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The unresolved question of the ^{10}He ground state resonance

Z. Kohley,^{1,*} J. Snyder,^{1,2} T. Baumann,³ G. Christian,^{1,2,†} P. A. DeYoung,⁴ J. E. Finck,⁵ R. A. Haring-Kaye,⁶ M. Jones,^{1,2} E. Lunderberg,⁴ B. Luther,⁷ S. Mosby,^{1,2,‡} A. Simon,¹ J. K. Smith,^{1,2} A. Spyrou,^{1,2} S. L. Stephenson,⁸ and M. Thoennessen^{1,2}

¹National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, Michigan 48824, USA

²Department of Physics & Astronomy, Michigan State University, East Lansing, Michigan 48824, USA

³National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, Michigan, 48824, USA

⁴Department of Physics, Hope College, Holland, Michigan 49422-9000, USA

⁵Department of Physics, Central Michigan University, Mt. Pleasant, Michigan 48859, USA

⁶Department of Physics and Astronomy, Ohio Wesleyan University, Delaware, Ohio 43015, USA

⁷Department of Physics, Concordia College, Moorhead, Minnesota 56562, USA

⁸Department of Physics, Gettysburg College, Gettysburg, Pennsylvania 17325, USA

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The ground state of ^{10}He was populated using a 2p2n-removal reaction from a 59 MeV/u ^{14}Be beam. The decay energy of the 3-body system, $^8\text{He} + n + n$, was measured and a resonance was observed at $E = 1.60(25)$ MeV with a 1.8(4) MeV width. This result is in agreement with previous invariant mass spectroscopy measurements, using the $^{11}\text{Li}(-p)$ reaction, but is inconsistent with recent transfer reaction results. The proposed explanation that the difference, about 500 keV, is due to the effect of the extended halo nature of ^{11}Li in the 1-proton knockout reaction is no longer valid as the present work demonstrates that the discrepancy between the transfer reaction results persists despite using a very different reaction mechanism, $^{14}\text{Be}(-2p2n)$.

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The evolution of radioactive ion beam facilities has made it possible to study nuclei at and beyond the limits of stability [1]. Measuring the properties of unbound nuclei, which are located beyond the neutron or proton driplines, allows for stringent constraints to be placed on theoretical calculations as they provide access to nuclei with extreme neutron-to-proton ratios (N/Z). The two-neutron unbound ^{10}He has the largest N/Z of any nucleus (bound or unbound) beyond the hydrogen isotopes and thus has been the focus of many experimental studies. The actual energy of the ^{10}He ground state resonance has been somewhat controversial as inconsistencies have been observed between different experimental measurements.

Recently, Sidorchuk *et al.* claimed to have observed the ground state resonance of ^{10}He at 2.1(2) MeV from the missing mass spectrum of the $^3\text{H}(^8\text{He},p)^{10}\text{He}$ transfer reaction measured at the JINR in Dubna [2]. A previous measurement of the same reaction, using the same detector apparatus at JINR, reported the ^{10}He ground state resonance to be at ~ 3 MeV [3]. This large 1 MeV difference between the nearly identical experiments was attributed only to increased statistics in the more recent work of Sidorchuk *et al.*. In comparison, Korsheninikov *et al.* [4] and, more recently, Johansson *et al.* [5, 6] used 1-proton knockout reactions from ^{11}Li to populate ^{10}He and, using invariant-mass spectroscopy, measured the ground state to be at 1.2(3) and 1.54(11) MeV, respectively. A clear discrepancy is observed with larger resonance energies being extracted from the transfer reaction experiments in comparison to the $^{11}\text{Li}(-p)$ experiments.

However, in both of the transfer reaction studies [2, 3] this discrepancy was reconciled through the theoretical calculations of Grigorenko and Zhukov [7], which showed that the observed peak energy in the $^8\text{He} + n + n$ spectrum would be dependent of the source size of the reaction. The calculations showed that the extended wavefunction, or increased source size, of ^{11}Li in comparison to ^8He (used in the transfer reactions) would produce a shift from ≥ 2 MeV to ~ 1 MeV in the ^{10}He energy spectrum [7]. This prediction was used to account for the difference between the transfer and invariant-mass measurements. Thus, it was claimed that the different ^{10}He resonance energies were consistent and the transfer measurements allowed for the actual (unshifted) ^{10}He ground state energy to be determined [2, 3].

