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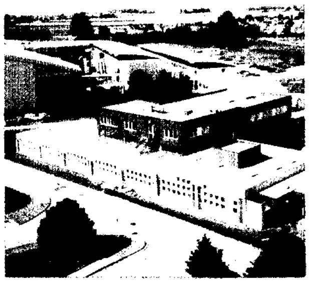

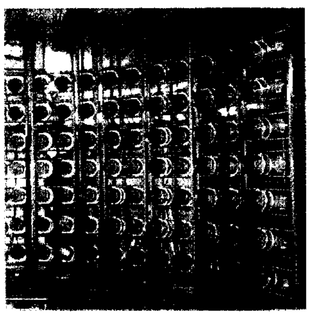

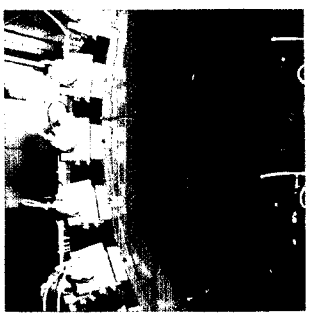

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March 1999 LPCC 99-05

Contributed paper to International Workshop xxvii on Gross Properties of Nuclei and Nuclear Exitations Waldemar-Petersen-Haus, Hirschegg, Kleinwalsertal (Austria), 17-23 january 1999

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Abstract

The multi-fragment production is discussed in nucleus-nucleus collisions around the Fermi energy. It is shown that two sources are generally involved which are reminiscent of the projectile and target nuclei as at lower bombarding energy (deep inelastic process). However many light fragments and particles are also emitted at intermediate velocity which reflect either the primary dynamics of the collision or shape effects in the nascent quasi-projectile and quasi-target.

1 Introduction

The Fermi energy range is the proper domain to study the liquid-gas phase transition of nuclear matter. As a matter of fact, the available energy in symmetrical collisions around 40 MeV/u incident energy is comparable with the total binding energy of the system. The complete vaporization of a system is then energetically possible and has indeed been observed[1]. In this context, multifragmentation which is observed in this energy domain and above is correlated with the phase transition and the coexistence between liquid and gas phases. At variance with the situation for macroscopic systems, the nuclear matter phase transition may be explored only in nucleus-nucleus collisions in which two difficulties occur. The first one is dealing with the role of time or dynamical features : one may speak about phase transition only in an equilibrium context in which the system may be described by collective thermodynamical variables like density, pressure and temperature. The second difficulty lies in the various mechanisms which can be induced depending on the collision parameters, especially the impact parameter.

At this point, it is necessary to distinguish "multifragmentation" which is devoted to a well-defined nucleus which has reached at least a partial equilibrium, and "multi-fragment-emission" which corresponds to reactions in which fragments of various origins are observed. In this second case, the study of multifragmentation implies the identification and the separation of the various origins of detected fragments. It is hence necessary to get a good knowledge of the underlying reaction mechanisms and to sort the detected events.

2 Event sorting and general outlook

The understanding of reaction mechanisms is now possible thanks to the 4π set up which are available all around the world. However, due to the numerous pieces of information which are obtained, it is necessary to concentrate them by using few global variables. The simplest one is the total detected multiplicity, which is however not very selective because it does not bring kinematical information. The transverse energy (total or limited to light charged particles -LCP) is a much better quantity which measures to which extent the initial energy has been shared among various degrees of freedom. Other quantities refer to the shape of the event which can be described from the associated momentum or energy tensor. The flow angle describes the orientation of its main axis relatively to the beam. The sphericity or the coplanarity or the isotropy are connected to the relative values of its main components.

None of these collective variables is ideal to achieve a perfect sorting of the events, i.e. to associate to each event an impact parameter. However, a proper combination of several of them may be used to succeed.

An example of an event sorting is given in figure 1 where $V_{par} - V_{per}$ plots are shown for alpha particles emitted in Xe + Sn collisions at 50 MeV/u. The sorting variable is here the LCP transverse energy. The evolution is continuous from peripheral to central collisions for spectra labels from 1 to 8.

