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Dynamical effects on the quasiprojectile temperature in the Ar + Al reaction

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Abstract. The temperature of the quasiprojectile (QP) emerging from binary collisions of the light Ar + Al system at 65 MeV/nucleon is studied theoretically in the framework of the Landau-Vlasov dynamical model. The slope parameter of a charged-particle kinetic-energy spectrum, calculated in the forward-hemisphere of the QP reference frame, is taken as the apparent temperature. The apparent temperature associated to the true QP emission displays a weak dependence on the impact parameter and the hottest primary QPs are formed at intermediate values of b.

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1 Introduction

The production and study of hot nuclei are one of the major axes of research in intermediate-energy heavy-ion collisions. A number of recent experimental studies seem to indicate that *binary dissipative collisions* (BDC), which strongly dominate the reaction cross-section above the Fermi energy [1–5], are considered as an efficient way to create very hot and thermodynamically equilibrated nuclei [2,4,6]. Very high temperatures (of the order of 20 MeV) and deposited excitation energies per nucleon largely beyond the nucleon binding energy have been reported for rather light systems [3,4]. The claimed experimental observation can be reproduced within the framework of a statistical model [7,8]. However, an obvious shortage of a statistical-model approach is the complete neglect of any possible dynamical effect. It is, therefore, essential to address the above issues using a dynamical approach, which is more appropriate to bring into prominence the possible role that the dynamics plays in binary processes, the excitation energy and temperature of formed nuclei being essential observables to be studied. Moreover, the most recent experimental results reported for charged particles [5, 9,10] and neutrons [11] explicitly urge to dynamical studies.

In this paper we report on the temperature of the quasiprojectile (QP) emerging in the Ar + Al reaction at 65 MeV/nucleon investigated by means of the Landau-Vlasov (LV) semiclassical transport model [12]. This reaction is chosen since it has recently been extensively studied experimentally [2,6,13]. The dynamical LV model with the momentum-dependent effective force D1-G1 due to Gogny generates a well-defined nuclear mean field and also includes the Coulomb interaction [14]. The residual interaction was treated as hard stochastic scattering taking into account energy and momentum conservation as well as the Pauli exclusion principle. Simulation was performed for five impact parameters spanning the entire range from peripheral to central collisions ($b = 0.5$–6.5 fm). All LV simulations were carried out up to 800 fm/c. Beyond that time the calculation was continued until 8 000 fm/c considering only the Coulomb repulsion due to reaction residues in order to achieve the correct asymptotic directions of emission.

2 Dynamical and statistical regimes of emission

In full accordance with the experiment [2], the model predicts no fusionlike residues at this energy and the collision is of binary nature for every b [15,16]. 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 quasitarget (QT). We show that the time $t_{\rm sep}$ cuts 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. Figure 1 displays the particle emission rate emphasizing its dependence on the $t_{\rm sep}$, which is marked by heavy vertical bars. Prior to $t_{\rm sep}$ the emission

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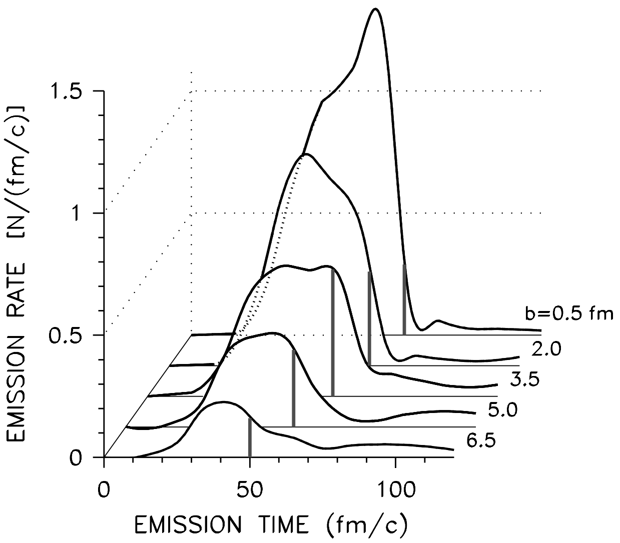

