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Zeptosecond Dynamics of Transfer-Triggered Breakup

Mechanisms, Timescales, and Consequences for Fusion

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Zeptosecond Dynamics of Transfer-Triggered Breakup

Mechanisms, Timescales, and Consequences for Fusion

Doctoral Thesis accepted by
the Australian National University, Canberra, Australia

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By convention sweet is sweet,
bitter is bitter,
hot is hot,
cold is cold,
colour is colour;
but in truth there are only atoms and the void.
Democritus (460–370 BCE)

To my parents.

Supervisor’s Foreword

The elements that make us, our planet, and the Universe result from nuclear reactions in the cosmos. Synthesis of elements occurs through fusion of atomic nuclei, reactions involving neutron-rich nuclei, and nuclear fission. Atomic nuclei, made of protons and neutrons, are quantum objects and their interactions are largely determined by the strong and electromagnetic forces. The outcomes of nuclear reactions are thus fundamentally determined by many-body quantum dynamics of strongly interacting systems. This results in striking consequences, as exemplified by the many-fold increase in fusion at energies below the Coulomb barrier due to couplings to low-energy quantum states of the two interacting nuclei. Accurate prediction, particularly at energies near the barrier where quantum structure and dynamics are clearly intertwined, is a formidable challenge to our understanding of many-body physics.

We are entering an era that promises a vastly improved understanding through a happy coincidence of new experimental techniques, new accelerators of intense beams of both stable and unstable (rare) isotopes, and increased computational power that allows microscopic many-body calculations. This thesis presents an incisive new method that demonstrates how the subtleties of quantum structure of light weakly bound nuclei affect reaction outcomes. This is of immediate interest due to the worldwide availability of accelerated beams of rare short-lived nuclei. Currently, there is no theoretical model that describes the (experimentally observed) routes that cause breakup of weakly bound fragile nuclei. The excited quantum states of such nuclei are typically particle-unbound resonances and the effect of couplings to these resonant states on fusion continues to generate controversy. For these reasons, a realistic understanding of the processes influencing near-barrier fusion of weakly bound nuclei remains elusive.

This thesis highlights the role of resonance lifetimes in determining reaction outcomes through selecting experimental observables that are sensitive to the location of breakup, and combined with stochastic model simulations. Lifetimes as short as 10^{-21}s must not be assumed to lead to “instantaneous” breakup, but must be treated explicitly to reproduce experimental results.

Breakup that occurs as the weakly bound projectile nucleus approaches the target nucleus could be separated from that occurring when the projectile recedes from the target. This separation led to another physics insight: breakup prior to reaching the barrier is insufficient to explain the experimentally observed suppression of complete fusion. This result means that efforts must now be directed towards finding a different mechanism that can cause the suppression of complete fusion.

The results described in this thesis make a compelling case for the practitioners in the field to design new experiments and develop theories to include the latest findings. The pedagogical treatment of nuclear reactions at energies near the fusion barrier, and the analysis methods presented for the large-coverage and high-granularity detector array will be helpful for graduate students entering the field. The ideas presented in this thesis, I hope, will open up innovations in experimental and theoretical methods that will ultimately allow prediction of the products of nuclear collisions, urgently needed for research with next-generation radioactive beams.

Canberra, Australia
June 2018

Prof. Mahananda Dasgupta

Abstract

Above-barrier complete fusion cross sections for reactions with light, weakly bound nuclei such as ^{6,7}Li and ^{9}Be are suppressed relative to expectations from theory and experiment. This has been interpreted to be a result of the weakly bound nucleus breaking up into its cluster constituents, reducing the probability of complete charge capture. However, experiments to probe mechanisms of breakup in below-barrier reactions of ^{9}Be and ^{6,7}Li with high atomic number targets have shown that breakup of unbound states formed following nucleon transfer dominates over direct breakup of the projectile into its cluster constituents. This thesis extends the study of breakup following transfer in interactions of ^{9}Be and ^{7}Li with light targets of $6 \leq Z \leq 28$. Below-barrier coincidence measurements of breakup fragments produced in these reactions show a vanishing amount of direct breakup, and the dominance of transfer-triggered breakup.

Since breakup can only suppress complete fusion if it occurs prior to the collision partners reaching the fusion barrier, the location of breakup is crucial. In turn, the location of breakup is intimately related to the lifetime of the unbound state that is populated. Nuclei produced in long-lived states cannot suppress complete fusion, since they will pass the barrier before breakup can occur. Conversely, nuclei produced in states with lifetimes comparable to the zeptosecond (10^{-21}s) timescale of the collision may break up before reaching the fusion barrier. Through the use of experimental observables that are sensitive to the location of breakup, the importance of a realistic treatment of resonance lifetimes to correctly reproduce experimental results with theoretical modelling will be established.

