Investigating quasi-fission dynamics through mass-angle distributions

D J Hinde, M Dasgupta, M Evers, C J Lin, D H Luong, R du Rietz, C. Simenel, A Wakhle and E Williams
Department of Nuclear Physics, RSPE, Australian National University, ACT 0200, Australia
E-mail: david.hinde@anu.edu.au

Abstract. Mass-angle distributions carry detailed information on the characteristics of quasi-fission, and thus of the dynamics of heavy element formation reactions. Recent experimental results are presented and discussed.

1. Introduction

In heavy-ion fusion reactions forming heavy elements, the heavy element yield is generally significantly suppressed [1] by quasifission [2]. Quasifission is a dynamical non-equilibrium process. It results when the combined system formed after capture breaks apart into two fragments before a compact compound nucleus is formed. Understanding the competition between quasifission and fusion is necessary to make reliable predictions of the best reactions to choose to form new isotopes of heavy and super-heavy elements (SHE) in nuclear fusion reactions.

The probability of quasifission, and the characteristics of the quasifission products, are understood to depend on the diffusive motion over the multi-dimensional potential energy surface. This motion results either in a compact shape (fusion) or in an elongating dinuclear shape leading to quasifission. The outcome of this competition will be determined by three key ingredients.

The first is the potential energy surface itself (PES) over which the system moves. This depends on the energy of the system as a function of important nuclear/dinuclear shape degrees of freedom. These include overall elongation and mass-asymmetry, and the deformation of, and necking between, the nascent fragments. The main characteristics of the PES will depend on the overall balance between the repulsive Coulomb force and the attractive nuclear force, which may be summarized in a generalized fissility parameter. However, the PES will also depend on nuclear structure, through shape-dependent modulations of the smooth liquid drop potential surface. These can have a large effect, most notably resulting in the well-known mass-asymmetric fission of the actinide elements.

The second key ingredient is the injection point into the PES. This is closely related to the capture configuration. In a simple picture, the closer the injection point is to the compact shape...
associated with fusion, the more likely fusion should be. Nuclear structure determines the shapes of the colliding nuclei, and for statically deformed nuclei, their relative orientations can lead to elongated or compact dinuclear systems at contact.

The final ingredient is perhaps the most complex, and the least understood - the dynamical behavior that determines the motion of the system from the contact point over the PES. This will be determined by the dissipation of the initial kinetic energy, and the subsequent diffusive motion over the PES. These dynamical processes can also be influenced by shell structure, through the dissipation and inertia tensors. Furthermore, since the effects of shell structure are damped with excitation energy \( (E_x) \), there will be a dynamical coupling between the strength of the dissipation and the excitation energy [3, 4].

Partly because quasifission characteristics can depend in a complex way on many variables, and partly from the overlap of quasifission and fusion-fission events generally found in experiments, quasifission is still not fully understood. As a wholly dynamical process, a key quantity characterizing quasifission is its timescale, that is the “sticking time” between capture and breakup (scission). Measurements of quasifission mass-angle distributions (MAD) at GSI in the 1980s [2, 5] showed that timescale to be typically shorter than the rotation time \( \sim 10^{-20}\)s. This is significantly shorter than the typical timescale of fusion fission. The measurement of MAD thus offers a key insight into the quasifission process. However, due to the challenging nature of the experiments, few measurements were subsequently made [6, 7], until about five years ago. Then a program of measurements was started at the ANU, which is showing a rich variety of phenomena in quasifission. Some recent results are shown in the following sections.

2. Principle behind the mass-angle distributions

The measurement of the full range of mass-splits between projectile and target over a wide range of scattering angles results in a two-dimensional matrix, which we refer to as a mass-angle distribution (MAD). The relationship of the MAD to the lifetime of the system before scission is illustrated schematically in Fig. 1. The projectile nucleus (blue) is incident from

![Figure 1](https://example.com/figure1.png)

**Figure 1.** (Color online). Qualitative illustration of the relationship between reaction time and mass-angle distribution. For the time sequence of shapes sketched in (a), the time dependence (arbitrary units) of angle (b) and mass-ratio (c) are plotted. Time is not directly measurable, but angle and mass-ratio are, the individual mass and angle dependencies combining to give a trajectory on the MAD (d) for a single impact parameter. Including a range of impact parameters, scission after half a turn (pink) or a full turn (blue) will tend to give strong or weak mass-angle correlations respectively.
the top of the page, and sticks to the larger target nucleus (red). The system then rotates, Fig. 1(b) illustrating schematically angle against time (in arbitrary units) for a single angular momentum value - in a real reaction a distribution will be present. For a parabolic potential, mass-symmetry is approached with an expected time dependence $1 - \exp(\tau/\tau_{eq})$, where $\tau_{eq}$ is the mass-equilibration time constant [2]. This dependence is sketched in Fig. 1(c).

