Strong enhancement of dynamical emission of heavy fragments in the neutron-rich ^{124}Sn + ^{64}Ni reaction at 35*A* MeV

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A quantitative comparison is made between the absolute cross sections associated with statistical and dynamical emission of heavy fragments in the ^{124}Sn + ^{64}Ni and ^{112}Sn + ^{58}Ni collisions experimentally investigated at 35*A* MeV beam energy using the multidetector CHIMERA. The result shows that the dynamical process is about twice as probable in the neutron-rich ^{124}Sn + ^{64}Ni system as in the ^{112}Sn + ^{58}Ni neutron-poor one. This unexpected and significant difference indicates that the reaction mechanism is strongly dependent on the entrance-channel isospin (N/Z) content.

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I. INTRODUCTION

Heavy-ion reactions at intermediate energies (20*A*–100*A* MeV) feature a characteristic transition in the appearance of dissipative reaction phenomena [1]. A characteristic signature of this transition regime is the copious production of intermediate-mass fragments (IMFs), usually defined as fragments with $Z \geqslant 3$, a process that is progressively replaced by the vaporization of the nuclear system into light particles as the incident energy is increased [2]. In the changing scenario of this energy domain, it is possible to observe distinctive reaction mechanisms and to probe the isospin degree of freedom of nuclear matter, predicted to play a crucial role in reaction dynamics and in IMF isotopic composition [3,4]. The experiment presented in this paper is part of a large program undertaken with the CHIMERA detector at Laboratori Nazionali del Sud in Catania, Italy, to study evolution of time scales in nuclear reactions induced by heavy ions [5] and to search for new decay modes of excited nuclei [6]. By applying the relative-velocity correlation method in the ^{124}Sn + ^{64}Ni and ^{112}Sn + ^{58}Ni reactions at 35*A* MeV [5,7–10], we have been able to shed light on the IMF production mechanism and to establish a clear emission chronology as a function of the IMF mass. It was shown that light IMFs ($Z \lesssim 10$) are preferentially emitted

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in fast fragmentation of the neck connecting projectilelike fragments (PLFs) and targetlike fragments (TLFs), within 40–80 fm/c from the beginning of reseparation. Conversely, the emission of heavier IMFs ($Z \gtrsim 10$) was shown to happen preferentially at the late stage of the neck expansion process or later. This latter result supported new arguments for interpretation of the scenario of heavy-fragment emission in peripheral collisions as "dynamical fission" reactions in those cases when two strongly correlated (in velocity space) heavy fragments originating from the binary splitting of PLF decay were observed [11,12]. The main signature of such a dynamical fission process was that the heavier of the two PLF fission fragments was usually faster, that is, it was forward-directed in the PLF reference frame, while the lighter fragment was situated preferentially between its heavier partner and the TLF, resulting in an aligned three-body configuration (aligned breakup [13–15]). In contrast, in the case of equilibrium PLF fission, the angular distribution of fissionlike fragments is expected to be forward-backward symmetric in the PLF reference frame.

Recently, a very fast (on a time scale of 70–100 fm/c) ternary and quaternary aligned breakup process, following deep inelastic binary reactions, has been observed in Au + Au collisions at 15A MeV [6,16]. However, the reaction mechanism observed in these deep inelastic collisions at rather low energies [6,17] probably differs from that observed at higher energies [11,13–15].

Our experimental observations have also motivated calculations in the framework of CoMD-II [18] and BNV [19] codes in order to describe the main features of the neck fragmentation and dynamical emission phenomena. CoMD-II is a molecular dynamics model [20]; its main feature is a self-consistent N-body approach that overcomes the main problems typically related to semiclassical many-body dynamics by solving the equations of motion using constraining procedures to satisfy the Pauli principle (event by event) and to respect the conservation rule regarding the total angular momentum. This last feature plays a crucial role in producing dynamical processes with different time characteristics.

In contrast, BNV is a stochastic mean field microscopic approach that describe the evolution of systems via a transport equation (of the Boltzmann-Nordheim-Vlasov type) with a stochastic fluctuating term that takes into account the dynamics of fluctuations (the so-called Boltzmann-Langevin equation). The transport equations are solved following a test particle evolution on a lattice. In the collision term, a parametrization of free nucleon-nucleon (NN) cross sections is used, with energy and angular dependence. The isospin effects on the nucleon cross section and Pauli blocking are consistently evaluated.

