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First observation of excited states in ^{12}Li

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The neutron-unbound ground state and two excited states of ^{12}Li were formed by the two-proton removal reaction from a 53.4-MeV/u ^{14}B beam. The decay energy spectrum of ^{12}Li was measured with the Modular Neutron Array (MoNA) and the Sweeper dipole superconducting magnet at the National Superconducting Cyclotron Laboratory. Two excited states at resonance energies of 250 ± 20 keV and 555 ± 20 keV were observed for the first time and the data are consistent with the previously reported s-wave ground state with a scattering length of $a_s = -13.7$ fm.

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Since the first report of an extended matter radius [1] ^{11}Li has been one of the most thoroughly studied halo nuclei and continues to be the subject of intense studies [2,3]. Although it is expected that ^{11}Li is the heaviest bound lithium isotope, properties of the heavier Li isotopes must be measured to locate the neutron dripline for $Z = 3$ and further refine the nuclear shell-model calculations. A step toward these goals comes from characterizing ^{12}Li. ^{12}Li is known to be unstable [4] and the energy of the presumed ground state was reported in Ref. [5]. Here we confirm the earlier findings but also report on excited states in ^{12}Li for the first time. This understanding of ^{12}Li states will also be useful for understanding the next obvious measurement, that of ^{13}Li, which, if it is unbound, will decay by the emission of two neutrons to ^{11}Li. The increased availability of intense radioactive beams has enabled spectroscopic studies of nuclei far from stability and in particular the selectivity of direct reactions at intermediate energies has been instrumental in populating and identifying states in neutron-rich systems [6,7]. In these studies the dripline is not limiting the exploration of the structure of very neutron-rich nuclei and direct reactions were successfully used in measuring the structure of very neutron-rich nuclei (see, for example, Refs. [5,8–10]).

In this measurement, we have utilized the two-proton removal reaction from ^{14}B to populate states in the unbound nucleus ^{12}Li. The ground state of ^{12}Li has recently been measured for the first time in the knockout reaction ^{1}H(^{14}Be,2pn)^{12}Li [5]. No excited states were observed in this reaction. The ground state was interpreted as a virtual s state with a scattering length of $a_s = -13.7(16)$ fm. The spin and parity of this resonance was deduced as either a 1^- or a 2^- in contradiction to early shell-model calculations which predicted the ground state to be a 4^- state [11]. These shell-model calculations also predicted two excited states at rather low energies of 410 keV (2^-) and 730 keV (1^-). The ground state of ^{14}B, the secondary beam, has spin and parity of 2^- and the two-proton removal reaction should populate these negative parity states in ^{12}Li.

The experiment was performed at the Coupled Cyclotron Facility of the National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University. The A1900 fragment separator [12] was used to produce a 53.4-MeV/u ^{14}B secondary beam from a 120-MeV/u ^{18}O primary beam. The momentum acceptance of the A1900 was set at 1%. Event by event time-of-flight measurements between two plastic scintillators located at the A1900 and in front of the reaction target, respectively, allowed for identification and removal of events caused by unwanted contaminant in the secondary beam. The ^{14}B beam impinged upon a 477-mg/cm^2 Be target and produced ^{12}Li through two-proton knockout. The ^{12}Li decayed immediately into ^{11}Li and a neutron which were detected in coincidence.

The ^{11}Li fragments were deflected by the Sweeper superconducting dipole magnet [13] which was set to a magnetic

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rigidity of 3.813 Tm. The deflected nuclei passed through an array of timing, position, and energy detectors. Two cathode-readout drift chambers (CRDCs) were separated by 1.816 m and used to track the position and direction of the ^{11}Li in the vertical and horizontal directions. Subsequently, the ^{11}Li passed through a thin (5-mm) scintillator for an energy-loss measurement before being stopped in a thick (15 cm) scintillator to measure the remaining energy of each fragment. A transformation matrix was created with the ion optics program COSY INFINITY [14] using the measured magnetic field map of the Sweeper to provide tracking of the ^{11}Li trajectories back to the target position.

