Doppler Shift as a Tool for Studies of Isobaric Analog States of Neutron-Rich Nuclei: Application to ^{7}He

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We have developed a new technique to study exotic neutron-rich nuclei via their isobaric analog states (IAS). We populate high-isospin states in resonant reactions of radioactive ion beams with protons. Characteristic γ rays emitted from excited decay products were used to identify the population of the IAS. We show that information on the differential and total cross section for formation of the IAS can be extracted from the energy spectrum of the Doppler-shifted γ rays. This technique was applied to the study of $T = 3/2$ states in ^{7}Li, which are analogs of states in ^{7}He. The analog of the ^{7}He ground state was clearly observed, whereas the presence of the analog of a narrow $1/2^-$ state at 0.6 MeV excitation in ^{7}He reported by M. Meister *et al.* [Phys. Rev. Lett. **88**, 102501 (2002)] was excluded at the 90% confidence level. Evidence is presented for a broad $1/2^-$ state at a higher excitation energy in ^{7}He.

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The availability of radioactive beams has opened new opportunities for the investigation of exotic dripline nuclei. Many features of radioactive ion beams (RIBs) (such as low intensity) are quite different from those of more conventional stable beams, creating significant challenges for the experimentalist. The purpose of this Letter is to introduce a new experimental technique that allows the study of exotic neutron-rich nuclei in inverse kinematics. The technique has two components: the population of isobaric analog states (IAS) of exotic nuclei through resonant reactions in a thick proton target [in line with ideas discussed in Ref. [1]], and subsequent measurement of the Doppler-shift profile of the γ rays emitted after neutron decay of the IAS. This approach allows for the simultaneous measurement of the excitation function of the resonant (p, n) process, which leads to the population of IASs over a wide energy range from the initial RIB energy to zero, and provides some information on the double differential cross sections in one self-consistent measurement. The first application of this technique is presented in this Letter for the case of the IAS of ^{7}He in ^{7}Li. The correct identification of single-particle states in ^{7}He tests our present understanding of nuclear forces and *ab initio* nuclear models. The structure of this nucleus has generated some sizable controversy in both theoretical and experimental studies [2–12]. Specifically, the controversy is focused on the existence of a surprisingly low-lying $1/2^-$ resonance ($E_{\text{ex}} \simeq 0.6$ MeV) with significant single-particle strength. This state was reported in Refs. [2,6], but its analog in ^{7}Li has not been found [9]. In this Letter, we use a new technique to show that there are no excited states with substantial single-particle strength up to 1.5 MeV of excitation energy in ^{7}He. Instead, we present evidence for a $1/2^-$ resonance at higher excitation energies and give limits on its width and excitation energy.

The Doppler-shift method we describe here involves the population of the IAS in neutron-rich nuclei and the measurement of a characteristic γ ray emitted from a decay product of the compound nucleus. Because of isospin conservation, only two decay channels are allowed for the IAS: proton decay to the initial channel and neutron decay with the population of $T_> = T_z + 1$ states in the daughter nucleus (see the decay scheme of $T = 3/2$ resonances of ^{7}Li in Fig. 1. Here $T_> = 1$).

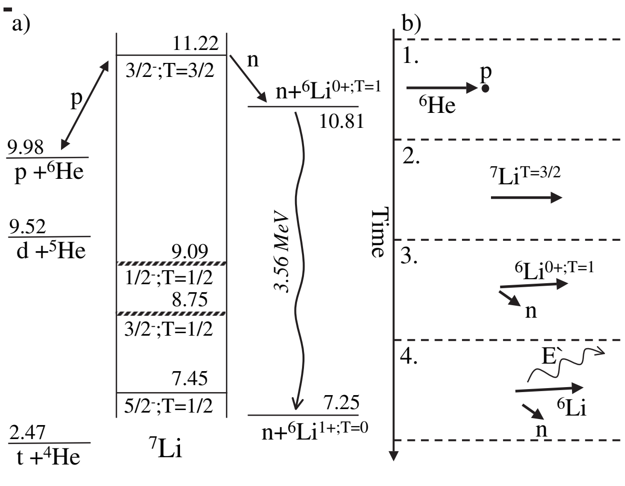

FIG. 1. (a) Decay pathways for the $T = 3/2$ resonance in ^{7}Li, and (b) the successive kinematics stages of the studied reaction.

