TOWARDS A BETTER UNDERSTANDING OF DYNAMICS IN NUCLEAR REACTIONS BELOW 100 MeV/nucleon

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Abstract

Features of emitted charged particles in heavy ion reactions have been studied in the framework of the semi-classical Landau-Vlasov approach for the light system Ar + Al at 65 MeV/nucleon incident energy. Most of the recent experimental results suggest the binary nature of the reaction mechanism over a large impact parameter range. We draw the same conclusion from our simulation. Contrary to the expectations that at these energies a mechanism reminiscent of low energy deep-inelastic reaction could create two very excited sources (the primary quasiprojectile and quasitarget), the model calculation shows that this reaction mechanism is closely connected to the participant-spectator picture. In such scenario, the primary quasiprojectile and quasitarget can be identified as not very hot spectators. This stems from an abundant dynamical (participant) emission centered at mid-rapidity but covering all the rapidity range accessible to the collision and coming from the overlapping, i.e. participant zone of both incoming nuclei. Owing to Coulomb interaction with the quasiprojectile and the quasitarget, these participant particles behave as evaporated particles. From an experimental point of view, it is thus a real challenge to disentangle between dynamical and thermodynamical components.

1 Introduction

In the incident energy range starting from Fermi energy up to 100 MeV/nucleon the reaction cross section is dominated by the so-called binary dissipative collision (BDC) [1–11]. In most of the experimental papers devoted to this topic [5–9], this reaction mechanism typical for intermediate energies is schematically described as a two-step process. In the first step, particles are emitted from the interaction zone. Depending of the authors, these particles are called either pre-equilibrium or participant or also midrapidity particles. Whatever the name is, this emission is governed by the dynamics of the collision. In this contribution we will call it Dynamical Emission (DE). The second step of the collision is characterized by the formation of two excited nuclei generally referred to as quasiprojectile (QP) and quasitarget (QT). These two nuclei decay by Statistical Emission (SE).

Below Fermi energy the number of mid-rapidity, i.e. "stopped" particles is negligible. On the contrary, at relativistic energies, this number is large and determined by the geometrical

overlap between the two incoming nuclei. Moreover, owing to the large rapidity domain accessible at high incident energies, this emission can be unambiguously separated from emissions coming from the spectators. In the incident energy range which we are interested in, it is more difficult to properly separate the mid-rapidity (DE) from SE particles mainly because of the small relative velocities of the QP and the QT. This can imply a mixing between the two emission components. In the light of very recent experimental works [12–15] many questions concerning the role of the dynamics in BDC are still opened: What is the relative contribution of the DE? How does it evolve with the impact parameter and the incident energy? Are we able to really decouple DE and SE in order to justify the study, in terms of thermodynamical variables, of the primary QP as a representative of very hot equilibrated nuclei? Related to the above questions, the obvious and crucial problem is: What are the consequences of the DE on hot nuclei formation and decay?

These questions have been addressed in many experimental publications devoted to the study of hot nuclei. In most of these works it is commonly assumed that all the particles emitted in the forward hemisphere of the QP have a statistical origin. This assumption is based on the fact that the measured angular distributions of charged particles in the frame of the QP are flat below 90° and thus consistent with an emission from an equilibrated nucleus. It is then possible to reconstruct the primary QP and to derive its physical properties. It has been concluded from such studies that:

- The DE is weak and slightly dependent of both the impact parameter and the incident energy.
- It is strongly located at mid-rapidity and negligible in the forward hemisphere of the QP.
- It is possible to decouple thermodynamical (SE) and dynamical (DE) components.
- Consequently, the BDC's are considered as a powerful tool for forming very hot nuclei. For light systems excitation energies and temperatures exceeding, respectively, 20 MeV/u and 18 MeV could be reached as it is the case with the QP formed in the Ar+Ni collision at 95 MeV/nucleon [8, 16, 17].

The goal of this work is to provide some theoretical answers on the above questions using a dynamical transport model. We used the Landau-Vlasov (LV) model which has been already successfully applied to describe a number of properties of heavy ion reactions in this energy range [18–21].

The LV model [22] is based on the quantum Boltzmann equation which is solved for a non-local effective force (Gogny D1-G1) [23, 24] by projecting the one-body nuclear phase space onto a continuous basis of thousands (here 100 per nucleon) of coherent states taken as elementary Gaussian functions. Without entering into the details of the model [22, 25], in the following we just outline the main features relevant to our present study.

