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Nucleon transfer reactions with exotic beams at ATLAS

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Abstract. We present some recent results from studies of light nuclei using exotic beams from ATLAS at Argonne National Laboratory. Light nuclei far from stability provide ideal testing grounds for modern theoretical methods, and may provide information about astrophysical environments. We focus on the nuclei ^{9}Li and ^{7}He, populated with the (d, p) and $(d,^3\mathrm{He})$ reactions.

PACS. 21.10.Jx Spectroscoptic factors – 25.60.-t Reactions with unstable beams – 25.70.Hi Transfer reactions

1 Introduction

Light, exotic nuclei provide us with an excellent laboratory for testing the predictions of modern nuclear-structure theories. Such methods include the Quantum Monte Carlo [1] (QMC) and No-Core Shell Model [2] (NCSM), as well as other varied shell-model and cluster-model approaches. The so-called *ab-initio* methods such as the QMC and NCSM in particular have been very successful in reproducing the properties of many bound and narrow states in a variety of light nuclei. Extending the comparison between theory and experiment to nuclei further from stability is more difficult, however, as few data exist with which to confront theory. Access to exotic beams, particularly at Coulomb-barrier energies, provides us with a new opportunity to make such comparisons. For many neutron- or proton-rich light nuclei, the particle binding energies are low, resulting in broad excited states rather than narrow resonances. Most available theoretical techniques are tailored to bound states, and so it is interesting to see how well these methods perform when predicting the properties of very short-lived resonances.

Such questions can best be addressed by using simple, single-nucleon transfer reactions whose mechanisms are well understood. For decades, single nucleon stripping or pickup reactions, such as (d, p), $(^3\mathrm{He},d)$ or $(d,^3\mathrm{He})$ have served as fundamental tools for studying the properties of nuclei throughout the periodic table. The availability of exotic beams at Coulomb-barrier energies now permit us to study nuclei further from stability by using these beams to perform such reactions in inverse kinematics. At the ATLAS facility at Argonne National Laboratory, a program of exotic-beam development and transfer reaction studies is underway.

Two examples of light, neutron-rich nuclei for which data are limited are ^{9}Li and ^{7}He. Both are p-shell nuclei whose properties can be calculated within the frameworks of these modern theoretical methods. In particular, predictions of spectroscopic factors for neutron transfer constitute a sensitive probe of the nuclear wave function, and can be obtained from these techniques [3, 4]. Also, data for neutron transfer in light nuclei may be useful for understanding some aspects of $^8\mathrm{Li}(n, \gamma)^9\mathrm{Li}$ capture reactions and the early stages of the r process [5]. In ^{7}He, considerable uncertainty remains regarding the nature of the first excited state in particular, and reports in the literature are contradictory [6–8]. To examine the nature of excited states of ^{7}He, we have employed complementary approaches, including the $^2\mathrm{H}(^6\mathrm{He},p)^7\mathrm{He}$ neutron-stripping and $^2\mathrm{H}(^8\mathrm{Li},^3\mathrm{He})^7\mathrm{He}$ proton-pickup reactions.

2 Experiment

The results presented here were obtained using ^{8}Li and ^{6}He beams obtained at the Argonne National Laboratory In-Flight production facility [9]. An 81 MeV ^{7}Li beam of intensity 45 pnA bombarded a cryogenically cooled D_2 gas cell kept at a pressure between 1000 and 1250 mbar. Secondary beams of ^{8}Li and ^{6}He were produced with the $^2\mathrm{H}(^7\mathrm{Li},p)^8\mathrm{Li}$, and $^2\mathrm{H}(^7\mathrm{Li},^3\mathrm{He})^6\mathrm{He}$ reactions, respectively, with intensities of 4–7 $\times$ 10^4 and 1 $\times$ 10^4 particles per

Table 1. Light exotic beams from the ATLAS In-Flight production facility.

