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**Fragmentation in central Pb + Au collisions
within a microscopic dynamic approach.**

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FRAGMENTATION IN CENTRAL Pb + Au COLLISIONS WITHIN A MICROSCOPIC DYNAMIC APPROACH

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Abstract : The prompt fragmentation of a very massive nuclear system obtained in heavy-ion collisions at intermediate energies is studied in the framework of the semi-classical Landau-Vlasov model taking into account the two-body residual interactions and the isospin dependence. In a first phase, compression and expansion take place. In a second stage, the strong Coulomb repulsion and asymmetry neutron-proton lead to the formation of an evanescent bubble-like configuration which decays rapidly into several fragments. Time evolution of the densities and energy components as well as dependence on the beam energy are particularly analyzed. Quantitative comparisons are made with experimental data obtained in the ^{208}Pb (29 MeV/u) + ^{197}Au reaction.

1.Introduction

With the advent of heavy-ion accelerators delivering incident energy up to around 100 MeV/u and of new fragment 4π detectors [1-2], the disassembly of highly excited nuclear systems can now be completely studied. Beyond the binary and ternary fission, the fragmentation process corresponding to the emission of several intermediate mass fragments is an important part of the cross section in relatively central collisions which are the most efficient to excite the nuclei.

This new decay mode has received a great deal of theoretical investigations. Its simultaneous or sequential nature has been debated. The answer is probably energy dependent since, for instance, it has been observed that the average time between two successive binary decays decreases from more than 500 fm/c to less than 50 fm/c when the beam energy increases from 30 to 60 MeV/u in the Ar + Au reaction [3]. The role of the dynamics in the fragmentation process is not still well known. From branching ratios for different decay channels, it has been asserted [4-5] that the dynamics plays only a role in the formation of the sources which then proceed to decay in an apparently statistical manner. Nevertheless, this role in the entrance channel is essential since, before the decay, a considerable portion of the mass and energy is radiated causing a significant reduction of the fragmentation width [6]. One may also think that the dynamics in such violent collisions does not lead necessarily to homogeneous quasi-spherical nuclear systems but perhaps rather to more exotic shapes like bubbles or toroidal nuclei [7-8]. This idea was early proposed more than three decades ago by Wheeler [9] and Siemens and Bethe [10]. Thus, the successful statistical fragmentation models [11-12] employ presently only sources with uniform interiors and should be perhaps generalized to shapes with central matter depression. To have a quantitative estimate of these new decay channels, the potential barriers for the simultaneous explosion into several fragments in a volume-like manner [13] as well as the barriers for fragmentation in a ring-like manner [14] have been determined within the liquid drop model including the nuclear proximity energy. The collisions between very massive nuclei cannot lead to stable compound nuclei and are, therefore, more efficient to generate the fragmentation process at relatively low intermediate energies [15-16]. Recently the ^{208}Pb (29 MeV/u) + ^{197}Au reaction has been investigated and production of several fragments has effectively been observed [17-19].

The purpose of the present work is to study the fragmentation of excited nuclear systems formed in very heavy ion collisions at intermediate energies in the framework of the microscopic dynamic Landau-Vlasov model [20]. This approach allows to remove shape constraint and to describe naturally the nucleon evaporation. The collective properties derive directly from the individual nucleon motion which is governed both by the mean field and residual interactions. The reliability of this method to describe long time processes such as hot fission and deep-inelastic collisions [21] as well as violent decay of an isolated rotating nucleus [22] has previously been demonstrated.

In this paper, the Pb (29 MeV/u) + Au reaction has been particularly investigated at small impact parameters where the fragmentation is expected to occur. The model is briefly reviewed in sect.2 and the main formulas given the basic observables are displayed in sect.3. In sect.4 the evolution of the nuclear densities resulting from the simulation is visualized. Signatures of the fragmentation process in the behaviour of the different energy components and of the density profiles are analyzed in sect.5. The strong influence of the Coulomb repulsion, isospin, residual interactions and equation of state are put forward in sect.6. In

sect.7, calculations are compared with experimental data : the generalized Wilczynski plot and the distribution of $V_{||}$ as a function of the atomic number. Finally, the dependence of the fragmentation process on the projectile energy is studied in sect.8.