Within the one-body approximation the distinction between coherent states bound in a nucleus and those which have already left it (referred as *emitted* or *free particles*, i.e., Gaussians), constitute a conceptual difficulty. Therefore, let us explain the two-step procedure which we used to define the set of particles forming massive cluster(s). In the first step, one searches regions of **r**-space for which the local spatial density is higher than the threshold $\rho_o/3$, ρ_o being the normal nuclear density. The chosen factor of 3 allows for the early recognition of massive clusters. In the second step the diffusivity of each primary detected cluster (PDC) is taken into account. Every non-bound particle sitting in the neighborhood

of a PDC and for which the local density is greater than $\rho_o/30$ is considered as belonging to this PDC. The rest of the system constitutes the ensemble of emitted particles. Concerning both the size of PDC and the amount of free particles, the explained procedure gives the equivalent result as the usual method in which a sharp cut-off at $\rho_o/8$ is performed.

We have chosen to investigate the Ar+Al collision at 65 MeV/u because this system has been extensively studied experimentally [7,26–34]. The simulation is performed at five impact parameters ranging from b=0.5 fm (central collisions with full overlap) to b=6.5 fm (peripheral collisions with less than 3 fm overlap between the projectile and the target). In order to follow the nuclear dynamics into the domain of statistical decay [35, 36] allowing for the quantitative comparison of experimental global observables, all simulations have been carried out up to 800 fm/c, and beyond this time up to 8 000 fm/c considering only the Coulomb repulsion.

2 The binary nature of reaction mechanism

To have a general overview of reaction mechanisms predicted by the model in Fig. 1 are shown the density-profiles contours projected onto the reaction plane for the five studied impact parameters. All these plots have been calculated at 100 fm/c, i.e. after the QP and the QT have been already separated. From the figure one concludes: i) The model agrees with the binary nature of the reaction mechanism in the sense that at all impact parameters two sources (QP and QT) are formed in the exit channel. ii) There is a strong memory of the entrance channel, even in the most central collision, as exemplified by columns b) and c) which show the density profiles of the particles initially belonging to the projectile and to the target. As can be observed in Fig. 1, only a small part of particles is transfered between collision partners. iii) In the full accordance with the experiment [7], there is no fusion-like residue at this incident energy.

The advantage of a dynamical model is an obvious possibility to follow in time the different steps of the collision. The simulated time evolution of the density profiles at b=3.5 fm is displayed in Fig. 2. For BDC the most crucial instant of the reaction is the separation time $t_{\rm sep}$ which corresponds to the birth of the primary QP and QT. We will show that time $t_{\rm sep}$ cut the emission process into the dynamical and the statistical regime. The separation time steadily evolves from 50 fm/c in peripheral collisions up to 80 fm/c in the most central collisions studied (see heavy vertical bars in Fig. 3), e.g. at b=3.5 fm $t_{\rm sep}$=60 fm/c (Fig. 2). Figure 3 displays the particle emission rate emphasizing its dependence with respect to the $t_{\rm sep}$. At all bs, the DE displays bell-shaped emission rate with its summit at about 40-50 fm/c whose value strongly decreases with increasing b but whose position slightly depends on b. Undoubtly, a large portion of particles is emitted before $t_{\rm sep}$. We consider all the particles emitted before $t_{\rm sep}$ as the DE and all the particles emitted after $t_{\rm sep}$ as the SE. Let us justify that a simple cut in time does separate dynamical and statistical components. The best way to do that is to determine the phase space origin of these two components. Indeed, one could think of a very fast evaporative process beginning before the separation of the two exit channel nuclei which would heat mutually by traversing each other. In this case, statistical emission might start before $t_{\rm sep}$.

Let us mention at this point that the clarity of the exposition guided us to deliberately