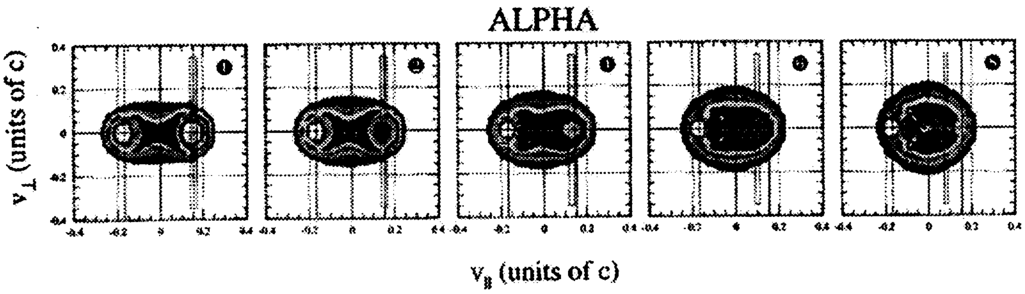


Figure 1: $V_{par} - V_{per}$ ***plots for peripheral to central collisions measured in the reaction Xe + Sn at 50 MeV/u ; from ref. 2.***

From figure 1, it may be clearly seen that most of the collisions are binary, but very central ones. One recognizes the quasi-projectile (QP) and quasi-target (QT) contributions, with in addition an intermediate velocity contribution in between. This feature may also be deduced from figure 2 where V_{par}-*charge* plots are drawn for various intermediate mass fragments (IMF : $Z \geq 3$) detected for two systems. The collisions have been sorted according to the impact parameter deduced from the LCP transverse energy measurement. The QP and QT contributions are clearly visible and the corresponding relative velocity is decreasing with the violence of the collision as it is observed at lower bombarding energies for deep inelastic collisions. However, an intermediate velocity emission appears, which corresponds mainly to light IMF.

It is possible to get the dissipated energy from the slowing down of the QP and QT. For this purpose, it is necessary to reconstruct them from their decay IMF. This has been achieved by using the thrust method in which one looks for the sharing of IMF which maximizes the quantity :

$$T = \frac{\sum_i \overrightarrow{p_i} + \sum_j \overrightarrow{p_j}}{\sum \mid \overrightarrow{p_k} \mid} \tag{1}$$

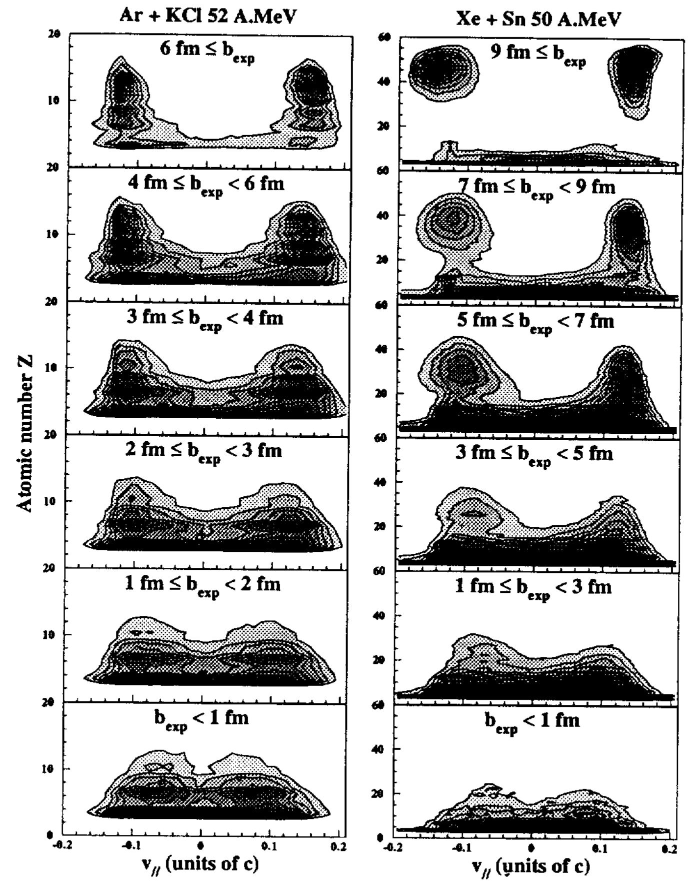


Figure 2: *V_{par}-charge plots for (IMF : $Z \geq 3$) detected in Ar + KCl and Xe + Sn reactions at 50 MeV/u. Collisions have been sorted according to the impact parameter deduced from the LCP transverse energy ; from ref. 3.*

$\overrightarrow{p_{i,j}}$ are the momenta of fragments attributed to the QP and QT respectively. The denominator is a normalization factor. This method is not fully correct because of the intermediate rapidity contribution which is included in the QP and QT. It has been however established that the corresponding error does not significantly modify the result. It is then possible to plot diagrams equivalent to the Wilczinsky plots of low energy heavy ion reactions. Such plots are shown in figure 3. The abscissa is the rotation angle of the QP - QT axis relatively to the beam and the ordinate is the QP - QT relative kinetic energy. One observes for various bombarding energies the familiar behaviour observed for deep inelastic collisions : a continuous slowing down which increases with the rotation angle from zero to the maximum possible value associated with Coulomb repulsion. This results holds for every system mass from light [3] to very heavy [4–6] ones (figure 3 is devoted to a medium mass system).

