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Characteristic time scale of cluster production at the Fermi energy

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The study of heavy-ion collisions in the Fermi energy domain (20 MeV/nucleon < E/A < 100 MeV/nucleon) is a fundamental research topic in modern nuclear physics. In the case of semi-peripheral collisions, the Fermi energy regime is characterized by the formation of a transient, neck-like structure that connects a projectile-like fragment (PLF) with a target-like fragment (TLF). The neck structure represents a precursor of the fireball which is a typical overlap of participating nucleons at relativistic energies (E/A> 200 MeV/nucleon). It undergoes an expansion phase in a short time scale of the order of 100 fm/c with the formation of a low-density region of nuclear matter, therefore favoring the clusterization of intermediate mass fragments (IMFs) of atomic number Z (typically) less than 20. Particular emphasis is given to some relevant results obtained by the CHIMERA collaboration in the last decade, regarding the time scale of the production mechanisms of the intermediate mass fragments in neck fragmentation and their neutron enrichment.

KEYWORDS

multifragmentation, nuclear density, clusters, neutron enrichment, Fermi energy

1 Introduction

Heavy-ion collisions (HICs) at the Fermi energy constitute a very interesting case in contemporary nuclear physics studies (1). The Fermi energy regime locates between the low-energy Coulomb regime, where the one-body (mean-field) dissipation mechanism plays the major role in deep inelastic collisions, fusion–fission or fusion–evaporation, and the relativistic regime, where the two-body (nucleon–nucleon collisions) dissipation becomes the dominant mechanisms (2). Thus, the Fermi energy is a transition regime where it is possible to carefully test the in-medium properties of the nuclear interaction in a, somehow complicated, multi-body case. Many innovative studies have been performed in the last decades in several laboratories worldwide. Research studies conducted at MSU and GSI discovered a characteristic rise and fall of the intermediate mass fragment (IMF) mean multiplicity by increasing the energy beam (3). A possible liquid–gas phase transition has been also evidenced (4–6) in projectile fragmentation. Important efforts have also been accomplished in order to face the complexity of new detection systems able to measure the charges (masses) of mostly the reaction products in a 4π geometry (7, 8). At the same time, studies on the isotope composition of IMFs were carried out at GANIL laboratories by using the INDRA multi-detector, carefully investigating central collisions and their thermodynamic properties (9). Research studies carried out at Texas A&M laboratories characterized reaction mechanisms, thermodynamic description, time scale of the IMF emission, and limiting temperature (10, 11).

The isotopic composition of the quasi projectile residues has been exploited by the FAZIA detector, suggesting neutron enrichment when the target is a neutron-rich isotope (12). In this mini-review, we will focus on a limited part of results obtained at the INFN-Laboratori Nazionali del Sud (LNS) by using the CHIMERA multi-detector (13–17), concerning the time scale and neutron enrichment in fragment production.

2 Time scale of neck fragmentation

At the Fermi energy (20–100 MeV/nucleon), signals of deep inelastic binary collisions (low-energy regime) and the participant–spectator scenario (high-energy regime) coexist in the same scheme (18, 19). The participating region (i.e., the overlapping matter between the projectile and the target nuclei) in semi-peripheral collisions assumes the characteristic of a transiently expanding neck structure that connects (on a short time scale ~100 fm/c) the projectile-like (PLF) and target-like (TLF) nuclei (20). The dynamic evolution of this neck fragmentation process has been clearly elucidated in the context of data taken with CHIMERA that is able to detect fragments from a very slow TLF to a very fast PLF, allowing in studying the correlations among various observables (14). The three fragments PLF, TLF, and IMF in the final state are observed together with a few light particles. It should be noted that neutrons are not observed. However, especially for future experiments with exotic beams, some experimental efforts are underway to upgrade the device for neutron detection (21). An example of correlation is given in Figure 1, where the atomic number (Z) against the laboratory velocity parallel to the beam direction (V_{par}) of the three main fragments PLF, TLF, and IMF is displayed, for the reaction ^{64}Ni + ^{124}Sn at the beam energy of 35 MeV/nucleon, corresponding to V_{par} ~ 8 cm/ns. TLF fragments (Sn-like elements) are detected with a broad velocity distribution in the range of 0.4 cm/ns–1.3 cm/ns, approximately. Figure 1 has been obtained by a constraint on the charged particle multiplicity (M ≤ 7) in order to select semi-peripheral collisions.