Beam	Production Reaction	Energy (MeV/u)	Intensity (sec^{-1})
^{6}He	^{2}H(^{7}Li,^{3}He)^{6}He	11	10^4
^{8}Li	^{2}H(^{7}Li,p)^{8}Li	9	7×10^4
^{12}B	^{2}H(^{11}B,p)^{12}B	6	1.5×10^4
^{14}O	^{1}H(^{14}N,n)^{14}O	10	10^5
^{19}Ne	^{1}H(^{19}F,n)^{19}Ne	5	3.5×10^5
^{16}N	^{2}H(^{15}N,p)^{16}N	5	$>10^6$
^{21}Na	^{1}H(^{21}Ne,n)^{21}Na	5	10^5–10^6
^{21}Na	^{2}H(^{20}Ne,n)^{21}Na	5	10^5–10^6

second incident on target. In addition to these beams, a number of other light beams have been recently produced for a variety of applications. Table 1 lists the properties of several beams developed over the past two years.

The ^{8}Li and ^{6}He particles bombarded $(CD_2)_n$ foils of areal density 540 μg/cm^2. The ejectiles were detected in a set of three annular segmented silicon detectors which recorded their position and energy at backward laboratory angles for (d,p), and forward angles for $(d,^{3}\text{He})$. The laboratory segmentation of the annular detectors was approximately 1°. Heavy beam-like fragments, including ^{7,8,9}Li, or ^{4,6}He ions were detected and identified in a set of silicon ΔE-E telescopes covering $1° < \theta_{lab} < 7°$. To determine the total number of incident ions, and to monitor the quality of the beam, beyond the ΔE-E array the beam particles scattered from a gold foil were detected in a second ΔE-E telescope. In addition, a fraction of singles events in the large ΔE-E array was recorded so as to monitor the beam scattering from the carbon nuclei in the $(CD_2)_n$ foil. The experimental setup is described in detail in [3,4].

3 Results

3.1 (d,p) reactions

Figure 1 shows Q-value spectra obtained for three (d,p) reactions: (a) ^{2}H(^{7}Li,p)^{8}Li (as a calibration reaction), (b) ^{2}H(^{8}Li,p)^{9}Li and (c) ^{2}H(^{6}He,p)^{7}He. These events represent protons in coincidence with identified ^{7,8,9}Li, or ^{6}He particles, respectively, in the forward ΔE-E detector array. The total detection efficiency of the setup is given by the thin histogram, and is obtained from a Monte-Carlo simulation that includes realistic detector geometries, and when appropriate the 3-body final states for excitation energies above the neutron binding energy in each case.

The observed Q-value resolution for the secondary-beam reactions is approximately 350 keV FWHM, and is dominated by beam spot size and detector segmentation. For ^{9}Li, the ground, first- and second-excited states are clearly observed. In the ^{7}He case, the ground state is strongly populated. At higher excitation energies there appears a broad distribution of counts in the excitation-energy range expected for a $1/2^-$ first-excited state as

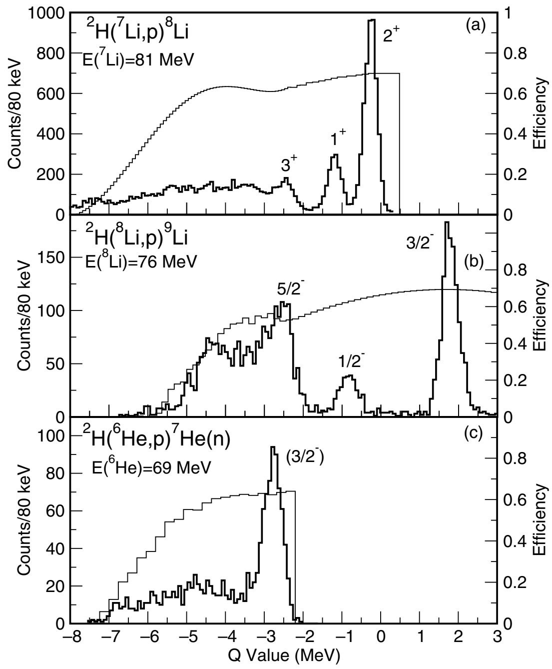

Fig. 1. Raw Q-value spectra for (a) ^{2}H(^{7}Li,p)^{8}Li (b) ^{2}H(^{8}Li,p)^{9}Li and (c) ^{2}H(^{6}He,p)^{7}He. The thin lines represent the Monte-Carlo simulated total detection efficiency.