Below-barrier measurements of transfer-triggered breakup, where capture is minimised, are used to determine the breakup probability as a function of distance of closest approach for reactions of ^{7}Li and ^{9}Be with light targets of $13 \leq Z \leq 28$, as well for reactions of ^{9}Be with heavy targets of $62 \leq Z \leq 83$. These probability functions are used as input into classical dynamical trajectory models to predict above-barrier complete and incomplete fusion cross sections. These fusion cross sections are found to be sensitive to the lifetime of the weakly bound nucleus produced after transfer. When realistically modelled, the inclusion of lifetime leads to the conclusion that breakup alone cannot account for the observed suppression of complete fusion in reactions ^{9}Be with ^{144}Sm to ^{209}Bi.

Experimental groundwork is laid for measurement of the ^{7}Be(d,p)^{8}Be reaction at the Australian National University, relevant to Big Bang nucleosynthesis. The efficacy of using a large solid angle array and kinematic reconstruction techniques for such studies is demonstrated through a measurement of αparticles produced in the mirror reaction ^{7}Li(d,n)^{8}Be. In this reaction, a high population of the broad 4^{+}resonance in ^{8}Be is observed, totalling 69% of the coincidence yield after efficiency correction. It is therefore crucial to investigate the excitation of ^{8}Be in the ^{7}Be(d,p)^{8}Be reaction. Test measurements of ^{7}Be production via the ^{10}B(^{6}Li, ^{7}Be)^{9}Be reaction are made using the SOLEROO RIB facility. Normalised secondary beam intensities above 10^{4}cts/s/mg/cm^{-2}/μeA are achieved with beam purity of $\sim$96%.

Preface

This thesis is an account of research undertaken between February 2013 and December 2016 at the Department of Nuclear Physics, Research School of Physics and Engineering, College of Physical and Mathematical Sciences, the Australian National University, Canberra, Australia. This thesis presents a study of breakup triggered by transfer in below-barrier reactions of ^{7}Li and ^{9}Be with targets of mass ranging across the nuclear chart, $6 \leq Z \leq 28$, in a series of four experimental runs. In addition, previously measured reactions of ^{9}Be with targets of $62 \leq Z \leq 83$, measured by Dr. R. Rafiei and colleagues, are reanalysed.

The project was originally proposed by Prof. M. Dasgupta and Prof. D. J. Hinde. Beams of accelerated ^{7}Li and ^{9}Be were provided by the 14UD tandem accelerator of the Heavy Ion Accelerator Facility at the Australian National University in Canberra, Australia. All measurements were carried out with the assistance of the nuclear reaction dynamics group and the technical staff of the Department of Nuclear Physics. Measurements were made with the Breakup Array for Light Nuclei (BALiN), a large, position sensitive array, originally commissioned by Dr. D. H. Luong and Dr. R. Rafiei. The array and associated electronics was set up by the author, with assistance from Dr. D. H. Luong, Prof. M. Dasgupta, Prof. D. J. Hinde, and Dr. E. Williams.

All data analysis was done by the author. Analysis was performed using the CERN ROOT analysis framework, using scripts originally written by Dr. D. H. Luong, extensively modified by the author. The author collaborated with Dr. D. H. Luong and Dr. Sunil Kalkal closely in the extraction, analysis, and interpretation of breakup events. Two classical dynamical trajectory models of breakup were utilised to establish the coincidence efficiency of BALiN for each measurement. The models were also used to predict the effect of breakup on incomplete and complete fusion cross sections at above-barrier energies from experimentally determined below-breakup probabilities. The first model was M-PLATYPUS, a modified version of PLATYPUS written by Dr. A. Diaz-Torres, and modified by Dr. E. C. Simpson. The second was KOOKABURRA, written by Dr. E. C. Simpson. Both models were tested by the author and Dr. Sunil Kalkal.

Developmental work was undertaken to measure the astrophysically relevant ^{7}Be(d,p)^{8}Be reaction at the Australian National University. The mirror reaction ^{7}Li(d,n)^{8}Be was measured using the BALiN array to establish the efficacy of the array and analysis techniques for such reactions. Targets of deuterated polyethylene were produced by the author with the assistance of Mr. S. McNeil. In addition to this measurement, this thesis describes the development of a ^{7}Be radioactive ion beam, using the SOLEROO RIB facility at the Australian National University. The commissioning of the facility was completed over the course of this thesis by Mr. I. P. Carter. Measurements were made by the author in collaboration with Mr. I. P. Carter and Dr. E. C. Simpson and with assistance from the nuclear reaction dynamics group.

