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Break-up Array for LIght Nuclei: A new tool for exploring nuclear reactions of relevance to the cosmological ^{7}Li problem

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The disagreement between observed ^{7}Li abundances in metal-poor halo stars and primordial ^{7}Li abundances predicted in Big Bang Nucleosynthesis (BBN) calculations has presented a challenge to the astrophysics community for some time. The absence of a clear astrophysical explanation of this problem has reignited a search for a possible nuclear solution. The Nuclear Reaction Dynamics group at the Australian National University has recently developed the Break-up Array for LIght Nuclei (BALIN), a new highly pixelated detector array capable of providing the most complete picture of nuclear reactions leading to the breakup of light nuclei. First measurements with this array have already yielded surprising new information about the breakup dynamics of sub-barrier collisions between ^{6,7}Li and ^{208}Pb. Results from these measurements are presented as a demonstration of the array's capabilities. Possible implications for reactions of relevance to BBN will be explored in the future.

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1. Introduction

The ‘cosmological ^{7}Li problem’ refers to the disagreement between ^{7}Li abundances observed in metal-poor Galactic halo stars and those predicted in big bang nucleosynthesis (BBN) calculations. This disagreement has been a cause for concern that all is not quite right with our standard model of light element formation during the Big Bang.

Primordial abundances have been measured for four isotopes: deuterium (d), ^{4}He, and ^{6,7}Li. Observations match the standard BBN predictions for d and ^{4}He [1]. ^{6}Li abundances, while available [2], are exceedingly difficult to measure, somewhat controversial [3], and will not be discussed here. For ^{7}Li, BBN calculations overpredicted observed abundances by a factor of three to four — a mismatch of 4-5 σ. A more recent measurement [4] of ^{7}Li in the low-metallicity Small Magellanic Cloud (SMC) inferred an abundance consistent with BBN predictions, but only if one can make the unlikely assumption (see, for example, [5]) that the formation of additional ^{7}Li by stellar and cosmic nucleosynthesis is severely constrained.

Several approaches for finding a solution to this cosmological ^{7}Li problem exist [1]: astrophysical approaches, approaches that require new physics, and nuclear physics solutions (which are the focus of this work). Because BBN calculations rely on nuclear physics input, it is possible that ^{7}Li abundances are inconsistent with prediction due to some failing in our understanding of the nuclear physics of light element formation.

The main reactions thought to significantly contribute to ^{7}Li formation during BBN are included in the simplified network shown in Fig. 1. The dominant method for primordial ^{7}Li formation is via the electron capture decay of ^{7}Be ($T_{1/2} \sim 53$ days). Several studies (e.g. [6, 7, 9, 8]) have considered the effect of varying many of the reaction rates contributing to ^{7}Be (and thus ^{7}Li) destruction and found a solution of this sort unlikely. However, recent work [10, 11] has provided an incentive to revisit reactions of relevance to cosmological ^{7}Be (and therefore, ^{7}Li) formation.

The work presented here focuses on ^{6,7}Li breakup mechanisms in reactions on ^{208}Pb. While these systems do not have direct relevance to the cosmological ^{7}Li problem, they do offer a clear

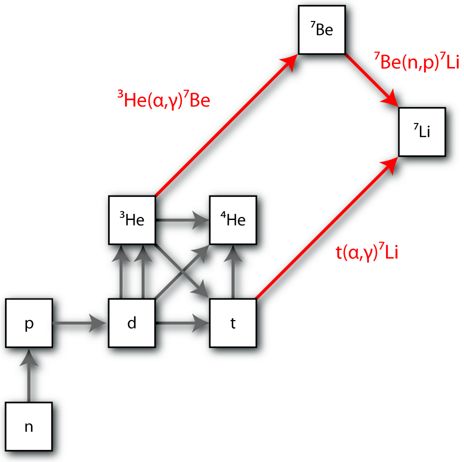

Figure 1: Simplified BBN network, highlighting the dominant paths for ^{7}Li formation. Adapted from [1].

