International Journal of Modern Physics E

HOW TO CALIBRATE THE TIME SCALE OF EMISSION OF INTERMEDIATE MASS FRAGMENTS?

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Received (received date)
Revised (revised date)

In order to obtain information on the time sequence and time scale of the production of intermediate mass fragments (IMF) in nucleus-nucleus collisions at intermediate energies it is proposed to analyze correlations between relative velocities of IMF's with respect to projectile-like fragments (PLF) and target-like fragments (TLF). Experimental data on the production of IMF's in the ^{124}Sn + ^{64}Ni reaction, taken with the CHIMERA multidetector array at 35 MeV/nucleon, have been analyzed with the proposed method.

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1. Introduction

Semi-peripheral nucleus-nucleus collisions at intermediate energies of about 20-40 MeV/nucleon are basically binary. However along with projectile-like fragments (PLF), target-like fragments (TLF) and evaporated light charged particles, a new class of reaction products, intermediate mass fragments (IMF) are also produced, especially at higher energies.[1−6] Usually all fragments of $Z \geq 3$ (which cannot be recognized as PLF's or TLF's) are classified as IMF's. It is rather well established that IMF's originate mostly from the neck region during reseparation of the colliding system, but the time scale of this process is not known.

2. Relative Velocity Correlations

We propose to deduce information on the time scale of IMF production from an analysis of relative velocity correlations in ternary events, in which along with the PLF and TLF only one IMF is produced. In so selected events, relative velocities in the IMF+PLF and IMF+TLF sub-systems, V_{rel}(IMF,PLF) and V_{rel}(IMF,TLF), can be determined experimentally in the event-by-event mode. For convenience, the relative velocities can be expressed in units of the velocity corresponding to the Coulomb repulsion energy of a given sub-system. The Coulomb repulsion velocity is given by the Viola systematics[7] for asymmetric systems[8]:

$$V_{Viola} = \sqrt{\frac{2}{\mu}\left(\frac{0.755\, Z_1 Z_2}{A_1^{1/3} + A_2^{1/3}} + 7.3 \text{ MeV}\right)}\,, \qquad (1)$$

where μ is the reduced mass of the sub-system.

Considering the time scale of IMF emission, one can assume that IMF's are either emitted *promptly* when all three fragments, PLF, TLF and IMF, are in close proximity, or in a later stage when the colliding system P+T first reseparates into two fragments,

$$P + T \rightarrow P' + T' \qquad (2)$$

and then, when both fragments P' and T' are already well separated, either P' or T' splits:

$$P' \rightarrow IMF + PLF \qquad \text{or} \qquad T' \rightarrow IMF + TLF. \qquad (3)$$

Asymptotically, when Coulomb interaction between P' and T' is negligibly small, the relative velocity of the decaying sub-system must be close to the corresponding value of V_{Viola}. Thus for well separated in time 2-step decay (i.e., sequential) of P' the ratio V_{rel}/V_{Viola}(IMF,PLF) should be close to 1, and similarly, for the "sequential" decay of T' the ratio V_{rel}/V_{Viola}(IMF,TLF) should also approach 1. Therefore, by plotting a two-dimensional diagram V_{rel}/V_{Viola}(IMF,PLF) vs. V_{rel}/V_{Viola}(IMF,TLF) we expect different localization of events for both two-step scenarios, Eq. (3), as well as for prompt IMF emission and all intermediate situations.