The following publications and conference proceedings, to which the author contributed to, are directly related to the work in this thesis:

1. **K.J. Cook**, E.C. Simpson, D.H. Luong, Sunil Kalkal, M. Dasgupta and D.J. Hinde, “Importance of lifetime effects in breakup and suppression of complete fusion in reactions of weakly bound nuclei”, *Physical Review C* **93**, 064604 (2016)
2. E.C. Simpson, **K.J. Cook**, D.H. Luong, Sunil Kalkal, I.P. Carter, M. Dasgupta, D.J. Hinde, and E. Williams, “Disintegration locations in ^{7}Li→^{8}Be transfer-triggered breakup at near-barrier energies”, *Physical Review C* **93**, 024605 (2016)
3. Sunil Kalkal, E.C. Simpson, D.H. Luong, **K.J. Cook**, M. Dasgupta, D.J. Hinde, I.P. Carter, D.Y. Jeung, G. Mohanto, C.S. Palshetkar, E. Prasad, D.C. Rafferty, C. Simenel, K. Vo-Phuoc, E. Williams, L.R. Gasques, P.R.S. Gomes and Linares, R. “Asymptotic and near-target direct breakup of ^{6}Li and ^{7}Li”, *Physical Review C* **93**, 044605 (2016)
4. M. Dasgupta, E.C. Simpson, D.H. Luong, Sunil Kalkal, **K.J. Cook**, I.P. Carter, D.J. Hinde and E. Williams, “Breakup locations: Intertwining effects of nuclear structure and reaction dynamics”, *EPJ Web of Conferences* **117**, 08005 (2016)
5. **K.J. Cook**, D.H. Luong, I.P. Carter, M. Dasgupta, D.J. Hinde, S. McNeil, D. Rafferty, K. Ramachandran, C. Simenel and E. Williams, “Breakup following interactions with light targets: Investigating new methods to probe nuclear physics input to the cosmological lithium problem”, *EPJ Web of Conferences* **91**, 00002 (2015)
6. I.P. Carter, M. Dasgupta, D.J. Hinde, D.H. Luong, E. Williams, K. Ramachandran, **K.J. Cook**, A.G. Muirhead, S. Marshall and T. Tunningley, “Recent developments of SOLEROO: Australia’s first high energy radioactive ion beam capability”, *EPJ Web of Conferences* **91**, 00001 (2015)
7. I.P. Carter, K. Ramachandran, M. Dasgupta, D.J. Hinde, R.Rafiei, D.H. Luong, E. Williams, **K.J. Cook**, S. McNeil, D.C. Rafferty, A.B. Harding, A.G. Muirhead and T. Tunningley, “An ion beam tracking system based on a parallel plate avalanche counter”, *EPJ Web of Conferences* **63**, 02022 (2013)

8. **K.J. Cook**, D.H. Luong, E. Williams, I.P. Carter, M. Dasgupta, D.J. Hinde and K. Ramachandran, "Developing new methods to investigate nuclear physics input into the cosmological lithium problem", *EPJ Web of Conferences* **63**, 03011 (2013)
9. **K.J. Cook**, D.H. Luong, E. Williams, "Nuclear physics solutions to the primordial lithium problem", *EPJ Web of Conferences* **35**, 05004 (2012)
10. D.H. Luong, **K.J. Cook**, E. Williams, M. Dasgupta, D.J. Hinde, R. duRietz, R. Rafiei and M. Evers, "Break-up Array for Light Nuclei: A new tool for exploring nuclear reactions of relevance to the cosmological ^{7}Li problem", *Proceedings of Science (NIC XII)*, 185 (2012)

The author also contributed to the following publications and conference proceedings published during her Ph.D. work:

11. D.C. Rafferty, M. Dasgupta, D.J. Hinde, C. Simenel, E.C. Simpson, E. Williams, I.P. Carter, **K.J. Cook**, D.H. Luong, S.D. McNeil, K. Ramachandran, K. Vo-Phuoc and A. Wakhle, "Multinucleon transfer in ^{16,18}O, ^{19}F + ^{208}Pb reactions at energies near the fusion barrier", *Physical Review C* **94**, 024607 (2016)
12. E. Prasad, D.J. Hinde, K. Ramachandran, E. Williams, M. Dasgupta, I.P. Carter, **K.J. Cook**, D.Y. Jeung, D.H. Luong, S. McNeil, C.S. Palshetkar, D.C. Rafferty, C. Simenel and A. Wakhle, "Observation of mass-asymmetric fission of mercury nuclei in heavy ion fusion", *Physical Review C* **91**, 064605 (2015)
13. K. Hammerton, Z. Kohley, D.J. Hinde, M. Dasgupta, A. Wakhle, E. Williams, V.E. Oberacker, A.S. Umar, I.P. Carter, **K.J. Cook**, J. Greene, D.Y. Jeung, D.H. Luong, S.D. McNeil, C.S. Palshetkar, D.C. Rafferty, C. Simenel and K. Stiefel, "Reduced quasifission competition in fusion reactions forming neutron-rich heavy elements", *Physical Review C* **91**, 041602(R) (2015)
14. D.J. Hinde, E. Williams, G. Mohanto, C. Simenel, M. Dasgupta, A. Wakhle, I.P. Cater, **K.J. Cook**, D.Y. Jeung, D.H. Luong, C.S. Palshetkar, E. Prasad, D.C. Rafferty, R. du Rietz and E.C. Simpson, "Systematic study of quasifission characteristics and timescales in heavy element formation reactions", *EPJ Web of Conferences* **117**, 08006 (2016)
15. E. Williams, D.J. Hinde, M. Dasgupta, I.P. Carter, **K.J. Cook**, D.Y. Jeung, D.H. Luong, S.D. McNeil, C.S. Palshetkar, D.C. Rafferty, K. Ramachandran, C. Simenel, E.C. Simpson and A. Wakhle, "Exploring dissipative processes at high angular momentum in ^{58}Ni+^{60}Ni reactions", *EPJ Web of Conferences* **117**, 08021 (2016)
16. D.C. Rafferty, M. Dasgupta, D.J. Hinde, C. Simenel, **K.J. Cook**, I.P. Carter, D.H. Luong, S.D. McNeil, K. Ramachandran, A. Wakhle and E. Williams, "Investigating energy dissipation through nucleon transfer reactions", *EPJ Web of Conferences* **91**, 00010 (2015)