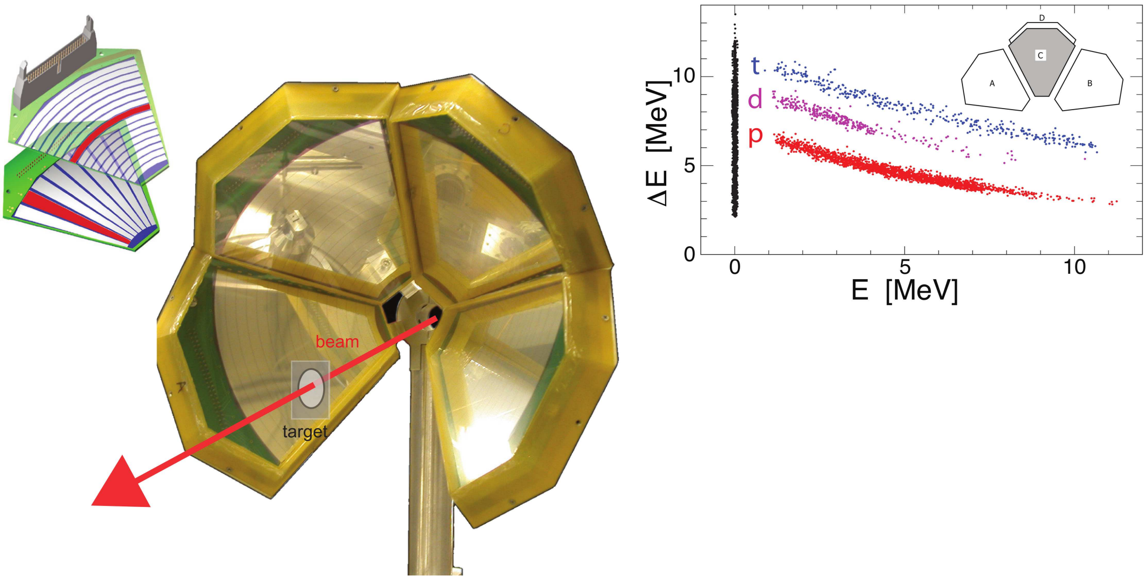

Figure 2: The ANU's Breakup Array for LIght Nuclei (BALIN). The top left inset shows how the Micron DSSD wedges are segmented. The figure to the right shows the E-$\triangle E$ information used to separate hydrogen isotopes in the detector configuration used for this work.

demonstration of the capabilities of the Australian National University's new Breakup Array for LIght Nuclei (BALIN), shown in Fig. 2. This instrument, which was designed to provide a relatively complete picture of breakup reactions [10, 11, 12], may be a powerful new tool for studying reactions of relevance to the cosmological ^{7}Li problem.

2. Experimental details

Beams of ^{6,7}Li were produced using the ANU's 14UD tandem accelerator at below-barrier energies of 24.0, 26.5, and 29.0 MeV. These beams impinged upon a 98.7%-enriched ^{208}PbS target with a thickness of 170 μg/cm^2 and a 15-μg/cm^2 carbon foil backing.

BALIN, shown in Figure 2, was used as the detection system for these experiments. BALIN is an array of four 400 μm-thick double-sided silicon strip detectors (DSSDs) arranged in a lampshade configuration at 45° from the beam axis. The DSSDs are 60° wedge detectors from Micron Semiconductor ltd.

In addition to providing kinetic energy information (E_i) for each event, the DSSDs provided position information (θ_i,ϕ_i) via the pixelation in each detector, as illustrated in Fig. 2 (left). Particle coordinates were randomised within each of the 128 pixels per detector to provide a continuous position spectrum, and data were only recorded when two detector arcs fired in order to reduce the data collection rate.

Throughout these experiments, two of the DSSDs were overlapped in order to provide energy loss ($\triangle E$) information. With this modification, the array allowed for the identification of isotopes of hydrogen and determination of the energy of protons. A sample E$-\triangle$E spectrum demonstrating isotope identification is shown in Fig. 2 (right). A full discussion of the experimental details and results presented here can be found in [10, 11].