Complete damping is reached for any bombarding energy which means that there is no saturation of the dissipation in agreement with results obtained for relativistic energy beams. However, complete damping is reached with a vanishingly small cross section.

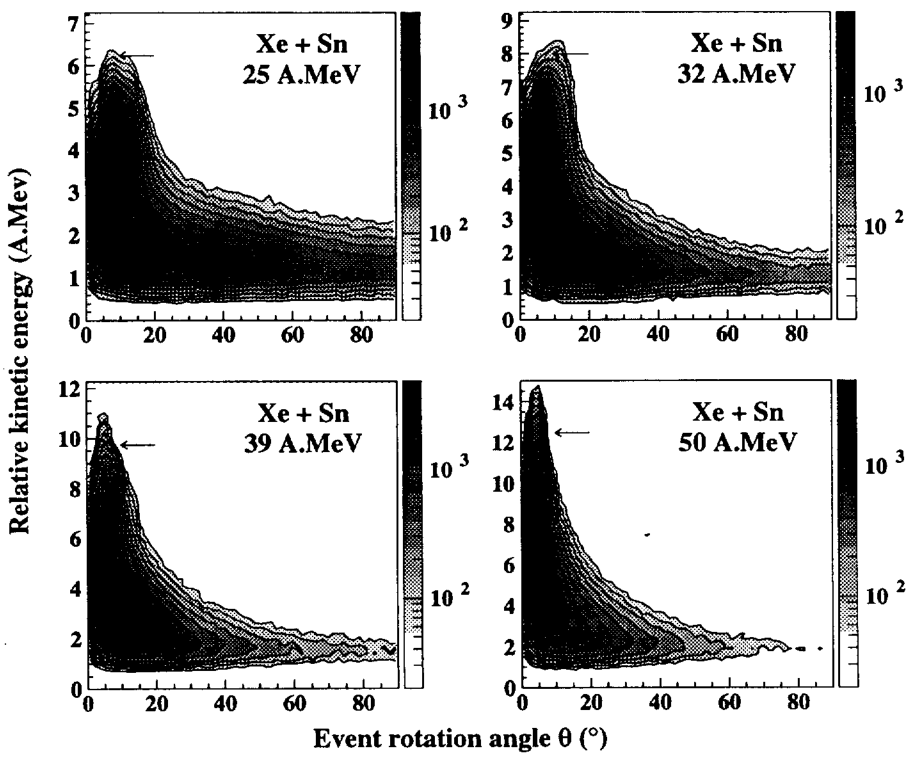


Figure 3: *Correlation between the rotation angle of the QP - QT axis and their relative kinetic energy for the Xe + Sn system at four bombarding energies from 25 to 50 MeV/u. One observes a behaviour quite similar to the deep inelastic features observed at lower bombarding energies. The arrows correspond to the relative kinetic energy in the entrance channel. From ref. 3.*

3 Separation of the intermediate rapidity emission

In order to study multifragmentation, it is necessary to disentangle various involved sources. The general method which is used for this purpose consists in asking for a symmetrical forward-backward decay of the QP or QT. Figure 4 illustrates the method. Alpha rapidity spectra are shown for the Ar + Ni system at 74 MeV/u. Mid-peripheral collisions have been selected. It is assumed that any alpha particle with a rapidity larger than the QP rapidity comes from the QP. The total QP contribution is obtained by symmetrizing the corresponding rapidity plot relatively to the QP velocity. A similar treatment holds for the QT contribution. The intermediate velocity component is then deduced by a subtraction procedure.