predicted by a variety of theoretical calculations. Little evidence for a low-lying first-excited state near 600 keV as was reported in [6,8] is observed in the data for the ^{2}H(^{6}He,p)^{7}He reaction.

Figure 2 shows angular distribution data for the (a) ^{2}H(^{8}Li,p)^{9}Li and (b) ^{2}H(^{6}He,p)^{7}He$_{g.s.}$ reactions. For the ^{2}H(^{8}Li,p)^{9}Li reaction, the data are plotted with curves calculated using the DWBA program PTOLEMY, using spectroscopic factors from the Variational Monte Carlo (VMC) calculations as described in [1] and given in [3]. The solid and dashed curves in (a) represent the predictions obtained using two different optical-model potential sets taken from [10]. The curves represent absolute predictions of the angular distribution with no further normalization and are in good agreement with the data. For the ground state of ^{7}He, the shape of the measured angular distribution is well described by the calculation, however the magnitude is slightly lower, suggesting an experimental ^{6}He$_{g.s.}+n$ spectroscopic factor approximately 0.69 times smaller than the calculated value (dot-dashed curve in figure 2(b)).

To address the question of possible excited states of ^{7}He, the ^{2}H(^{6}He,p)^{7}He Q-value spectrum, corrected for detection efficiency, appears in figure 3(a). To reproduce the spectrum, we generated simulated spectra for the ground state, and a set of hypothetical broad states whose line shapes were obtained from the R-Matrix formalism with modifications from the dependence of the cross section on Q value from the PTOLEMY calculations described above. The data are best described by including the ground state (thin line), a broad excited state at $E_X = 2.6$ MeV and width $\approx$2.0 MeV (dot-dashed line),

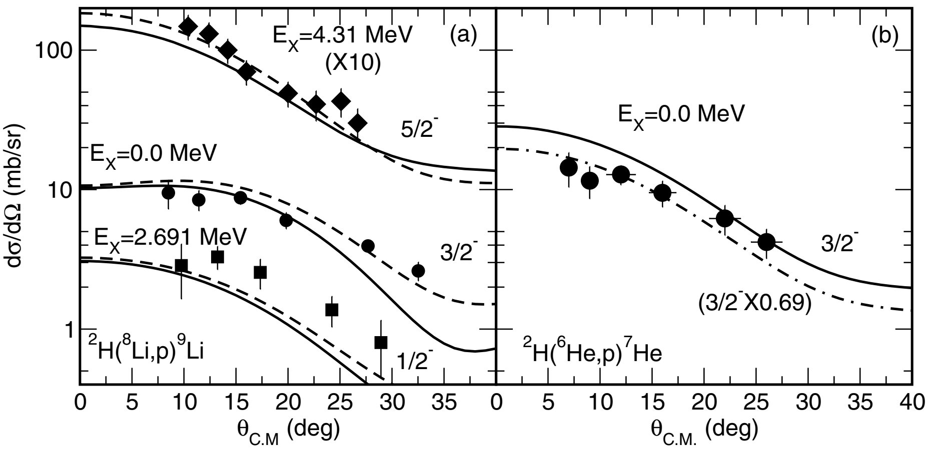

Fig. 2. Angular distribution data for (a) ^{2}H(^{8}Li,p)^{9}Li and (b) ^{2}H(^{6}He,p)^{7}He. The curves represent DWBA calculations described in the text.