If scission occurs soon after initial contact, then little mass change can occur, and a projectile-like fragment is ejected with mass-ratio $M_R$ at backward angle $\theta_{c.m.}$. $M_R$ is defined as the mass of one fragment divided by the total mass involved in the collision. Its complementary binary fragmentation partner with mass-ratio $(1-M_R)$ is found at $(\pi-\theta_{c.m.})$, a forward angle. A longer sticking time of the system results in larger rotation angles, and also allows more mass exchange. This evolution is illustrated on the MAD shown in Fig. 1(d). Rotation of the system by $\sim 180^\circ$ still results in a substantial mass-angle correlation (pale pink shading in Fig. 1(b), (d)), whilst once the system has turned $\sim 360^\circ$ or more, the correlation between the mass ratio and fragment emission angle is washed out, resulting in symmetric mass splits on average, independent of angle (blue shading).

3. The experimental mass-angle distribution
Using two MWPC detectors having a wide angular coverage, the kinematic coincidence method [8, 9] allows the determination of a MAD in a single measurement. Two examples of MAD recently measured at the ANU are shown in Fig. 2. The shaded regions at the top and bottom show where the efficiency falls to zero, reflecting the angular acceptance of the MWPC detector configuration used (described in Refs. [3, 10]). Because both fragments are detected, the matrix is populated twice [10, 11] (as indicated by the white squares in the left panel) across the indicated symmetry lines passing through $M_R = 0.5$ and $\theta_{C.M.} = 90^\circ$. For reactions with light projectiles like $^{16}$O (left panel) the beam-like particles can be separated from fission-like events by thresholds in the electronics and in the off-line analysis, thus elastic-like events are not displayed. This is not the case for heavy projectiles like $^{48}$Ti (right panel), thus all events are shown in the MAD. The MAD shown in the left panel is characteristic of fusion-fission, being
Figure 3. (Color online). Typical MAD for reactions of $^{48}$Ti with target nuclei from $^{144}$Sm to $^{208}$Pb, as a function of energy with respect to the capture barrier. The vertical bars represent the beam energy scale, and the MAD are placed with their centre at the energy of each measurement. The colour scale to the right indicates the counts per pixel.

The colour scale is symmetric both about $M_R = 0.5$ and $\theta_{C.M.} = 90^\circ$. For the $^{48}$Ti + $^{186}$W reaction shown in the right panel, the mean mass ratio is strongly correlated with angle. This means that the system “remembers” the initial projectile-target alignment and mass ratio throughout the dynamics.

4. Quasi-fission in $^{48}$Ti-induced reactions

To investigate systematic behaviour in quasi-fission dynamics, extensive measurements of MAD for reactions of $^{48}$Ti with ten target nuclei, from $^{144}$Sm to $^{208}$Pb, were made at energies close to and just above the capture barriers. Some results are reported in Refs. [10, 11, 12, 13]. MAD for representative measurements are shown in Fig. 3. They are arranged according to the beam energy with respect to the average capture barrier energy $E/V_B$ (horizontal direction) and the mass of the target nucleus (vertical scale). The lightest target nucleus is $^{144}$Sm, which has no static deformation. The lowest energy MAD for this reaction shows no mass-angle correlation. As the energy (and maximum angular momentum) increases, a correlation of mass with angle gradually becomes apparent. This indicates the development of a component of non-compound fission (quasifission) even for this reaction. These projected mass-ratio spectra are shown in the top left panel of Fig. 4, whilst the fitted Gaussian $\sigma$ values are shown below. A gradual increase in mass-width is found with increasing energy. The MAD in Fig. 3 show that this increase is at least in part a result of the increasing quasifission component.

The statically deformed $^{174}$Yb shows a very different behavior as a function of beam energy. Here the mass distribution is widest at the lowest (sub-barrier) energy. This is clearly seen in the
Figure 4. (Color online). The upper panels show mass-ratio spectra for the indicated reactions at various lab. beam energies. The spectra are normalized at mass-splits close to symmetry (MR=0.5). The lower panels show the fitted Gaussian σ values as a function of the ratio of the beam energy to the average capture barrier energy.