The $T_>$ state in the daughter nucleus can undergo nuclear decay only through isospin-forbidden channels, and as a result the probability for γ decay is strongly enhanced. In the case of the $T_>$ ($T = 1, 0^+; 3.56$ MeV) state in ^{6}Li, populated via neutron decay from $T = 3/2$ states in ^{7}Li, there is a 100% probability for γ-ray decay due to parity conservation. The chain of events described above should be typical for analog states of neutron-rich nuclei, leading to the idea of detecting characteristic γ rays in IAS studies. Since the γ decay is $\Delta T = 1$ and the energy of the γ rays is on the order of an MeV or higher, the decay time is much shorter than the stopping time in the medium. In an inverse kinematics experiment, the excited heavy daughter nucleus does not slow down in the target and its velocity is very close to the velocity of the beam at the time of the (p, n) reaction. Therefore, the Doppler shift of the characteristic γ ray strongly depends on the beam velocity at the moment of interaction between the beam and the target proton, thus providing information about the total excitation function. The neutron decay of the IAS spreads out the velocity of the recoiling γ-ray source [see Fig. 1(b)]. This spread depends upon the neutron decay energy and angular distribution as well as on the ratio of the neutron mass to the mass of the recoil nucleus; the heavier the recoil, the smaller the spread. However, it is shown in the present work that the decay manifests itself as a peak of reasonable width even in transmutation of the lightest nuclei. The peak shape and area was reproduced with unique J^π assignments for the populated compound states in ^{7}Li. Thus the observed structure allows for the extraction of the excitation function of the ^{6}He$(p, n)^6$Li(0^+) reaction, and provides some information on the angular distribution of IAS decay.

The experiment was carried out at the *TwinSol* RIB facility [13] located at the University of Notre Dame Nuclear Structure Laboratory. A ^{6}He beam was obtained with an intensity of 2×10^5 pps and an energy of 24 MeV. Details regarding the production of the ^{6}He beam are given in Ref. [9]. A 57.4 mg/cm^2 $(CH_2)_n$ target was used. This was enough to stop the ^{6}He ions. Two γ-ray detectors were placed around the target: a HPGe-Clover at 0° and a single-crystal 55% efficiency HPGe detector at 90° relative to the beam direction. The absolute γ-ray efficiency of each detector was determined with calibrated sources. A parallel plate avalanche counter (PPAC) detector was used to improve the beam purity and to count the ^{6}He nuclei which bombarded the target. In the analysis, absolute cross sections were calculated using the number of ^{6}He particles detected in the PPAC and ^{6}He-γ coincidence were required.

A portion of the 90° γ-ray spectrum is shown in Fig. 2(a). The main features of the spectrum are two narrow peaks at 3.68 and 3.85 MeV, and a broad bump with a centroid at 3.56 MeV. The two narrow peaks are from the decay of ^{13}C excited states populated in the ^{12}C$(^6$He$, ^5$He$)^{13}$C* reaction. The bump at 3.56 MeV is the Doppler broadened 3.56 MeV γ-ray transition from the 0^+ state of ^{6}Li. A γ-ray spectrum obtained with a carbon target (corrected for differences in running time) is shown by the thick dotted curve. The 3.56 MeV structure is not present in this case, providing clear evidence that it results from the interaction of ^{6}He with protons.

