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# Exploring dissipative processes at high angular momentum in $^{58}$Ni+$^{60}$Ni reactions

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**Abstract**

Current coupled channels (CC) models treat fusion as a coherent quantum-mechanical process, in which coupling between the collective states of the colliding nuclei influences the probability of fusion in near-barrier reactions. While CC models have been used to successfully describe many experimental fusion barrier distribution (BD) measurements, the CC approach has failed in the notable case of $^{16}$O+$^{208}$Pb. The reason for this is poorly understood; however, it has been postulated that dissipative processes may play a role. Traditional BD experiments can only probe the physics of fusion for collisions at the top of the Coulomb barrier ($L = 0\hbar$). In this work, we will present results using a novel method of probing dissipative processes inside the Coulomb barrier. The method exploits the predicted sharp onset of fission at $L \sim 60\hbar$ for reactions forming compound nuclei with $A < 160$. Using the ANU's 14UD tandem accelerator and CUBE spectrometer, reaction outcomes have been measured for the $^{58}$Ni+$^{60}$Ni reaction at a range of energies, in order to explore dissipative processes at high angular momentum. In this reaction, deep inelastic processes have been

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found to set in before the onset fission at high angular momentum following fusion. The results will be discussed in relation to the need for a dynamical model of fusion.

# 1 Introduction

In the study of nuclear reactions, one of the most elusive goals of the field has been to develop a comprehensive model of nuclear reactions: one which is capable of predicting the probabilities of the full range of possible reaction outcomes, for the complete range of nuclear collisions. The challenge in creating such a model arises from the complex dynamics of the nuclear reactions process. For a given reaction, many degrees of freedom are at play, including nuclear shell structure, collective excitations, reaction kinematics, energy damping, and angular momentum. Experimentally, we cannot vary one degree of freedom while holding all others fixed. At best, we can minimise the importance of one or two variables through clever tricks, or compare data with models reliant on different assumptions in an effort to tease out the physics behind any disagreement.

Unfortunately, no single answer exists for most experiment-model disagreements. One example of this can be found in the body of work surrounding $^{16}$O+$^{208}$Pb fusion cross sections. High precision cross section data below and well above the Coulomb barrier cannot be consistently reproduced with a coupled channels model of fusion, unless one is willing to use different nuclear potential parameters to reproduce the data below and above the Coulomb barrier [1]. Different methods of addressing this discrepancy have been put forth, ranging from altering the ion-ion potential [2,3] to a realistic representation of energy dissipation within the model [4]. For now, though, all explanations amount to adding another parameter or two into an already parameter-heavy model, in an effort to make the model fit the data.

In this work, we aim to investigate the role energy dissipation plays in fusion, because it is an essential component of the fusion process but is not explicitly included in the coupled channels model of fusion. In the coupled channels approach [5,6], fusion is rendered irreversible via the use of either an imaginary potential or the Incoming Wave Boundary Condition, both of which set in at an internuclear separation $r$ inside the fusion barrier. This onset of the irreversibility of fusion is not angular momentum dependent; the condition is either there or it is not for a given $r$. This sharp onset of irreversibility can have very different effects on fusion outcomes as a function of angular momentum.

Experimentally, partial fusion cross sections $\sigma_L$ cannot be measured independently, making it very difficult to get a sense of whether the means by which the coupled channels approach mocks up fusion irreversibility is a reasonable approximation. For reactions forming a compound nucleus of mass $A_{cn} < 160$, the fission barrier becomes sufficiently low for fusion with angular momenta $L > 60\hbar$. Fission can be used as a high-angular momentum fusion tag, providing us with a unique opportunity to study high angular momentum fusion outcomes.

In this paper, we present the first study to test this high angular momentum separation method, for the $^{58}$Ni+$^{60}$Ni reaction. We will outline the preliminary findings, and discuss the possible implications of our findings on the $^{16}$O+$^{208}$Pb problem and the coupled channels approach to fusion.

## 2 Experimental methods

The $^{58}$Ni+$^{60}$Ni experiment was performed at Australian National University's Heavy Ion Accelerator Facility, using the 14UD tandem accelerator and CUBE two-body fission spectrometer [7]. The $^{58}$Ni beam impinged upon the 60 $\mu$g/cm$^2$-thick $^{60}$Ni target for 22 separate beam energies ranging from $E_{lab}$ =198-266 MeV ($E/V_B \sim 0.97 - 1.35$). The CUBE spectrometer, consisting of two large-area multiwire proportional counters, was placed at forward angles 45° relative to the beam axis and a distance of 22.24 cm from the target. The detectors provided energy loss, time of flight, and $(x, y)$ position information with a resolution of 1 mm.

Two calibration runs with a $^{58}$Ni beam at 160 MeV in the lab frame bombarding $^{58,60}$Ni targets of thicknesses 50 and 60 $\mu$g/cm$^2$, respectively were also carried out. The Mott scattering patterns for the former and Rutherford scattering data for the latter were both used to calibrate the geometry of the setup, define the resolution of the CUBE detector system, and provide a solid angle calibration for cross section determinations.