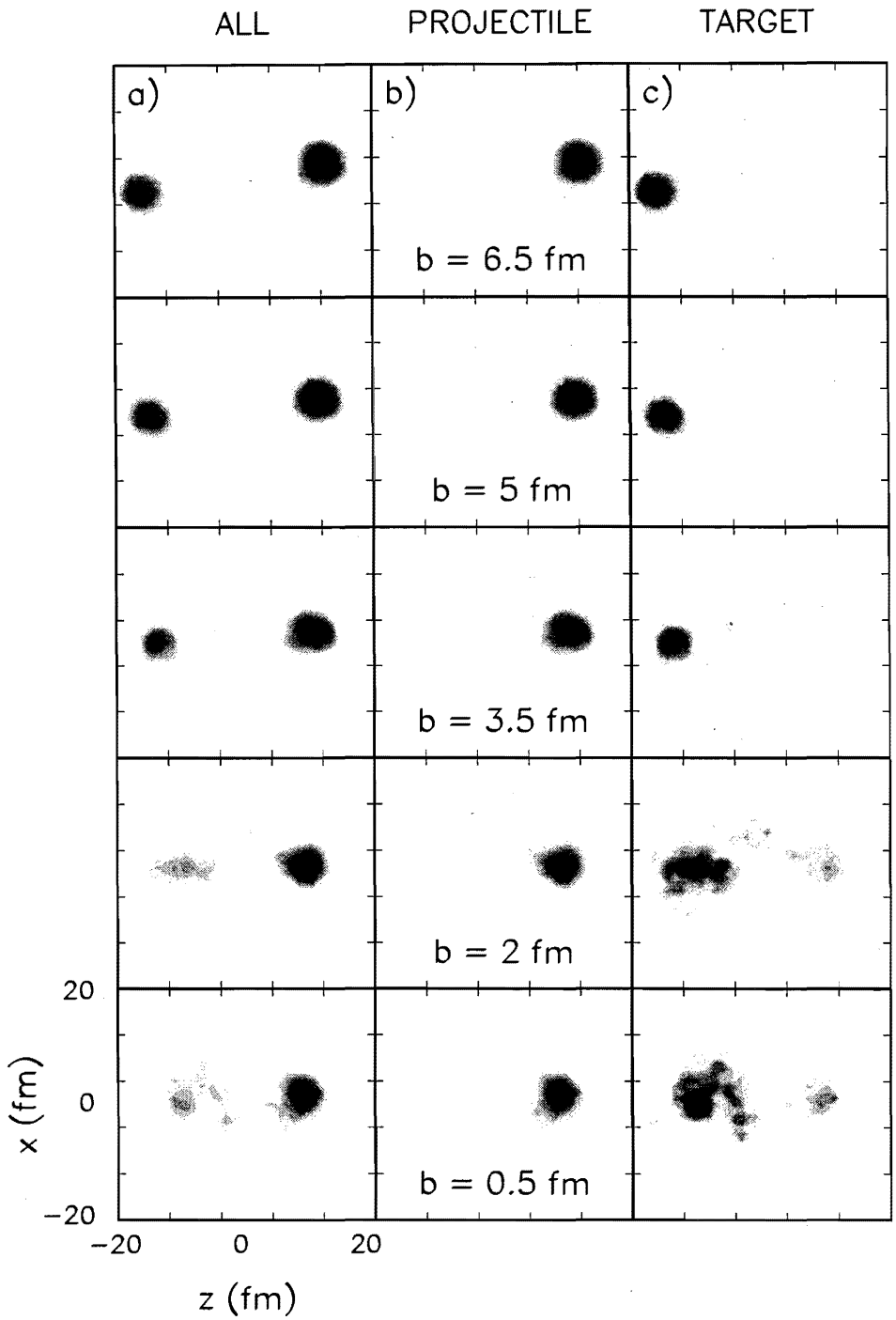

Figure 1: Equidistant density-profiles contours projected onto the reaction plane for b varying from 0.5 fm (bottom) to 6.5 fm (top) [column a)]. Columns b) and c) show density profiles of the particles initially belonging to the projectile and to the target, respectively at 100 fm/c. The z axis is along the projectile direction.