As Grigorenko and Zhukov noted, it is important to pursue measurements of the ^{10}He ground state resonance through additional reactions not utilizing ^{11}Li [7]. Such experiments would also test the proposed consistency between the transfer and $^{11}\text{Li}(-p)$ measurements [2, 3]. In the following, we report on the observation of the two-neutron unbound ^{10}He ground state resonance populated from a 2p2n-removal reaction from a ^{14}Be beam. Even though ^{14}Be , like ^{11}Li , has a halo structure [8] the predicted shift in the ^{10}He energy spectra should be significantly altered, if present at all, because the reaction mechanism is very different in comparison to the 1-proton knockout from ^{11}Li .

The Coupled Cyclotron Facility at the National Superconducting Cyclotron Laboratory at Michigan State University was used to produce a 120 MeV/u ^{18}O primary beam which bombarded a thick 3196 mg/cm² Be produc-

tion target. The A1900 fragment separator allowed for the secondary beam of interest, ^{14}Be , to be selected from the other fragmentation products and primary beam. The 59 MeV/u ^{14}Be secondary beam, at a rate of roughly 1000 pps, impinged on a 435 mg/cm² deuterated carbon target. The time-of-flight between the A1900 focal-plane and a scintillator placed in front of the reaction target allowed for the ^{14}Be to be cleanly selected from other contaminants in the secondary beam. The two-neutron unbound ^{10}He was populated from the 2p2n-removal reaction and immediately decayed into $^8\text{He} + n + n$.

The decay energy of the 3-body system can be reconstructed using invariant-mass spectroscopy by measuring the four-momentum of the ^8He fragment and the two neutrons. The 4-Tm large-gap Sweeper magnet [9] was used to deflect the ^8He fragments $\sim 43^\circ$ into a set of position and energy sensitive charged particle detectors. The He isotopes were selected from the ΔE - E measurement made with thin (0.5 cm) and thick (15 cm) plastic scintillators. The correlations between the time-of-flight, dispersive position, and dispersive angle of the fragments were used to separate the different He isotopes (see Ref. [10] for further details on the mass identification procedure). The ^8He was easily identified from ^6He , as ^7He is unbound. The two position-sensitive cathode-readout drift chambers, placed after the Sweeper magnet, allowed for the tracking of ^8He fragments through the magnet. The position and momentum of the fragments at the target were reconstructed using an inverse transformation matrix [11] for ray tracing created from the ion optics program COSY INFINITY [12].

The two neutrons emitted in the decay of ^{10}He were measured using the Modular Neutron Array (MoNA) [13, 14]. MoNA consists of 144 plastic scintillator bars, each 200 cm \times 10 cm \times 10 cm. The array was configured into two blocks of detector bars. Each block consisted of nine walls, each eight bars high, resulting in a total active area 4 m wide by 0.8 m tall. The first block of detectors provided angular coverage from $0^\circ \leq \theta \leq 12^\circ$ in the lab-frame while the second block covered $10^\circ \leq \theta \leq 35^\circ$. The extended angular coverage of this configuration, in comparison to previous experiments [10, 15–17], provided increased efficiency for higher decay energies.

Recently, MoNA has been used to measure the ground state resonances of other two-neutron unbound nuclei [16, 17] and an important component in each analysis was the discrimination of false 2n events from true 2n events. In each event with a coincident ^8He fragment, the first and second time-ordered interactions in MoNA are analyzed. Both interactions could result from the interactions of two separate neutrons (true 2n event) or a single neutron scattering twice within the array (false 2n event), which is often referred to as cross-talk. These false 2n events are greatly reduced, relative to the true 2n events, by applying causality cuts which require that the distance between the first and second interaction (D_{12})

