. Neutron separation energies for selected nuclei: (a) one-neutron (squares) and two-neutron (circles) separation energies for Be isotopes. Filled symbols are according to measured values [2], open symbols are from calculations [3,4]. (b) Comparison of two-neutron separation energies from experiments (filled symbols) [2] and from a mean-field and shell-model configuration mixing model (open symbols) [3,4].

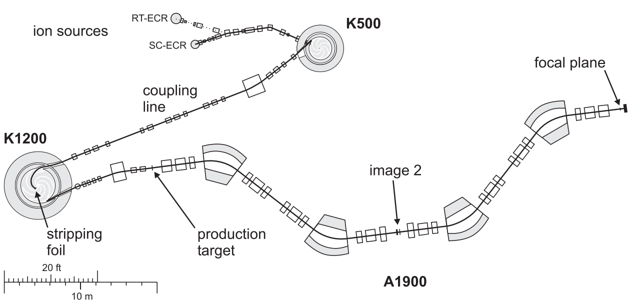

FIG. 2. Schematic view of the experimental setup showing the ion source (SC-ECR), the two cyclotrons (K500 & K1200), and the fragment separator (A1900).

TABLE I. Comparison of production cross sections for ^{19}B and ^{16}Be in projectile fragmentation of ^{40}Ar on a beryllium target.

Isotope	EPAX 1.0 [14] (mb)	EPAX 2.15 [15] (mb)	Experiment [1] (mb)
^{19}B	2.35×10^{-6}	2.13×10^{-8}	4.86×10^{-7}
^{16}Be	1.40×10^{-5}	2.41×10^{-7}	

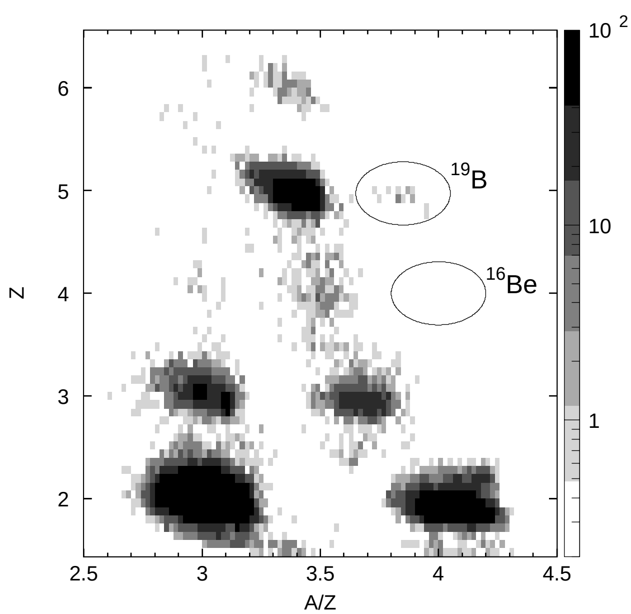

FIG. 3. Particle identification plot measured at the focal plane using energy-loss and time-of-flight data. While 15 counts can be attributed to ^{19}B, no events for ^{16}Be were recorded.

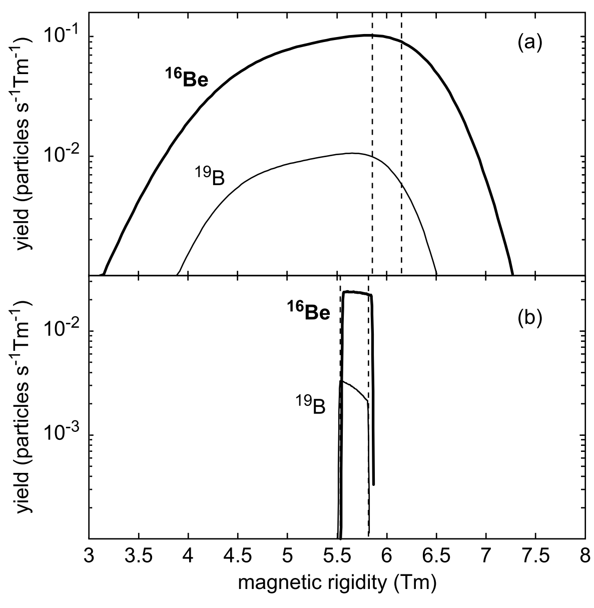

FIG. 4. Calculated magnetic rigidities of the ^{19}B and ^{16}Be isotopes: (a) after the production target and (b) following the achromatic degrader. Dashed lines indicate the momentum acceptance of the first and second separator stage, respectively. The momentum distributions and ion-optical transmissions were calculated using LISE++ [11–13].

