Tracking saddle-to-scission dynamics using N/Z in projectile breakup reactions

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Abstract. Fragments produced in binary splits of an excited projectile-like fragment (PLF\textsuperscript{*}) formed in the reactions \textsuperscript{124}Xe + \textsuperscript{112,124}Sn at an incident energy of 50 MeV/A are examined. The dependence of the isotopic composition of light fragments (4 \leq Z_L \leq 8) on rotation angle allows one to explore changes in N/Z on the timescale of the rotational period of the PLF\textsuperscript{*}. Entrance channel effects are examined by comparing the isotopic composition of fragments produced in the binary decay following \textsuperscript{64}Zn + \textsuperscript{27}Al, \textsuperscript{64}Zn, \textsuperscript{209}Bi at an incident energy of 45 MeV/A.

1. Introduction
The density dependence of the nuclear symmetry energy impacts a broad range of phenomena from the composition of a neutron star crust to the formation of heavy elements in a supernova explosion [1–3]. One probe of the density dependence of the nuclear symmetry energy is the preferential transport of neutrons from regions of high density to regions of low density [4, 5]. On general grounds probing this density dependence is favored by examining a system that is sufficiently long lived to sense the underlying density-dependent potential. The dinuclear systems formed in strongly damped collisions of two heavy-ions, either N/Z symmetric [6] or N/Z asymmetric [7], present such an opportunity. While neutron and proton transport in strongly damped collisions has been the focus of several investigations in the 1980’s [8, 9], the density dependence of the underlying potential was not considered. To establish the characteristic timescale of N/Z equilibration, we therefore focus in this initial work on examining systems which are sufficiently long lived.

Peripheral collision of the projectile and target nuclei at intermediate energies results in the formation of an excited, transiently deformed projectile-like fragment, denoted the PLF\textsuperscript{*}, which can subsequently decay into two or more large fragments [10–14]. This decay mode.
is reminiscent of low-energy fission modified by the collision dynamics. Governed by its spin and lifetime, the decaying PLF* exhibits a characteristic angular distribution. Aligned breakup occurs with characteristic correlations between the size and velocity of the fragments [12], on the timescale of $\approx 300$ fm/$c$ [13, 15, 16]. It is reasonable to assume that since regions of low and high density exist during the collision phase, that these regions persist and continue to equilibrate during this secondary stage. In this work we examine for the simplest case of binary decay of the projectile-like fragment, whether $N/Z$ equilibration occurs after the initial separation of the projectile-like and target-like fragments. Moreover, using reactions spanning a wide range of targets while conserving the same projectile the influence of the target on the $N/Z$ equilibration is explored.

2. Experimental details

The experiment was conducted at the GANIL facility in Caen, France, where beams of $^{124,136}$Xe ions accelerated to $E/A = 50$ MeV impinged on $^{112,124}$Sn targets 800 $\mu$g/cm$^2$ thick with an average beam intensity of $\approx 10^8$ p/s. The experimental details of the experiment have been previously published [16] and are summarized below for completeness. Charged products of the reaction were identified by the array FIRST [17], which subtended the angular range 3$^\circ$ to 14$^\circ$. The forward telescope in FIRST spanned the angular range 3$^\circ$ to 7$^\circ$ and provided identification by atomic number of all products up to $Z=55$ and isotopic information for $Z \leq 14$. The larger angle telescope in FIRST provided $Z$ identification for $Z \leq 24$ and $A$ identification for $Z \leq 8$. The high segmentation of FIRST provided an angular resolution of $\pm 0.05^\circ$ ($3^\circ \leq \theta_{lab} \leq 7^\circ$) and $\pm 0.44^\circ$ ($7^\circ \leq \theta_{lab} \leq 14^\circ$) in polar angle and $\pm 11.25^\circ$ in azimuthal angle. The energy resolution obtained was approximately 1%.