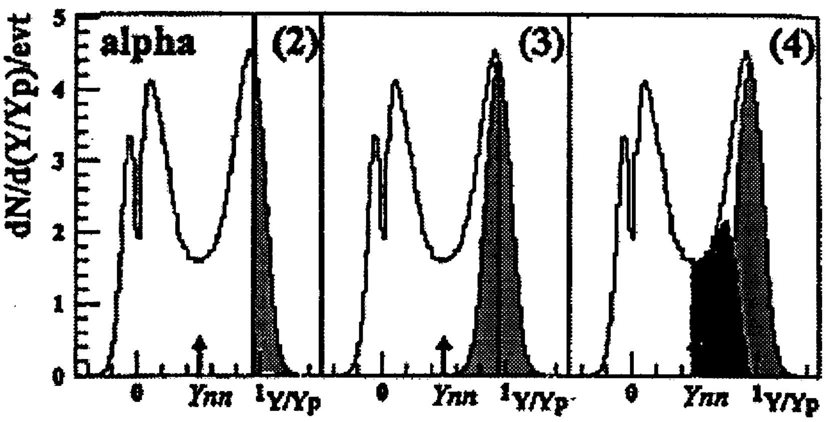


Figure 4: *The intermediate velocity contribution is extracted from the rapidity spectra by use of a substraction procedure of the QP or QT contributions. See text. From ref. 7.*

Two remarks have to be done on this method. At first, its main source of error lies in the extraction of the QP velocity which implies the recontruction of the initial QP from its decay products. This procedure which has to be applied for each event is not so simple because various emission sources are somewhat mixed-up. The second remark concerns the method itself : one asks for a symmetrical forward-backward decay on the QP or QT. In doing so, one asks for a complete equilibrium of the QP and QT before decay, i.e one selects QP (QT) emission which takes place on a rather long time scale, typically larger than the equilibrium time for the shape degrees of freedom. We will come back later on this point.

Fig. 5 is a result on the intermediate emission contribution as a function of the impact parameter. Its magnitude is expressed as a percentage of the total charge of the system. Two systems are considered. On the left side, a medium mass system (Xe + Sn) at 50 MeV/u. The two curves correspond to two methods for the extraction of the QP velocity. Their difference indicates an order of magnitude of the corresponding uncertainties. The abcissa is an impact parameter (in Fermi units) deduced from a LCP transverse energy analysis. Since the QP and QT contributions are severely mixed up for central collisions, the curves have been suppressed in the corresponding dashed area. It may be seen that up to 25% of the total system charge is emitted at intermediate velocity for semi-peripheral collisions. This percentage is even higher for a lighter system (right part of figure).

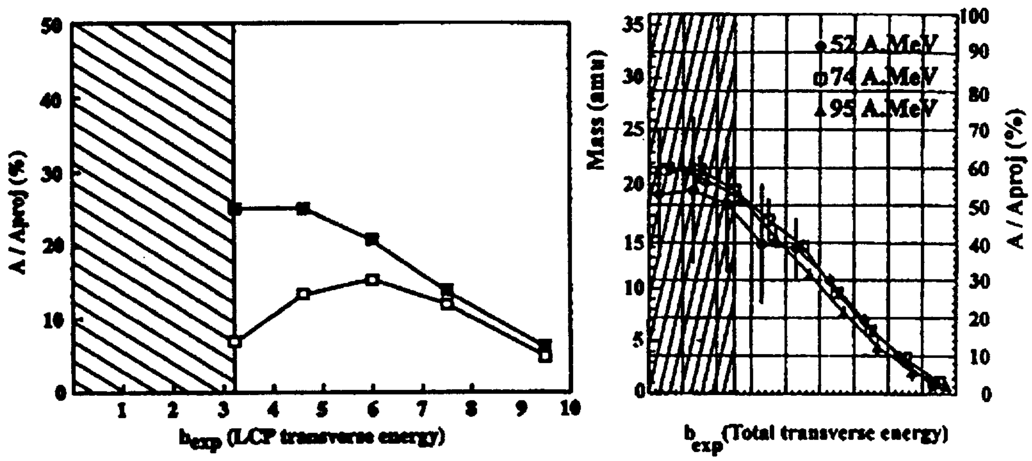


Figure 5: *Evolution with the centrality of the collision of the percentage of charge concerning intermediate velocity emission for two systems : Xe + Sn and Ar + Ni. See text for details. Extracted from ref. 2 and 7.*