17. D.J. Hinde, E. Williams, R. du Rietz, M. Dasgupta, A. Wakhle, C. Simenel, D.H. Luong, and **K.J. Cook**, “Mapping quasifission characteristics in heavy element formation reactions”, *EPJ Web of Conferences* **86**, 00015 (2015)
18. D.J. Hinde, R. du Rietz, E. Williams, C. Simenel, C.J. Lin, A. Wakhle, **K.J. Cook**, M. Dasgupta, M. Evers, and D.H. Luong, “Mass-angle distributions: Insights into the dynamics of heavy element formation”, *EPJ Web of Conferences* **66**, 03037 (2014)
19. D.J. Hinde, M. Dasgupta, I.P. Carter, **K.J. Cook**, M. Evers, D.H. Luong, K. Ramachandran, D. Rafferty, C. Simenel, A. Wakhle, and E. Williams, “Nuclear reaction dynamics research at the Australian National University”, *EPJ Web of Conferences* **63**, 02005 (2013)

Canberra, Australia Kaitlin Jennifer Cook

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> *There are certain calculations I should like to make with you,*
> *To be sure that your deductions will be logical and true;*
> *And remember, "Patience, Patience," is the watchword of a sage,*
> *Not to-day nor yet to-morrow can complete a perfect age*
> Sarah Williams 1837–1868

First and foremost, I thank my supervisors, Nanda Dasgupta and David Hinde. It is hard to imagine a better pair of supervisors. Thank you for your mentorship, good humour, and ability to shed light on the most stubborn of problems. Your constant endeavour towards excellence has been a source of personal inspiration.

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Finally, my deepest gratitude goes to Kira for her love, laughter, and unflagging belief in me. I'm not sure I have the right words to thank you.

Contents

Chapter 1
Introduction

> *Let's think the unthinkable, let's do the undoable. Let us prepare to grapple with the ineffable itself, and see if we may not eff it after all*
>
> Douglas Adams 1952–2001

Every nucleus heavier than ^{1}H is the product of a nuclear reaction. We are, in a very real way, the result of billions of years of nuclear physics. Therefore, to study nuclear reactions is to study our origins. Nuclear reactions involve fleeting collisions of finite quantum systems which occur on timescales of 10^{-21} s and on distances of 10^{-15} m. These collisions, which are governed by the electromagnetic and strong interactions, have many possible outcomes, ranging from elastic scattering, where the colliding remain in their ground states, through to complete fusion, where the two nuclei combine to produce a single compound nucleus. As a field, nuclear reaction dynamics is concerned with understanding the physical mechanisms that dictate the outcomes of nuclear collisions.

Arguably, the modern approach to nuclear physics, where accelerated beams of nuclei are collided with a stationary target, began with the work of Cockcroft and Walton in 1932 [1, 2]. Cockcroft and Walton produced an accelerated beam of protons and used them to bombard a target of lithium. The resulting p + ^{7}Li $\rightarrow \alpha + \alpha$ reaction was the first entirely artificial nuclear reaction. More than eighty years later, the processes through which light weakly-bound nuclides such as ^{7}Li disintegrate are still not fully understood. This thesis is a continuation of the work towards understanding the interactions of light weakly-bound nuclei.