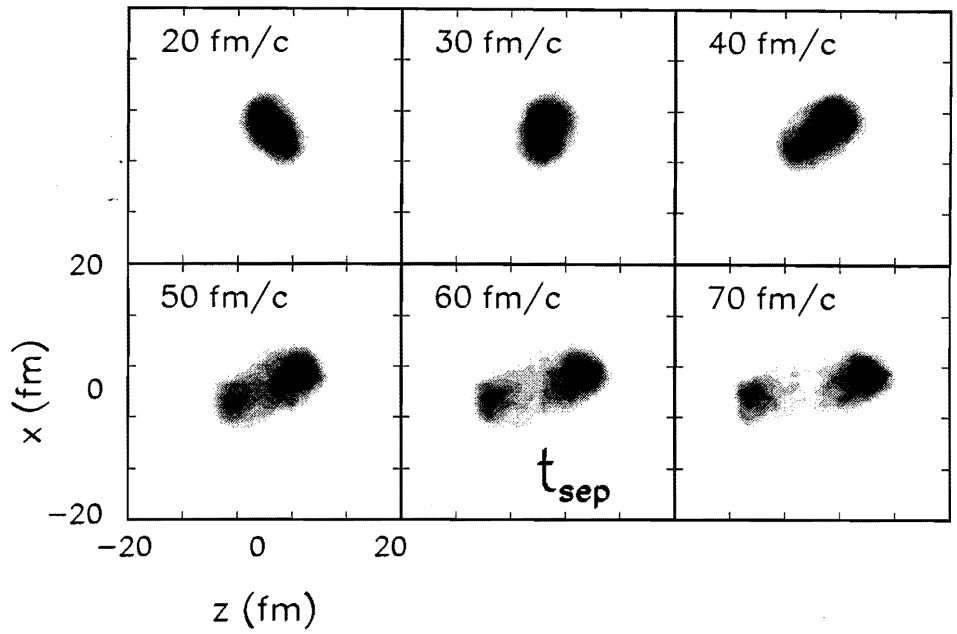

Figure 2: Time evolution of the equidistant density-profiles contours projected onto the reaction plane at b=3.5 fm. The separation time $t_{\rm sep}$ is equal to 60 fm/c. The z axis is along the projectile direction.

forget that DE in fact consists of two components: the small pre-equilibrium component and the dominant mid-rapidity component (for more details see Ref. [37]).

3 Phase space origin of the emitted particles

Figure 4 displays density profiles in both the configuration (top) and the momentum space (bottom) calculated for b=5 fm. Results are presented at three particular times: at the instant of maximal compression (20 fm/c), at the time at which the local momentum distribution becomes spherical, i.e. when the dynamical emission actually begins [37] (35 fm/c) and at $t_{\rm sep}$=60 fm/c. In columns a) to c) are presented the profiles of those particles which will be among emitted particles at $t_{\rm sep}$ (DE), the column d) shows the density profiles of the entire system and column e) shows profiles of those particles which will be emitted after $t_{\rm sep}$ (SE). Column a) refers to DE belonging to the projectile, b) to DE of the target and c) displays profiles of all DE. In fact, Fig. 4 shows the **r**- and **p**-space origin of selected emitted-particles groups by reversing the flash of time.

Let us discuss first the configuration space. If we look for example at 35 fm/c, it appears that particles emitted before $t_{\rm sep}$ are located unambiguously in the overlapping zone of the projectile and the target. Obviously, these particles do not come from any hypothetical pre-formed source which would correspond to a very early formation of the primary QP and QT, i.e. before their spatial separation. On the other hand, particles emitted after $t_{\rm sep}$ come from two distinct sources, the QP and the QT [see column d) at t=60 fm/c], and which are before $t_{\rm sep}$ regularly distributed over the whole system (see either at 20 or 35 fm/c). The

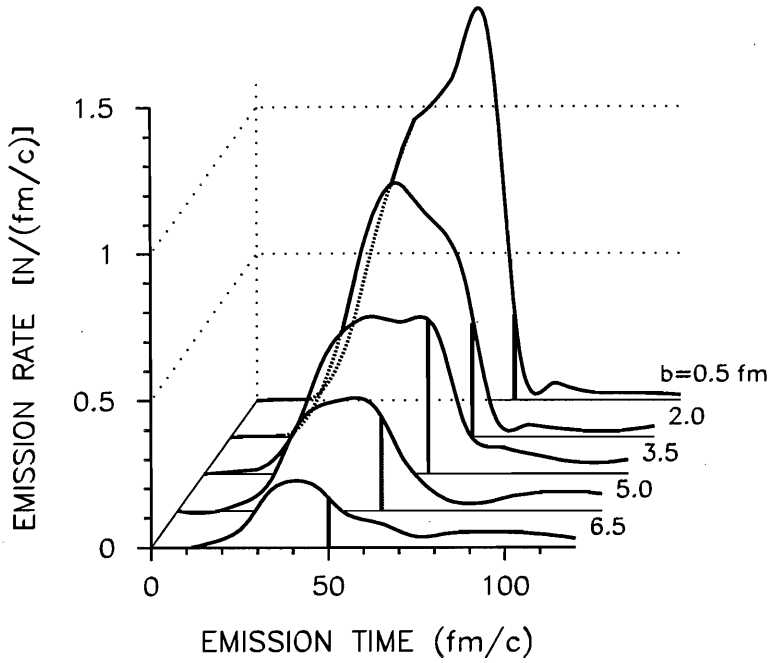

Figure 3: Number of emitted particles per 1 fm/c as a function of time for five impact parameters. The vertical solid bars correspond to the separation time $t_{\rm sep}$.

