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Selective population of unbound states in ^{10}Li

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Abstract

Unbound positive-parity states in ^{10}Li have been populated with a two-proton removal reaction from a 71 MeV/u ^{12}B beam. The ^{9}Li fragments and emitted neutrons were measured with the MoNA-LISA-Sweeper setup. The measured decay energy spectrum was best fit with three states at 110 ± 40, 500 ± 100, and 1100 ± 100 keV decay energy. This is the second observation of a resonance below 200 keV. The lower two states likely belong to the expected 1^+, 2^+ doublet.

Keywords: Neutron spectroscopy; Exotic nuclei

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Three-body calculations for the two-neutron halo nucleus ^{11}Li rely on accurate descriptions of both the core–neutron interaction and the neutron–neutron interaction. Hagino et al. found that the behavior of neutrons emitted from the dipole excitations of ^{6}He and ^{11}Li was more strongly influenced by the core–neutron interaction than by the interactions between the neutrons [1]. These core–neutron interactions are adjusted by reproducing the structure of the $A-1$ system, where A is the mass of the two-neutron halo nucleus; for ^{11}Li, the core is ^{10}Li. The continuum state structure of ^{10}Li and in particular the energies of the $1s_{1/2}$ and $0p_{1/2}$ single-particle levels are used in fitting these interactions [2,3]. As an example, the measurement of a low-lying negative parity state in ^{10}Li [4,5] and its subsequent inclusion in theoretical calculations was essential to reproducing the binding energy of ^{11}Li [2,6].

All discovered two-neutron halo nuclei, however, are also Borromean systems, meaning that the $A-1$ isotope is unbound. The unbound nature of ^{10}Li was determined in 1966 by Poskanzer, Cosper, and Hyde [7]. Almost ten years later, Wilcox and collaborators made the first measurement of the unbound nucleus, using a (^{9}Be,^{8}B) reaction to measure a mass excess of 33.83 ± 0.25 MeV [8]. This placed the first measured unbound state at 0.8 ± 0.25 MeV decay energy [8]. The next measurement was made 15 years later [9] and since then, there have been many measurements of energies of the continuum structure of ^{10}Li [4,5,10–29,34].

In a simple single-particle picture, ^{10}Li should have two doublets corresponding to the coupling of an unpaired $0p_{3/2}$ proton to the unpaired $1s_{1/2}$ or $0p_{1/2}$ neutron. The $\pi 0p_{3/2}$ and $\nu 0p_{1/2}$ coupling produces a 1^+, 2^+ doublet and the $\pi 0p_{3/2}$ and $\nu 1s_{1/2}$ coupling produces a 1^-, 2^- doublet. Based on the Nordheim rules, the 1^+ and 2^- states are expected to have the lower energies in these doublets [31]. The systematics of the $N = 7$ isotones suggest that the energy difference between the $1s_{1/2}$ and $0p_{1/2}$ energy levels is small and that the order of the two levels should be inverted, with the $1s_{1/2}$ level lower than the $0p_{1/2}$ level [32]. A measurement of either the $1s_{1/2}$ or $0p_{1/2}$ single particle energies requires clean identification and measurements of both states of the associated doublet.

The ^{10}Li ground state is now known to be unbound to ^{9}Li $+ n$ by only ∼50 keV [11,15,18, 20,22–25] and to decay to the negative-parity ground state of ^{9}Li by emitting an $\ell = 0$ neutron. This identifies the ground state as part of the negative-parity doublet. Almost all measurements of the ^{10}Li unbound structure identify a state around 500 keV that decays by emitting an $\ell = 1$ neutron, which should be one of the two states of the positive-parity doublet [5,12,16,17,24,25, 29,33,34]. Previous measurements of low-lying positive-parity unbound states in ^{10}Li are shown in Fig. 1. Bohlen et al. identified two low-lying positive parity states in different reactions: a state at 240 ± 40 keV decay energy in a ^{10}Be(^{12}C,^{12}N) reaction as well as one at 530 ± 60 keV in a ^{9}Be(^{13}C,^{12}N) reaction [13]. In that experiment, negative-parity states were weakly populated and those two low-lying states were assigned spins and parities of 1^+ and 2^+, respectively, based on the expected low-lying states and the selectivities of the two reaction mechanisms. The experiments by Bohlen et al. are the only measurements that selectively populated positive-parity states [10,13]. In all other measurements, significant population of the wide, negative-parity ground state made analysis of the low-lying positive-parity state(s) difficult. The low-lying state (at <0.2 MeV) reported by Santi et al. in 2003 and included in Fig. 1 did not assign a parity, but the (d, p) reaction mechanism would be expected to populate the negative-parity ground state. The measurement by Caggiano et al. was best fit with a single resonance but could also be fit by two resonances, one at 100 ± 60 keV and the other at 525 ± 60 keV [17].

Here we report on a measurement of ^{10}Li with a new reaction that is expected to principally populate positive-parity states. The ground state of the ^{12}B beam has spin and parity of 1^+ due to the coupling of a $1p_{3/2}$ proton with a $1p_{1/2}$ neutron. A two-proton removal from ^{12}B populates