Using the position and time of flight information provided by the CUBE detector, a full kinematic reconstruction of each fission event was performed using the kinematic coincidence method [7,8], providing total kinetic energy, mass ratio,

$$M_R = \frac{m_1}{m_1 + m_2}, \tag{1}$$

and scattering angle information.

The total angular coverage for this experiment can be seen in Fig. 1, where the lab angle for one detector versus the folding angle ($\theta_1 + \theta_2$ is shown for the highest energy run in this experiment, at 135.19 MeV.

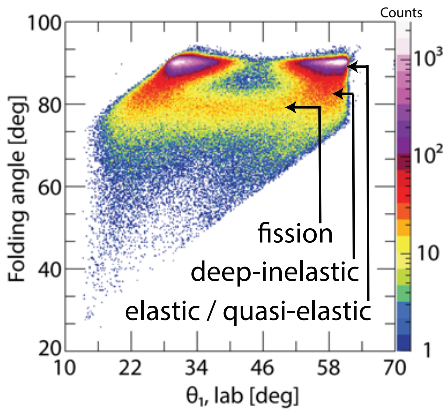


Figure 1: Lab angle for one detector versus the folding angle ($\theta_1 + \theta_2$) for the $^{58}$Ni+$^{60}$Ni reaction at 135.19 MeV.

In this work, our interest in studying the influence of dissipation on fusion reactions at high angular momentum led to a focus on the observed mass ratio versus total kinetic energy. Before producing the final mass versus total kinetic energy plots, gates were placed on (1) the detector positions and times to exclude unphysical events, (2) the folding angle to exclude heavy target impurities, and (3) on the out-of-plane velocity of the fission fragments, in order to exclude random coincidences. The TKE results are presented below, and full discussion of the analysis will be given in a forthcoming publication.

# 3 Results and discussion

The results of this work are summarized by the mass ratio versus total kinetic energy (TKE) plots shown in Fig. 2 for three representative above-barrier runs.

The data show a distinct evolution as a function of energy. Just above the barrier in Fig. 2 (a), elastic and quasielastic scattering dominate the results, and the projectile-like and target-like species can be distinguished in mass and appear at a total kinetic energy consistent with that of elastic scattering. As the energy increases (Fig. 2 (b)), a lower TKE component appears below the original elastic scattering component, and no clear distinction between the projectile-like and target-like species is observed. This lower TKE group is consistent with deep inelastic scattering (energy is dissipated, some mass

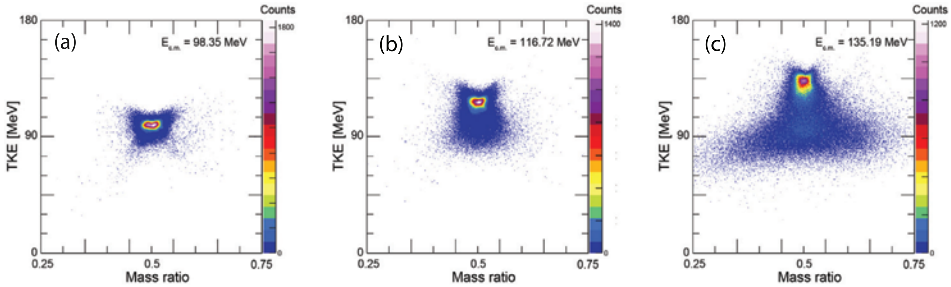


Figure 2: Mass ratio versus total kinetic energy for three representative above-barrier runs: (a) 98.35 MeV, (b) 116.72 MeV, and (c) 135.19 MeV. Note the excellent mass resolution of the CUBE detector; in the lowest energy dataset shown—the projectile-like and target-like species are distinguishable.

equilibration, very little change in the mass of the two fragments). While the intermediate energies are not shown here, the progression from (a) to (b) is smooth, with the onset of deep inelastic scattering appearing at progressively lower TKE values above ∼105 MeV. From Fig. 2 (b) to (c), a third class of reaction outcomes appears with a threshold of ∼125 MeV, corresponding to events with a wide spread in mass and full energy damping, consistent with expectations for fusion-fission.

The appearance of deep inelastic scattering before fission was an unexpected outcome in this experiment. Traditionally, one might expect deep inelastic scattering to set in at high angular momentum, higher than fusion-fission. The early onset of deep inelastic scattering provides firm evidence of the role dissipation plays even at lower angular momenta.

## 4 Conclusions

In this work, two-body reaction outcomes were used to search for evidence of dissipative processes in high angular momentum $^{58}$Ni + $^{60}$Ni reactions. Deep inelastic scattering was observed to play a significant role in this reaction, with its onset ($\sim$ 105 MeV) preceding that of fusion-fission ($\sim$ 125 MeV). While these results are preliminary, they demonstrate that deep-inelastic scattering competes with fusion, and should be taken into account in fusion models. The inclusion of deep inelastic scattering as a process that competes with fusion may offer a potential solution for experiment-model disagreements below and above the barrier, e.g., for the case of $^{16}$O+$^{208}$Pb, though this cannot be confirmed in the current experiment. This work does, however, provide further evidence [9, 10] for the need for a dynamical model of reactions, in which all possible reaction outcomes can be calculated within a single consistent framework.

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