momentum space density profiles corroborate the above conclusions. While at 35 fm/c the DE are located at midrapidity, the SE shows the same behavior observed for global system without any privileged direction of emission as expected for a statistical emission from a thermalized source. Taking the above results at their face value, one concludes that the emission process occurring before the $t_{\rm sep}$ is dominated by the dynamical effects while as soon as the primary QP and the primary QT appears in the exit channel the emission process is governed by statistics. This justifies our appellation SE and DE.

Let us underline that the DE behaves like the participant emission observed at higher energies and explained within the geometrical participant-spectator picture. However, in this picture, it is supposed that the nucleons are swept out the projectile and the target overlapping zone identified as a hot quasi-equilibrated fireball which decays as an ideal gas. For the shown peripheral collision (namely, b=5 fm) one remarks two components in the "participant zone" [bottom column c)]. This is a clear signature that no global equilibrium is achieved in the participant zone and that the memory of the entrance channel is preserved. This last point is illustrated by the columns a) and b) of Fig. 4. Let us notice that such pattern disappears when impact parameter decreases (see Fig. 7 in Ref. [37]). That can be interpreted as a consequence of growing interaction zone with collision centrality. The nucleons have to cross a larger and denser nuclear matter that favors an increasing number of nucleon-nucleon collisions inside the participant zone. This implies a quasi-complete mixing of the projectile and the target nucleons. The separation time is then longer, bringing the system to forget the kinematics of the entrance channel and forming a system which has properties very similar to those of a single equilibrated source [38]. Such an anisotropic effect in the participant zone could have been seen in Xe+Sn collision at 50 MeV/u [39].