Fig. 1. Number of emitted particles per 1 fm/c as a function of time for five impact parameters indicated on the right side of each curve. The vertical solid bars correspond to the separation time of the primary QP and QT.

rate displays a bell-shaped curve with its summit at about 40–50 fm/c. The value of the summit decreases strongly with increasing b, but its position depends slightly on b. Undoubtedly, a large portion of particles is emitted before $t_{\rm sep}$ [15,17]. We consider all particles emitted before $t_{\rm sep}$ as *dynamical emission* (DE)[1]. The question of the dynamical emission at midrapidity is an extremely difficult experimental problem. However, it has recently been addressed in several works [11,18]. The emission rate after $t_{\rm sep}$ is calm and very much evaporationlike [15,17,19]. Hereafter, we call it *statistical emission* (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 each of them.

Figure 2 displays density profiles in the configuration (top) and the momentum space (bottom) calculated for $b = 5$ fm. In fact, it shows the **r**- and **p**-space origin of selected emitted-particle groups by reversing the flash of time. Columns a) to c) present the profiles of those particles which will be among emitted particles at $t_{\rm sep}$ (DE), column d) shows the density profiles of the entire system, and column e) shows the profiles of those particles which will be emitted after $t_{\rm sep}$ (SE). Column a) refers to the DE of the projectile, b) to the DE of the target, and c) displays the profiles of full DE. The 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 and which is approximately the time when the dynamical emission actually begins (35 fm/c), and at $t_{\rm sep} = 60$ fm/c.

Let us first discuss the configuration space. For example, looking 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 preformed 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 e) at $t = 60$ fm/c), and are regularly distributed over the whole system before $t_{\rm sep}$ (compare columns d) and e) at 20 or 35 fm/c). The momentum-space density profiles corroborate the above conclusions. Whereas the DE at 35 fm/c is located at midrapidity, the SE shows the same behavior observed for the global system, *i.e.*, without any privileged direction of emission, a feature typical for the statistical emission from a thermalized source. The fundamental difference in the physical properties of these two emission groups is remarkably displayed through their rapidity distributions. Whereas DE dominates the midrapidity region, SE displays a two-component structure: one sitting at the QT and the other at the QP rapidity (see fig. 3 in [20]). Taking the above results at their face value, one concludes that *the emission process occurring before $t_{\rm sep}$ is dominated by the dynamical effects, whereas the emission process is governed by statistics as soon as the primary QP and the primary QT appear in the exit channel.* This justifies our appellation DE and SE.

Let us mention that the behavior of DE reminds us of the participant emission observed at higher energies and explained within the geometrical participant-spectator picture [21]. According to this picture, the nucleons are swept out of the projectile and target overlapping zone, a hot quasiequilibrated fireball, which decays as a gas. For the shown semiperipheral collision, however, one observes two components in the "participant zone", one of the projectile and the other of the target (bottom column c), but also columns a) and b) of fig. 2). This indicates that no global equilibrium is achieved in the zone of overlap and that the memory of the entrance channel is preserved. For smaller b, the zone of overlap will increase inducing an increasing number of nucleon-nucleon collisions due to larger and denser nuclear matter which nucleons have to cross. Therefore, in central collisions one may expect a quasicomplete mixing of the projectile and target nucleons. The separation time would then be longer, bringing the system to forget the kinematics of the entrance channel and to possibly attain properties similar to those of a single equilibrated source [22]. A detailed study of DE as a function of energy, b, and system size and symmetry is reported elsewhere [17].

3 Results and discussion

We have shown that the simple cut of the emission process into two components as a function of time is the most nat-

[1] Let us mention at this point that, for the clarity of presentation, we deliberately forget that DE in fact consists of two components: the small pre-equilibrium component and the dominant midrapidity component. Also, we do not consider the less important problem of the necklike emission in small systems. For more details on these issues, see ref. [15].