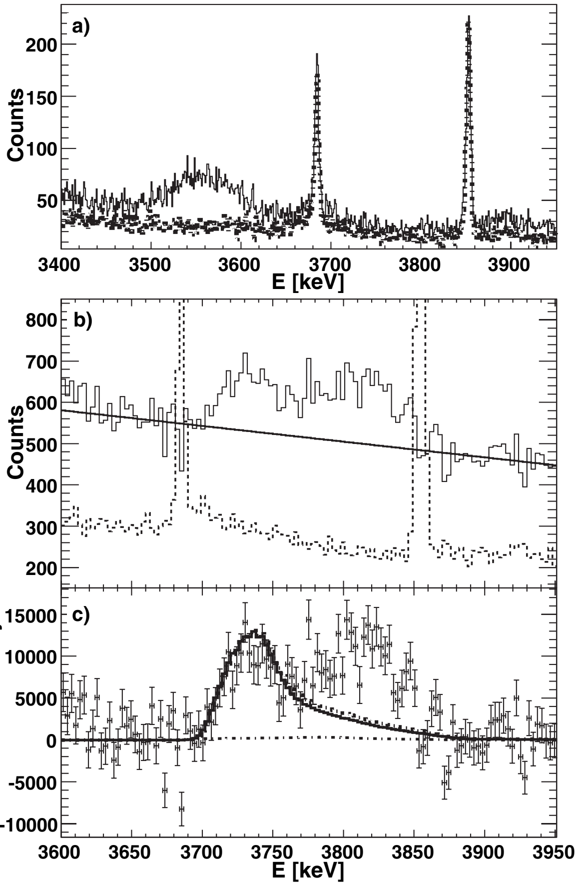

FIG. 2. (a) Part of the γ-ray spectrum from the 90° Ge detector. The solid curve was obtained with a CH_2 target; the dotted curve was taken with a carbon target. (b) The spectrum in the 0° Clover detector obtained by subtraction of the carbon contribution; the dotted curve was taken with a carbon target. The Compton background is approximated by a straight line as shown. (c) The final spectrum of the Doppler-shifted 3.56 MeV γ rays. The solid line shows the contribution from the known $T = 3/2$, $J^\pi = 3/2^-$ state in ^{7}Li. The dotted line includes the effect of $T = 1/2$ resonances. The dash-dotted line close to the abscissa axis shows the contribution of the direct charge-exchange process.

The γ-ray spectrum in the 0° Clover detector obtained by subtraction of the carbon background is shown in Fig. 2(b). The spectrum obtained with a carbon target is shown with dotted lines on the same figure. The absence of the two carbon peaks at 3.68 and 3.85 MeV in the subtracted spectrum verifies the correct carbon background subtraction. In the subtracted spectrum there are two broad bumps with centroids around 3.7 and 3.8 MeV. They are related to the interaction of ^{6}He with protons in the CH_2 target. The final spectrum [Fig. 2(c)] is obtained by subtracting a linear Compton background and dividing by the detector efficiency function. In the presented measurement the statistical errors were dominant. The errors shown in Fig. 2(c) were calculated from the statistical errors in the spectra taken with CH_2 and carbon targets. The systematic error from uncertainty in the linear fit of the Compton background was less than 5% from the subtracted spectrum shown in Fig. 2(b). The combined systematic error in the absolute efficiency and the stopping powers of ^{6}He in CH_2 target was on the level of 10%.

The isobaric analog of the ^{7}He ground state (g.s.) in ^{7}Li is well known [14]. Its parameters are: $J^\pi = 3/2^-$, E [above the (p, p) threshold] $= 1.24$ MeV, and $\Gamma = 0.25$ MeV. We used these parameters to obtain the shape of the Doppler shifted γ-ray spectrum resulting from the population of this state. The contribution of the direct charge-exchange process was estimated with the code TWAVE [15] and found to be negligible.

We estimated that about 50% of 3.56 MeV γ-ray events coincide with neutrons scattering in the Clover detector. They influence the observed spectrum through true coincidence of a γ ray with a neutron from the same reaction; the latter elastically scatter on Ge nuclei in the detector. The effect was estimated using the optical-model cross section for neutron elastic scattering on Ge with potential parameters taken from Ref. [16], and detector response to the recoiled germanium nuclei taken from Ref. [17]. The contribution to the spectrum is mainly to the low-energy part of the bump.

The effect of the ^{7}He g.s. IAS population is shown as a continuous curve in Fig. 2(c). There is no arbitrary normalization of the curve to the experimental data; the cross section and angular distribution for the $^6\mathrm{He}(p, n)^6\mathrm{Li}(0^+)$ reaction were obtained from a two channel R-matrix calculation. The only assumption made is that only two channels are involved in the decay of the $(T = 3/2, 3/2^-)$ resonance in ^{7}Li. These are proton decay to the ground state of ^{6}He and a mirror neutron decay to the first $T = 1$ state in ^{6}Li. The ratio of the reduced widths for proton and neutron decay is defined by the isospin Clebsh-Gordan coefficients ($\gamma_p^2:\gamma_n^2 = 1:2$). A channel radius of 5 fm was used in the calculation. The boundary conditions were -0.1 for the (p, p) channel and -0.9 for the (p, n) channel. It is clear that the first bump in Fig. 2(c) is related to the population of the known $T = 3/2$ state in ^{7}Li. Additional assumptions have to be made in order to reproduce the second bump.