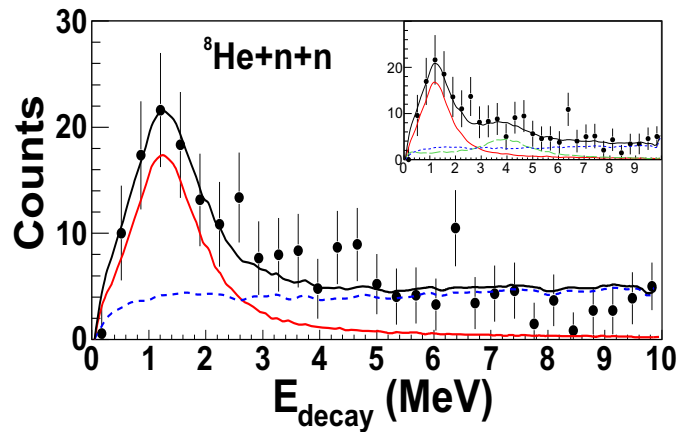


FIG. 1. (Color online) The experimental 3-body decay energy of ^{10}He is shown as solid black circles with statistical error bars. A Breit-Wigner resonance (solid red line) and non-resonant background (short dashed blue line) from the Monte Carlo simulation have been fit to the experimental distribution. The sum of the Breit-Wigner and non-resonant components is shown as a solid black line. As discussed in the text, the 2n causality cuts have been applied to the experimental data and the remaining cross-talk component estimated from the simulation has been removed. The insert shows a fit to the experimental data which includes the population of the first excited state (long dashed green line) as measured in Ref. [5].

be greater than 30 cm and relative velocity (V_{12}) calculated between the two interactions be greater than the beam velocity, ~ 10 cm/ns. The relative velocity is calculated as $V_{12} = D_{12}/(t_2 - t_1)$, where t_1 (t_2) is the time of flight recorded from the first (second) interaction in MoNA. Since the velocity of a scattered neutron will be reduced with respect to its initial velocity (roughly 10 cm/ns), the V_{12} calculated from the scattered neutron interactions must be less than that initial velocity. Additional information on the use of similar causality cuts can be found in Refs. [16–19]. As shown in Ref. [17], while the majority of the false 2n events are removed by the causality cuts some component of the cross-talk will remain present. This remaining cross-talk can be estimated from the Monte Carlo simulation (discussed below) and removed from the experimental 3-body decay spectrum [17].

The 3-body decay energy of ^{10}He was defined as $E_{\text{decay}} = M_{^{10}\text{He}} - M_{^8\text{He}} - 2M_n$, where $M_{^{10}\text{He}}$ ($M_{^8\text{He}}$) is the mass of ^{10}He (^8He) and M_n is the neutron mass. The invariant mass, $M_{^{10}\text{He}}$, was calculated from the experimentally measured four-momenta of the ^8He and two neutrons. Fig. 1 shows the experimental 3-body decay energy of ^{10}He with the above mentioned 2n causality cuts applied and the remaining cross-talk estimated from the simulation removed. A clear peak in the energy spectrum is observed around 1.5 MeV indicating the presence of a broad resonance in the $^8\text{He} + n + n$ system.

A Monte Carlo simulation was used to simulate the

decay of ^{10}He accounting for all efficiencies, acceptances, and resolutions of MoNA, the Sweeper magnet, and the charged particle detectors. As detailed in Ref. [19], the interaction of the neutrons in MoNA was simulated within the GEANT4 [20, 21] framework with the addition of the MENATE_R physics class [22] which has been shown to accurately reproduce the experimental observables associated with multiple neutron scattering. This allows for the causality cuts to be applied to the Monte Carlo simulation and for the remaining cross-talk to be accurately estimated and removed from the data [17, 19].

The ground state resonance of ^{10}He was simulated using a Breit-Wigner lineshape with an energy-dependent width and the partitioning of the energy between fragment and two neutrons was determined from a 3-body phase space decay [23, 24]. An angular momentum of $L = 1$ was used for the energy-dependent width of the Breit-Wigner as the ^{10}He ground state, in the standard shell model, would have a $\nu(p_{1/2})^2$ configuration. Along with the presence of a resonance, the experimental 3-body decay energy spectrum extends past 10 MeV indicating either a non-resonant background or the presence of higher lying excited states which could not be resolved. A component of the non-resonant background could be from the detection of the neutrons removed in the 2p2n-removal reaction. The background presented in Fig. 1 was simulated as a thermal Maxwellian distribution where the energy of each of the two neutrons was sampled separately.