Projected mass spectra in the top right panel of Fig. 4. Despite the increasing maximum angular momentum associated with the higher beam energies, increasing energy results in narrower distributions. The fitted Gaussian σ_{MR} values are shown in the lower right panel of Fig. 4. The comparison with the behavior for $^{144}$Sm shows a dramatic difference. The explanation of this difference rests with the static deformation of $^{174}$Yb. Fig. 5 sketches the geometry for beam energies $E$ below (left) and above (right) the average capture barrier energy $V_B$, for the extremes in the alignment of the heavy deformed nucleus. The below-barrier beam energy

Figure 5. (Color online). Diagram illustrating the effective deformation alignment of statically deformed nuclei at sub-barrier energies (left panel), and the averaging over all orientations at above-barrier energies (right panel). The arrowed distances represent the different distances of closest approach at each energy.
Figure 6. (Color online). Measured MAD for $^{48}$Ti-induced reactions, at the ratio of beam energy to barrier energy indicated by $E/V_B$ (upper panels). The scaling factor multiplies the maximum counts of the MAD logarithmic color scale (right). In the projected mass ratio spectra below, the scale factor multiplies the counts scale (left). Gaussian fits to the region around $M_R=0.5$ are shown (turquoise lines). Gaussian functions with $\sigma_{MR}=0.07$ (thin red lines) are shown for reference. The $\beta_2$ of the target nucleus is also indicated (see text). The two data sets for $^{208}$Pb correspond to different experiments, with DC and pulsed beams.

(E < $V_B$) corresponds to a large distance of closest approach in the collision, and only the deformation-aligned configuration, with the lower capture barrier energy, results in capture, and the possibility of fusion or quasi-fission [14, 15]. The configuration at capture is elongated, favoring quasi fission. In contrast for beam energies higher than the barrier for the anti aligned configuration, all orientations result in capture. As suggested in [9], the more compact shape at capture for the anti-aligned configuration might be expected to favor fusion over quasi fission. Since the sub-barrier energies give the largest quasi fission yield, the sub-barrier MAD and mass distributions are selected to investigate the detailed dependence of quasi fission on various reaction variables.

5. Quasi-fission in sub-barrier reactions
For several statically deformed target nuclei, mass distributions were found to be widest at sub-barrier beam energies [3, 10, 11, 12]. This is consistent with other evidence, from increased angular anisotropies [3, 9, 16, 17, 18] and reduced evaporation residue yield [19, 20], indicating that fusion is suppressed and quasi-fission enhanced at sub-barrier energies for deformed target nuclei.
The measured MAD (upper panels) and projected mass-ratio spectra (lower panels) are shown in Fig. 6 for the reactions and beam energies indicated, generally at a few percent below the average barrier energy [21]. The $\beta_2$ value coupling the ground-state with the first $2^+$ state of the target nucleus is indicated at the bottom of the mass-ratio plots; for $\beta_2 > 0.1$, it is reasonable to associate it with the static deformation. For the heavier target nuclei, the MAD show a correlation of mass with angle, indicating a time scale for a substantial fraction of events of order $10^{-20}$ s, and this is correlated with a broadening of the mass-ratio distributions. Gaussian fits to the range $0.35 \leq M_R \leq 0.65$ are indicated by the turquoise curves on the $M_R$ plots. The $\sigma_{MR}$ values for above-barrier $^{16}$O-induced fission (expected to be predominantly fusion-fission) range from $\sim 0.06$ [11] to 0.08 for fission of Fm [9]. Thus Gaussian functions with $\sigma_{MR} = 0.07$ are shown (red curves) for reference in the mass-ratio plots. For the $^{48}$Ti-induced reactions, it is only the mass-ratio spectra for the lightest (Sm and Dy - forming CN with charge $Z_{C.N.}=84,86$) and heaviest (Pb - forming a CN with $Z_{C.N.}=104$) nuclei that come close the expectations for fusion-fission. Reactions with Ca projectiles on a smaller number of targets in the same mass range have also found similar behavior [22, 23].

Between Sm and Pb, the $M_R$ spectra show two main trends. From $^{154}$Sm to $^{178}$Hf ($\beta_2 > 0.25$), the mass ratio spectra become rapidly wider with $Z_{C.N.}$, which can be attributed to the increasing fissility of the composite system, since there is only a small change in target nucleus deformation. However, from W to Hg, the mass ratio spectra show no systematic change in overall width. This may be associated with compensation of the increasing fissility of the composite system by the decrease in static deformation, the influence of shells in the PES. Thus the nuclear structure-driven shape changes occurring from mid-shell towards the double closed shell of $^{208}$Pb seem to have as large an effect on the reaction dynamics as the global fissility change, for these sub-barrier reactions.