Particles that underwent charge-changing reactions at the intermediate image were excluded.

The focal-plane particle identification plot is shown in Fig. 3. In this plot, we can clearly identify ^{6,8}He, ^{9,11}Li, ^{12,14}Be, ^{17,19}B, and ^{20}C. No counts for ^{16}Be were recorded.

We used the simulation code LISE++ [11–13] to calculate event rates taking into account extrapolated production cross sections (EPAX 1.0 [14] and EPAX 2.15 [15]) and ion optical transmission. Table I lists production cross sections for ^{19}B and ^{16}Be from ^{40}Ar on a beryllium target at relativistic energies. Figure 4 shows the magnetic rigidities directly behind the production target and behind the achromatic wedge for ^{19}B and ^{16}Be. Indicated with dashed lines are the acceptances of the following separator stages.

From these cross sections one would expect to detect ^{16}Be at a higher rate than ^{19}B if the beryllium isotope was bound. Both isotopes have a very similar magnetic rigidity. The calculated transmission through the separator is approximately 2.8% for ^{16}Be and 3.8% for ^{19}B, according to LISE++. This should still leave us with roughly five to eight times more ^{16}Be than ^{19}B. However, while we detect fifteen counts of ^{19}B, no counts for ^{16}Be were recorded.

The fact that ^{16}Be was not detected leads to the conclusion that it is unbound. The location of the neutron dripline has been unambiguously determined for $Z=4$. A recent unsuccessful search for ^{21}B establishes ^{19}B as the last bound boron isotope [16]. Thus, the change of the shell structure for neutron-rich isotopes has not led to any previously unexpected observations of new isotopes.

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[1] A. Ozawa *et al.*, Nucl. Phys. **A673**, 411 (2000).
[2] G. Audi and A. H. Wapstra, Nucl. Phys. **A595**, 409 (1995).
[3] B. A. Brown, Prog. Part. Nucl. Phys. **47**, 517 (2001).
[4] B. A. Brown (private communication).
[5] D. R. Tilley, H. R. Weller, and C. M. Cheves, Nucl. Phys. **A564**, 1 (1993).
[6] Guillemaud-Mueller *et al.*, Phys. Rev. C **41**, 937 (1990).
[7] M. Fauerbach *et al.*, Phys. Rev. C **53**, 647 (1996).
[8] H. Sakurai *et al.*, Phys. Lett. B **448**, 180 (1999).
[9] F. Marti *et al.*, in *Cyclotrons and Their Applications, 2001*, edited by Felix Marti, AIP Conf. Proc. No. 600 (AIP, Melville, NY, 2001), p. 64.
[10] D. J. Morrissey *et al.*, Nucl. Instrum. Methods Phys. Res. B (to be published).
[11] D. Bazin, O.B. Tarasov, M. Lewitowicz, and O. Sorlin, Nucl. Instrum. Methods Phys. Res. A **482**, 307 (2002).
[12] O. B. Tarasov and D. Bazin, preprint NSCL MSU, MSUCL-1248, 2002.
[13] D. Bazin and O. B. Tarasov, code for the simulation of fragment separators LISE++, version 6.1.21, available at www.nscl.msu.edu/lise (cited 14 April 2003).
[14] K. Sümmerer *et al.*, Phys. Rev. C **42**, 2546 (1990).
[15] K. Sümmerer *et al.*, Phys. Rev. C **61**, 034607 (2000).
[16] A. Ozawa *et al.*, Phys. Rev. C **67**, 014610 (2003).