In this work, we have applied the useful concept of separation of the dynamical and equilibrium decay effects in fragment emission to evaluate absolute weights of the dynamical and equilibrium fission of PLFs in the ^{124}Sn + ^{64}Ni (neutron-rich) and ^{112}Sn + ^{58}Ni (neutron-poor) systems investigated at a laboratory energy of 35A MeV using the forward part ($1^\circ < \theta_{\rm lab} < 30^\circ$) of the 4π CHIMERA multidetector [21].

II. RESULTS

A. Event selection

In order to select peripheral collisions, in which scattering of the PLF is followed by its fissionlike splitting into two massive fragments, we first used the method of Cavata *et al.* [22] to estimate the impact parameter from the total charged-particle multiplicity $M_{\rm tot}$. This method is based on the assumptions that the total cross section is purely geometrical and that there is a monotonic correlation between a global variable, like the total charged-particle multiplicity, and the impact parameter. Under these assumptions, the multiplicity dependence of the measured cross section can be interpreted as an impact parameter dependence of the geometrical reaction cross section. In this way we tested, within the accuracy of the method, that our experimental trigger condition allowed us to measure up to impact parameter $b_{\rm red} = (b/b_{\rm max}) \sim 1$ where $b_{\rm max}$ corresponds to the total (geometrical) nucleus-nucleus cross section. The absolute cross sections were obtained from normalization on elastic scattering measurements. Then the events with reduced impact parameter $b_{\rm red} = (b/b_{\rm max}) \geqslant 0.7$ for both Sn + Ni systems were selected; this selection corresponds to slightly different total charged-particle multiplicities, namely, $M_{\rm tot} \leqslant 6$ for the neutron-rich ^{124}Sn + ^{64}Ni system and $M_{\rm tot} \leqslant 7$ for the neutron-poor ^{112}Sn + ^{58}Ni system. The difference of one unit in the upper limit of multiplicity is consistent with Ref. [23], where an enhancement of proton emission in the neutron-poor ^{112}Sn + ^{58}Ni system with respect to the neutron-rich ^{124}Sn + ^{64}Ni was found in the experimental data. However, we have verified that our main results concerning the difference in strength of the dynamical emission between the two Sn + Ni systems (see below) is not influenced by our impact parameter selection.

In the following, we concentrate our attention on the two heaviest fragments of the chosen subset of events, and select those events, as already described in [11], that satisfy the following conditions: (i) The combined charge of the two selected fragments (heavy and light) $Z_{2F} = Z_H + Z_L$ is close to the charge of the PLF ($Z_{\rm proj} = 50$), that is, $37 \leqslant Z_{2F} \leqslant 57$, and (ii) the heavy-to-light-fragment mass ratio is $A_H/A_L < 4.6$, so that the lighter fragment of the two has charge $Z_L \gtrsim 9$.

Under these two conditions, our analysis has shown that the heavier of the two selected fragments has the component of the velocity parallel to the beam axis ($V^H_{\rm par}$) very close to the value of $\sim$7.5 cm/ns, that is, slightly below the beam velocity of $V_{\rm beam} \sim 8$ cm/ns. In contrast, the lighter of the two fragments has a wider distribution of the parallel velocity, ranging from the velocity of the TLF ($V^L_{\rm par} \sim 0.5$ cm/ns) up to velocities exceeding the velocity of the PLF. This broad distribution of the parallel velocity proves that our selection criteria did not introduce artificial bias in the available momentum space. This latter property is seen in Fig. 1, where, using a logarithmic intensity scale, we present the $V_{\rm per}$ versus $V_{\rm par}$ Galilean-invariant cross-section plots for light fragments produced in the ^{112}Sn + ^{58}Ni reaction, for three ranges of mass asymmetry A_H/A_L (columns), and for three ranges of the total kinetic energy of the two selected fragments $E_{2F} = E_H + E_L$ (rows). The analogous plot for the neutron-rich system has already been reported in Fig. 2 of