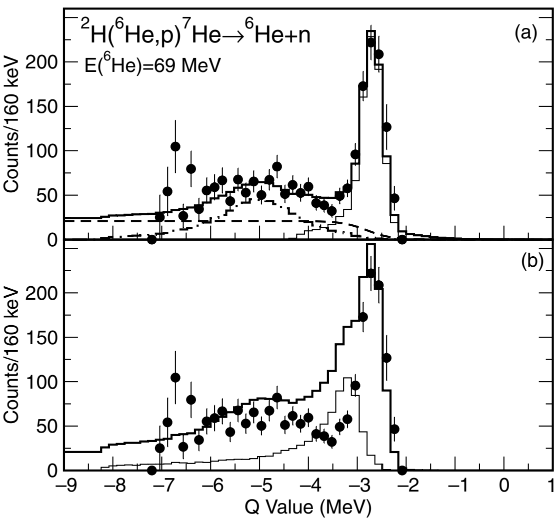

Fig. 3. Efficiency-corrected Q-value spectra for the ^{2}H(^{6}He,p)^{7}He reaction. The histograms are described in the text.

and also a smooth empirical background (dashed line). The thick histogram in figure 3(b) represents a fit including contributions that well describe the data plus a contribution from the proposed low-lying first excited state described in [6] expected if it were populated with the theoretically anticipated spectroscopic factor (thin line). The data do not support the presence of such a state populated with that magnitude in the (d,p) reaction.

Q-value spectra for different ^{7}He decay channels are plotted in figures 4(a)–(c). These represent proton coincidences with ^{4,6}He (a), ^{6}He alone(b), and ^{4}He alone (c). The efficiencies for these possibilities are similar. The data shown in (b) and (c) correspond to ^{7}He decays through the ^{6}He ground, and 2^+ first-excited states, respectively. The yield for the excited-state decay is small, with a constant background from interactions of the ^{6}He beam with the carbon in the target. The small yield suggests that if a broad excited state in ^{7}He is populated in ^{2}H(^{6}He,p)^{7}He, it does not possess a large ^{6}He(2^+) decay branch, consistent with the expectations for a first excited state with spin and parity $1/2^-$.

3.2 The ^{8}Li(d,^{3}He)^{7}He reaction

Given the uncertainties about the broad excited states in ^{7}He, a study of other, complimentary reactions could provide additional information. Another reaction accessible at ATLAS is ^{2}H(^{8}Li,^{3}He)^{7}He. This reaction should populate the ground state and $5/2^-$ state strongly, but possesses only a very small spectroscopic amplitude for a $1/2^-$ transition, according to QMC calculations. The predicted spectroscopic factors for proton pickup from ^{8}Li are 0.561 and 0.166 for the $3/2^-$ and $5/2^-$ states, respectively, whereas for the $1/2^-$ level this quantity is only 0.009. Thus, the results for this reaction could be compared to the reports from [7] of a $5/2^-$ level near 3 MeV excitation energy. This reaction has the additional advantage, in comparison to (d,p), that higher excitation energies are attainable due to the forward kinematics, and the experiment is insensitive to low-energy thresholds in the particle detectors.

Figures 4(d)–(f) show preliminary Q-value spectra for the ^{8}Li(d,^{3}He)^{7}He reaction, compared to similar results for the ^{6}He(d,p)^{7}He reaction. Figure 4(d) shows the Q value, integrated over detector angle, for events with a ^{3}He in coincidence with either an identified ^{6}He or ^{4}He nucleus. The spectrum resembles that obtained from (d,p) (figure 4(a)) with a strong ground-state peak, and broad distribution of counts at higher excitation energies. Figure 4(e) illustrates the Q-value spectrum obtained solely for ^{3}He-^{6}He coincidences. Whereas in the (d,p) case, the yield at higher excitation energy is largely still present in the spectrum, for the (d,^{3}He) case only the ground state remains. For coincidences with ^{4}He, which probe decays of ^{7}He through ^{6}He(2^+), only a small fraction of the high-excitation energy yield remains in the (d,p) case, but virtually all strength appears in this decay channel for the (d,^{3}He) case. This comparison indicates that different amplitudes in the final nucleus are being probed by the two