To focus on binary decays, events were selected in which two fragments ($Z \geq 4$) were detected within the laboratory angular range 3$^\circ$ to 14$^\circ$. The two fragments were distinguished by their atomic number, with the larger (smaller) atomic fragment designated as $Z_H$ ($Z_L$). In addition, in order to ensure that the PLF* under investigation comprised a large fraction of the initial projectile, events selected were required to have $Z_H > 20$. Selection of these events corresponds to approximately 20% of the measured yield in which one fragment with $Z > 20$ was detected. In contrast to previous work [16], as we are interested in using the rotation of the PLF* as a clock, we extend our analysis from the angular range 3$^\circ$ to 7$^\circ$ to a broader angular range of 3$^\circ$ to 14$^\circ$.

3. Experimental results

3.1. Angular distribution

A simple characteristic quantity for defining the binary decay is the angle between the direction of the two fragments center-of-mass velocity, $v_{c.m.}$, and their relative velocity, $v_{REL}$ [11, 16]. We construct this angle $\alpha$, as indicated within the inset of Fig. 1, with the relative velocity vector, $v_{REL}$, defined as $v_{REL}=v_{H}-v_{L}$. Consequently, aligned decays with $Z_L$ emitted backward (forward) of $Z_H$ correspond to $\cos(\alpha) = 1$ (-1). Momentum correlations observed between $Z_H$ and $Z_L$ reveal that these two fragments originate from a common parent [16]. This parent nuclear system comprised of $Z_H$ and $Z_L$ is designated as the PLF*. Previous studies have demonstrated that the PLF* is an elongated, rapidly rotating transient system which subsequently decays [11, 15, 18, 19].

A defining feature of the binary decay of the PLF* at intermediate energies is the enhancement in yield for backward emission from the PLF* relative to forward emission [10, 11, 20]. In Fig. 1 we present the angular distributions for $Z_L = 4$ within the angular range of this analysis. Data for the $^{124}$Xe + $^{112}$Sn system is represented by the black solid line histogram. The angular distribution presented is markedly asymmetric with a large enhancement in yield for backward emission ($\cos(\alpha) = 1$). Moreover, this yield enhancement in the backward direction is also
Figure 1. The angular distribution of binary splits ($Z_L-Z_H$) for $Z_L=4$, representative of other fragments, is shown. Data for the $^{124}$Xe + $^{112}$Sn and $^{124}$Xe + $^{124}$Sn systems are represented by the black, solid and red, dashed histograms respectively. 

characterized by a narrow peak, indicating a strong alignment of $v_{REL}$ relative to $v_{c.m.}$. While both the yield enhancement and the alignment decrease as $Z_L$ increases, they persist up to $Z_L=18$. Also shown in Fig. 1 is the angular distribution for the $^{124}$Xe + $^{124}$Sn system indicated by the dashed red histogram. The distribution for the $^{124}$Sn target has been area normalized in the range $-1 \leq \cos(\alpha) \leq 0$ to the $^{112}$Sn target data. With this normalization it is observed that the angular distributions for the two targets are virtually identical. In effect the two targets manifest the same yield enhancement as a function of angle. We therefore do not observe a dependence of the backward emission probability on the target composition. This result is in contrast to published results for dynamical emission in Sn+Ni reactions [21]. In the case of the Sn+Ni reactions however both the $N/Z$ of the target and the projectile were simultaneously varied.