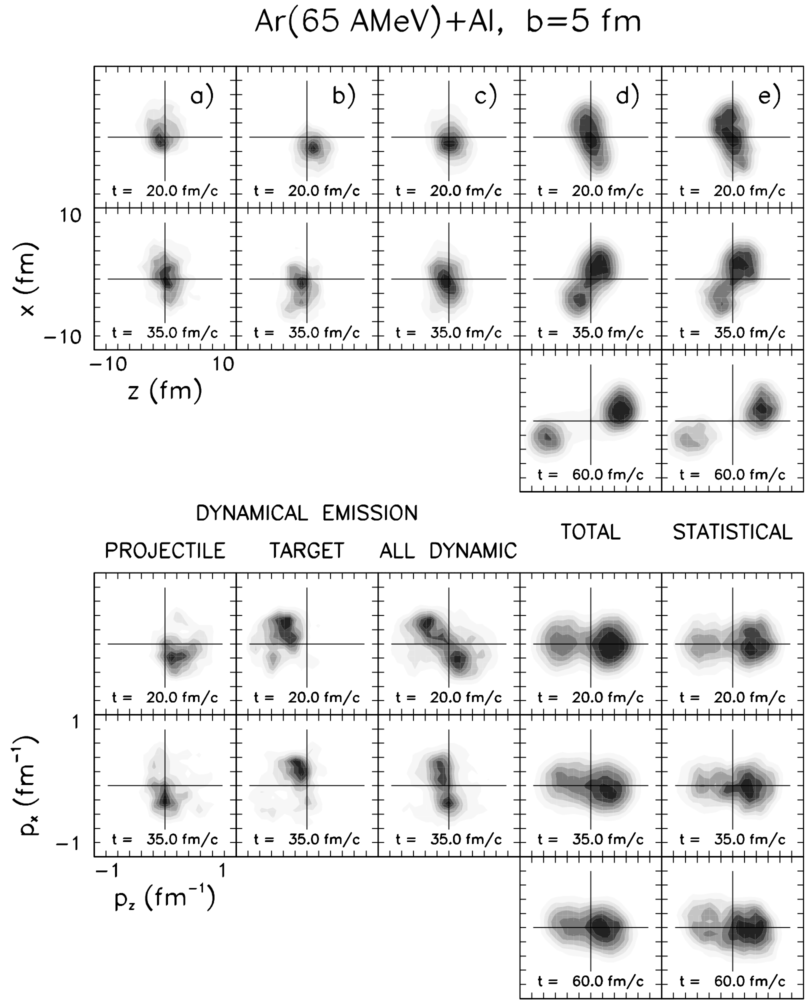

Fig. 2. Equidistant density-profile contours projected onto the reaction plane for $b = 5$ fm at three different times. The z-axis is along the projectile direction. For more details, see text.

ural way to disentangle the fast and abundant emission induced dynamically from the slow statistical one. The time t_{sep} is defined with a precision of about 10 fm/c [17] and this ambiguity has some influence on the relative amount of DE and SE. Nevertheless, the agreement between the available Ar+Ni experimental data on the DE emission component between 52 and 95 MeV/nucleon [9] and our LV calculation [17] is excellent. Some difficulties in separating DE and SE emission components can, however, be foreseen at lower energies when system may undergo rotation in deep inelastic reaction regime forming a dinuclear system which may last long enough to thermalize before separation. The incident energy in the present study is much higher than the Fermi energy and, in particular, the precise value of t_{sep} has no appreciable consequence on the properties of DE and SE discussed in this paper. Similarly, changing the criteria for the definition of the ensemble of emitted particles [16] may somewhat change the amount of the DE and SE particles but not their physical properties like their phase-space origins or energy spectra.

Now let us investigate the energy spectra of each component. (A number of other dynamical and kinematical observables have been studied elsewhere [15].) Following the prescription used in the extraction of the apparent temperature S in the experimental works [2,4,6], we study the energy spectra of emitted particles in the *forward hemisphere of the QP reference frame*. Figure 3 shows the energy spectra of DE (left), SE (middle), and of all particles emitted, *i.e.*, for the sum of the DE and SE components (right). The dynamical component is very weak for the peripheral collision and, therefore, the $b = 6.5$ fm spectrum is not shown in fig. 3 a). One observes that these spectra display a Maxwellian shape and consequently can be fitted by a function of the form

$$W(E) = \alpha \frac{E-B}{S^2} \exp\left(-\frac{E-B}{S}\right), \qquad (1)$$

where E is the particle kinetic energy, B the Coulomb barrier, and S the slope parameter (apparent temperature). The spectra were integrated between 0° and 90°. Whereas a satisfactory fit of the SE component (Fig. 3 b)) is fully expected, the almost equal quality of the obtained fit for the DE component (Fig. 3 a)) appears less natural. In fact, as we have demonstrated in [15], the particles