Important findings on the mechanism of the production of these three fragments were obtained from the analysis of the relative fragment–fragment velocities, as follows. The relative velocity of the IMF with respect to the PLF and the relative velocity of the IMF relative to the TLF, that is, V_{REL} (IMF and

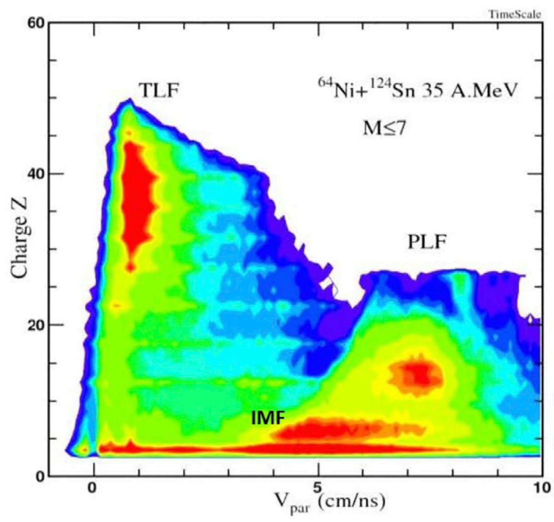

FIGURE 1
Typical correlation between the atomic number and velocity for the PLF, TLF, and IMF fragments.

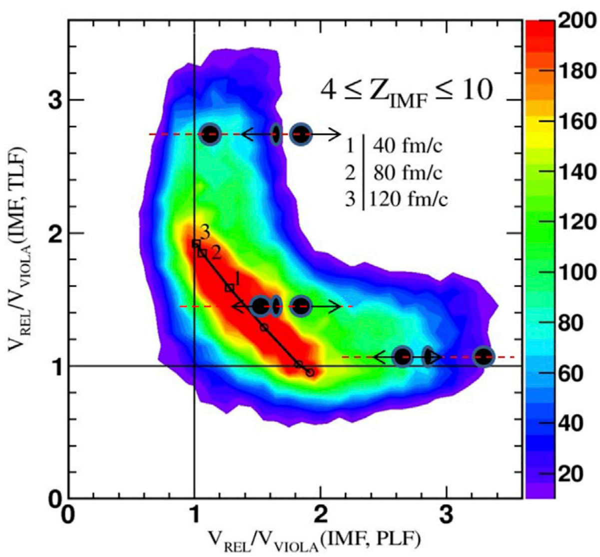

FIGURE 2
WILC2-Plot relative velocity correlations for semi-peripheral collisions in the reaction ^{64}Ni +^{124}Sn at the beam energy of 35 MeV/nucleon. The labels 1, 2, and 3 indicate chronological steps of different emission times of fragments from the prompt emission (40 fm/c) to a more delayed emission (>120 fm/c). The time chronology has been evaluated by Wilczynski et al. (20, 24) under the assumption of a sequential two-step model.

PLF) and V_{REL} (IMF and TLF), respectively, have been measured in an event-by-event analysis. The two relative velocities have been normalized to the corresponding relative velocity as evaluated by the Viola systematics (22–24) that gives the relative kinetic energy of the pure Coulomb repulsion between the two sub-systems PLF–IMF and TLF–IMF, respectively. In Figure 2, the experimental correlation plots V_{REL}/V_{VIOLA} (IMF and PLF) and V_{REL}/V_{VIOLA} (IMF and TLF) are shown for light IMFs of atomic number in the range $4 \leq Z_{IMF} \leq 10$, for the same reaction of Figure 1.

Simple kinematical analysis (20, 24) showed that the correlation between the two ratios gives information on the IMF emission scenario, in particular on the time scale in which the neck region re-separates from the PLF or TLF (or both in the case of instantaneous ternary emission). In Figure 2, as a solid line, an evaluation of the time scale of the process is shown. It is obtained by assuming that the IMF splits into a collinear configuration with respect to the relative velocity vector PLF–TLF, and it is evaluated by assuming a two-step process: in the first step, the projectile and the target undergo a fast inelastic scattering producing a PLF–TLF (excited) binary system. After a short delay (second step), the PLF (or the TLF) emits the IMF. Along with the two lines perpendicular to the *X* and *Y* axes (at a value equal to one), the IMF experiences the pure sequential Coulomb repulsion either from TLF or, alternatively, PLF residues. As an example of calculations, the second step separation times (ternary emission) of 40, 80, and 120 fm/c, respectively, have been considered after the first (binary) separation step of TLF–PLF [more details and kinematic calculations are reported in the appendix of (24)].