3.2. Isotopic composition

Depicted in Fig. 2 is the angular dependence of the isotopic composition of different elements. A clear trend is evident for all $Z_L$ shown in Fig. 2. For all fragments emitted at backward angles, an enhancement in $\langle N \rangle/Z$ is observed as compared to the forward direction ($-1 \leq \cos(\alpha) \leq 0$). A similar behavior has been observed for $^{124}$Sn + $^{64}$Ni when integrating over fragments with $Z = 5-8$ [22]. This enhancement of $\langle N \rangle/Z$ for backward decay is most striking for $Z_L=4$. For the case of $Z_L=4$, at the most backward angles one observes that $\langle N \rangle/Z$ is enhanced relative to the forward direction by 7%. As the rotation angle increases, this enhancement in $\langle N \rangle/Z$ decreases monotonically. For $Z_L>4$, while an enhancement is still observed, the magnitude of the enhancement is smaller than for $Z_L=4$. The $\langle N \rangle/Z$ values observed for forward emission are consistent with values previously observed in projectile fragmentation studies at 600 MeV/A [23]. Data for the $^{124}$Xe + $^{124}$Sn system (open symbols) manifests a similar enhancement as did the $^{124}$Xe + $^{112}$Sn system (closed symbols). For the neutron-rich $^{124}$Sn target, slightly larger values of $\langle N \rangle/Z$ are observed for most fragments, particularly $Z_L=4$. Although changing the target from $^{112}$Sn to $^{124}$Sn corresponds to an increase of $\approx 20\%$ in $N/Z$, only a relatively small
enhancement is observed for the $\langle N \rangle/Z$ of the fragments. The similarity of the two systems suggests that when keeping the Z of the target constant, the neutron content of the target does not play a dominant role in either the yield (Fig. 1) or the composition, $\langle N \rangle/Z$, of the fragments emitted backward in the decay of the PLF*. The decay angle could be related to the separation between $Z_H$ and $Z_L$, with small angles corresponding to short lifetime [16]. The observed $\langle N \rangle/Z$ dependence on decay angle could therefore be associated with a decreasing $\langle N \rangle/Z$ as the $Z_H-Z_L$ system lives longer.

4. Target effect
In order to further study the influence of the target on the fragment isotopic composition as well as the $N/Z$ equilibration, a similar analysis was performed for the $^{64}$Zn + $^{27}$Al, $^{64}$Zn, $^{209}$Bi systems at an incident energy of 45 MeV/A. The experimental setup was similar to the one for the $^{124}$Xe + $^{112,124}$Sn systems. In addition to the two forward telescopes of FIRST [17], a third telescope allowed mass identification for $Z \leq 7$ for the angular range $4.5^\circ \leq \theta_{lab} \leq 27^\circ$. A more complete description has been previously published [6]. Events with two fragments in the covered angular range were selected. In addition, the requirement that $Z_H > 12$ was made to select PLF* representing a large fraction of the projectile.

4.1. Angular distribution
In Fig. 3, we show the angular distributions associated with binary decay of the PLF* for those lighter systems. For the symmetric $^{64}$Zn + $^{64}$Zn system (solid black line), the angular distribution is largely asymmetric with an excess of yield at backward angles ($\cos(\alpha)=1$). While the angular distribution for $^{124}$Xe + $^{112}$Sn showed an increase of yield for $\cos(\alpha) \approx -1$ (Fig. 1),
Figure 3. The angular distribution of binary splits for $Z_L=4$ is shown. Data for the $^{64}\text{Zn} + ^{64}\text{Zn}$, $^{27}\text{Al}$ and $^{209}\text{Bi}$ systems are represented by the black solid line, blue open symbols and red closed symbols respectively.

indictive of angular momentum for the decaying PLF*, the distribution for $^{64}\text{Zn} + ^{64}\text{Zn}$ shows, if anything, a decrease of yield for $\cos(\alpha) \approx -1$. This indicates that the angular momentum of the PLF* induced by the interaction of the projectile with the target is minimal for such mass system in the studied angular range. The distributions for the $^{64}\text{Zn} + ^{27}\text{Al}$ and $^{64}\text{Zn} + ^{209}\text{Bi}$ systems are also shown in Fig. 3 as open and closed symbols. These distributions have been area normalized in the range $-1 \leq \cos(\alpha) \leq 0$ to the $^{64}\text{Zn}$ target data. The similarity of the normalized angular distributions for the three different targets is remarkable. With the exception of one point in excess for data with the $^{209}\text{Bi}$ target, the three distributions exhibit the same angular dependence. While the projectile is the same for all three systems, the mass of the target changes by almost an order of magnitude. Also notable is the broadening of the angular distribution for the reactions induced by the $^{64}\text{Zn}$ projectile as compared to the $^{124}\text{Xe}$ projectile. This might be due to the larger experimental angular coverage for the former.