The central theme of this thesis is to understand the mechanisms through which the weakly-bound ^{7}Li and ^{9}Be nuclides break up in reactions with targets of atomic number Z varying from 1 to 83, and to understand the way in which these processes affect complete and incomplete fusion. This work lies in the broader context of the continuing work in nuclear reactions towards forming a consistent framework for relating the nuclear structure of light weakly-bound nuclei to reaction outcomes. Understanding the reaction dynamics of these nuclides is a pressing need in light of

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the increasing availability of Radioactive Ion Beams (RIBs) that probe the limits of nuclear existence. Of key interest is the effect of weak binding on complete fusion.

1.1 Complete Fusion Suppression

Fusion measurements of ^{9}Be + ^{208}Pb, ^{209}Bi [3–6] and ^{6,7}Li + ^{209}Bi [3, 7] were amongst the first to show that above-barrier complete fusion cross-sections (experimentally defined as capture of the full charge of the projectile) are reduced by $\sim$30%, both in comparison with those predicted by standard fusion models and with measurements for well-bound nuclei forming the same compound nucleus [3, 8]. An example of the suppression of complete fusion is shown in Fig. 1.1 for complete fusion of ^{7}Li + ^{209}Bi compared to ^{18}O + ^{198}Pt, where cross-sections have been normalised to the fusion barrier radius, and energies normalised to the fusion barrier energy (both of these concepts are defined in the following chapter). It is readily apparent that the normalised complete fusion cross-sections are suppressed relative to both ^{18}O + ^{198}Pt and expectations from single barrier penetration model calculations [3]. This suppression has been observed to varying extents for reactions of stable light weakly-bound nuclides ^{6,7}Li, ^{9}Be with targets in the range $28 \leq Z \leq 83$

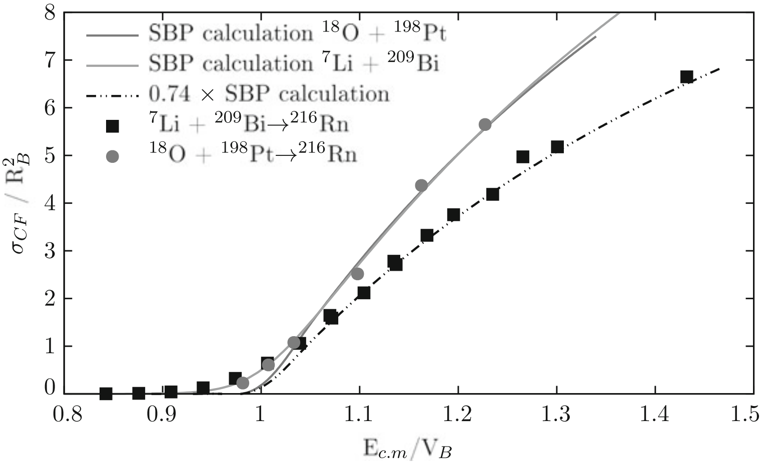

Fig. 1.1 Complete fusion cross-sections σ_{CF} for ^{7}Li + ^{209}Bi and ^{18}O + ^{198}Pt, forming the same compound nucleus, normalised to the average barrier radius (R_B), as a function of centre-of-mass energy normalised to the average barrier energy (V_B). Fusion reactions with weakly-bound ^{7}Li are suppressed relative to the fusion with the well bound ^{18}O nucleus. Single Barrier Penetration (SBP) model calculations are shown for ^{7}Li + ^{209}Bi and ^{18}O + ^{198}Pt, showing the validity of normalising cross-sections in this manner. The SBP calculation needs to be scaled by 0.74 to correspond to the ^{7}Li + ^{209}Bi experimental data, demonstrating the suppression of complete fusion relative to model calculations. Adapted from [3]

[3–19]. Smaller suppressions have been observed for reactions of the less weakly-bound ^{11}B and ^{10}B nuclides [20, 21]. Detailed reviews on the fusion of light weakly-bound nuclei may be found in Refs. [22, 23].

Although complete fusion suppression has been observed in reactions with heavy targets, the status of complete fusion suppression is not clear in reactions with light targets, since the separation of complete and incomplete fusion (experimentally defined as partial charge capture) is very difficult. This is due to the significant charged particle evaporation that will occur for compound nuclei with lower Z. As a result, the same reaction product can be formed via complete fusion following particle evaporation and by incomplete fusion. This has precluded a systematic understanding of the trends of complete fusion suppression.

While the phenomenon of above-barrier complete fusion suppression for weakly-bound nuclei is by now well established in reactions with heavy targets, the mechanism responsible is not. It was originally suggested that complete fusion suppression should result from direct breakup of the weakly-bound nucleus [e.g. ^{9}Be($\rightarrow \alpha + \alpha + n$), ^{7}Li($\rightarrow \alpha + t$), ^{6}Li($\rightarrow \alpha + d$)] prior to reaching the fusion barrier [4]. It was conjectured that breakup reduces the probability of the full charge of the projectile-like nucleus being captured, thus suppressing complete fusion (CF), and increasing the incomplete fusion (ICF) cross-sections, shown schematically in Fig. 1.2.

