Analog States of ^{7}He Observed via the ^{6}He(p, n) Reaction

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Isobaric analog states of ^{7}He have been investigated by a novel technique involving the observation of the resonant yield of neutrons from the ^{6}He(p, n) reaction in coincidence with γ rays from the decay of the $(0^+, T = 1)$ state in ^{6}Li. The γ rays provide a clean signature for the isospin-conserving neutron decay of the low-lying isobaric analog resonances. It is conclusively shown that the analog of the recently observed low-lying spin-orbit partner of the ^{7}He ground state does not exist. Evidence is presented that this state lies at much higher energies, in agreement with microscopic calculations.

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Studies of neutron-rich nuclei can provide fundamental insights into nuclear structure and interactions that are not manifest in the valley of stability. Light exotic nuclei such as the heavy helium isotopes are the perfect proving ground for our understanding of the behavior of nuclear matter at extreme neutron to proton ratios. While modern theoretical methods are capable of *ab initio* calculations for nuclei with $A \leq 10$, experimental studies of neutron-rich nuclei near the drip line are difficult. One can, however, study properties of these nuclei as isobaric analog states (IAS). For example, it is possible to study the IAS of nucleus (N, Z) via resonant elastic scattering of the $(N - 1, Z)$ nucleus on hydrogen [1,2]. Information obtained this way can be directly related to the spectroscopy of the (N, Z) nucleus. In very neutron-rich drip-line nuclei, the analog states can undergo isospin-symmetric neutron decay as well as proton decay (see the inset in Fig. 3 for the case of ^{7}Li). The following relationship holds true for the total wave function of the IAS with $T_> = T_z + 1$ if isospin is a good quantum number:

$$\Psi(T_>) = \frac{1}{\sqrt{1 + 2X}}(\psi_{N-1,Z}\psi_p + \sqrt{2X}\psi_{N-2,Z+1}\psi_n), \quad (1)$$

where $X = T_z + 1/2$. Once the IAS of a neutron-rich nucleus is populated, neutron decay will dominate, so the resonance yield of protons from population of analog states of neutron-rich nuclei is very small [1], about an order of magnitude smaller than that for resonant proton scattering at the limits of proton stability [3,4].

In this Letter, we report on the measurement of the IAS of ^{7}He. The resonance yield of n-γ coincidences in the interaction of ^{6}He with ^{1}H was observed. This experiment takes advantage of two aspects of the decay of the IAS: domination by neutron decay, and suppression of subsequent nucleon decays from the $T_>$ states in the daughter nucleus due to the isospin conservation law. Furthermore, the $\Delta T = 1$ γ-ray transitions should be especially strong [5], and neutron decay followed by a strong γ-ray transition is a unique signature for population of the IAS of neutron-rich nuclei.

Only the IAS of the ^{7}He ground state in ^{7}Li has previously been observed [6], and its width was found to be 268 ± 30 keV. There are no reports of the decay modes of this state. In ^{7}He, until very recently only the ground state was known [7], but excited states have now been reported in Refs. [8–11]. A $1/2^-$ state is reported recently at a very low excitation energy of 0.6 MeV [10,11]. This is particularly important since the confirmation of this result would provide evidence for the complete breakdown of the shell model in neutron-rich drip-line nuclei.

The experiment was carried out with the TwinSol radioactive nuclear beam facility [12] at the University of Notre Dame. A beam of ^{6}He was produced via the ^{2}H(^{7}Li, ^{6}He)^{3}He reaction. The experimental setup is shown in Fig. 1. A primary ^{7}Li beam with an average intensity of 200 electrical nA and an energy of 35 MeV was incident on a 2.5 cm (length) gas cell containing deuterium at a pressure of 1.3 atm. A Faraday cup placed after the gas cell was used to stop the primary beam. Two large superconducting solenoids act as thick lenses to separate ^{6}He from the scattered primary beam and other reaction products. ^{6}He ions were focused into a 1 cm (diameter) spot at the secondary target position. Under these conditions, a ^{6}He beam was obtained with an intensity of 2×10^5 s^{-1}, an energy of 24 MeV, and an energy spread of 750 keV full width at half maximum (FWHM). The secondary beam was further analyzed using two parallel-plate avalanche counters (PPACs) placed after the solenoids. The distance between the PPACs was 2.0 m, and the first PPAC was position sensitive in both the x and y directions. The PPACs were used