2.1 Kinematic reconstruction.

For ^{6,7}Li, breakup proceeds via two charged fragments. Beginning with this assumption, kinematic reconstruction of each breakup event could be completed with the energy of the recoiling target-like nucleus (E$_{rec}$), the measured kinetic energies of the two breakup fragments (E_1, E_2), and the kinetic energy of the incident projectile in the lab frame (E_{lab}). E_{lab} is corrected for energy loss in the target. The Q-value (Q) for a given reaction, which provides the energy change for a given breakup process, is important for identifying breakup modes and particle identities. Q can be calculated as follows:

$$Q = E_1 + E_2 + E_{rec} - E_{lab}. \tag{2.1}$$

The relative energy between the two breakup fragments (E_{rel}) is also of interest in breakup studies, because it provides insight into the internuclear separation at breakup in a classical framework [13]. E_{rel} is given by

$$E_{rel} = \frac{m_2E_1 + m_1E_2 - 2\sqrt{m_1E_1m_2E_2}cos(\theta_{12})}{m_1 + m_2}, \tag{2.2}$$

and can be calculated from the measured energies $E_{i,j}$, deduced masses $m_{i,j}$ [11], and the observed angular separation θ_{ij} between two coincident breakup fragments.

Details of the model calculations involved are provided in [10, 11]; here, it is sufficient to note that E_{rel} spectra are expected to show both delayed and prompt breakup components. Delayed breakup occurs over longer timescales (after reflection) and corresponds to peaks at low E_{rel} values, centred at $E_{rel} = E^* + Q_{BU}$. E^* is the excitation energy of the state from which breakup occurs and Q_{BU} is the Q-value for the breakup reaction. Prompt breakup, which occurs on shorter timescales (before reflection), corresponds to peaks at high E$_{rel}$ values with comparably broad distributions. This fast breakup process, which occurs in close proximity to target nuclei, is responsible for fusion suppression.

3. Results

3.1 Q-values

Q-value spectra for ^{6,7}Li+^{208}Pb at E_{beam}=29.0 MeV, obtained using Eq. (2.1) following particle identification and kinematic reconstruction, are shown in Fig. 3(a,b). Equivalent spectra for lower beam energies show similar patterns with reduced yield.

For ^{6}Li, the main breakup channels are $\alpha + d$, $\alpha + p$, and $\alpha + \alpha$, as shown in 3(a). For all projectile energies, the most prominent peak is $\alpha + d$, which corresponds to the breakup of excited states of the projectile into its cluster constituents, as expected. However, the two other processes—$\alpha + p$ and $\alpha + \alpha$—are surprisingly probable. These two processes correspond to transfer reactions with the doubly-magic target nucleus, ^{208}Pb. The peaks in the $\alpha + p$ distribution provide further evidence that $\alpha + p$ events result from the stripping of a neutron from the projectile, producing unbound ^{5}Li, as well as ^{209}Pb in its five lowest energy states. After efficiency correction, this channel is more probable than that of $\alpha + d$. The $\alpha + \alpha$ process, which is less probable than either of the two other channels, requires the pick-up of a proton and a neutron from the target nucleus, forming ^{8}Be.