The neutrons created from the ^{12}Li breakup were detected using the Modular Neutron Array (MoNA) [15,16]. The individual scintillator bars were arranged in nine layers, each 16 bars high. The distance from the target to the center of the first layer was 844 cm. In those cases where a neutron interacts with more than one element of MoNA, the neutron energy was calculated based on the interaction associated with the highest neutron velocity.

Using the reconstructed four-momentum of the ^{11}Li fragment as it leaves the target and the measured four-momentum of the neutron from MoNA, it is possible to reconstruct the invariant mass of ^{12}Li from the four-momentum of the neutron and fragment:

$$m^2_{^{12}\mathrm{Li}} = m^2_{^{11}\mathrm{Li}} + m^2_{\mathrm{n}} + 2(E_{^{11}\mathrm{Li}}E_{\mathrm{n}} - p_{^{11}\mathrm{Li}}p_{\mathrm{n}}\cos\theta),$$

where m is the rest mass of the respective particle, E the total energy, p the magnitude of the momentum, and θ the angle between the neutron momentum and the fragment momentum. The decay energy of ^{12}Li is then given by $E_{\mathrm{decay}} = m_{^{12}\mathrm{Li}} - m_{^{11}\mathrm{Li}} - m_{\mathrm{n}}$.

In order to account for the effects of detector resolution and acceptances of the experimental configuration, simulations of the decay energy, opening angle, neutron energy, and fragment energy were made. The population of ^{12}Li was described within the Glauber reaction model [17]. The simulation parameters, including the unbound-state properties, were adjusted to reproduce the experimental distributions. Figure 1 shows the good agreement of the simulation with the data for the fragment energy (top), neutron kinetic energy (middle), and neutron-fragment opening angle (bottom). Further details about the MoNA-Sweeper setup, detector parameters, and the simulations can be found in Ref. [18].

The shape of the measured decay-energy spectrum shown in Fig. 2 differs significantly from the decay energy spectrum of ^{12}Li measured in the reaction ^{1}H(^{14}Be,2pn)^{12}Li with the ALADIN-LAND setup at GSI [5]. The differences cannot be explained by the different efficiencies and acceptances of the two setups alone and it appears that the present reaction populates additional states. The presence of the s-wave state reported by Aksyutina *et al.* can be inferred in the present data from the shape of the decay-energy spectrum at the lowest energies. The sharp rise indicates a negative curvature of an $l = 0$ state, while an $l = 1$ or $l = 2$ resonance would exhibit a positive curvature [19]. It is clear that due to the strong contribution of additional resonances at higher energies it is not possible to extract detailed properties of this $l = 0$ contribution from the present data. Thus we simulated the decay energy distribution of an s state with the scattering length of $a_s = -13.7$ fm taken from Ref. [5]. This scattering length can be related to a decay energy of 120 keV. The s-wave line shape was calculated with a time-dependent projectile fragmentation model taking the initial wave function of ^{14}B in a Wood-Saxon potential which was parameterized to fit the experimental binding energy. Further details of the calculation can be found in Ref. [20]. The calculated line shape was then included in the simulation.