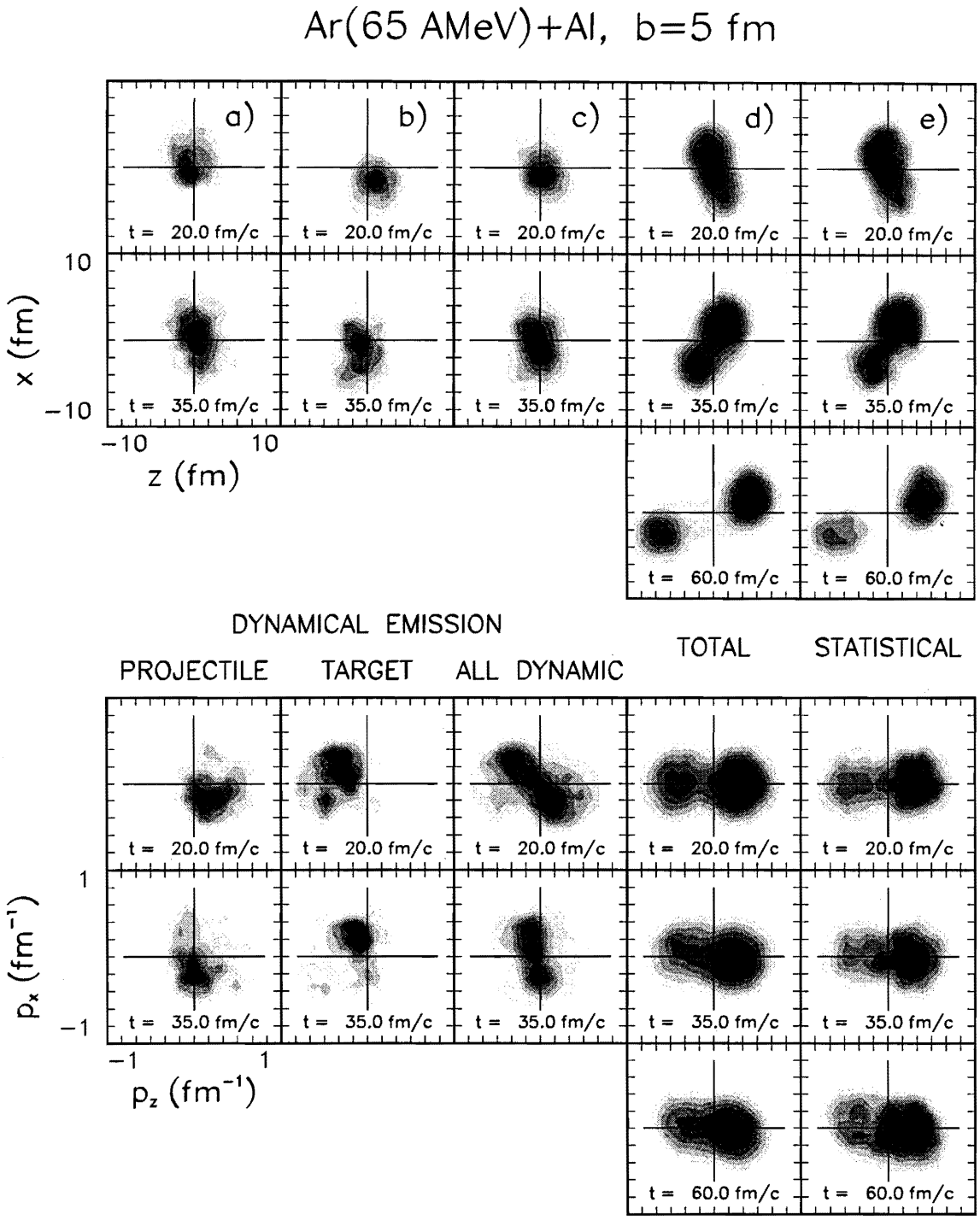

Figure 4: Equidistant density-profiles contours projected onto the reaction plane for b=5 fm at three different times (see text for more details).

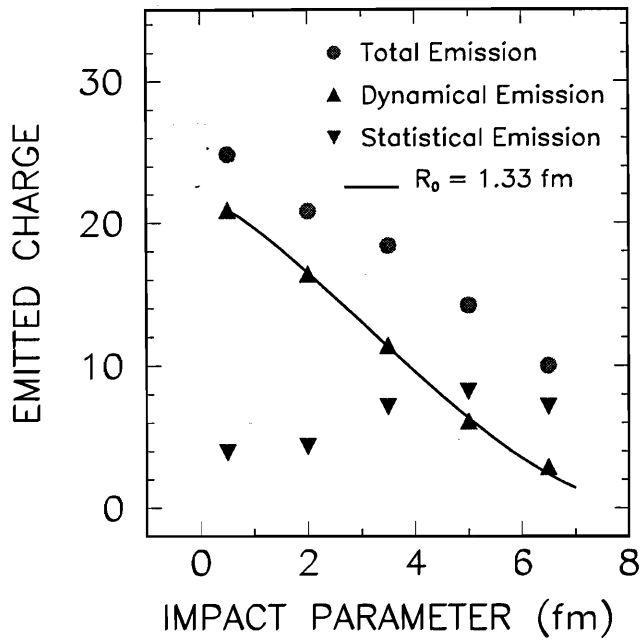

Figure 5: Calculated multiplicity of emitted charged particles for various particle groups as a function of b. Presented is dynamical component consisting of particles emitted before t_{sep} (triangles) and statistical component emitted after t_{sep} (reversed triangles). The summed contribution of both components is shown by circles.

4 Properties of dynamically emitted particles

In our one-body approach each particle carry the same charge so that the total emitted charge is equivalent to the multiplicity of charged particles. This quantity is shown in Fig. 5 as a function of impact parameter. As expected, the total multiplicity increases steadily with the violence of collision (circles). It displays close-to-linear dependence on b and does not saturate with centrality. Such a behavior results from presenting the total charge and not the true particle multiplicity.

The most striking feature is the strongly increasing contribution of the DE with the violence of the collision. Below $b \approx 4$ fm DE becomes dominant. This behavior can be very well reproduced in the participant-spectator scenario as shown by the solid curve which represents the geometrical overlap of two spheres having the radii $R = R_0 A^{1/3}$ with $R_0 = 1.33$ fm. To fit the data this curve is normalized by a factor of 0.75. Although one does not face the pure participant-spectator scenario, the geometry obviously plays a major role in the emission process at incident energy as low as 65 MeV/u.

As a consequence of the large amount of DE (up to 70% of the system charge), the second striking feature is that the SE does not increase with the centrality of the collision. That is a qualitative indication that the total excitation energy of the QP and the QT is not maximal in central collision.

