# Challenges in describing nuclear reactions outcomes at near-barrier energies

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**Abstract.** The properties of light nuclei such as $^6$Li, $^7$Li, $^9$Be and $^{12}$C, and their reaction outcomes are known to be strongly influenced by their underlying α-cluster structure. Reaction models do not yet exist to allow accurate predictions of outcomes following a collision of these nuclei with another nucleus. As a result, reaction models within GEANT, and nuclear fusion models do not accurately describe measured products or cross sections. Recent measurements at the Australian National University have shown new reaction modes that lead to breakup of $^6$Li, $^7$Li into lighter clusters, again presenting a further challenge to current models. The new observations and subsequent model developments will impact on accurate predictions of reaction outcomes of $^{12}$C - a three α-cluster nucleus – that is used in heavy ion therapy.

## 1. Introduction

Energetic beams of $^{12}$C, used in heavy ion therapy, undergo a range of reaction processes as they slow down in matter. This is schematically illustrated in Fig. 1. At high energies, knockout, fragmentation and spallation reactions occur, whilst at medium and low energies transfer, breakup and fusion reactions are dominant. No single model can describe the reaction outcomes over such a large energy range (~200 MeV/u to stopping), and thus different models are used depending on the energy of the ion, as shown in Fig. 1.
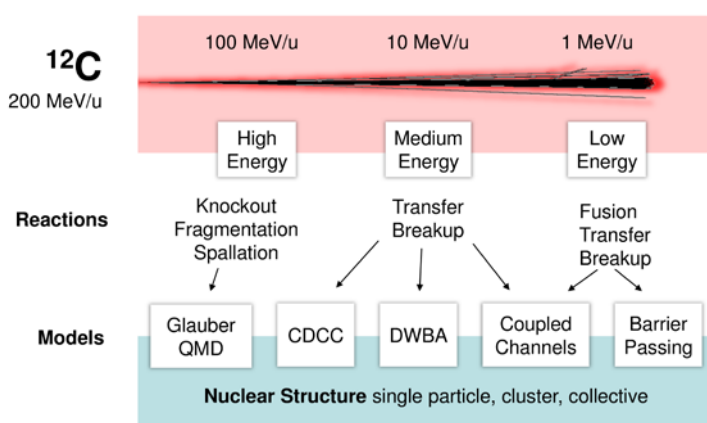


**Figure 1.** Schematic diagram showing the dominant nuclear reactions that occur as high energy carbon nuclei slow down in matter. Different models, each suited to a particular energy regime, are used. For example Glauber and quantum molecular dynamics (QMD) models are used at high energies, whilst continuum discretised coupled channels model (CDCC) and distorted wave Born approximation (DWBA) are used at medium energies. All models need to include the effects of nuclear structure.

The quantum structure of the nucleus plays an important role in reaction outcomes at all energies. Nuclear structure fundamentally arises from the strong interactions of the constituents of the nucleus. However, we cannot yet calculate all aspects of nuclear structure from first principles (i.e. starting from quarks). Thus structure models highlight specific aspects, e.g. of single particle nature or of collective nature where all constituents participate, leading to vibrations or rotations of the nucleus. The description of nuclear structure is an essential ingredient in all reaction models, as the reaction dynamics is strongly influenced by nuclear structure.

The nucleus $^{12}$C is known to have an α-cluster structure [1], which fundamentally arises due to the large binding energy of the $^4$He nucleus (α-particle). Interactions of energetic beams of $^{12}$C with matter produces Li, Be and B fragments, which as well as carbon, contribute to the depth-dose distribution [2]. Production of α-particles is also observed but their yields at low energies are underestimated [2] by up to a factor of 10 in simulations. This underestimation has been attributed to effects of α-clusters in $^{12}$C. Nuclear collisions near the Coulomb barrier are very sensitive to nuclear structure effects, and thus studies of reactions near the barrier can reveal the link between structure and reaction outcomes. This is particularly relevant for nuclei with α-clusters, as they can disintegrate via many mechanisms as shown by measurements in the last several years. This complexity means that some major reaction outcomes are not described by the current quantum models of nuclear reactions.