States with $T = 1/2$ and $T = 3/2$ are populated in the $^6\mathrm{He}(p, n)$ reaction. There are many open decay channels for the $T = 1/2$ resonances. As a result, population of these states is suppressed in the $^6\mathrm{He}(p, n)^6\mathrm{Li}(T = 1, 0^+)$ reaction. Nonetheless, $T = 1/2$ resonances decaying to $^6\mathrm{Li}(T = 1, 0^+)$ could give a contribution to the excitation function associated with decay of the $T = 3/2$ resonances. To estimate this effect, we used data from the latest compilation of Tilley *et al.* [18]. Some information on two wide $T = 1/2$ resonances in the energy range of this experiment is available. However, the partial widths of these resonances, necessary for an R-matrix calculation, are unknown. Thus we performed the calculation using the shell-model results from Ref. [19] as a guide, and total widths and excitation energies from Ref. [18]. The effect of these two wide resonances ($J^\pi = 3/2^-$, $E_{\mathrm{ex}} = 8.75$ MeV, $\Gamma = 4.7$ MeV and $J^\pi = 1/2^-$, $E_{\mathrm{ex}} = 9.09$ MeV, $\Gamma = 2.8$ MeV) which overlap with the $^6\mathrm{Li}(T = 1, 0^+) + n$ threshold is shown as the dotted curve in Fig. 2(c); the $T = 3/2$ g.s. resonance is also included in the calculation. The difference between the two curves is statistically insignificant and therefore we will not include the $T = 1/2$ resonances in the following discussion.

An interesting finding was reported in the study of ^{7}He by Meister *et al.* [2]. Evidence for a very low-lying $1/2^-$ state, the spin-orbit partner of the ground state having a single-particle [$^6\mathrm{He}(\mathrm{g.s.}) + n$] structure, was presented in this work. A subsequent attempt to identify the analog of this $T = 3/2$, $J^\pi = 1/2^-$ resonance in ^{7}Li revealed no narrow structure in this region [9]. In that work [9], the excitation function for resonant $^6\mathrm{He}(p, n)$ scattering to the $^6\mathrm{Li}(T = 1, 0^+)$ state was measured at only one angle. Data from the present experiment give information on the total cross section as well as the angular distribution of the reaction.

The calculated profile of the Doppler-shifted γ rays for population of a resonance with parameters from Refs. [2,6] is shown by the dotted line in the Fig. 3(a). The magnitude and shape of the data are not reproduced. We were, however, able to reproduce the second bump in the observed spectrum using a two channel R-matrix calculation and introducing a $(T = 3/2, 1/2^-)$ resonance in ^{7}Li at an excitation energy of 3.1 MeV relative to the first $T = 3/2$ state. We failed to find any other value of J^π for this state which can simultaneously describe the present experimental data and that of Ref. [9]. The best-fit calculation, with a $1/2^-$ resonance at excitation energy $E_{\mathrm{ex}} = 3.1$ MeV having a formal width [18,20] $\Gamma = 10$ MeV, is shown by the solid line in Fig. 3(a). Since the $1/2^-$ resonance is very wide, it is difficult to fix its excitation energy and width from the present data (our energy range is limited to 2.3 MeV excitation energy). We performed a χ^2 fit of the presented experimental data and that of Ref. [9] to set limits on the $(T = 3/2, 1/2^-)$ resonance parameters. A minimum $\chi^2 = 2.1$ was obtained at $E_{\mathrm{ex}} = 3.1$ MeV and $\Gamma = 10$ MeV. Figure 3(b) shows 50% confidence region for the values of the excitation energy and the formal width of this state. For excitation energies higher than 2.1 MeV, only the lower limits for the resonance width can be set (the χ^2 function becomes insensitive to width increase at higher energies). The systematic errors are not included in the calculation of χ^2. If a maximum systematic shift is applied to the data then the best-fit value is $E_{\mathrm{ex}} = 2.9$ MeV and $\Gamma = 11$ or 7.4 MeV depending on the direction in which the data are systematically shifted. It is important to note that the large width of the proposed $(T = 3/2, 1/2^-)$ state is a manifestation of its single-particle nature. The result-