The experimental 3-body decay energy distribution was fit by allowing amplitudes of the Breit-Wigner lineshape and Maxwellian distribution to vary. Additionally, the Breit-Wigner energy (E) and width (Γ) as well as the Maxwellian distribution energy were free parameters in the fit. The best fit from the χ^2 analysis is presented in Fig. 1 with a $\chi^2/\nu = 0.75$. The experimental energy spectrum is reproduced well from the sum of the Breit-Wigner resonance and non-resonant background, shown as the solid black line. The minimum χ^2 corresponded to $E = 1.60(25)$ MeV, $\Gamma = 1.8(4)$ MeV, and a 4 MeV energy for the Maxwellian distribution. The relatively large width is in good agreement with values extracted from previous works suggesting $\Gamma \sim 2.0$ MeV [2, 5, 6]. The associated error in the energy and width of the Breit-Wigner resonance includes both statistical and systematic errors. The systematic error was estimated by varying the form of the high decay energy background between a Maxwellian distribution (as shown in Fig. 1), a correlated background function based on the initial state of ^{14}Be [25], and the inclusion of previously observed excited states in ^{10}He [2, 5, 6, 26]. The experimental decay energy spectrum was fit with each of the background functions, including the Breit-Wigner lineshape, and the systematic error was determined from the variation in the energy and width from the best fits. An example is shown in the insert of Fig. 1 where the fit of the experi-

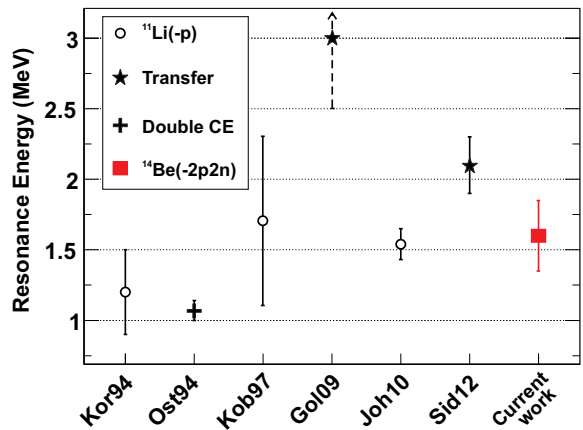


FIG. 2. (Color online) Compilation of all experimental measurements of the ^{10}He ground state resonance. The reaction mechanism used to populate ^{10}He is described in the legend. The associated references for each entry are: Kor94 [4], Ost94 [26], Kob97 [27], Gol09 [3], Joh10 [5, 6], and Sid12 [2]. Note that the Sid12 datum represents an updated measurement of the Gol09 experiment (shown with the dashed line).

mental data includes the first excited of ^{10}He as measured in Ref. [5] with $E = 3.99$ MeV and $\Gamma = 1.64$ MeV. Although we cannot extract details on the first excited state from our measurement, the previously discovered state around 4 MeV fits nicely into the decay spectrum. However, due to the discrepancies in the energy and width of the excited state [2, 5, 6, 26] the final fit (Fig. 1) is shown unbiased by its inclusion.

The measured ^{10}He ground state resonance at $E = 1.60(25)$ MeV from the current work is compared to all other experimental measurements in Fig. 2. As previously discussed, the experiments using the $^3\text{H}(^8\text{He}, p)^{10}\text{He}$ transfer reaction to populate ^{10}He (solid stars) show a larger resonance energy in comparison to the ^{11}Li 1-proton knockout reactions (open circles). The results of the different $^{11}\text{Li}(-p)$ measurements, within the reported uncertainties, are consistent. An additional measurement was made by Ostrowski *et al.* using a double charge exchange reaction, $^{10}\text{Be}(^{14}\text{C}, ^{14}\text{O})^{10}\text{He}$, and a resonance energy of 1.07(07) MeV was extracted (solid cross) [26]. However, a large discrepancy is observed between the very narrow widths reported from the double charge exchange measurement for the ground state ($\Gamma = 0.3$ MeV) and excited states in comparison to all other measurements. Thus, the resonance energy reported by Ostrowski *et al.*, which is significantly lower than the recent measurements, has to be regarded with circumspection.

In focusing on the most recent results, the measurement from the current work is in excellent agreement with the resonance energy measured by Johansson *et al.* at GSI [5, 6] using the LAND detector [28]. In both cases, the ^{10}He ground state resonance was measured