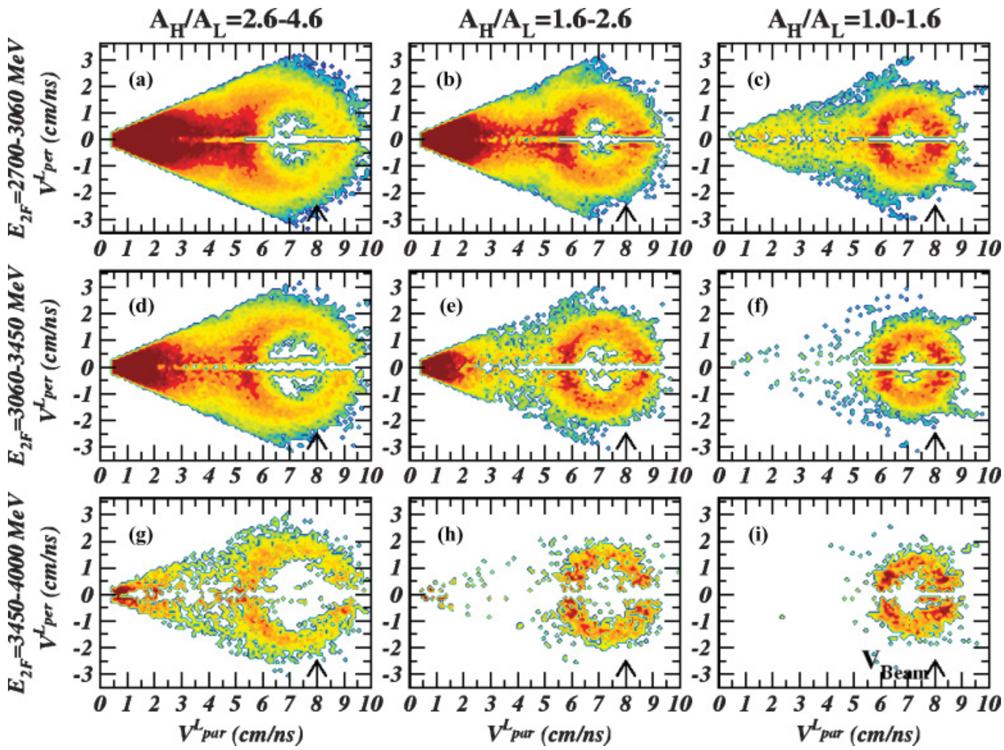

FIG. 1. (Color online) Invariant V_{per} versus V_{par} cross-section plots for the light fragment of the PLF breakup in the $^{112}Sn + ^{58}Ni$ reaction. Different panels correspond to different values of mass asymmetry A_H/A_L and the total kinetic energy $E_{2F} = E_H + E_L$. The distributions are shown in logarithmic scale. The red color corresponds to the largest cross sections and the arrows indicate the beam velocity.

Ref. [11]. The quantity E_{2F} is a simple measure of the collision violence: Larger values of E_{2F} are associated with more gentle (peripheral) collisions, while more violent collisions lead to smaller E_{2F} values. Indeed, we prove that E_{2F} is sensitive to the fragment multiplicity. Our analysis has been limited to the less dissipative collisions with $E_{2F} > 2700$ MeV, in order to reduce to vanishing values the probability of detecting events with more than two heavy fragments in the final state.