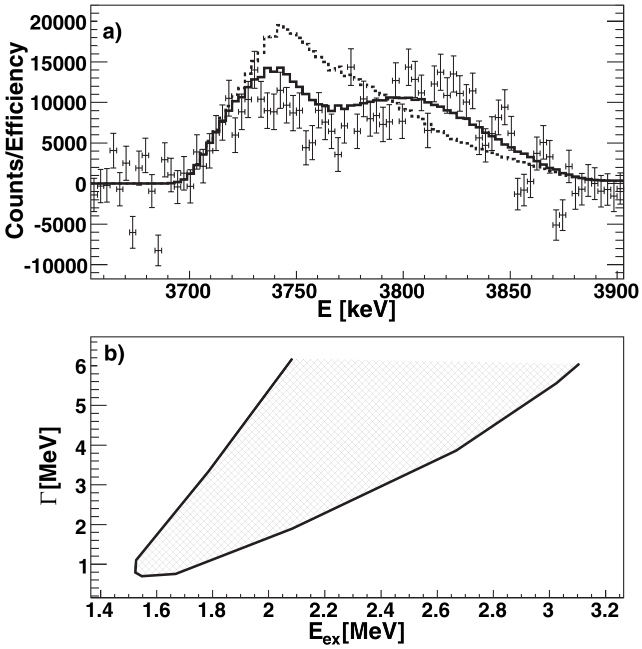

FIG. 3. (a) The solid curve shows a calculation of the γ-ray spectrum including the analog of the ^{7}He g.s. and a $J^\pi = 1/2^-$, $E_{\rm ex} = 3.1$ MeV, $\Gamma = 10$ MeV excited state. The dotted line is the effect from the g.s. resonance plus a state at $E_{\rm ex} \simeq 0.6$ MeV having $\Gamma \simeq 1$ MeV. (b) Plot of the probable resonance parameters for the $T = 3/2$, $J^\pi = 1/2^-$ state. The shaded area shows the 50% confidence level of the χ^2 fit. For excitation energies higher than 2.1 MeV, only a lower limit is set for the resonance width.

ing resonance parameters are in agreement with those proposed in Ref. [9]. The existence of an IAS of the ^{7}He resonance with parameters $E_{\rm ex} \simeq 0.6$ MeV and width $\Gamma \simeq 1$ MeV reported in Ref. [2] is excluded at more than the 90% confidence level. The χ^2 corresponding to this state was 27.

A broad resonance with $E_{\rm ex} = 5.8$ MeV and $\Gamma = 3$–5 MeV was reported in Ref. [3]. This is well above the excitation-energy range of the present experiment (2.3 MeV), so this state cannot contribute significantly to the measured yield. A state at $E_{\rm ex} = 2.9$ MeV, having $\Gamma \approx 2$ MeV [3,8], is within the energy range of the present work. Its decay modes were reported in Ref. [8]; it decays predominantly to the first excited state of ^{6}He. The analog of such a state in ^{7}Li would therefore decay predominantly to the second $T = 1$ state of ^{6}Li, which in turn decays into $\alpha + p + n$ with no γ-ray branching. Thus, it could not be detected in the present experiment.

In summary, we have proposed a new experimental technique to study resonances in neutron-rich exotic nuclei. The method gives information about the total cross section as a function of energy while maintaining sensitivity to the angular distribution. The IAS of ^{7}He in ^{7}Li was chosen as the first application of this technique. A ($T = 3/2, 3/2^-$) state in ^{7}Li, the known IAS of the ^{7}He ground state, was clearly observed. Evidence for the population of a broad ($T = 3/2, 1/2^-$) resonance in ^{7}Li is presented here along with limits on its excitation energy and width.

Two important advantages of the proposed method are its sensitivity to the single-particle strength of the isobaric analog resonances, coupled with insensitivity to the energy resolution of the radioactive nuclear beam. As a result, we believe that it will be a useful tool for studying exotic systems. As an example, the method could be used to probe the single-particle structure of ^{10}Li.

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