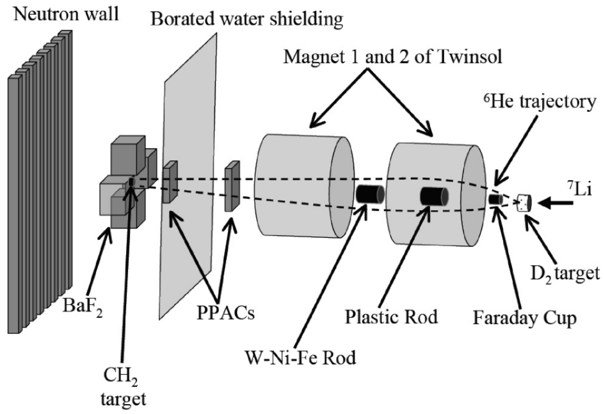

FIG. 1. The experimental setup.

to count the ^{6}He ions, to track the secondary beam, and to separate ^{6}He from contaminants (mainly α particles and ^{7}Li ions) using the time of flight technique. In addition, the primary ^{7}Li beam was pulsed with a repetition rate of 10 MHz and a pulse width of approximately 2 ns. The 7.4 m distance from the primary target to the second PPAC was adequate to obtain a clean separation of ^{6}He from all contaminant beams. After the second PPAC, the beam struck a 57.4 mg/cm^2 thick CH_2 target which stopped the ^{6}He ions. This target was surrounded by an array of four large BaF_2 detectors which were used to detect γ rays from the decay of the ^{6}Li(0^+, 3.56 MeV) state populated via ^{6}He$(p, n)^6$Li. The absolute total efficiency of the BaF_2 array was found to be 8.7% at 3.56 MeV.

Neutrons were measured in a position sensitive 150 cm × 150 cm × 5 cm plastic-scintillator neutron wall placed 3.8 m behind the secondary target. The efficiency of the wall, calibrated with a ^{252}Cf source, was energy dependent and had a maximum of 20% at 3.5 MeV. The neutron energy was determined from time of flight corrected for the position of the hit in the wall. Special care was taken to avoid neutron background from the primary target. A combination of borated plastic shielding placed around the primary target, plus neutron-absorbing rods and a borated water wall (see Fig. 1), suppressed the neutron background. The ^{6}He ions were slowed to a complete stop inside the target, spanning the laboratory energy range from 24 MeV to zero. A $T = 3/2$ resonance in the ^{7}Li compound system would manifest itself as a peak in the neutron energy spectrum. Because of the binary nature of the reaction, the laboratory neutron energy can be simply converted into center-of-momentum (c.m.) energy. By defining the reaction channel with the n-γ coincidence and measuring the energy of the neutrons, one obtains a complete excitation function in a single run. As a result, the method is very efficient. It is also important to note that the neutrons do not lose any energy in the target, so the energy resolution of the method is not affected by the energy spread in the ^{6}He beam and is limited only by the precision of the neutron energy determination.