B. Velocity distributions

In all panels of Fig. 1 we observe the characteristic "Coulomb rings" centered slightly below the beam velocity of about 8 cm/ns. The presence of these rings points to PLFs as a well-defined decay source and suggests the scenario of two separate reaction steps: first the scattering of the PLF, followed by its splitting into two fragments. The same scenario had been proved in analysis of the relative velocity correlations for three fragments in the final state, including TLFs [5]. At somewhat intermediate velocities ($3 < V_{par}^L < 5$ cm/ns), we observe (Fig. 1) some fragments not evidencing any ringlike structures, whose emission can be attributed to a prompt neck emission mechanism [5]. It is seen that, for near-symmetric splitting, the fragments sequentially emitted from PLFs (positioned on the Coulomb rings) dominate over the mid-velocity fragments, although this dominance gradually diminishes with increasing mass asymmetry and with kinetic energy loss. Notice that, in almost symmetric divisions after less dissipative collisions [Fig. 1(i), $E_{2F} = 3450$–4000 MeV and $A_H/A_L = 1.0$–1.6], the light fragments' distributions are forward-backward symmetric, that is, the light fragment has equal probability to be emitted forward or backward in the reference frame of the PLF source. This result is characteristic for an equilibrated fission (the nucleus is supposed to be completely equilibrated in all its degrees of freedom). In these events, the PLF scission is expected to occur a long time ($\sim 10^{-20}$ s or more) after the preceding binary step in which the PLF + TLF system was produced. Consequently, equilibrated fission may take place after a number of PLF rotations. In examining more dissipative collisions and/or more asymmetric splits, we observe that the population of the Coulomb ring is no longer forward-backward symmetric. In fact, lighter fragments populate preferentially the low-velocity side of the Coulomb ring, which means that they are backward-emitted in the PLF reference frame, that is, toward the TLF (seen at the lowest velocities around $V_{par} \approx 1$ cm/ns). Nonetheless, a forward-backward symmetric component is still present. Therefore we assume that the observed distributions represent a superposition of a forward-backward symmetric component and an asymmetric one. The observed forward-backward asymmetry is the main signature of the dynamical fission, and it indicates that this PLF fissionlike split is a fast process. Otherwise, the averaging over the possible emission directions would result in forward-backward symmetry. In contrast, the equilibrated PLF fission is much slower.

Note that all these features indicate that the PLF fission process is not fully equilibrated even for heavy IMFs ($Z \gtrsim 9$).

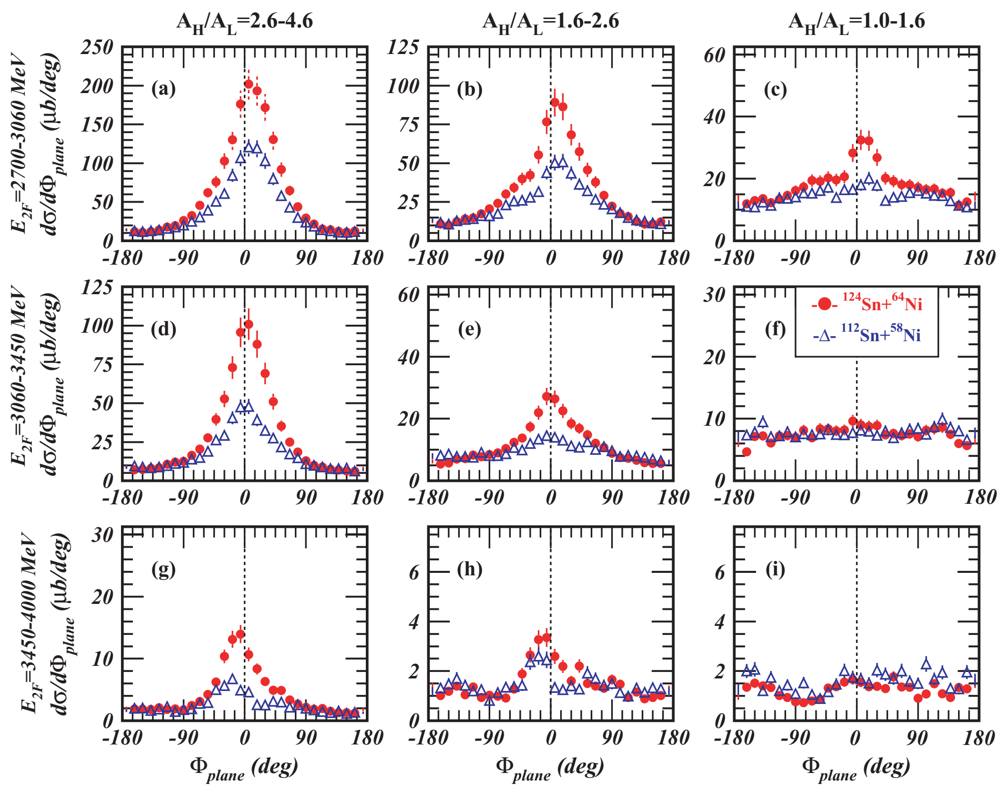

FIG. 2. (Color online) "In-plane" angular distributions of the PLF breakup fragments for the ^{124}Sn + ^{64}Ni (full circles) and ^{112}Sn + ^{58}Ni (empty triangles) reactions at 35*A* MeV for different bins of the total kinetic energy (E_{2F}) and fragment mass asymmetry (A_H/A_L). According to the adopted convention [11], for $\Phi_{\rm plane} = 0^\circ$ the heavier of the two fragments is emitted forward, along the PLF flight direction.