Figure 7. (Color online). 3-D isometric and 2-D contour representation of the systematics of the experimental mass-ratio ($M_R$) distributions, as a function of the atomic number $Z$ of the composite nucleus, for the reactions indicated. The target nucleus $\beta_2$ values are plotted for each reaction. The overlaid joined circles and squares on the 2-D map show the positions of the empirical neutron and proton numbers correlated with the low energy asymmetric fission of the same actinide elements.
6. Shell effects in $^{48}$Ti-induced quasi-fission mass distributions

The shape of the wide mass distributions seen for most $^{48}$Ti reactions must be controlled by two variables: (i) the probability of quasi-fission and (ii) the mass ($M_R$) distribution of the quasi-fission. To investigate the role of shell structure, a representation of systematic experimental $M_R$ distributions is presented that highlights persistent shell features, which can be difficult to isolate in limited statistics sub-barrier measurements. Fig. 7 shows the experimental distributions of fission yield (color scale) as a function of $M_R$ (X-axis) and atomic number $Z$ of the composite system (Y-axis), for all the $^{48}$Ti reactions shown in Fig.6. Contour graphs are presented both as a 3-D isometric view (left) and as a 2-D map (right). The yield is normalized to 1050 at the highest point in the distribution, to allow easy visualization of changes of shape with $Z$. From $^{154}$Sm to $^{174}$Yb ($\beta_2 \sim 0.33$) the $M_R$ distributions start to show mass-asymmetric shoulders (see also Fig.6), whose yield increases with system fissility. These are qualitatively consistent with results for $^{48}$Ca+$^{168}$Er, attributed [24] to quasi-fission. The mass distribution is broadest for $^{178}$Hf ($\beta_2 = 0.28$) even showing indications of a dip at symmetry. However, for still heavier targets, having decreasing $\beta_2$ but increasing fissility, the shoulders appear to become narrower. Quasi-fission may be decreasing in probability, and/or shell effects may be modifying the quasi-fission mass distributions.

To investigate whether this behavior could be consistent with the effect of shell structures, we treat within the same framework the systematics for spontaneous and low-energy fission of isotopes of the same actinide elements - which exhibit shell-driven mass-asymmetric fission, with different mass-split modes [25, 26]. Fig. 8 shows $M_R$ as a function of the atomic number $Z$ of the fissioning nucleus. The large symbols represent the centroids of the empirically determined fission modes for the indicated isotope of each element, taken from Appendix A of Ref. [27] and Ref. [28]. The “Standard II” fission mode (shown by the green squares labeled S II) generally has the highest yield. The yellow circles (S I) represent the “Standard I” fission mode, except at Fermium ($Z=100$), where it represents symmetric fission found [29] for mass number $\geq 258$, associated with two fragments close to the doubly-magic $^{132}$Sn. Assuming the $N/Z$ ratios of the...
Entrance-channel closed shells in quasi-fission dynamics

Figure 9. (Color online). Measured mass-angle distributions for each reaction (upper panels). The factor multiplies the maximum counts of the logarithmic color scale (right). In the projected mass ratio spectra (lower panels) the scale factor multiplies the counts scale on the left. Gaussian fits to the region around $M_R=0.5$ are shown (turquoise lines), whose standard deviations $\sigma_{MR}$ are given below. Gaussian functions with $\sigma_{MR}=0.07$ (thin red lines) are shown for reference.

fragments are the same as that of the fissioning nucleus ($N_0/Z_0$), for a given particle number $Z_{\text{Shell}}$ or $N_{\text{Shell}}$ in the fragment, the associated mass ratio $M_{R_{\text{Shell}}}$ is given by the ratio $Z_{\text{Shell}}/Z_0$ or $N_{\text{Shell}}/N_0$. The joined small circles indicate the $M_{R_{\text{Shell}}}$ values associated with the spherical closed shells $Z=50$ and $N=82$. The small squares show the expected trends associated with $Z=55$ and $N=86$, the proton and neutron numbers empirically found to be closely associated [27] with the generally predominant “Standard II” mode. The systematic behavior of the mass-splits is consistent with the trends expected if fixed proton and/or neutron numbers in the nascent fragments [27] are responsible. It appears that the spherical shells do not play the most significant role in low energy mass asymmetric fission.