The experiments [3-6] and model developments [7] at the Australian National University (ANU) are addressing this challenge. The measurements [4-6] have concentrated on lithium – the next higher element to $^4$He. The isotopes $^6$Li and $^7$Li have α-$^2$H and α-$^3$H ground state cluster structure. The reaction outcomes are influenced by their cluster structure, e.g. complete fusion cross sections are found to be reduced by ~30% compared with expectations [8, 9]. It was thought that this suppression arises due to breakup of lithium nuclei into their cluster constituents. However, experiments at the ANU, described below, show that breakup of lithium is more complex and can occur via many routes.
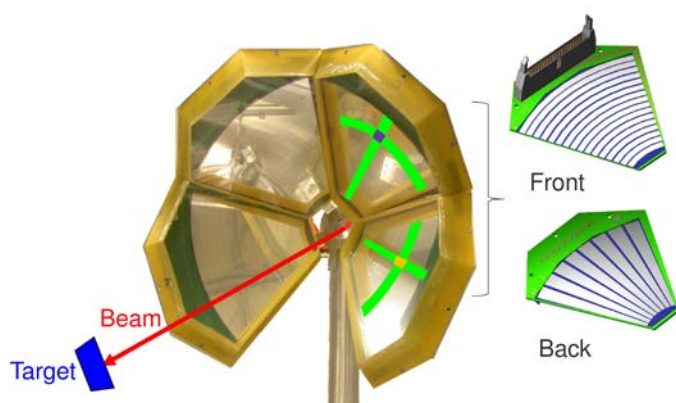


**Figure 2.** Four double-sided silicon strip detectors are used to detect coincident charged breakup fragments. The front of each detector is divided into sixteen arcs and the back is divided into eight sectors. Positon of each breakup fragment can be determined from the intersection of the arc and the sector, as illustrated in the figure. The figure shows a schematic sketch of the beam (red arrow), hitting the target foil, with two charged fragments being registered at backward angles (purple and yellow pixels) by the detector array.

## 2. Experimental Methods

The experiments were performed using beams of $^6$Li and $^7$Li from the 14UD electrostatic accelerator, at the Heavy Ion Accelerator Facility at the ANU. Beams were incident on thin isotopically enriched targets. The evolution of reaction mechanisms with decreasing target mass was studied by using targets ranging from $^{209}$Bi via $^{208}$Pb, $^{144}$Sm, $^{64}$Zn, $^{58}$Ni, $^{27}$Al, $^{12}$C, to $^2$H. Interactions of the $^{6,7}$Li beams with the target nuclei at energies below the barrier result in coincident charged breakup fragments (e.g. $^4$He, $^3$H, $^2$H, and $^1$H). The coincident charged breakup fragments were detected using an array of four 400 μm thick double-sided silicon-strip detectors. The position information of the coincident fragments, together with their measured energies were used to reconstruct the kinematics [3-6]. Thus the energetics of the reactions (Q-values) could be determined, giving information on the state of the heavy (target-like) nucleus. Newly identified experimental variables that give information on the

position of breakup have recently been determined [9], leading to an understanding of the reaction dynamics with in detail.
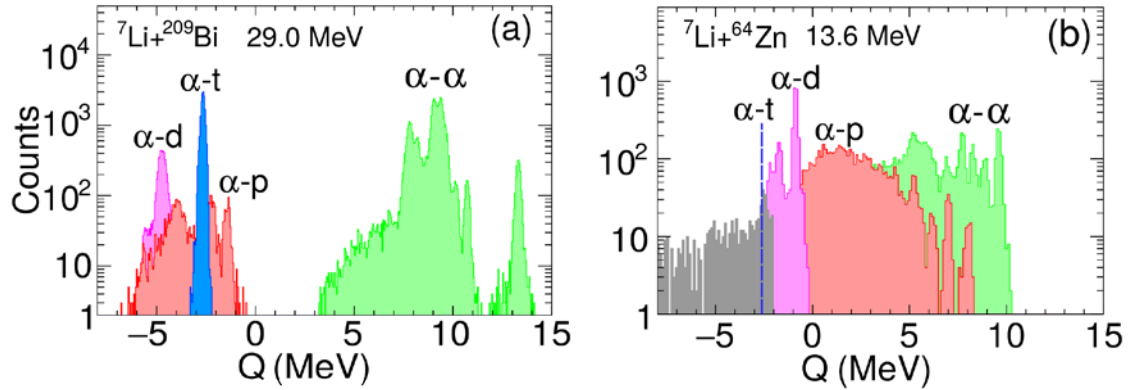