However, the most distinct dynamical signals were observed for light IMF emission ($Z \lesssim 9$), characteristic of the neck emission. These processes have been interpreted in terms of the neck fragmentation scenario [5,18,19]. The dynamical fission processes associated with heavier fragments seem to represent an intermediate class of reactions situated between the prompt neck rupture reactions and completely equilibrated PLF fission.

A possible explanation of the phenomenon of dynamical fission is that it originates from very strong deformations of the projectile during its interaction with the target [13–15,17]. It was proposed in [14] that, just after the collision, the deformation of the colliding nuclei can be so large that the projectilelike fragment can be deformed beyond its saddle point and thus inevitably it must break up. As a matter of fact, it should be recalled that stochastic BNV calculations [19] show that, after the primary collision stage, the outgoing PLFs and/or TLFs are strongly deformed (see Fig. 1 of Ref. [19]), so they can undergo a dynamically induced fast-fission path that is definitely faster than the equilibrium fission process. Unfortunately, up to now, the increasing numerical inaccuracy of the transport model simulations prevents following the complete time evolution of the excited and deformed PLF up to its scission point.

More recently, CoMD-II calculations [18] have reproduced some characteristic features of the dynamical fission process, such as the degree of alignment and the asymmetric mass splitting of PLF. According to the CoMD-II calculations, the dynamical fission might be triggered both by centrifugal forces in the rotating PLF and its deformation.

In order to compare the dynamical fission strength in the two Sn + Ni systems we have analyzed the angular distributions of the PLF decay fragments. Since the light fragments cover a very broad range of parallel velocities, we have limited this range to $V^L_{\rm par} > 4$ cm/ns. In this way we strongly reduced a possible contribution (contamination) to the cross section of fragments originating from TLFs. Our selection method takes advantage of the detailed studies already performed for the neutron-rich system. A more detailed description of the applied selection method can be found in [11].

C. Angular distributions

In Fig. 2 we present the differential cross sections $d\sigma/d\Phi_{\rm plane}$ for the two Sn + Ni systems, plotted as a function of the "in-plane" angle $\Phi_{\rm plane}$. The angular distributions are shown for three bins of the mass asymmetry A_H/A_L (columns) and three bins of the total kinetic energy of the two selected fragments, $E_{2F} = E_H + E_L$ (rows). $\Phi_{\rm plane}$ is the PLF fission angle projected on the reaction plane (see Fig. 4 of [11] for the definition). The value $\Phi_{\rm plane} = 0^\circ$ corresponds to the heaviest fragment moving forward, strictly in the PLF flight direction. Equilibrated fission of PLFs is expected to have a flat $\Phi_{\rm plane}$ distribution because the memory of the

TABLE I. Cross sections σ_{dyn} in mb of the dynamical fission component in the $^{124}Sn + ^{64}Ni$ reaction at 35*A* MeV, for different bins of the total kinetic energy E_{2F} and fragment mass asymmetry A_H/A_L.

E_{2F} (MeV)	A_H/A_L		
	2.6–4.6	1.6–2.6	1.0–1.6
2700–3060	15.9 ± 1.6	6.5 ± 0.6	1.4 ± 0.1
3060–3450	7.2 ± 0.7	1.7 ± 0.2	0.2 ± 0.3
3450–4000	0.8 ± 0.1	0.1 ± 0.1	<0.1

TABLE III. Cross sections σ_{equil} in mb of the equilibrium fission component in the $^{124}Sn + ^{64}Ni$ reaction at 35*A* MeV, for different bins of the total kinetic energy E_{2F} and fragment mass asymmetry A_H/A_L.