To compare with the quasi-fission data, overlaid on the 2-D contour map in Fig.7 are plotted the $M_{R_{\text{Shell}}}$ values for the same shell numbers. For the measured distributions with $Z\geq94$, areas of high yield away from symmetry apparently show a systematic correlation with the trends of the shell structures. This suggests that shell structure in the PES does contribute to the observed mass distributions in these quasi-fission reactions, although not necessarily the spherical shells. Shell structure in both $N$ and $Z$ at the same mass-ratio should affect mass distributions most strongly. In these measurements the empirical $Z=55$ and $N=86$ lines are not as close together as in low energy fission, because the isotopes formed following capture of $^{48}$Ti projectiles are less neutron-rich. Their occurrence at different mass-splits means that we should not necessarily expect to see in these quasi-fission measurements asymmetric fission peaks identical to those in low energy fission of more neutron-rich isotopes.

| $\sigma_{MR}$ | 0.081 | 0.237 | 0.120 | 0.114 | 0.084 | 0.126 | 0.068 |
|-------------|-------|-------|-------|-------|-------|-------|-------|
| err         | 0.001 | 0.018 | 0.003 | 0.002 | 0.006 | 0.004 | 0.002 |
| $N_{\text{magic}}$ | 2 | 0 | 2 | 2 | 3 | 4 | 4 |
Figure 10. (Color online). Standard deviations $\sigma_{MR}$ of the fission-like mass distributions as a function of the number $N_m$ of magic numbers in the entrance channel. The dashed line guides the eye. The expectations of $\sigma_{MR}$ for fusion-fission are in the range 0.06 to 0.08 (see text).

7. Closed shells and N/Z asymmetry in the entrance channel

Comparing the results shown in Fig.6 and Fig.7 for $^{200}$Hg (which has only a small $\beta_2$ deformation parameter and forms $Z_{C.N.}=$102) with the neighboring spherical $^{208}$Pb, which forms $Z_{C.N.}=$104, the former gives a very much broader $M_R$ distribution compared with the neighboring doubly-magic nucleus $^{208}$Pb. This suggests a strong but localized influence of spherical closed shells in the entrance-channel on quasi-fission characteristics. In particular, it is attractive to hypothesize that the quasifission probability is affected by the entrance channel spherical shells, since the change in $M_R$ values of the fragment shells (see Fig.7 is much smaller between $Z=102$ and 104 than the observed change in the mass width. However, quasi-fission is not eliminated for $^{48}$Ti+$^{208}$Pb, as shown in the MAD (Fig. 6) by the visible correlation of fission mass with angle.

To investigate this striking feature seen in the mass distribution systematics, additional measurements [30] were made of MAD for $^{40,44,48}$Ca projectiles bombarding targets of $^{208,204}$Pb, forming $^{248,252}$No ($Z_{C.N.}=$102). Again the measurements were made a few percent below the average fusion barrier energy. The MAD and projected $M_R$ spectra are shown in Fig. 9, together with data for the $^{16}$O + $^{238}$U reaction, forming Fm ($Z_{C.N.}=$100) at an above-barrier energy. Also given are the Gaussian $\sigma_{MR}$ values, with experimental uncertainties, together with the $\sigma_{MR}$ value for the $^{48}$Ca + $^{208}$Pb reaction from Ref. [31]. Despite forming similar compound nuclei, there is a wide variation in the $\sigma_{MR}$ values, indicating a significant variation in the probability/characteristics of quasifission. To test whether the “magicity” of the reaction is important, Fig. 10 shows $\sigma_{MR}$ as a function of the number of magic numbers $N_m$ in the entrance channel. There is a strong correlation, with $\sigma_{MR}$ approaching the expectation for fusion-fission with increasing $N_m$. This suggests that reactions involving nuclei having several magic numbers form a true compact compound nucleus with higher probability. It seems likely that this is associated with reduced energy dissipation as the two nuclei overlap, allowing more compact shapes to be reached. Supporting this hypothesis, systematic analysis of xn evaporation residue cross sections in reactions forming Th isotopes has suggested enhanced fusion probabilities for two magic numbers in the entrance channel [32].