4.2. Isotopic composition
The isotopic composition dependence on decay angle for different $Z_L$ is shown in Fig. 4. An enhancement in $\langle N \rangle / Z$ for all fragments is observed at backward angles as compared to forward angles. For the $^{64}\text{Zn} + ^{64}\text{Zn}$ system, this enhancement, while observed for all fragments shown, is the largest for $Z_L = 4$. The $\langle N \rangle / Z$ of $Z_L = 4$ fragments observed at very backward angles is $\approx 20$ % larger than the one of fragments emitted at forward angles. Data for the $^{64}\text{Zn} + ^{27}\text{Al}$ (open triangles) show slightly smaller values of $\langle N \rangle / Z$ as compared to data for the symmetric system. While the mass of the $^{64}\text{Zn}$ and $^{27}\text{Al}$ targets are different by a factor of $\approx 2$, their $N/Z$ is very similar (1.13 and 1.08 respectively). The observed $\langle N \rangle / Z$ for the $^{64}\text{Zn} + ^{209}\text{Bi}$ system exhibits an enhancement as compared to the data for the other systems. In order to better compare the different systems, in particular the isotopic composition dependence on decay angle, the ratio of the $\langle N \rangle / Z$ for the $^{64}\text{Zn} + ^{208}\text{Bi}$ and $^{64}\text{Zn} + ^{27}\text{Al}$ systems relative to the $\langle N \rangle / Z$ for the $^{64}\text{Zn} + ^{64}\text{Zn}$ system has been constructed. The resulting ratio as a function of the decay angle is shown in the right side of Fig. 4 (panel (d)-(f)). For $Z_L = 4$, the ratio is constant except for fragments...
emitted at forward angles. The relative neutron enhancement for these light fragments is of the order of 10% for the $^{64}\text{Zn} + ^{209}\text{Bi}$ system as compared to the $^{64}\text{Zn} + ^{64}\text{Zn}$ system. The corresponding change in $N/Z$ for the two targets is $\approx 34\%$. For $Z_L > 4$, namely $Z_L=5,6$, the ratio is constant with decay angle indicating that the enhancement or reduction is independent of the separation time between $Z_H$ and $Z_L$. While the fragments are initially prepared with a higher (lower) $\langle N \rangle/Z$ for the $^{64}\text{Zn} + ^{209}\text{Bi}$ ($^{27}\text{Al}$) as compared to the $^{64}\text{Zn} + ^{64}\text{Zn}$ system, the change with rotation angle is similar for all systems. This indicates that the exchange between the two partners ($Z_H$ and $Z_L$) is independent of the target.

5. Conclusions
We have established that fragments produced in the dynamical binary breakup of a PLF* exhibit a correlation of their $\langle N \rangle/Z$ with rotation angle. While fragments are produced more neutron-rich for reactions involving more neutron-rich targets for a given projectile, this enhancement represents only a fraction of the change of the target $N/Z$. The angular dependence of $\langle N \rangle/Z$ reveals that the composition of $Z_L$ continues to decrease for times of the order of the decaying
PLF* rotation period. The continuous evolution of $\langle N \rangle / Z$ on such timescale is only accessible because of the relatively long-lived dinuclear complex.

Two principal factors influence the evolution of $\langle N \rangle / Z$ with time. The first factor is any initial N/Z asymmetry between the nascent $Z_H$ and $Z_L$ fragments. While the different systems studied show that the initial fragment composition correlated with the entrance channel, namely the neutron content of the target, the evolution in time of the fragment composition seems to be independent of the entrance channel. The second factor influencing the evolution of $\langle N \rangle / Z$ with time is the existence of a low-density region in the middle of the dinuclear system combined with a density-dependent symmetry energy. It has previously been established that a net preferential flow of neutrons to low density occurs for a system initially symmetric in both A and N/Z [6]. Whether the observed decrease of $\langle N \rangle / Z$ with time for a given $Z_L$ is due to preferential neutron transport to the low-density region, exchange with the normal-density $Z_H$ fragment, or neutron emission as the descent from initial configuration to scission occurs, is presently unclear. Isotopic identification of both the $Z_H$ and $Z_L$ fragments together with measurement of free neutrons could resolve this ambiguity.

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