2.Description of the microscopic dynamic model

In the Landau-Vlasov model [20,23], the evolution of the one-body density distribution $f(\vec{r}, \vec{p}; t)$ is governed by the highly non linear equation :

$$\frac{\partial f}{\partial t} + \{f, H\} = I_{\text{coll}}(f). \quad (1)$$

H is the one-body Hamiltonian describing the mean-field taken as only density dependent. $\{ \}$ stands for the Poisson bracket. I_{coll} is the collision integral calculated in the Uehling-Uhlenbeck approximation. The free nucleon-nucleon cross section with its isospin and energy dependence has been adopted. $f(\vec{r}, \vec{p}; t)$ gives the probability to find, at the instant t , a particle at the point $(\vec{r}, \vec{p})$. The function f is expanded on a basis of coherent states taken as normalized Gaussians with fixed widths in $\vec{r}$ and $\vec{p}$ spaces (the centers of which following Ehrenfest-like equations) :

$$f(\vec{r}, \vec{p}) = \frac{A}{N_g} \sum_i w_i g_x(\vec{r} - \vec{r}_i) g_p(\vec{p} - \vec{p}_i). \quad (2)$$

A is the mass number, N_g is the number of coherent states (N_g/A equals 40 in the present study) and w_i are weight factors. The local density follows

$$\rho(\vec{r}) = \int f(\vec{r}, \vec{p}) d\vec{p}. \quad (3)$$

The mean field is described within the soft local Skyrme interaction (Zamick force) with an extra isospin dependent term :

$$U_q(\rho, \xi) = t_0 \frac{\rho}{\rho_0} + t_3 \left(\frac{\rho}{\rho_0} \right)^{1+\nu} + c \frac{\xi^2}{\rho_0^2} + 4 \frac{cq\rho\xi}{\rho_0^2}, \quad (4)$$

where $q = 0.5$ for neutrons and -0.5 for protons.

$$\rho(\vec{r}) = \rho_n(\vec{r}) + \rho_p(\vec{r}) \quad \text{while} \quad \xi(\vec{r}) = \rho_n(\vec{r}) - \rho_p(\vec{r}) \quad (5)$$

The parameters values are :

$$t_0 = -356 \text{ MeV}, t_3 = 303 \text{ MeV}, \nu = 1/6 \text{ and } c = 20 \text{ MeV}. \quad (6)$$

c is related to the volume symmetry coefficient J of the mass formula [24]. For such very heavy systems where $(N-Z)/A$ reaches 0.2, the isospin term plays an important role in the research of the ground state of the two incoming nuclei which is performed self-consistently like in Hartree-Fock calculations as well as in the subsequent dynamics. In section 6, a stiff local Skyrme interaction will be also used, the parameters values of which being :

$$t_0 = -123 \text{ MeV}, t_3 = 70 \text{ MeV}, \nu = 1 \text{ and } c = 20 \text{ MeV}. \quad (7)$$

3.Basic observables

The total energy is the sum of the potential energy E_{pot} , the kinetic energy E_k and the energy E_{emit} removed by the evaporated particles. E_k can be defined as

$$E_k = E_{int}^* + E_{coll} + E_0, \quad (8)$$

where E_{int}^* is the excitation energy of the heavy residue, E_{coll} the collective kinetic energy and E_0 the 'cold' internal kinetic energy. From the local collective velocity field in the center of mass frame given by :

$$\vec{V}_{coll}(\vec{r}) = \frac{1}{m\rho(\vec{r})} \int \vec{p} f(\vec{r}, \vec{p}) d\vec{p} \quad (9)$$

one can estimate E_{coll} reading

$$E_{coll} = \frac{1}{2} m \int \rho(\vec{r}) V_{coll}^2(\vec{r}) d\vec{r}. \quad (10)$$

In the common Thomas-Fermi approximation, the cold internal kinetic energy is written as

$$E_0 = \frac{\hbar^2}{2m} \frac{5}{3} \left(\frac{3}{2} \pi^2 \right)^{2/3} \int \rho(\vec{r})^{5/3} d\vec{r}. \quad (11)$$

In the initial stage of the collision, the momentum distribution is not still spherical and E_0 is calculated for two sharp Fermi surfaces [25].