Kinematically DE and SE behave quite differently: while SE is centered around the QP and the QT rapidity as expected for a two-sources emission process, DE is for all bs sitting at mid-rapidity (see Fig. 6). An interesting feature of the DE is that these particles also cover the whole rapidity domain kinematically accessible to the collision including the rapidity beyond the QP rapidity [37] where its contribution is generally considered as negligible in experimental studies.

The experimental angular distributions exhibit fairly constant behavior below 90° in the

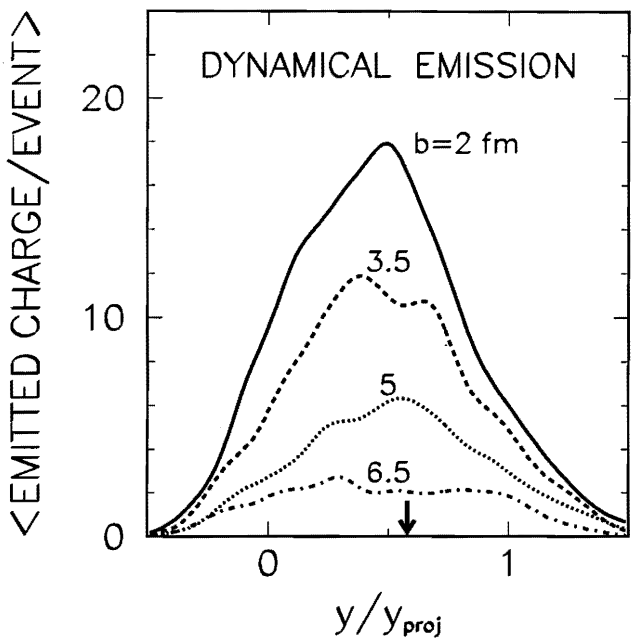

Figure 6: Rapidity distributions of dynamically emitted charged particles as a function of impact parameter. The c.m. rapidity is marked by an arrow.

QP forward hemisphere [7, 32]. Therefore, it has been admitted that the source (primary QP) was in thermal equilibrium. To avoid contamination from the non-QP sources, only particles emitted into the forward hemisphere of the QP have been integrated and the obtained result has been multiplied by two. The theoretical global angular distributions are also flat below 90° in the QP reference frame [37]. In the simulation, however, not only SE but also DE displays flat distribution in the forward QP hemisphere. Such a behavior is due to the QP Coulomb field which distorts the initial characteristics of the DE [37] rendering impossible the distinction between DE and SE via angular dependence. By integrating these angular distributions as in the experimental analysis, one quantitatively derives presumed primary QP emitted charge (circles in Fig. 7) and also the DE (triangles) and SE (reversed triangles) contributions. The calculation agrees favorably well with the experimental total emitted charge (hatched area in Fig. 7). The DE, originating from the interaction zone, dominates the reconstructed central-collisions multiplicity and exhibits almost linear rise with centrality. The true primary QP emission (SE) is almost b independent. Above results are in favor of conclusion that, independently of the violence of the collision, the primary QP is not very hot.

From the known multiplicity of emitted particles it is straightforward to reconstruct the mass of the primary QP. In Fig. 8 open triangles show the measured QP residue mass as a function of b [7]. The experimental reconstruction of the primary QP mass suggests that, independently of b, its value is very close to the projectile mass (dashed line) [7]. The calculated QP mass (open circles) agrees reasonably well with experimental findings (open triangles). On the contrary, the primary QP mass determined in the simulation at the instant $t_{\rm sep}$ (filled circles) differs substantially from the values extracted in the experimental analysis (filled triangles). The calculated primary QP mass grows linearly with b. In central collisions the discrepancy is as large as 18 mass units. For peripheral collisions the DE becomes a small portion of the total emission (cf. Fig. 7) and the theory and experiment give the same