E_{2F} (MeV)	A_H/A_L		
	2.6–4.6	1.6–2.6	1.0–1.6
2700–3060	5.4 ± 0.5	4.9 ± 0.5	5.1 ± 0.5
3060–3450	3.1 ± 0.3	2.4 ± 0.3	2.5 ± 0.3
3450–4000	0.6 ± 0.1	0.4 ± 0.1	0.5 ± 0.1

entrance-channel direction is lost after a long PLF rotation. For peripheral collisions characterized by a large total kinetic energy [Fig. 2(i)], the nearly symmetric splitting, for both investigated systems, shows flat angular distributions characteristic of equilibrium fission. However, with increasing mass asymmetry and collision inelasticity, we observe the rise of the forward-peaked component, with maxima located close to 0°, superimposed on the flat "equilibrium fission" distribution. This implies that the light complementary fragment is emitted backward in the PLF reference frame, that is, toward the TLF (aligned breakup). By integrating the angular distributions according to the method reported in Sec. III.c.1 of [11], we have estimated the dynamical (nonisotropic) and equilibrated (flat) contributions to the cross section. The values obtained are listed in Tables I–IV. The extraction of absolute cross sections is very important for direct comparison of the strength of the dynamical effects in the two investigated systems. Our analysis shows that for all asymmetry and total kinetic energy bins the equilibrated fission cross section is approximately the same for both nuclear systems. On the contrary, the dynamical component is larger for the neutron-rich system by a factor of about 2, as compared with the neutron-poor system. For both systems, we observe that the strength of the dynamical component increases with the mass asymmetry and with increasing violence of the collision, in agreement with conclusions of Refs. [11,13,14]. However, the equilibrium fission probability appears to be almost independent of the mass asymmetry, which may be consistent with the fact that the mass of PLFs is close to the Businaro-Gallone point [24]. We suggest that the origin of the enhancement of the dynamical fission component is due to the very different N/Z ratio of the two systems studied. Here we would like to note that neither the 7% geometrical cross-section difference nor the 10% available energy difference between the two systems can explain the observed enhancement by a factor of 2.

D. Relative velocities

Other valuable information on the properties of the dynamical fission phenomenon is obtained from analysis of the relative velocities of the PLF breakup fragments. In Fig. 3, we present for both Sn + Ni systems the Φ_{plane} angular dependence of the mean value of the fragment-fragment relative velocity normalized to the relative velocity of fission fragments, $\langle V_{rel}/V_{Viola}\rangle$, evaluated event by event by using the Viola systematics of the kinetic energy released in fission [25]. Thus the equilibrated fission of PLF should result in a flat distribution of the relative velocity at the level of $\langle V_{rel}/V_{Viola}\rangle \approx 1$, characteristic of the energy of mutual Coulomb repulsion.

Regarding the plots of Fig. 3, we observe that for asymmetric splitting the relative velocities agree with the Viola systematics only for fragments emitted at large angles ($|\Phi_{plane}| > 90^\circ$), while for the "dynamical" events ($\Phi_{plane} \sim 0^\circ$) the most probable relative velocity is larger by about 25%. A similar trend is observed for symmetric splitting in more violent collisions [Fig. 3(c)]. However, for symmetric splitting in less violent collisions, the relative velocities approach the Viola systematics limit [Fig. 3(i)]. This confirms our conclusion based on the analysis of angular distributions (Fig. 2), suggesting the equilibrated fission scenario. The observation of the deviations of relative velocities from the equilibrium fission limit is compatible with the concept of a dynamical instability of the PLFs; for example, the breakup triggered by a large deformation acquired by the PLFs during the interaction with TLFs [18,19]. It should be emphasized, however, that a comparison of the two Sn + Ni systems shows that the deviations from the Viola systematics associated with the dynamical emission around $\Phi_{plane} = 0^\circ$ are significantly larger for the neutron-rich than for the neutron-poor system.

Other interesting information on these phenomena is expected to come from new experimental data (ISOSPIN campaign) on the Sn + Ni and Sn + Sn reactions at 25 and

TABLE II. As Table I for the $^{112}Sn + ^{58}Ni$ reaction at 35*A* MeV.

E_{2F} (MeV)	A_H/A_L		
	2.6–4.6	1.6–2.6	1.0–1.6
2700–3060	9.2 ± 0.9	3.3 ± 0.3	0.6 ± 0.1
3060–3450	3.3 ± 0.3	0.6 ± 0.1	<0.1
3450–4000	0.3 ± 0.1	<0.1	<1

TABLE IV. As Table III for the $^{112}Sn + ^{58}Ni$ reaction at 35*A* MeV.