Macroscopically and disregarding the nucleon evaporation, the evolution of a nuclear system depends mainly on the balance between the repulsive Coulomb forces and the attractive surface tension forces (including the proximity effects). For sake of comparison with the liquid drop model estimation, a first evaluation of the surface energy reads :

$$E_{surf} = \frac{a_s}{4\pi\alpha_0^2} \frac{A}{\langle \rho \rangle} \frac{\int \rho(\vec{r}) |\text{grad}(\rho(\vec{r}))| d^3\vec{r}}{\int \rho(\vec{r})^2 d^3\vec{r}}. \quad (12)$$

4. Simulation of the $^{208}\text{Pb}(29 \text{ MeV/u}) + ^{197}\text{Au}$ reaction at $b = 2 \text{ fm}$

This experiment performed recently [17-19] leads to one of the heaviest nuclear systems investigated at intermediate energies. The Coulomb repulsion and the asymmetry neutron-proton are very high and, even after a large evaporation, one cannot hope to obtain a relatively stabilized residue. A Landau-Vlasov simulation is displayed in figure 1 where density profiles are shown in three different planes of the configuration space. The vertical x axis, in the reaction plane, corresponds to the impact parameter and the horizontal z axis indicates the beam direction. In a first step, a strong compression occurs in the overlap region and, later on, in the whole nuclear mass which becomes very compact. In a second stage, the system expands practically uniformly due to the saturation of the nuclear forces and the Coulomb repulsion. In a third phase, a matter depletion grows in the heart of the matter while simultaneously a slow external expansion continues. This central depression appears in all planes containing the center of mass of the nucleonic distribution indicating that this exotic deformation mode is of bubble type rather than of toroidal type. Later on, instabilities develop to minimize the surface tension leading to the fragmentation of the bubble-like configuration into several massive fragments. To better display this cluster distribution with increasing time, projection of the densities has been realized on one plane (lower part of figure 1) but the result is almost independent of the selected plane. During this violent reaction, a large number of nucleons are evaporated continually. More precisely, at the end of this simulation, the fragment masses are 78, 67, 65, 55 and 35, in addition 105 nucleons have escaped.

Within this description, the question to know whether the fragmentation is sequential or instantaneous loses its importance. There is no successive splitting of excited spherical nuclei but rather a first fragmentation of the thin-skinned bubble mostly in two very oblate and distorted unstable pieces of matter (sorts of nuclear magma) which subsequently break in two or three other fragments. At each step, the fragments are more cold and spherical, which points out the efforts of the surface tension to return to sphericity. So, this suggests that the surface instabilities [26] which develop on the exotic bubble-like configuration are really the main explanation of this production of several fragments ; the correlations playing only a minor role although they could nevertheless influence the details of the predictions. As already stated [23], when the mean density does not differ drastically from the saturation one, the mean field remains a valid concept and the main responsible of the evolution of the density fluctuations.

Nuclear disassembly time scales have been advanced recently [27] for this reaction in the hypothesis of a deep inelastic scattering followed by successive splittings of the partners. They have evaluated the time separating the contact point and the maximum overlap of the two initial nuclei to ~ 50 fm/c and the interaction time to 150~200 fm/c. A value of 150 fm/c has also been obtained for the lifetime of one partner before the first splitting. The time between the first and second splitting is still longer since the decaying fragment is less excited. Even though the physical assumptions are somewhat different, our time-scale is compatible with these estimates ; our interaction time could be nevertheless slightly longer.

5. Signature of the fragmentation process

The aim of this section is to extract the main quantitative informations which characterize this type of fragmentation. The figure 2 shows that the evaporation takes place during all the stages of the reaction. It tends to vanish for $t \sim 800$ -900 fm/c when the fragments are well separated and relatively cold. The ratio of the mass and charge numbers of escaped nucleons follows closely the initial value $Z/A \sim 2.5$. Despite the long reaction time, let us recall that the spurious evaporation in such a microscopic dynamic approach is limited to about 5% [21].

In figure 3a, the different steps of the reaction appear in the evolution of the mean density as well as in the variations of the different components to the total energy. At the beginning of the collision, the two nuclei are stopped and the collective kinetic energy decreases considerably till about 80 fm/c. The matter is compressed and the density and the Coulomb energy increase while the surface energy diminishes. The variation of the density is only of about 20%. It underlines the difficulty to reach experimentally, even in very violent collisions, density values very far from the standard one.