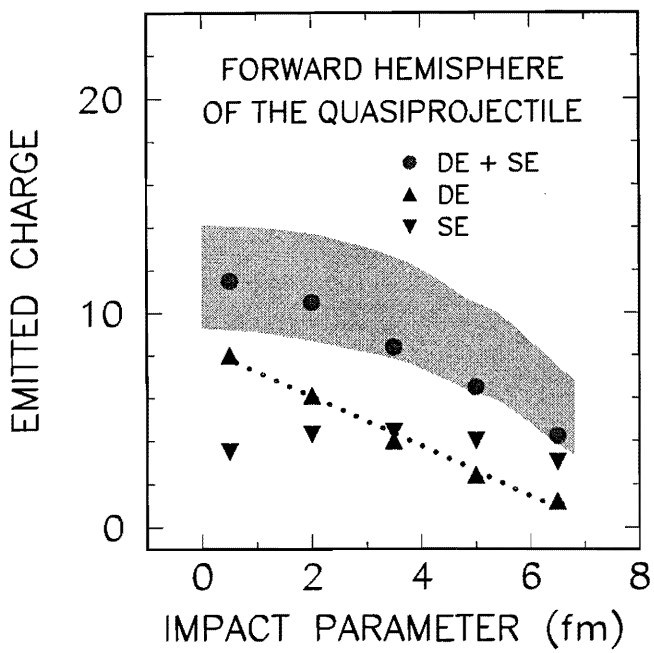

Figure 7: Reconstructed charge "emitted by primary QP" as a function of impact parameter. Triangles show the contribution of the dynamical component (coming from the mid-rapidity source prior to the birth of the QP and the QT), reversed triangles of the thermal component (the genuine primary QP emission), and circles show the sum of both. The hatched area represents the experimental multiplicity. Lower edge is due to the contribution of the $Z = 1$ and 2 particles exclusively, whereas the upper edge includes all detected species.

values for primary QP mass.

5 Conclusions

The theoretical studies of the collision of Ar + Al at 65 MeV/u with the semi-classical Landau-Vlasov transport model are in fair quantitative agreement with the global experimental distributions. The meticulous dynamical analysis of emitted charged particles suggests that before the birth of the QP and the QT, there is an abundant dynamical emission (DE) coming unambiguously from the overlapping zone between the two partners of the collision. The DE reminds of the fireball-participants particles of the participant-spectator picture of high-energy collisions. Negligible in peripheral reactions, DE amounts up to 70% of the total emission for the most central collisions. Mainly located at mid-rapidity, this emission covers the entire rapidity range accessible to the reaction and, therefore, contaminates the forward hemisphere of the QP. This portion of the phase space is in the analysis of experimental data solely attributed to the QP de-excitation [7, 17, 32]. This observation has a strong impact on the formation of very hot primary QP and QT in the exit channel. Our simulation suggests that in the analysis of experimental violent collisions both the mass of primary QP and the amount of particles emitted by it have been largely overestimated [7, 17, 32]. Indeed, DE amounts 70% of the forward QP emission for the most central collisions probably reducing the excitation energy of the primary QP. Unfortunately, from our calculation it turns out that it is virtually impossible to distinguish in the experimental data DE and SE component.

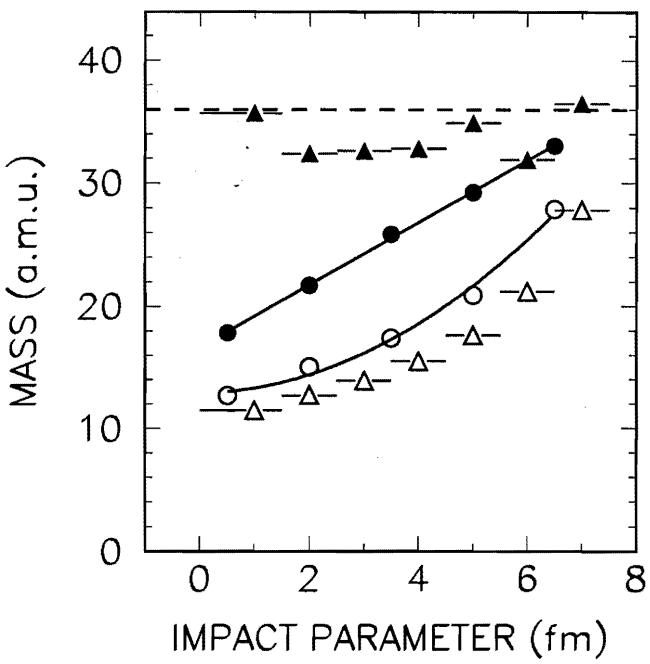

Figure 8: Impact parameter dependence of the cold QP (open symbols) and the primary QP (filled symbols) masses. Triangles show the experimental and circles the theoretical results. Dashed horizontal line shows the projectile mass. The solid line and curve through calculated values are drawn to guide the eye and are due to the fit with a linear and quadratic function, respectively.

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