**Figure 3.** Breakup of $^7$Li nucleus, which has an $\alpha$-$^3$H cluster structure, proceeds via many modes. The various breakup modes are clearly seen in the Q-value plot shown for measurements with targets of (a) $^{209}$Bi and (b) $^{64}$Zn. Breakup into $\alpha$ and $^3$H (triton, t), shown in blue, is observed for the heavy target, but not the lighter target – the vertical blue line in (b) indicates the expected Q-value. Breakup following transfer of nucleons is dominant. Proton transfer from the target to $^7$Li leading to $^8$Be, which breaks up into two alpha particles, is shown in green; one and two neutron transfer from $^7$Li forms $^6$Li and $^5$Li, which then breakup into $\alpha$-deutron ($\alpha$-d) and $\alpha$-proton ($\alpha$-p) pairs respectively.

## 3. Results

The experiments show that for $^{6,7}$Li induced reactions, in addition to direct breakup into $\alpha$-d and $\alpha$-t clusters respectively, breakup via other modes is very significant [4-6]. These modes arise following transfer of nucleons (protons or neutrons) between the colliding nuclei that can populate nuclei that are themselves weakly bound or unbound. These modes are present in interactions with nuclei ranging from bismuth through nickel down to deuteron; the breakup modes for bismuth and zinc are shown in Fig. 3. The figure shows that the direct breakup component (that can, in principle, be described theoretically) is negligible for interactions with Ni; essentially the direct breakup component is absent for collisions with lower mass target nuclei [6].
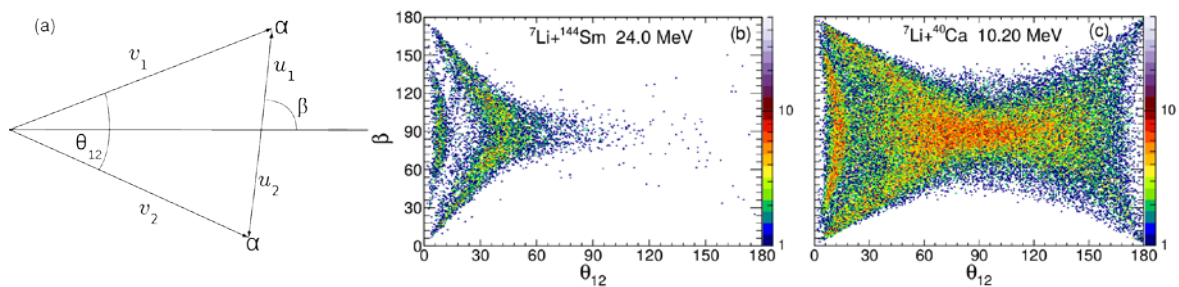


**Figure 4.** The angle between the two $\alpha$-particles $\theta_{12}$, following the disintegration of $^8$Be $\rightarrow \alpha + \alpha$, as a function of the angle $\beta$ for the indicated targets. The relationship between angles $\theta_{12}$ and $\beta$ is sketched in panel (a). The angle at which the $\alpha$-particle emerges depends on the location of breakup and the atomic number of the target.

Helped by classical breakup simulations, experimental observables have been found that are sensitive to the breakup location [9], i.e. whether breakup occurs close to the target or asymptotically far from the target. The breakup location depends on the meanlife of the parent state; sensitivity to sub-

zeptosecond lifetimes is found. An example is shown in Fig. 4, for breakup of 7Li following proton pickup from 144Sm and 40Ca; the nucleus 8Be is formed which subsequently breaks up into two α-particles. In the context of heavy ion therapy, the location of the breakup and the atomic number of the target affect the angular distribution of the breakup fragments.

The figure shows the angle between the α-particles $\theta_{12}$ against β which is the orientation of the relative velocity (of the two α-particles) with respect to the velocity of the center of mass of the fragments [sketched in Fig. 4 (a)].

## 4. Conclusions

The experiments demonstrate that breakup in reactions of $^{6,7}$Li is largely triggered by transfer. The dominance of transfer triggered breakup increases as the target mass is lowered. These transfer triggered breakup mechanisms are not currently incorporated in models (nor in simulations) of nuclear reactions near the barrier. The experimental results necessitate new developments in modelling nuclear reactions. The experimental advances also pave the way to study the breakup mechanisms of other nuclei such as $^{12}$C, $^{13}$C and light radioactive nuclei such as $^{6}$He, $^{8}$Li, $^{11}$Li, $^{11}$Be etc. that are beginning to be available from rare isotope accelerator facilities world-wide.

## 5. Acknowledgments

## 6. References

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