Within the macroscopic liquid drop model the surface and Coulomb energies are defined as

$$E_{\text{surf}} = 17.9439 (1 - 2.6 I^2) A^{2/3} \quad \text{and} \quad E_{\text{coul}} = 3e^2 Z^2 / 5R. \quad (13)$$

A and Z are the total mass and charge. For this reaction, one obtains ~ 900 and 2500 MeV respectively, to be compared with our results at 80 fm/c. These values show a good agreement between the different prescriptions. In a second step during till ~ 175 fm/c , the system expands in all directions; the surface grows and the Coulomb energy decreases while the mean density reaches its lowest value ~ 0.055 (nucl/fm³). From here on the matter contracts at the vicinity of the surface producing a hole in the central region. The mean density increases again while the Coulomb energy is relatively constant (at around 200 fm/c); the diminution of the Coulomb repulsion in the center being compensated for the

increase of the Coulomb energy in the bulk of the thin-skinned bubble. Finally, the clusterization occurs smoothly and the fragments go away lowering the Coulomb energy which progressively turns into collective kinetic energy.

To illustrate the influence of fluctuations on the fragmentation processes, the time evolution of the mean density has been displayed in fig 3a for different cases leading to four or five heavy fragments. The fluctuations have been numerically induced changing the random seeds of the nucleon-nucleon scattering in the collision term. The time evolution of global properties like mean densities, collective kinetic energies,... remains unchanged. Then, the mean field rules the global behavior of the fragmentation process, even if the detailed structure of the exit channel is dependent on the microscopic fluctuations.

Figure 3b reports the variations of the internal excitation energy E_{int}^* , the emitted particle energy E_{emitt} , the collective kinetic and Coulomb energies. The excitation energy is maximum when the density is the highest at the end of the compression phase then decreases till a minimum when the nuclear matter is the most dilute. It increases again till the skin of the bubble attains the normal density and diminishes slightly after. All along the reaction, the energy E_{emitt} removed by the evaporated nucleons moderates the heating of the nuclear matter.

In figure 4, the probability distribution of the projectile nucleons in the whole system is displayed, in the reaction plane, and compared at the end of the reaction with the target nucleon probability distribution. The projectile nucleons fills in the whole volume of the composite system indicating an important relaxation of the initial velocity field. Nevertheless, the two distributions of matter have not completely lost memory of the entrance channel and an analysis of the composition of the different fragments shows that the two nucleon distributions have slightly passed through each other.

6. Influence of the Coulomb forces, isospin, residual interactions and equation of state

As shown in figures 5a and 5b, the fragmentation does not take place when the Coulomb forces are disconnected. Phases of compression and expansion follow each other ; the evaporation and the nucleon-nucleon collisions damping the oscillations. In the first stage of the reaction, the surface energy increases of only 1000 MeV which must be compared to the gain of 1500 MeV when the Coulomb repulsion acts. Then, a backward and forward motion from the center of the system to the periphery exists but the available energy is not sufficient to allow the formation of a bubble.

For such a massive system the asymmetry neutron-proton is very important and the isospin dependent terms have been introduced in the Skyrme forces. If these contributions are disregarded, a hole begins to appear at the center of the nuclear mass but it is progressively filled up and the fragmentation does not happen (figure 6).

The sole effects of the pure mean field are displayed in figures 7a and 7b, the two body and residual interactions being neglected. The Coulomb repulsion and saturation of the nuclear forces slacken the incoming nuclei and the collective kinetic energy decreases strongly at the beginning of the reaction. Later on, the absence of nucleon-nucleon collisions does not allow the redistribution of the individual velocities and the heating of the nuclear matter (E_{int}^* is about 925 instead of 1500 MeV). The two nuclei pass through each other and the collective kinetic energy is very high in the exit channel. During this rapid interaction the

nucleon evaporation is less important. The completely different nature of the reaction in this case puts forward the crucial role of the two-body collisions.

Finally, we display in figures 8a and 8b Landau-Vlasov calculations for $^{208}\text{Pb}(29 \text{ MeV/u}) + ^{197}\text{Au}$ at $b = 2 \text{ fm}$ performed with a stiff equation of state (see sect.2). The essential result is that the fragmentation in a bubble-like manner still takes place. The different phases : compression, expansion, hole formation and clusterization still appear. Naturally, due to a highest incompressibility, the variations of ρ , E_{surf} and E_{coul} are smaller within a stiff equation of state. More precisely, $\frac{\Delta\rho}{\rho_{\text{mean}}}$ is about 35% with a soft EOS and 17% with a stiff one. So, it is not obvious that such reactions could provide information about the stiffness of the equation of state. In return, the stability of the nature of the fragmentation process against very different values of the compressibility coefficient allows to have confidence in its existence.