The time scale calibration reported earlier was an important step in understanding the dynamic component of the reaction mechanism: the fragmentation of the neck processes. The new type of the Wilczynski plot (WILC2-Plot, Figure 2) is the most convincing correlation for calibrating the time scale of IMF emission in semi-peripheral collisions, providing that, in addition to the IMF, both the slow TLF and fast PLF are measured in the same event (triple coincidence folding). The assumption of collinear emission PLF–IMF–TLF is crucial in reproducing the pattern emission of Figure 2. Both reverse and direct kinematics were investigated for the ^{58,64}Ni and ^{112,124}Sn isotopes at the energy of 35 MeV/nucleon. The analysis of the emission chronology was supported by different transport model simulations such as the stochastic mean-field (SMF) (19) and the constrained molecular dynamic model (CoMD-II) (25). The experimental WILC2-Plot (as described earlier) gives the time of separation of the IMF from the neck starting from the beginning of the separation between the PLF and the TLF. It gives us no information about the initial phase of overlap and compression which, at present, is estimated by the simulation of the transport code to be about 120 fm/c (26). Complementary experimental methods to define the time scale of the first phase of IMF production could be obtained by particle–particle (intensity interferometry methods) correlation (including uncharged particles) function (27). The stochastic mean-field (SMF) transport model (19, 28, 29) followed by sequential evaporation allows to accurately constrain the asymmetry term of the nuclear equation of state (NEOS) for the dynamical production of the light IMFs (30, 31). For the light IMF production in neck fragmentation, also a clear tendency of migration of neutrons against protons from high-density regions (PLF and TLF) toward the low-density neck region and consequent neutron enrichment of IMFs emitted by the neck has been evidenced, in favor of an asy-stiff symmetry energy behavior (30). The production of heavy fragments (Z > 10) has been interpreted within a larger time scale ranging from a non-equilibrated fission process (>300 fm/c) to a full equilibrated fission process of much longer times (32, 33). However, for the production of heavy fragments, the comparison between data and transport simulations either with the (CoMD-II) (25) or (AMD) (26) model requires some further improvements.

In conclusion, the experimental information obtained in these studies allowed for a more complete understanding of the light cluster production mechanism in heavy-ion collisions at the Fermi energy.

By using the CHIMERA detector, much effort has been recently devoted to fission studies and heavy residue production in central collisions by comparing different entrance isospin degrees of freedom enhancing the role of the neutron-rich isotopes (15) in view of new investigations with exotic beams by exploiting the incoming upgrade of the high-intensity beams at LNS in Catania (34) and the possibility offered by the "In Flight method" (35) that has been proven to be also implemented at the LNS (7, 36).

These envisaged studies will, therefore, open a fascinating perspective for future analyses with heavy ions at the Fermi energy. It should be noted that, in exotic nuclei, the detection of neutrons along with charged particles will be a necessary requirement for new investigations. Furthermore, with the implementation of the high intensity of the primary beam of a factor ≥20 that is expected to be operational in the next future at LNS, the exotic fragmentation will be a strong opportunity for developing more sophisticated experimental equipment incorporating neutron detection (21, 37, 38).

3 Conclusion

The time scale of a nuclear reaction and the isospin degree of freedom are important concepts in heavy-ion physics in order to describe the dynamical character of the reaction from the first phase of the collision (10 fm/c) up to the last stage of the sequential decay and equilibrium emission (≥1,000 fm/c). In the study, the time scale of neck fragmentation and the neutron enrichment of the neck have been emphasized. However, the measurements of the reaction time involved in different reaction channels are unique tools to probe the in-medium effective interaction and to constrain modern advanced transport simulations in order to predict the collision dynamics of heavy ions. We also emphasize the importance for reaction studies induced by exotic beams for future investigations. These reactions represent fundamental and necessary steps toward the study of the dependence of the equation of state of nuclear matter with respect to the baryon density and the isospin degrees of freedom.

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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