Experiments were undertaken to probe the extent of the role of breakup in complete fusion suppression. Coincidence measurements of breakup fragments were made at below-barrier energies with a large position sensitive array, and key kinematic quantities were reconstructed. These experiments were performed at below-barrier energies to allow clearer investigation of breakup mechanisms, as there is essentially no absorption of the charged fragments [24]. These investigations found that transfer to particle unbound states of neighbouring nuclei followed by breakup contributes much more than direct breakup to the total breakup probability [25–28]. In the case of ^{9}Be, breakup in interactions with targets ranging from ^{144}Sm to ^{209}Bi is dominated by neutron stripping forming ^{8}Be which subsequently breaks up into $\alpha + \alpha$, rather than ^{9}Be undergoing direct breakup into $\alpha + \alpha + n$ or ^{8}Be+n [25]. In reactions of ^{7}Li with ^{144}Sm, ^{207,208}Pb and ^{209}Bi, below-barrier breakup yields are dominated by proton pickup forming ^{8}Be($\rightarrow \alpha + \alpha$), neutron stripping forming ^{6}Li($\rightarrow \alpha + d$) and two neutron stripping forming ^{5}Li($\rightarrow \alpha + p$) [26–28]. In reactions of ^{6}Li with ^{207,208}Pb and ^{209}Bi, one neutron stripping forming ^{5}Li and deuteron pickup forming ^{8}Be dominate over direct ^{6}Li$\rightarrow \alpha + d$ breakup [26–28]. These results explained earlier work that showed unexpectedly high α singles production cross-sections relative to t in reactions of ^{7}Li with ^{208}Pb [29] as well as unexpected proton production in ^{6}Li + ^{208}Pb reactions [30]. It is only through coincidence measurements of fragments that clear pictures of these reactions emerge [31, 32].

It is now very clear that it is not only direct breakup that should be considered as a candidate for above-barrier complete fusion suppression, but also transfer populating particle unbound states of neighbouring nuclei that subsequently break up. The breakup of neighbouring nuclei populated following transfer is termed "transfer-triggered breakup". Following transfer, the projectile-like nucleus may break up

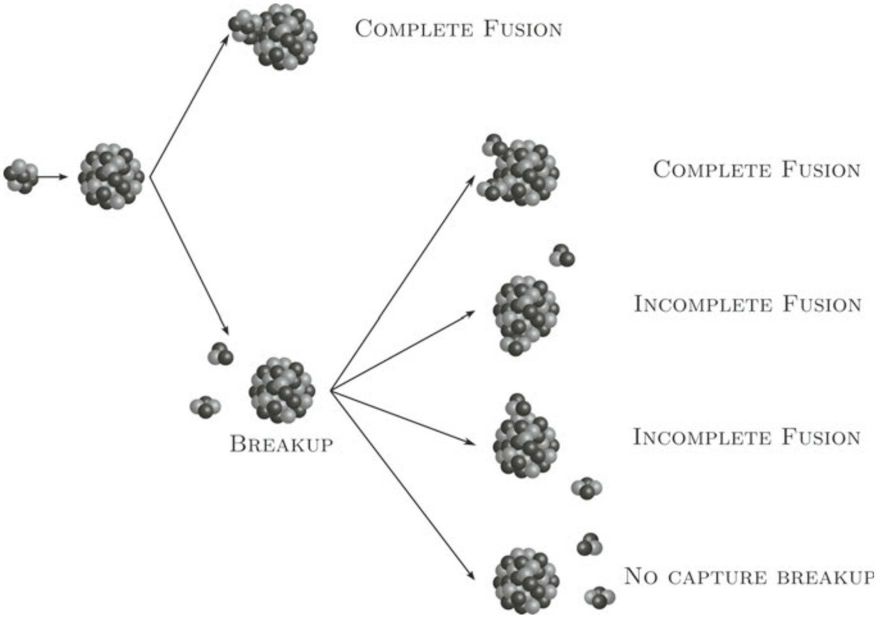

Fig. 1.2 Reaction pathways affecting complete fusion. If a weakly-bound nucleus breaks up as it approaches another nucleus, the resulting fragments may both be captured, and so undergo sequential complete fusion. On the other hand, one of the fragments may be captured, resulting in incomplete fusion. When neither fragment is captured, this is no capture breakup. These processes reduce the probability of complete fusion. Note that transfer and incomplete fusion can lead to the same final product. However, within the coupled channels framework, transfer is not thought to suppress complete fusion significantly

before it can be captured. As a result, there will be a decreased probability of complete fusion, and a corresponding increase of incomplete fusion and no capture breakup.