Despite the strong trend seen in most reactions studied, there is one significant exception. This is for the $^{40}$Ca + $^{208}$Pb reaction, which has maximal magicity, but a rather large $\sigma_{MR}$. This reaction is unique amongst those studied in having a very large N/Z asymmetry in the entrance channel. Thus protons and neutrons will tend to be transferred early in the reaction to equalize...
Figure 11. (Color online). The left panels show the experimental MAD and corresponding projections onto $M_R$ for $^{64}\text{Ni}+^{184}\text{W}$, $^{48}\text{Ti}+^{186}\text{W}$ and $^{34}\text{S}+^{186}\text{W}$ (see text). The right panels show simulated MAD and $M_R$ spectra for the same reactions and energies, with the sticking time distributions (above) which give good agreement between the simulations and the measurements.

the N/Z of the two colliding nuclei. TDHF calculations [30] of nucleon exchange prior to capture confirm this. Using a particle number projection technique [33], the probability of no transfer was calculated to be only $\sim 10^{-4}$, and the most probable outcome from the multiple transfers, at the moment of capture, being the system $^{42}\text{Ar} + ^{206}\text{Po}$, which has $N_m=0$. In contrast, the $^{48}\text{Ca} + ^{208}\text{Pb}$ reaction (also having $N_m=4$, but where the N/Z values of the colliding nuclei are similar) is calculated to remain in its initial mass and charge partition with probability $\sim 0.5$, thus largely retaining the initial magicity. Thus matching of N/Z in the entrance channel is an important condition in the enhancement of fusion inferred in reactions of magic (and especially doubly-magic) nuclei.

8. Extracting times from mass-angle distributions

MAD can in principle give accurate characteristic times for reactions where less than a full rotation occurred. MAD were measured in Ref. [34] for the reactions of $^{34}\text{S}+^{186}\text{W}$, $^{48}\text{Ti}+^{186}\text{W}$ and $^{64}\text{Ni}+^{184}\text{W}$, for a range of beam energies, to compare with crystal blocking measurements for reactions of the same elements. The latter were interpreted as giving mean times of $\sim 10^{-18}$ s for all reactions [35]. The measured MAD are shown in Fig. 11. For the $^{34}\text{S}$ reaction, the grey shaded region around $\theta_{c.m.} = 90^\circ$ indicates the region where the detector geometry gave no coverage. The panels below show the $M_R$ projections for $45^\circ \leq \theta_{c.m.} \leq 135^\circ$. They show marked differences between the three reactions. The $^{64}\text{Ni}$ reaction gives a minimum in yield at symmetry ($M_R = 0.5$), $^{48}\text{Ti}$ a broad peak around symmetry, whilst $^{34}\text{S}$ gives a narrow peak. Together with the correlation of mass and angle seen in the MAD, quasi-fission with short average reaction times appears dominant in the $^{64}\text{Ni}$ and $^{48}\text{Ti}$ reactions. To obtain more quantitative reaction time scales for the dominant quasi-fission, a classical Monte Carlo MAD simulation was developed [34]. The quasi-fission sticking time distributions were parameterized using a half Gaussian followed by an exponential decay, assuming that the parameters are independent.
of angular momentum. The average and width of the Gaussian, and the decay time, were individually adjusted to reproduce measured MAD. Using the time distributions shown in the top right panels of Fig. 11, the simulated MAD (shown below) reproduce the experimental MAD (left panels in Fig. 11) quite well. The corresponding $M_R$ spectra for $45^\circ \leq \theta_{c.m.} \leq 135^\circ$, shown in the lowest right-hand panels of Fig. 11, also agree with the experiment. Although similar MAD can be obtained by complementary adjustment of the peak time and decay time, the mean scission time for quasi-fission in the model is quite well defined for these reactions, at $5 \times 10^{-21}$ s for $^{64}$Ni, and $10 \times 10^{-21}$ s for $^{48}$Ti. These are two orders of magnitude faster than the times extracted from the blocking measurements. For the $^{34}$S reaction, the reaction times (rotation angles) are too large to specify anything more than that few events occur before $10 \times 10^{-21}$ s. These recent MAD results raise significant questions about the interpretation of crystal blocking measurements, and suggest the need for a consistent assessment of all experimental techniques for determination of fission times, including pre-fission neutrons [36, 37, 38, 39].

9. Conclusions

Nuclear structure has been shown to play a major role in heavy element formation dynamics. This can occur through the strong influence of static deformation on the probability of quasi-fission, associated with the alignment or anti-alignment of the poles and equator of deformed nuclei with the collision axis. Furthermore, strong evidence is shown that the presence of several magic numbers in the two colliding nuclei makes it easier for the system to reach compact shapes, and thus undergo true fusion, with a concomitant increase expected in ER cross sections. It is important to note that experiment suggests that this effect is substantially attenuated if the N/Z ratios of the two colliding nuclei are significantly mismatched. This may have important implications for eventual use of radioactive beams to form new isotopes of heavy elements.

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