The neutron spectrum obtained with the $(CH_2)_n$ target is shown in Fig. 2. Its most obvious feature is the presence of a narrow resonance at 2.8 MeV neutron energy, corresponding to the $3/2^-$, $T = 3/2$ state in ^{7}Li, the known [6] isobaric analog of the ^{7}He ground state. The coincidence requirement of a ^{6}He in the PPAC, a 3.56 MeV γ ray in the BaF_2 array, and a neutron in the wall eliminates almost all the random background. The contribution of the remaining random background is illustrated by the dotted curve in Fig. 2. There is, however, another source of background, associated with the interaction of ^{6}He with ^{12}C. It originates from the ^{12}C(^{6}He, ^{5}He) reaction, resulting in the population of levels in ^{13}C around 3.5 MeV, which decay by emitting γ rays in coincidence with neutrons from ^{5}He decay. This background cannot be eliminated by the n-γ-^{6}He coincidences due to insufficient energy resolution in the BaF_2 array. To eliminate it, a measurement with a thick natural carbon target was made under similar experimental conditions as for $(CH_2)_n$. The inset in Fig. 2 shows the neutron spectrum measured with the carbon target, and the dashed curve in Fig. 2 illustrates the relative contribution of this background to the total neutron spectrum. The excitation function for the ^{6}He$(p, n)^6$Li(0^+) reaction, obtained from the spectrum shown in Fig. 2 by subtraction of the random and carbon backgrounds and transformed to the c.m. system, is shown in Fig. 3. (Note that the maximum c.m.

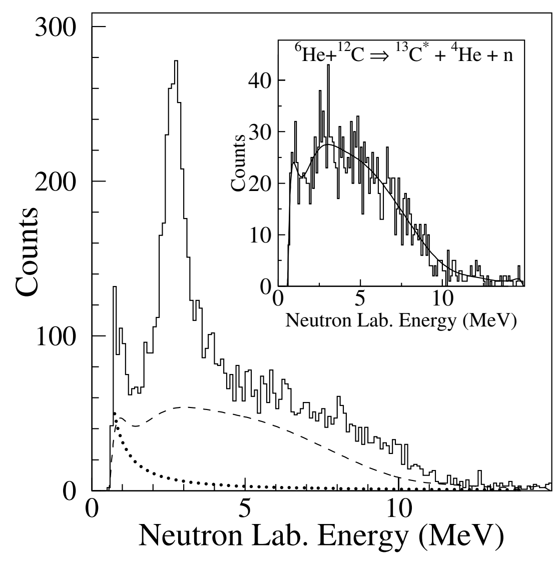

FIG. 2. The spectrum of neutrons in coincidence with ^{6}He and a 3.56 ± 0.30 MeV γ ray, measured with a $(CH_2)_n$ target. The inset shows a neutron spectrum obtained with a natural carbon target. The contribution of the carbon background is shown by the dashed curve, and the dotted curve gives the contribution from the random background (a constant in the time-of-flight spectrum).

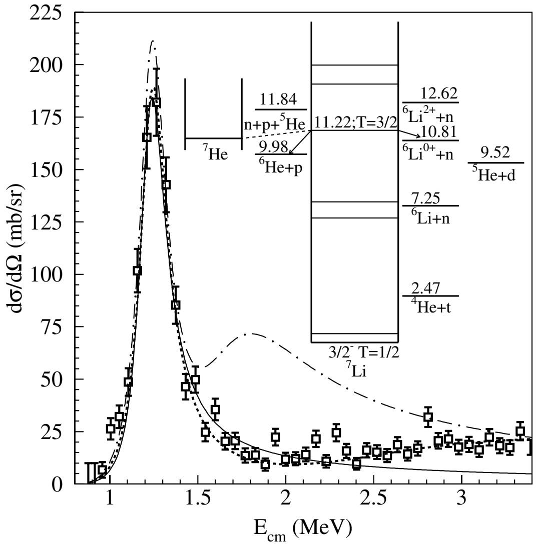

FIG. 3. The excitation function for the ^{6}He$(p, n)^6$Li$(0^+; T = 1)$ reaction measured at $180 \pm 8°$. See the text for a discussion of the curves. The inset shows the decay channels for the $T = 3/2$ resonances in ^{7}Li.

energy of the neutrons is 3.4 MeV, since neutrons of higher energy cannot be produced in ^{6}He$(p, n)^6$Li(0^+) at 24 MeV.) No narrow $T = 3/2$ states other than the isobaric analog of the ^{7}He ground state were observed.