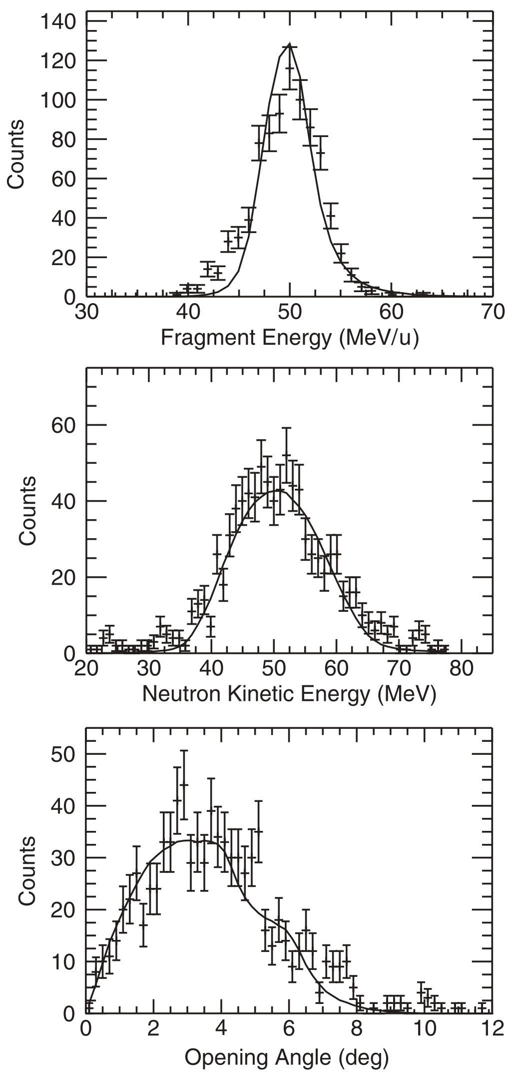

FIG. 1. Comparison of the data to simulation results. The solid lines are the results of the simulation with the best fit parameters for the decay energy for the fragment energy (top), neutron kinetic energy (middle), and neutron-fragment opening angle (bottom).

The best overall fit to the data was achieved by including two resonance states in addition to the virtual s state as shown in Fig. 2. The resonances were parameterized using energy-dependent Breit-Wigner line shapes assuming d waves for reasons described below. A χ^2 search was performed where the d-wave resonance energies and widths as well as the relative strength of the three components were free parameters. It was not possible to describe the data with just a

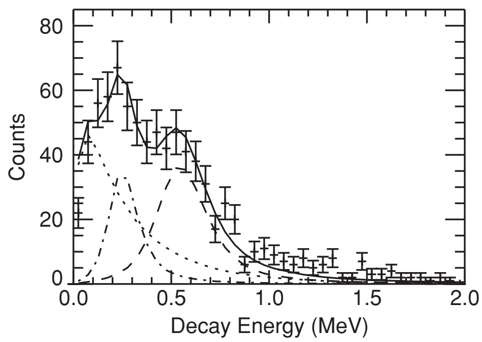

FIG. 2. ^{12}Li decay energy spectrum. The solid line corresponds to the sum of simulations of an s ground state (dotted) and two d excited states with decay energies of 250 keV (dot-dashed) and 555 keV (dashed).

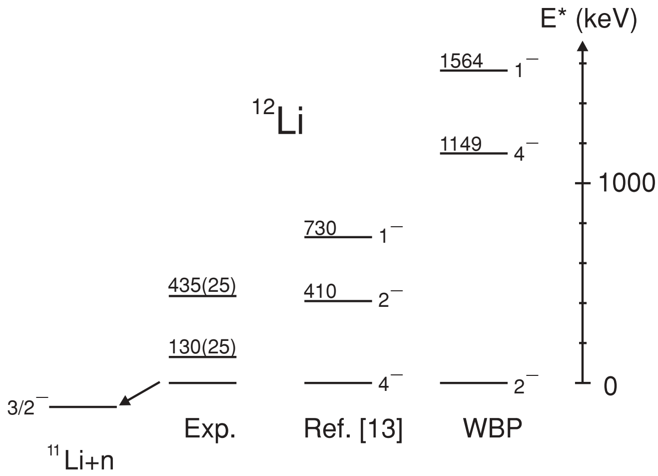

FIG. 3. Level and decay scheme of ^{12}Li. The measured states are compared to shell-model calculations from Ref. [11] and with the WBP interaction.

single d-wave resonance or s-wave component. The extracted resonance energies for the two excited states were 250(20) keV and 555(20) keV, respectively. The measured widths of these two resonances states were dominated by detector resolution and only upper limits of 15 and 80 keV, respectively, could be extracted.

^{11}Li does not have any bound excited states, therefore the observed coincidences between a neutron and ^{11}Li correspond to the decay of ^{12}Li to the ground state of ^{11}Li. The s-wave component of the decay energy spectrum corresponds to the ground state of ^{12}Li. As mentioned before the properties of the s-wave component included in the fit were taken from Ref. [5]. Thus ^{12}Li is unbound with respect to neutron emission by 120(15) keV. The other two resonances at decay energies of 250(20) and 555(20) keV represent excited states at energies of 130(25) and 435(25) keV, respectively.