E_{2F} (MeV)	A_H/A_L		
	2.6–4.6	1.6–2.6	1.0–1.6
2700–3060	5.1 ± 0.5	4.9 ± 0.5	4.6 ± 0.5
3060–3450	3.1 ± 0.3	2.8 ± 0.3	2.8 ± 0.3
3450–4000	0.6 ± 0.1	0.5 ± 0.1	0.6 ± 0.1

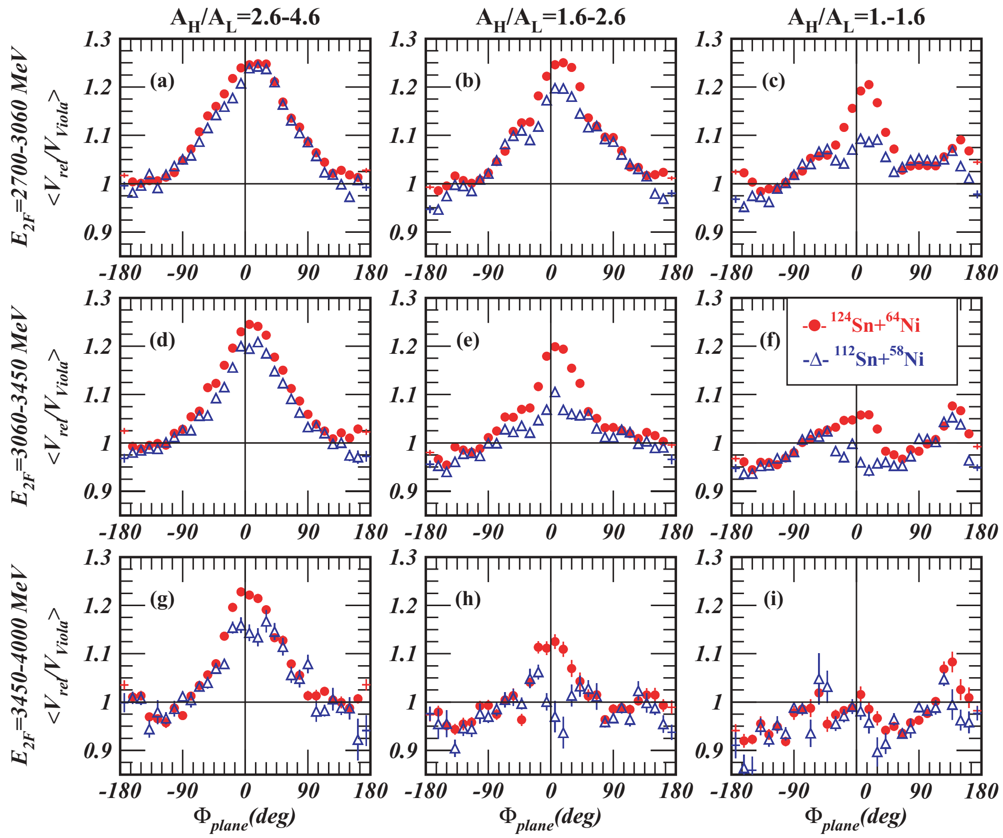

FIG. 3. (Color online) Mean values of the relative velocity ($V_{\rm rel}$) of the PLF breakup fragments normalized to the value corresponding to the Viola systematics ($V_{\rm Viola}$), as a function of the in-plane angle for different bins of the total kinetic energy (E_{2F}) and fragment mass asymmetry (A_H/A_L), for neutron-rich (full circles) and neutron-poor (empty triangles) Sn + Ni systems.

35 *A* MeV investigated by use of the CHIMERA multidetector in full 4π configuration.

III. CONCLUSIONS

The dynamical fission of projectilelike fragments was studied in two reactions representing a neutron-rich system ^{124}Sn + ^{64}Ni and a neutron-poor one ^{112}Sn + ^{58}Ni. While it was already established that the dynamical fission cross section in peripheral heavy-ion reactions increases with target size, asymmetry of the PLF split, and energy dissipation, practically no data existed on a possible isospin dependence. A surprising result of the present study is that the equilibrated fission of PLFs has approximately the same probability for both colliding systems, while the dynamical fission of PLFs is about two times more probable for the neutron-rich ^{124}Sn + ^{64}Ni system as compared with the neutron-poor one ^{112}Sn + ^{58}Ni. The origin of this enhancement appears to be related to a higher value of the N/Z ratio for the former system. Therefore theoretical simulations of this effect would be of great importance.

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