An important feature of these results is that they do not depend on the bombarding energy as it is expected if the intermediate velocity component reflects mainly the geometry of the collision rather than the dissipated energy. Particles emitted at intermediate velocity are mainly LCP or light IMF. Most of tritons or deuterons and many light IMF ($Z = 3 - 5$) are emitted in this range at least for peripheral and semi peripheral reactions. Figure 6 illustrates this feature for the Ar + Ni system. Their chemical abundance reflects the incident energy rather than the dissipated energy as it appears in figure 7 where the apparent temperature deduced from the double ratio of p, d, ^{3,4}He isotopes is plotted as a function of the particle rapidity. The events have been sorted as a function of the dissipated energy in each event (the dissipated energy has been measured by calorimetry). The apparent temperatures in the intermediate rapidity region (Y / $Y_p \sim 0.5$) do not depend on the dissipated energy (various symbols), at variance with what is observed in the QP region (Y / $Y_p \sim 1$). This is a clear indication that the LCP observed at intermediate velocity for this system (Ar + Ni) originate mainly from the early stage of the collision and from the initial overlap region between the QP and the QT. They are the first signals of the participant region observed at higher bombarding energy.

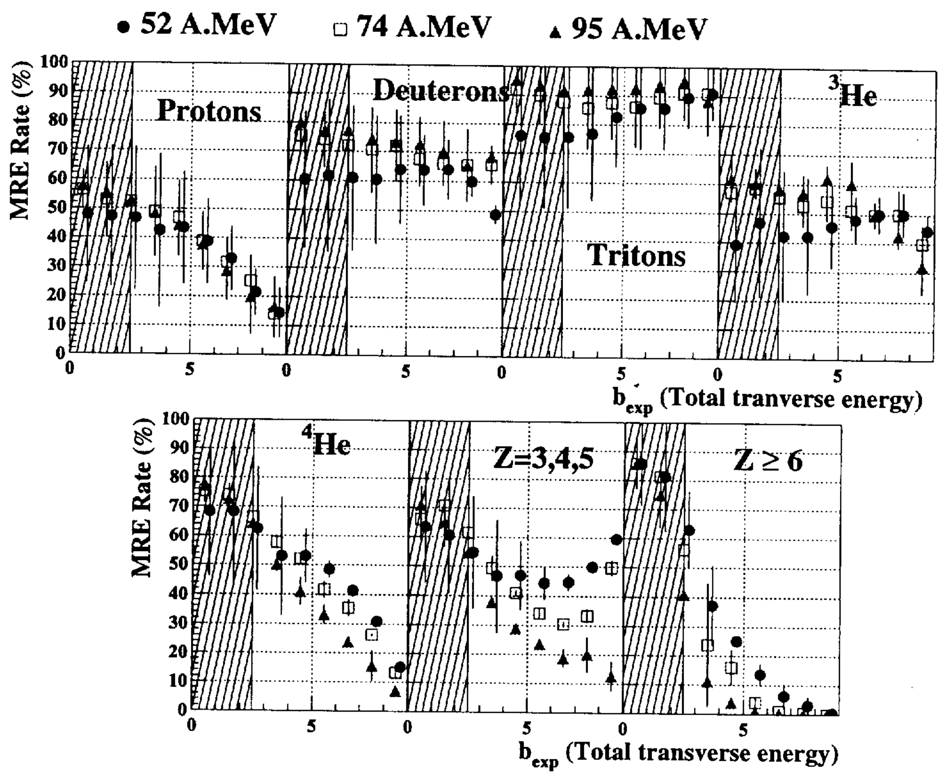


Figure 6: *Percentage of various products emitted at intermediate velocity as a function of the impact parameter and for several bombarding energies for the Ar + Ni system. Extracted from ref. 7.*

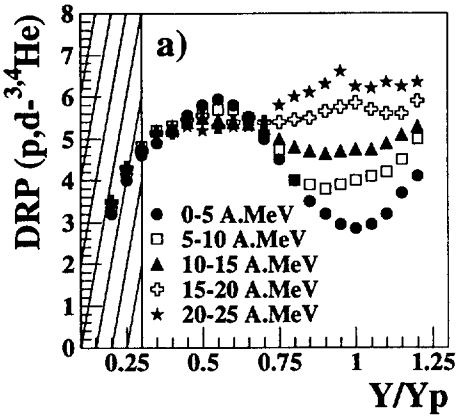


Figure 7: *The apparent temperature deduced from the double ratio yields of p, d, ^3He, ^4He is plotted as a function of the rapidity of the selected particles. The events have been sorted according to the dissipated energy. The results obtained in the intermediate velocity region do not depend on the dissipated energy at variance with those obtained in the QP rapidity region. Ar + Ni system at 70 MeV/u. Extracted from ref 7.*

4 On the predominant role of deformation

The above observations on an early emission of intermediate velocity products does not mean that they are all early emitted. It is also established that heavy IMF are later emitted from a QP or QT which has been released very deformed (beyond the fission saddle point) in the early stage of the collision.