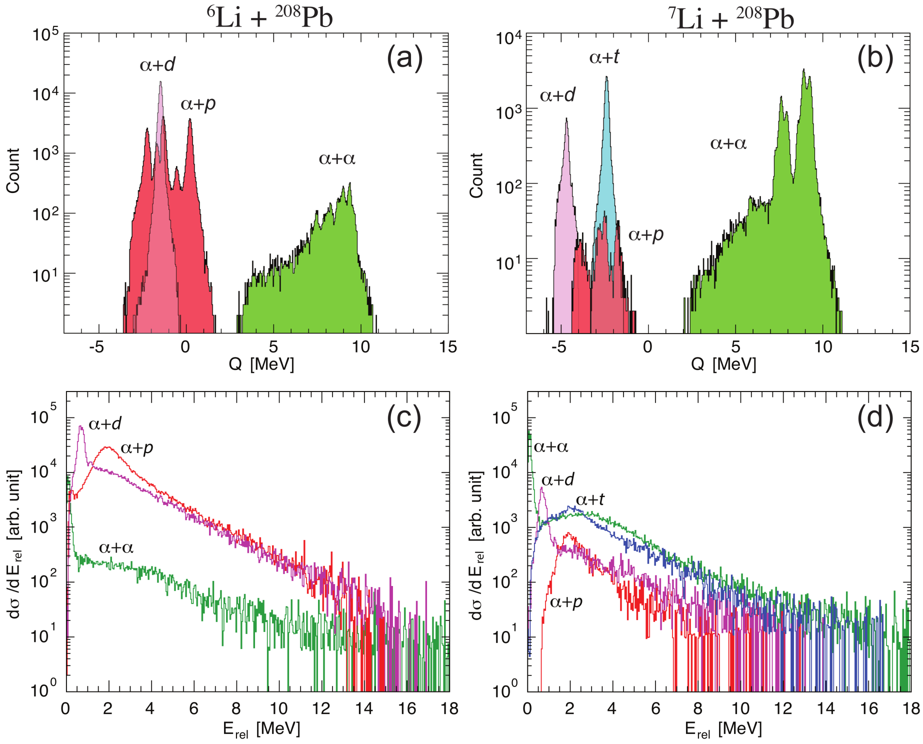

Figure 3: (a,b) Q-spectra for ^{6,7}Li+^{208}Pb at E_{beam}=29.0 MeV. For ^{6}Li (a), the primary breakup processes are α+d (pink), α+p (orange), and α+α (green). For ^{7}Li (b), one additional process, α+t (blue), is observed. (c,d) Efficiency-corrected E_{rel} spectra for ^{6,7}Li+^{208}Pb at E$_{beam}$=29.0 MeV; colour scheme is consistent with that used in (a,b). Both expected components of E_{rel}—sharp peaks at low energies, and diffuse distributions at higher energies—are evident.

For ^{7}Li, Fig. 3(b) shows that cluster breakup into $\alpha + t$ is probable, as expected. However, the strongest breakup route is via pick up of a proton by ^{7}Li from the doubly-magic target nucleus, resulting in the production of ^{8}Be and its subsequent decay into two α particles. The four-peak structure of the $\alpha + \alpha$ Q-spectrum in Fig. 3(b) results from population of the four lowest energy states in the resulting target-like product, ^{207}Tl. The other breakup modes correspond to neutron stripping reactions leading to ^{5,6}Li formation.

3.2 Relative energy of breakup fragments

The efficiency-corrected E_{rel} histograms for ^{6,7}Li+^{208}Pb, also at E_{beam}=29 MeV, are shown in Fig. 3(c,d). Figs. 3 (c) and (d) confirm the presence of both of the expected E$_{rel}$ components: the sharp, low energy peaks and broad, high energy peaks in the E_{rel} spectrum. Sharp peaks, including the $\alpha + \alpha$ 92-keV peak in both ^{6,7}Li spectra and the $\alpha + d$ 700-keV peak in the ^{7}Li spectrum, correspond to breakup processes that occur after reflection, when the projectile-like nucleus is far from the target-like nucleus. The first peak results from the slow ^{8}Be ground state decay, while the second peak corresponds to the first excited state decay of ^{6}Li, populated either by direct excitation of ^{6}Li, or, for ^{7}Li, via neutron transfer.

Broad, higher energy distributions are evidence of prompt breakup events, which occur on timescales of $\sim 10^{-22}$ seconds. For ^{6}Li, prompt breakup occurs both directly ($\alpha + d$) and following neutron transfer ($\alpha + p$). For ^{7}Li, prompt cluster breakup ($\alpha + t$) is strong, as expected. However, the presence of broad, high E_{rel} peaks in the $\alpha + \alpha$ channel, corresponding to the breakup of ^{8}Be, indicates that prompt breakup following proton-pickup is surprisingly probable. A full discussion of the efficiency corrections and final E_{rel} spectra can be found in [10, 11].

4. Conclusions and Outlook

As the above results show, direct cluster breakup is not the most dominant process for destruction in ^{6,7}Li, despite the extremely stable (doubly-magic) target nuclei. This surprising conclusion illustrates the importance of using a detector like BALIN for reactions whose potential outcomes are not well understood.

Because BALIN offers relatively complete information for kinematic reconstruction, one can observe how, when, and why breakup occurs for a wide variety of reactions without having to make assumptions about how such reactions might proceed. For the cosmological ^{7}Li problem, BALIN may provide us with a complete picture of reactions of direct relevance to the BBN, and reveal how breakup may influence reaction outcomes more generally at astrophysically relevant energies.

Our group is currently investigating the possibility of conducting breakup experiments using lighter target nuclei. These experiments, which will be at energies achievable at the ANU Heavy Ion Accelerator Facility, will provide an essential test of BALIN's performance for lighter projectile-target combinations. Once the analysis is complete, options for using BALIN to observe reactions of direct relevance to the cosmological ^{7}Li problem at astrophysically-relevant energies will be considered.

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