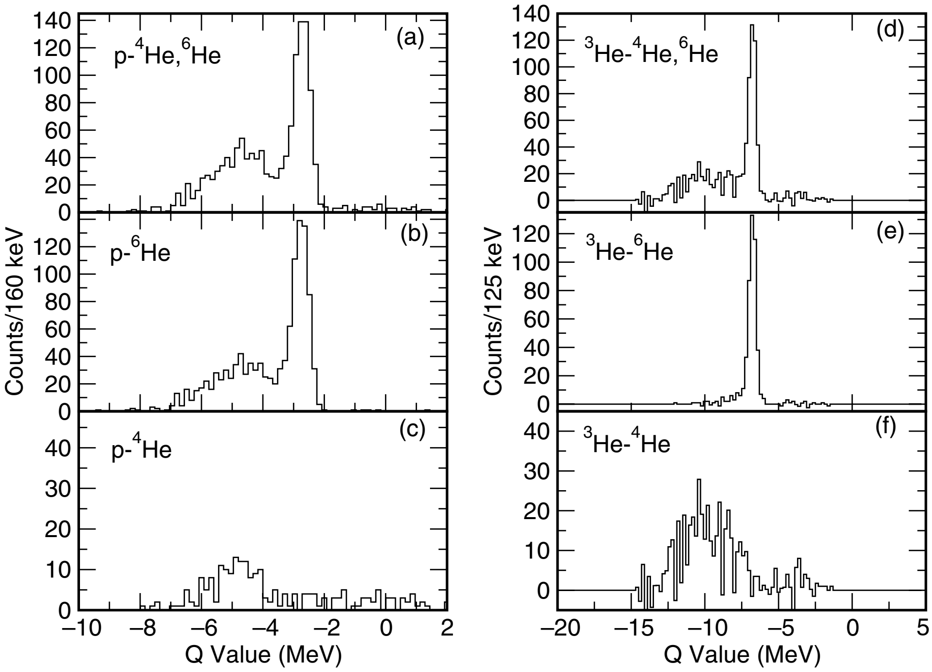

Fig. 4. Comparison between (d,p) and $(d,^3\text{He})$ reactions populating ^{7}He. (a),(b),(c) Q-value spectrum for (d,p) for $p-(^4\text{He},^6\text{He})$, $p-^6$He, and $p-^4$He coincidences, respectively. (d), (e), (f) Q-value spectrum for $(d,^3\text{He})$ for ^{3}He-(^{4}He,^{6}He), ^{3}He-^{6}He, and ^{3}He-^{4}He coincidences, respectively.

reactions, as would be expected from the calculated spectroscopic factors. Work is underway to quantify this observation.

4 Discussion and conclusions

The present results show that nucleon transfer reactions performed in inverse kinematics with light radioactive beams can be an effective tool for probing the detailed structure of exotic light nuclei. For ^{9}Li, the measured (d,p) angular distributions and spectroscopic factors are in good agreement with modern *ab-initio* calculations, confirming the suggested $1/2^-$ assignment for the first-excited state and suggesting $J^\pi = 5/2^-$ for the second-excited state. In ^{7}He, the results for the ground state are also in accord with theoretical expectations. For possible excited states in ^{7}He, no evidence is found for a low-lying $1/2^-$ first-excited state, although the data do possibly suggest a broad resonant state centered at $E_X = 2.6$MeV, within the range for a first- excited state predicted by several theories. With new data from the ^{2}H(^{8}Li,^{3}He)^{7}He reaction, a consistent picture of excited states in ^{7}He may be emerging.

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