Only two isospin-conserving channels with decay energies below 1.8 MeV are open in this system. (Here and below we refer to the energy above the ^{6}He + p threshold for ^{7}Li as the decay energy.) These are proton decay and neutron decay to the $(0^+, T = 1)$ state in ^{6}Li at 3.56 MeV (see the inset in Fig. 3). Therefore, the two-channel R-matrix approach can be applied. Using Eq. (1), one can fix the ratio of the reduced widths for proton and neutron decay ($\gamma_n/\gamma_p = \sqrt{2}$). Under these conditions, the cross section depends only on the spin and energy of the resonance, which allows for a spin assignment based on the 180° cross section alone. (We assume here that no other channels except isospin allowed ones contribute to the resonance width.) A calculation for the $3/2^-$ isobaric analog of the ^{7}He ground state is shown by the solid curve in Fig. 3. This R-matrix calculation has not been renormalized to the experimental cross section and represents a prediction of the absolute yield. The excellent agreement with the experimental data ensures the validity of the two-channel R-matrix approach and the spin assignment to the resonance in question. The resonance parameters ($E_{\rm decay} = 1.24 \pm 0.03$ MeV, $E^*(^7\text{Li}) = 11.22$ MeV, and $\Gamma = 265 \pm 40$ keV) agree well with literature values [13].

The mass excess of ^{7}He, obtained from that of its analog in ^{7}Li by adding the neutron-proton mass difference and subtracting the Coulomb energy difference of the ^{6}He-^{6}Li$^*(T = 1)$ pair, is 26.07 MeV. ^{7}He is therefore unbound by 0.41 MeV to neutron decay, in good agreement with the literature value of 0.445 MeV [13]. We use this approach below when transforming ^{7}Li decay energies to the energies of states in ^{7}He. The width of the $(3/2^-, T = 3/2)$ state in ^{7}Li is 1.77 times greater than that of the ^{7}He ground state because the proton decay channel is open in ^{7}Li. This must be kept in mind when comparing properties of isobaric analog states.

An excited state in ^{7}He with very low excitation energy [$E^* = 0.56(10)$ MeV] was claimed in two recent publications [10,11] and identified as the $1/2^-$ spin-orbit partner of the $3/2^-$ ^{7}He ground state. If confirmed, this would be a very important result since the low energy of the state indicates a dramatic breakdown of the shell model at large neutron excess. The width of the state was found to be $\Gamma = 0.75(8)$ MeV, close to the single-particle limit, implying a nearly pure $p_{1/2}$ neutron configuration coupled to the ^{6}He ground state. Hence, this state is expected to decay predominantly to the ground state of ^{6}He. Our measurement is very sensitive to the presence of such a state. Since only two isospin-conserving decay channels are open, the two-channel R-matrix approach is valid. Using the procedure described above and starting with the data from Refs. [10,11], one obtains $E^* \approx 11.8$ MeV and $\Gamma \approx 1.5$ MeV for the corresponding $(1/2^-, T = 3/2)$ analog state in ^{7}Li. The dash-dotted curve in Fig. 3 shows the result of including both the $3/2^-$ and $1/2^-$ states. It follows that our data conclusively rule out the low-lying, narrow $1/2^-$ state claimed in Refs. [10,11].