The capability of any breakup process to suppress above-barrier complete fusion depends on its location. It was recognised early on [24] that the population of long-lived states, such as the 0^+ ground-state of ^{8}Be, which has a mean life of $\sim 10^{-16}$ s [33], results in breakup far from the target-like nucleus at energies below the barrier. At above-barrier energies, the ^{8}Be nucleus in its ground-state will pass inside the fusion barrier and be absorbed long before decay can occur. It therefore cannot contribute to complete fusion suppression. Similarly, population of ^{6}Li in its long-lived 3^+ state (mean life $= 2.74 \times 10^{-20}$ s) located 711 keV above the $\alpha + d$ breakup threshold [34] cannot suppress complete fusion. However, population of broad resonances with much shorter mean lives will result in breakup close to the target-like nucleus. It is this type of breakup that may suppress complete fusion.

As an example, measurements of transfer reactions populating ^{8}Be show the population of ^{8}Be in its 0^+, 2^+, and at higher excitations, 4^+ states [35, 36]. The 3.03 MeV 2^+ state of ^{8}Be has an on-resonance width of $\Gamma(E_R) = 1513 \pm 15$ keV, and thus a mean life of $\tau = \hbar / \Gamma(E_R) = 0.44 \times 10^{-21}$ s [33]. Breakup from this state will occur very close to the target-like nucleus. To determine the effect on complete fusion, it is then necessary to quantitatively understand whether such short mean lives carry a significant fraction of excited projectile-like nuclei inside the fusion barrier before breakup occurs, thus reducing the suppression of complete fusion due to breakup.

The question then is: what is the quantitative contribution of near-target transfer-triggered breakup to the suppression of complete fusion? This was previously addressed by first obtaining breakup probabilities as a function of distance of closest approach ("breakup functions") [25] at below-barrier energies. These breakup functions were then used as input to the classical dynamical model code PLATYPUS [37, 38], to predict complete and incomplete fusion cross-sections at above-barrier energies [25, 37] that agreed satisfactorily with experimental results [3, 6, 12, 15].

In PLATYPUS, the lifetimes of the intermediate states populated are not explicitly taken into account. However, locations of breakup and the lifetimes of states are intimately related: finite but small mean lives will change the positions at which breakup occurs along the trajectory of the nuclei. Therefore, accurate simulation of excitation and lifetime of states is essential to reliably predict the effect of breakup on fusion suppression. Indeed, recent work [39] has highlighted that the precise location of breakup relative to the target-like nucleus is critical to reaction outcomes, and further, that there exist experimental observables that can probe these effects. This thesis makes use of coincidence measurements of breakup fragments to investigate the role of zeptosecond lifetimes in breakup and fusion suppression. Further, this thesis presents a re-analysis of the extensive sub-barrier breakup measurements of Rafiei et al. [25], using a modified version of PLATYPUS which incorporates resonance lifetimes. After taking into account these lifetimes, new predictions of the contribution of breakup to fusion suppression will be presented. Finally, the magnitude of complete fusion suppression in reactions of ^{7}Li and ^{9}Be with light targets will be predicted using a new classical trajectory model code KOOKABURRA.

1.2 Cosmological Lithium Problem

An additional focus of this thesis lies in the use of the coincidence measurement and kinematic reconstruction techniques developed for the study of breakup for the study of reactions of astrophysical interest. Specifically, the interest lies in the ^{7}Be(d,p)^{8}Be reaction, which destroys ^{7}Be during Big Bang Nucleosynthesis (BBN), and is therefore a candidate for a nuclear physics solution to the cosmological lithium problem.

The cosmological lithium problem is a long-standing problem in concordance models of the Big Bang, wherein the abundances of ^{7}Li predicted in models of BBN are a factor of 2.4–3.2 times larger than those inferred from spectroscopic observations of metal-poor halo stars [40, 41]. These stars have very small convection zones, and thus cannot modify the composition of their surface layers by nuclear reactions. As a result, it is thought that the ^{7}Li abundances in these stars represent the abundance of ^{7}Li arising from BBN (i.e. the abundance is "primordial"). The