7.Comparison with experimental data

To take into account an arbitrary number of fragments, the following tensor has been defined [17]

$$F_{ij} = \sum_{n=1}^{M_f} \frac{1}{2m_n} P_i^{(n)} P_j^{(n)} \quad (i, j = 1, 2, 3), \quad (14)$$

where $P_i^{(n)}$, $P_j^{(n)}$ are the i^{th} and j^{th} cartesian coordinates of the momentum $P^{(n)}$ of the n^{th} fragment with mass m_n . The eigenvector associated to the largest eigenvalues defines the flow direction and the angle θ_{cm} relatively to the beam axis. For each fragment, $V_{||}$ is the projection of the center of mass velocity on this major axis. In figure 9a the experimental correlations between the Total Kinetic Energy (TKE) and the flow angle (θ_{cm}) are given by contour plots while the dots indicate our Landau-Vlasov calculations at different impact parameters. For the most dissipative reactions and flow angles above 30° , the given values correspond to different induced numerical fluctuations at $b = 2 \text{ fm}$. For one impact parameter, the TKE remains independent of the numerical fluctuations contrarily to the flow angle. It is beyond the scope of this paper to address the problem of the fluctuations around the mean behaviour. Nevertheless, these results point out that the development of density fluctuations by the mean field reproduces the mean trend of the experimental data. This fact is endorsed by the observation in experimental data as well as in simulations of the independence of the global observables on the fragment multiplicity [17]. For the peripheral collisions corresponding to the greatest TKE values, some departures between the theoretical values and the experimental ones exist. They might result from the lack of non-locality in the effective interaction used here since it plays a significant role in the fragment deflexion in peripheral reactions as observed in Ref [28].

The dinuclear structure in the multifragment distribution is currently put forward in the interpretation of the data relative to the central collisions of heavy systems. In figure 9b, the fragment charge versus $V_{||}$ is displayed in contour plots. Results of simulations at different impact parameters are given by dots. The binary structure appears effectively experimentally for events corresponding to the most central collisions for a multiplicity of heavy fragments equals to four. As already stated, the sampling of the phase space performed in the simulation induces numerical density fluctuations propagated by the mean field. The LV

simulation giving only the mean behaviour of the observables cannot reproduce the experimental large dispersion. Nevertheless, the charge distribution of the produced fragments follows a "U" shape coherent with the experimental trend reminiscent of a di-nuclear structure and indicating a memory of the entrance channel as already underlined in figure 4. The overall correct agreement with the data for all impact parameters authorizes further investigation at different beam energies.

8. Dependence of the fragmentation process on the projectile energy

The evolution of the disassembly mode with energy is described in figures 10 and 11 for the $^{208}\text{Pb}(29 \text{ MeV/u}) + ^{197}\text{Au}$ reaction at $b = 2 \text{ fm}$. The compression and expansion phases occur at all energies. With increasing energies the compression stage is more rapid and lead to slightly higher maximal densities. Nevertheless, the threshold of $0.12 \text{ nucleon/fm}^3$ is not exceeded. The minimal density at the end of the matter expansion is more energy dependent. At 55 MeV/u , the mean density reaches a minimal value as low as $0.033 \text{ (nucl/fm}^3\text{)}$ while the expansion time remains almost constant. The increasing dilution with energy in this second stage explains the highest loss of collective and Coulomb energies and their conversion in surface energy. On an average, the number of fragments and their sphericity increases with the beam energy while the formation time diminishes. At 20 MeV/u the reaction looks like a binary deep-inelastic scattering. It might be possible that the two deformed fragments, later on, undergo fission but we cannot deal with such a long time of the order of perhaps 10^{-20} s . In contrast, at 55 MeV/u the great amount of available energy does not allow the relaxation of the expanded system through exotic shapes like bubbles. The clusterization phase follows immediately the expansion phase, releasing simultaneously several spherical fragments but also elongated fragments which subsequently will decay. Then, the fragmentation in a bubble-like manner takes place only in an energy window excluding the highest intermediate energies where the fragmentation rather looks like a condensation process of dilute nuclear matter.