using invariant mass spectroscopy. However, very different reaction mechanisms were used to populate the resonance. In comparison, the transfer reaction measurement by Sidorchuk [2] is about 500 keV above the invariant mass spectroscopy results. Despite the halo nature of ^{14}Be , it is unlikely that the 2p2n-removal reaction would produce the same predicted shift in the ^{10}He energy spectrum as the 1-proton knockout from ^{11}Li . The calculations by Grigorenko and Zhukov assume a “sudden removal” of the proton from the ^{11}Li and that the recoil momentum transferred to the ^{10}He is relatively small, such that it can be neglected [7]. In the 2p2n-removal from ^{14}Be both of these assumptions may not be valid as the time-scale of the reaction mechanism will be longer in comparison to the 1-proton knockout and the recoil momentum from a four nucleon removal may not be negligible. Previous studies of ^{14}Be and ^{14}B fragmentation at similar energies have shown that multistep dissipative processes, in comparison to direct reactions, are the dominant reaction mechanism [29, 30]. A signature of these non-direct reactions, where the sudden-removal approximation is invalid, was that the velocity distributions of the fragments were shifted below that of the beam velocity [29]. In the sudden-removal approximation the velocity distribution should be centered around the beam velocity. In the present experiment, the mean velocity of the ^8He fragments was 8.85 cm/ns in comparison to a beam velocity of 10 cm/ns, which strongly suggests that the $^{14}\text{Be}(-2\text{p}2\text{n})$ is not a direct reaction. Additionally, the two neutrons removed from ^{14}Be could be from the ^{12}Be core or the halo. In the latter case, the source size should no longer be representative of the extended ^{14}Be wavefunction and, thus, would not produce a shift in the ^{10}He energy spectrum. For these reasons, it appears that the discrepancy between the transfer reaction measurement of Sidorchuk *et al.* [2] and the invariant mass spectroscopy results of Johansson *et al.* [5, 6] as well as the present work persists.

It is also important to recognize that the calculated shift in the ^{10}He energy spectra, due to an extended source size, is strongly dependent on the position of the $1/2^-$ state (neutron $p_{1/2}$ single particle state) and s -wave scattering length (a_s) in ^9He [7]. The predicted ~ 1 MeV shift in the ^{10}He energy was calculated with the $1/2^-$ state at 2 MeV and a positive s -wave scattering length of 2.9 fm. It should be noted that these inputs also allowed for the measured ^{10}He ground state and excited states from Sidorchuk *et al.* [2] to be reproduced. While Golovkov *et al.* measured the $1/2^-$ state energy to be 2.0(2) MeV [31], three other separate experiments reported energies between 1.13 and 1.33 MeV [5, 32, 33]. Additionally, measured isobaric analog states in ^9Li indicated that the ^9He $1/2^-$ state should be at 1.1 MeV [34]. If the $1/2^-$ state is near 1.1 MeV, the theoretical shift in the ^{10}He energy spectrum is significantly reduced [7]. Similarly, if the $^8\text{He} + n$ scattering length is small (large

negative number) the shift in the ^{10}He energy is, again, reduced. Much like the $1/2^-$ state, different experimental constraints on the scattering length have been reported. Chen *et al.* set a limit of $a_s < -10$ fm, while Golovkov *et al.* extracted a limit of $a_s > -20$ fm [31]. The invariant mass spectroscopy measurement from Johansson *et al.* reported $a_s = -3.17(66)$ fm [5]. Thus, the wide variations in the experimentally measured ^9He structure do not allow for the theoretical ^{10}He shift calculation to be constrained. Studies aimed at resolving the discrepancies in the $1/2^-$ state energy and s -wave scattering length of the ^9He system are encouraged.

In summary, a 2p2n-removal reaction from ^{14}Be was used to populate the ground state resonance of the two-neutron unbound ^{10}He . The experimental 3-body decay energy spectrum was fit with a Breit-Wigner lineshape and a non-resonant background. The best fit corresponded to a resonance with $E = 1.60(25)$ MeV and $\Gamma = 1.8(4)$ MeV. This is in good agreement with previous invariant mass spectroscopy measurements [5, 6] of ^{10}He populated from 1-proton knockout reactions of ^{11}Li . However, recent transfer reaction measurements [2, 3] indicated that the ^{10}He resonance is at a higher energy than the $^{11}\text{Li}(-p)$ measurements. Grigorenko and Zhukov provided a theoretical explanation, based on a shift in the peak energy of ^{10}He system due to the halo structure of the ^{11}Li beam, which allowed for the different measurements to be considered consistent [7]. However, this appears to no longer be a viable explanation due to the $^{14}\text{Be}(-2\text{p}2\text{n})$ measurement and, therefore, demonstrates that inconsistencies are still present in the existing ^{10}He and ^9He experimental data.

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* zkohley@gmail.com

† Present address: TRIUMF, 4004 Wesbrook Mall, Vancouver, British Columbia V6T 2A3, Canada

‡ Present address: Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA

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