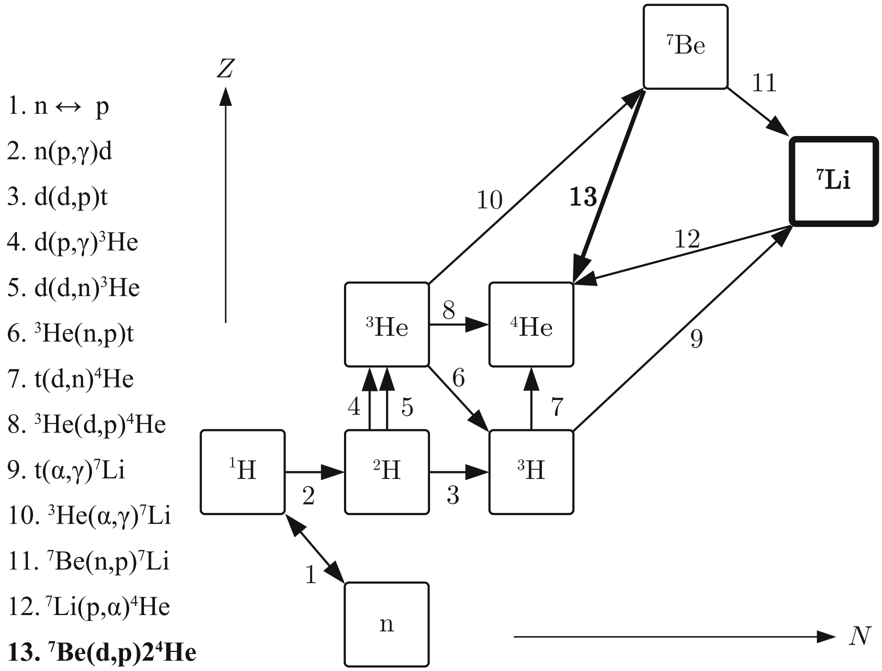

Fig. 1.3 Simplified nuclear reaction network showing the important reactions forming ^{7}Li during BBN, plus ^{7}Be(d,p)^{8}Be. Adapted from [41, 54]

discrepancy, which has been well established since 1982 [42], has a significance of $4 - 5\sigma$ and is yet to find satisfactory conclusion, although there has been significant effort to achieve one.

Proposed solutions to the cosmological lithium problem can be found in many areas of nuclear astrophysics, and include (but are by no means limited to): stellar models with increased turbulence and diffusion between surface and burning layers [43]; inferring primordial abundances from low metalicity gases in the Small Magellanic Cloud [44]; non-standard cosmologies [45, 46]; particle physics beyond the standard model [47–49]; and improved understandings of relevant nuclear reaction rates [50–53].

Nuclear physics solutions centre around the determination of the most relevant reactions that contribute to the abundance of ^{7}Li produced during BBN and the subsequent measurement of these cross-sections. Shown in Fig. 1.3 is a simplified nuclear reaction network, showing the dominant reactions that contribute to ^{7}Li abundances. Importantly, the main reaction forming ^{7}Li during BBN isn't the direct ^{3}H$(\alpha, \gamma)^7$Li fusion reaction, but instead the production of ^{7}Be and its subsequent decay into ^{7}Li via electron capture ($t_{1/2} = 52.3$ days). The production rate of ^{7}Be is strongly constrained by observations of solar neutrino production [55, 56]. Therefore, the search for nuclear physics solutions to the cosmological lithium problem focus on reactions that destroy ^{7}Be without producing ^{7}Li.

One such candidate is the ^{7}Be(d,p)^{8}Be($\rightarrow \alpha + \alpha$) reaction. A sensitivity study [54] has shown that this reaction is able to resolve the ^{7}Li problem if the reaction rate is one hundred times larger than the adopted estimate [57]. A measurement of this reaction swiftly followed, which found a value ten times *smaller* than the previously adopted value [58]. This measurement was performed by measurement of the recoiling protons. This means that the measurement of low energy protons was precluded, such as those that will be produced when ^{8}Be is excited to its broad 4^+ resonance at 11.35 MeV, which may be expected to be populated with high probability. Instead, the population of the 4^+ state had to be estimated. To fully determine the contribution of the ^{7}Be(d,p)^{8}Be reaction to ^{7}Li abundances in BBN, it is imperative that this reaction be remeasured through the coincidence measurement of α particles in coincidence, which will have high energy when ^{8}Be is produced in highly excited states.

1.3 Aims

In light of the above discussion, this thesis has several key goals.

1. To identify the modes of breakup in interactions of ^{7}Li and ^{9}Be with light targets of $6 \leq Z \leq 28$ using coincidence measurement techniques, and to extract breakup probabilities as a function of the distance of closest approach.
2. To investigate *qualitatively* the kinematic signatures of breakup through short-lived resonant states, and so provide experimental guidance into the essential physics input in classical models of breakup.
3. To *quantitatively* predict the effect of the lifetime of short-lived resonant states on breakup processes and the resultant incomplete fusion, and thus the suppression of complete fusion for targets of $13 \leq Z \leq 83$.
4. To explore the use of coincidence measurement and kinematic reconstruction techniques developed for the study of breakup in measurements of the astrophysically relevant ^{7}Be(d,p)^{8}Be reaction. In addition, to test the production of ^{7}Be beams using the radioactive ion beam facility SOLEROO [59–61] at the Australian National University.

1.4 Thesis Outline

Chapter 2 contains an overview of the key nuclear physics concepts required in this thesis. The role of the resonant structure of light weakly-bound nuclei in reaction outcomes will be introduced, as well as key kinematic observables that provide insight into the mechanisms of breakup. The classical models of breakup that are used extensively throughout this thesis are introduced.