9. Conclusion

We have reported calculations on the dynamics of the $^{208}\text{Pb}(29 \text{ MeV/u}) + ^{197}\text{Au}$ reaction within the semi-classical Landau-Vlasov model including a Uehling-Uhlenbeck collision term and a soft equation of state with an isospin dependence. Fragmentation following the formation of a bubble-like nuclear system is predicted. The different phases of the reaction are successively : compression till a density value of about $0.11\text{-}0.12 \text{ nucleon/fm}^3$, expansion till a threshold of $\rho \sim 0.05\text{-}0.06 \text{ nucleon/fm}^3$, formation of a hole at the center of the matter distribution leading to a thin skinned bubble-like configuration and development of surface instabilities causing the emission of several fragments. The fragmentation does not take place if the Coulomb interaction or the asymmetry neutron-proton are disregarded. On the contrary, fragmentation in a bubble-like manner occurs also if a stiff equation of state is used but the density variations and the expansion are less important. Results of simulations at several impact parameters are in agreement with the experimental Wilczynski diagrams and plots of charge number versus $V_{||}$. At $b = 2 \text{ fm}$ and for a beam energy of 20 MeV/u the reaction looks like a deep-inelastic scattering. At 55 MeV/u the reaction is so violent that the expansion phase leads to very low mean densities ($\sim 0.033 \text{ nucleon/fm}^3$)

and the condensation of the very dilute matter into several fragments happens immediately without the formation of an exotic bubble.

In this type of fragmentation, the dynamics plays an essential role since it brings the nuclear system through the very peculiar path leading to the bubble-like configurations on the multi-dimensional potential surface. This does not exclude the fragmentation to be statistical later on. The symmetry and the very high mass involved in this reaction explain the initial compression and, consequently, the nature of the fragmentation. Very asymmetric reactions even at higher intermediate energies cannot induce such compression effects and the observed fragmentation in such a case has probably another origin.

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FIGURE CAPTIONS

Figure 1 : Time evolution of the nuclear densities. The time (fm/c unit) is given in the right upper corner of each panel. The horizontal and vertical coordinates are in fm. The upper and middle parts show the densities in the different planes indicated on the right side while the lower part displays the projected densities on the reaction plane.

Figure 2 : Number of evaporated nucleons and protons as a function of time in the Pb (29 MeV/u)+Au reaction at $b = 2$ fm.

Figure 3a : Time evolution of the mean density ρ (nucl/fm³), the surface, Coulomb and collective energies (in MeV).

Figure 3b : Energy contributions as a function of time for the central reaction Pb (29 MeV/u)+Au at $b = 2$ fm.

Figure 4 : Time evolution of the nuclear density (nucl/fm³), of the projectile in the reaction plane (upper and middle parts). For comparison, the projected densities (arbitrary units) on the reaction plane of the projectile and target at the end of the reaction are displayed in the lower part. The horizontal coordinates are in fm.

Figure 5a : Time evolution of the mean density ρ and the surface energy in the reaction Pb (29 MeV/u)+Au at $b = 2$ fm when the Coulomb interaction is not taken into account.

Figure 5b : Energy components as a function of time when the Coulomb interaction is not taken into account.

Figure 6 : Comparison of the densities averaged along all directions for the Pb (29 MeV/u)+Au reaction at $b = 2$ fm calculated with an isospin dependent interaction (upper part) and without isospin dependence (lower part).

Figure 7a : Time evolution of the projected nuclear densities in the Pb (29 MeV/u)+Au reaction at $b = 2$ fm when the collisions are not taken into account.

Figure 7b : Energy components as a function of time when the collisions are not included.

Figure 8a : Time evolution of the densities in the different planes calculated with a stiff equation of state.

Figure 8b : Time evolution of the mean density ρ (nucl/fm³), the surface, Coulomb and collective energies (in MeV) calculated with a stiff equation of state.

Figure 9a : Comparison between the generalized Wilczynski diagram (extracted from [17]) for a fragment multiplicity $M_f > 3$ and our theoretical results (indicated by dots) obtained from different simulations and different impact parameters. The solid line corresponds to the mean value calculated within a macroscopic model [17-18].

Figure 9b : Comparison between the experimental plots [17] of atomic number Z versus $V_{||}$ for a fragment multiplicity $M_f = 4$ and theoretical results.

Figure 10 : Time evolution of the projected nuclear densities for three different beam energies : 20, 40 and 55 MeV/u.

Figure 11 : Comparison of the evolution of the mean density, the surface, Coulomb and collective energies for four different incident energies (indicated on the upper left panel).

Figure 2

Figure 1

Figure 4

PROJECTILE

TARGET

Figure 5b

Figure 5a

Figure 6

Figure 7a

Figure 7 b

Figure 8 a

Figure 9 a

Figure 8 b

Figure 9b

Figure 10

Figure 11