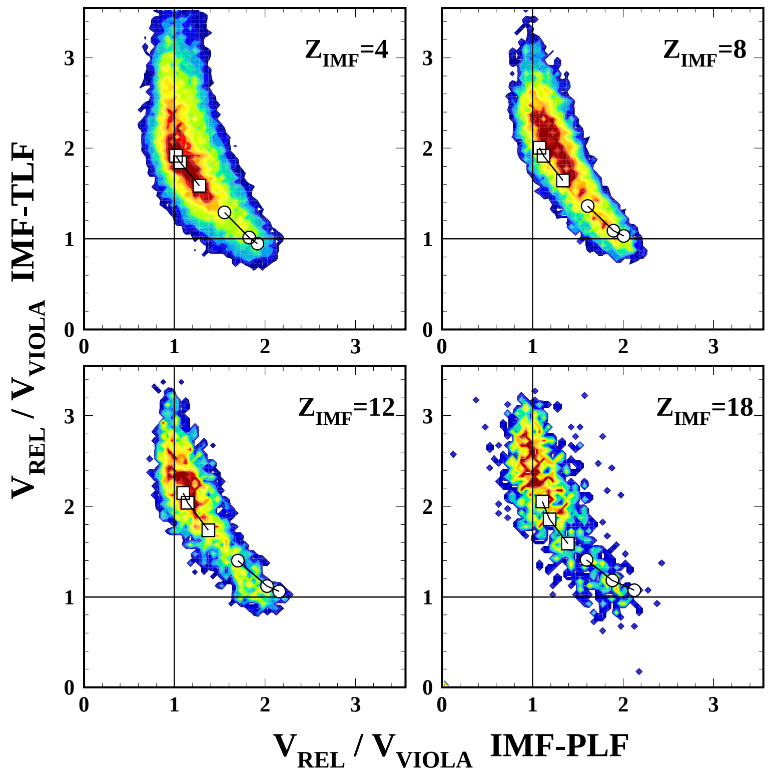

Fig. 1. Correlation between relative velocities V_{rel}/V_{Viola}(IMF,PLF) and V_{rel}/V_{Viola}(IMF,TLF) for different intermediate mass fragments of $Z_{IMF} = 4$, 8, 12 and 18. The relative velocities are expressed in units corresponding to the kinetic energy of the Coulomb repulsion of a given binary sub-system. The experimental distributions are compared with simple model calculations assuming that the IMF is released as a result of a two-step neck rupture process taking place 40, 80 or 120 fm/c after reseparation of the primary binary system. Two branches of the calculated correlation correspond to either projectile breakup (squares) or target breakup (circles); the shortest indicated times $\Delta t = 40$ fm/c correspond to the location near the diagonal.

3. Analysis of the ^{124}Sn + ^{64}Ni Reaction

In Fig. 1 we show results of analysis[9] of semi-peripheral collisions in the ^{124}Sn + ^{64}Ni reaction at the beam energy $E(^{124}\text{Sn}) = 35$ MeV/nucleon studied at Laboratori Nazionale del Sud in Catania using the CHIMERA multidetector array (see Ref.[10] and references therein). A selected class of almost completely reconstructed ternary events involving a PLF, TLF and one IMF was analyzed. The relative velocities V_{rel}/V_{Viola}(IMF,PLF) and V_{rel}/V_{Viola}(IMF,TLF) were calculated in the *event-by-event* mode and the correlation between these two quantities is displayed in Fig. 1 separately for four selected IMF's: $Z_{IMF} = 4$, 8, 12 and 18. As suggested above, the correlation between V_{rel}/V_{Viola}(IMF,PLF) and V_{rel}/V_{Viola}(IMF,TLF) gives information on the scenario of the IMF formation.

In order to "calibrate" the time scale of the observed IMF emission we carried out simple calculations of the relative motion of three fragments: PMF, TLF and IMF assuming that the IMF is produced in a two-step process, i.e., released either by the projectile fragment P' or target fragment T' (Eq. (3)) after an assumed time interval Δt elapsed from the binary reseparation of the colliding system. For simplicity, it was assumed that the IMF is released colinearly with the velocity vectors of PLF and TLF, and thus the final velocities were calculated numerically only in one dimension. For both sequential scenarios (breakup of P' or T') the calculations were done for $\Delta t = 40$, 80 and 120 fm/c.

It is seen from Fig. 1 that majority of IMF's are produced within 100-150 fm/c after the colliding system starts to reseparate. This result can be interpreted as indication that IMF's are emitted from the neck between the two interacting nuclei during the reseparation of the system. Dynamical expansion of the neck leads then to its fragmentation. As it is seen from the correlation diagrams in Fig. 1, light IMF's (see Be fragments) are produced earlier than heavy fragments (e.g., Mg and Ar fragments). Emission of heavy IMF's takes place at least 100-150 fm/c after the colliding system starts to reseparate. Therefore emission of heavy IMF's can be interpreted as resulting from two-step rupture of a massive and very elongated neck in the late stage of its expansion.

Our conclusions concerning the time scale of IMF emission are basically consistent with theoretical predictions of Baran, Colonna and Di Toro,[11] who demonstrated IMF emission in neck fragmentation processes in the stochastic BNV transport model simulations.

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