It is also clear from Fig. 3 that the solid curve, which shows the contribution from only the $(3/2^-, T = 3/2)$ resonance, underestimates the yield at higher energies, suggesting a contribution from higher-lying $T = 3/2$ resonances in ^{7}Li. Two other excited states of ^{7}He have been found during the last five years. A broad resonance with excitation energy 5.8 MeV reported in Ref. [9] is well above the excitation-energy range of this experiment (up to 2.2 MeV), so it cannot contribute significantly to the measured yield. A state at an excitation energy of 2.9 MeV having a width of about 2 MeV was reported in Refs. [8,9]. This low-lying, broad state might have a strong influence on the high-energy part of our excitation function if it had spin/parity $1/2^-$ or $3/2^-$. However, its decay modes have been measured [8] and it was found that the main branch is neutron decay to the first excited state of ^{6}He. No decay to the ground state was observed. Based on these results, a tentative spin assignment of $5/2^-$ for the resonance in question was given, and its structure was taken to be a $p_{1/2}$ neutron coupled to a ^{6}He core in its 2^+ excited state [8]. Such a state cannot be observed in our experiment because it will undergo mainly neutron decay to the $(2^+, T = 1)$ excited state of ^{6}Li, which directly decays to $\alpha + p + n$ without a γ ray. Also, the production cross section is proportional to the ratio $\Gamma_p/\Gamma_{\rm total}$ which is very small for this structure. We conclude that none of the known states in ^{7}He can account for the excess neutrons at $E_{\rm c.m.} > 2.5$ MeV observed in Fig. 3. The direct (nonresonance) charge-exchange process was found to contribute only 2–4 mb/sr, which is 15% of the cross section at higher energies and only 1% at the $3/2^-$ resonance energy. These calculations were made using the distorted wave Born approximation (DWBA) code TWAVE [14], and the optical-model potential was taken from Ref. [15].

Good agreement with the data can, however, be obtained. The dotted curve in Fig. 3 shows a calculation for a $1/2^-$ state at a decay energy of 3.9 MeV having $\Gamma =$ 8 MeV. The fit is only weakly sensitive to the parameters of the $1/2^-$ resonance due to the limited excitation-energy range and the very large width of the state. Agreement with experiment can be achieved if this state has a decay energy above 3.4 MeV (2.2 MeV excitation energy in ^{7}He) and a width ≥ 6 MeV. Measurements with ^{6}He beams at higher energies are necessary to fix the parameters of this state.

Interestingly, a very broad $1/2^-$ state in ^{7}He was introduced in Ref. [8] to explain the branching ratio for the decay of the $5/2^-$ resonance, which should decay only to the ^{6}He(2^+) state. Instead a branching ratio of 70% was measured, and the missing 30% branch was assigned to a transition to an unobserved $1/2^-$ resonance which would decay to the ^{6}He ground state.

A high-lying $1/2^-$ state is a feature of all recent microscopic calculations. A shell-model calculation in a $(0 + 2)\hbar\omega$ model space puts the $1/2^-$ state at 2.5 MeV [16], and a large-basis, no-core shell-model predicts $E_x =$ 2.3 MeV [17]. The resonating-group method gives values from 2.3 to 3.8 MeV [18], and the most recent result from the Green's-function Monte Carlo method places E_x near 3.0 MeV [19]. Our experimental lower limit of 2.2 MeV is compatible with all these predictions.

In conclusion, a new approach to the spectroscopy of neutron-rich nuclei was tested for the case of $p(^6\mathrm{He}, n)^6\mathrm{Li}(0^+)$ and was found to give excellent results. The high cross section for the (p, n) reaction channel, the simplicity in the interpretation of the results, the excellent energy resolution, and the ability to measure the entire excitation function in one run make this technique very attractive for the spectroscopy of neutron drip-line nuclei.

The previously known $(3/2^-, T = 3/2)$ state in ^{7}Li, the analog of the ^{7}He ground state, was observed at an excitation energy of 11.22(3) MeV with $\Gamma = 265(40)$ keV, in very good agreement with literature values [13]. None of the other resonances reported in Refs. [8–11] were seen, and it was conclusively shown that the low-lying $1/2^-$ state reported in Refs. [10,11] at an excitation energy of 0.6 MeV does not exist. Instead, we give evidence that the analog of a very broad $(1/2^-, T = 3/2)$ resonance lies at an excitation energy above 2.2 MeV in ^{7}He.

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