Such an evolution may be easily understood from Landau Vlasov calculation results (figure 8) which indicate how the geometry of peripheral collisions may lead to very elongated shapes for the released QP and QT. It has been observed in selecting 3 fragment events for medium mass systems from 25 to 50 MeV/u bombarding energies [3,9–12]. In these cases, it has been measured that the fusion axis is preferentially aligned with the QP-QT axis, and that the lighter "fission" fragment is preferentially emitted in between the heaviest QP and/or QT remnants (figure 9). The relative energy between two QP (or QT) fission fragments reflects mainly a Coulomb behaviour except for the most asymmetrical fissions for which the influence of the QT (or QP) partner is clearly observed[11].

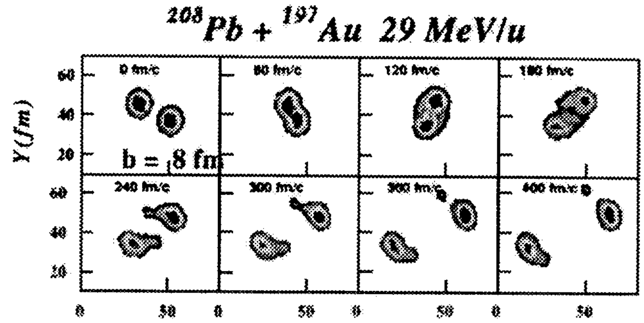
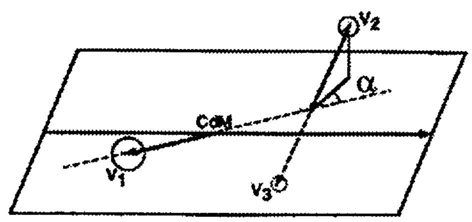


Figure 8: Contour plot in the coordinate space obtained in Landau Vlasov calculations for the Pb + Au at 29 MeV/u (peripheral collisions : b = 8 fm). The contribution at intermediate velocity may be due to an elongated shape of the released QP or QT. Extracted from ref. 8.



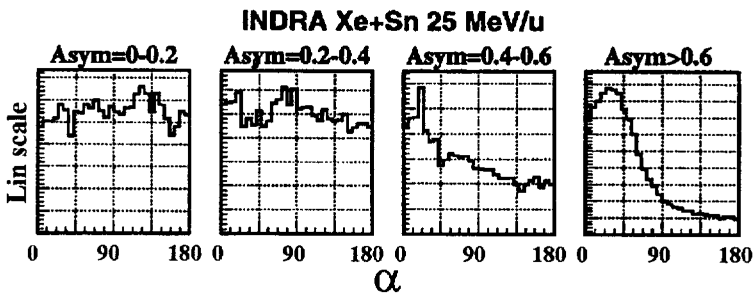


Figure 9: Upper part : shematic drawing for the definition of the α angle. Bottom : corresponding α angle distribution for peripheral collisions ($b/\ b_{max}$ = 0,8 - 1); system Xe + Sn at 25 MeV/u. Various plots correspond to various fission mass asymmetry $(A_1 - A_2)/(A_1 + A_2)$.

5 Conclusion

We have seen how nucleus-nucleus collsions in the Fermi domain lead to very different values of the incident energy damping. Most collisions are binary and one observes a continuous evolution from small to large energy dissipation with a rotation of the main axis of the events relatively to the beam direction. From this point of view, nucleus-nucleus collisions in the Fermi domain look like deep inelastic collisions at lower bombarding energy. However two main differences are observed. First of all, complete damping is rare and the corresponding cross section is vanishingly small. The second difference concerns the intermediate velocity emission in which one observes a sizeable fraction of the whole system mass (several tens of percent). Many LCP, most light IMF and some larger fragments belong to this zone. Some of them (mostly composite LCP or light IMF) seem to be emitted in the early stage of the reaction. They reflect the incident velocity and the geometry of the reaction rather than the dissipated energy. Some others (especially heavier IMF) correspond to a QP or QT fission like process which has been dynamically initiated because the initial QP and QT are released highly deformed. Such a phenomenon reflects probably the evolution with the dissipated energy of the nuclear matter viscosity.

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