Although it is not possible to deduce the spin and parities of each observed state from the decay energy spectrum alone, the selectivity of the two-proton removal reaction can give insight about the probability of populating certain states and possibly explain the differences with respect to the decay energy spectrum observed in the ^{1}H(^{14}Be,2pn)^{12}Li. In addition to the different beams (^{14}B and ^{14}Be), the two main differences between this and the present reaction are the beam energies and targets. While the ^{14}Be reaction was performed at 360 MeV/u on a hydrogen target the present experiment used a 53.4-MeV/u ^{14}B beam on a beryllium target. Possible target dependent differences of reaction mechanisms at relativistic energies were recently discussed in the decay of ^{7}He [21]. In addition, the data from the ^{14}Be reaction could possibly contain neutrons from the decay of ^{13}Li which can be populated in the (p,2p) reaction.

The two-proton removal reaction from ^{14}B will most likely remove two protons from the p shell without disturbing the neutron configurations [22,23]. The ground state of ^{14}B has a spin and parity of 2^- [24,25] and the neutrons are expected to be ∼30% and ∼66% in the $\nu(0d_{5/2})^1$ and $\nu(1s_{1/2})^1$ configurations, respectively [20]. Shell-model calculations using the WBP interaction [26] in the s-p-sd-pf model space are consistent with this configuration of the ^{14}Be ground state. With a valence proton in the $\pi(0p_{3/2})^1$ configuration ^{12}Li can be formed in odd-parity states from 1^- to 4^-.

Figure 3 compares the data with shell-model calculations from Ref. [11] and with the WBP interaction [26]. While the earlier calculations predict two excited states below 1 MeV consistent with the data, the more recent WBP interaction predicts the first excited state to be located above 1 MeV. However, it should be noted that these are continuum states and the accuracy of the shell-model calculations for these states is about 1 MeV [27]. The observation of an $l = 0$ to the $I^\pi = 3/2^-$ ground state of ^{11}Li implies a $I^\pi = 2^-$ assignment for the ground state of ^{12}Li consistent with the WBP calculations. A 4^- assignment predicted by the earlier shell-model calculations [11] cannot be correct because the $l = 0$ decay is forbidden.

The 4^- state can decay only by the emission of an $l = 2$ neutron and likely corresponds to the observed first excited state. The calculated single-particle width for this decay at a decay energy of 250 keV is about 15 keV which coincides with the observed upper limit for the width of this resonance.

The calculated single-particle width for an $l = 2$ decay at 555 keV is about 80 keV, which again agrees with the measured upper limit of the width. Unless forbidden, the $l = 2$ decay competes with the emission of an $l = 0$ neutron which is favored by about a factor of 50 at this energy. Thus, the

TABLE I. Calculated levels of ^{12}Li using the WBP interaction. The excitation energy (E^*), spin and parity (I^π), and the spectroscopic factors (SF) of the s- and d-wave component with respect to the ground state of ^{11}Li are listed.

E^* (MeV)	I^π	SF	
		$s_{1/2}$	$d_{5/2}$
0	2^-	0.60	0.18
1.149	4^-	–	0.85
1.564	1^-	0.83	0.01
2.758	2^-	0.22	0.58
2.797	1^-	0.01	0.81

$l = 2$ decay can only be observed if the spectroscopic factor for the $l = 0$ decay is very small. The spectroscopic factors for ^{12}Li extracted from the shell model calculations using the WBP interaction [26] are shown in Table I. The table lists the excitation energy (E^*), spin and parity (I^π), and the spectroscopic factors (SF) of the $s_{1/2}$- and $d_{5/2}$-orbits components with respect to the ground state of ^{11}Li for the first four excited states. As can be seen from the table, the second 1^- state is a possible candidate for the second observed excited state.

In summary, the ground state and two excited states of ^{12}Li were populated by the two-proton removal reaction from ^{14}B. The excited states at decay energies of 250(20) keV and 555(20) keV were observed for the first time. The previously reported virtual s state as the ground state of ^{12}Li with a scattering length of $-13.7(16)$ fm [5] was confirmed. Thus ^{12}Li is unbound with respect to neutron emission by $\sim$120 keV and the two excited states are located at excitation energies of 130(25) and 435(25) keV.

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