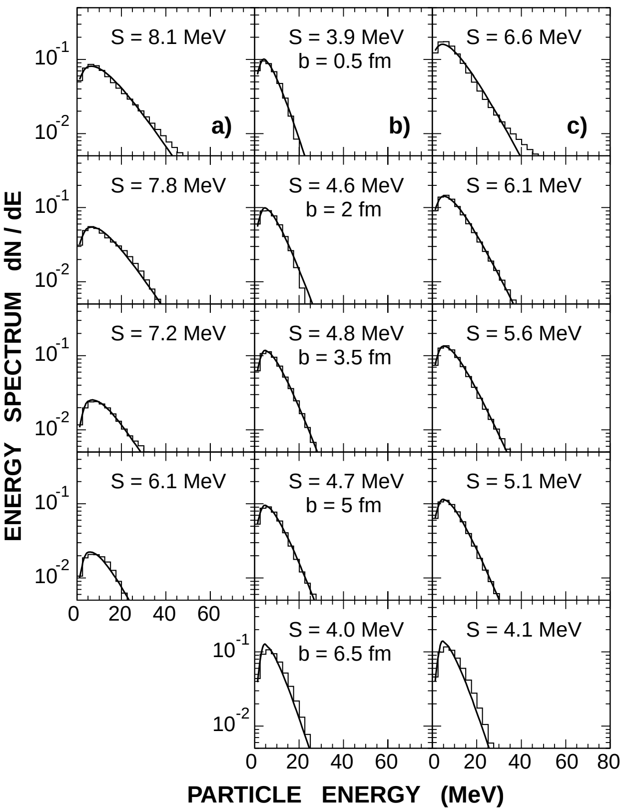

Fig. 3. Kinetic-energy spectra of emitted particles in the QP reference frame as obtained by the LV-model simulation of the Ar + Al collision at 65 MeV/nucleon (histograms). The spectra are integrated between 0° and 90°. The curves display the result of the fit with a Maxwellian distribution with three free parameters according to eq. (1). Energy spectra are shown separately for a) the dynamical and b) the statistical emission components, as well as for c) the sum of both.

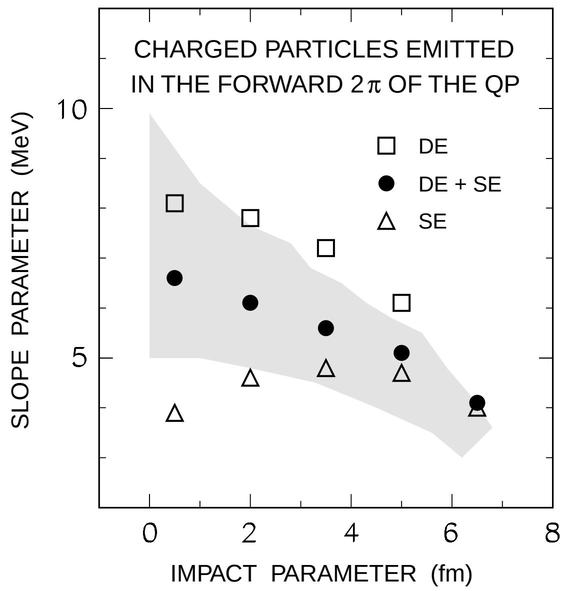

Fig. 4. Slope parameter as a function of b deduced from the fit with a Maxwellian distribution of the calculated kinetic-energy spectra in the QP reference frame for DE (open squares), SE (open triangles), and all emitted particles (DE+SE; filled circles). The grey area represents the values extracted in two different experimental analyses [2,6]. For further details, see text.

emitted at the first instances of the collision, *i.e.*, even before the birth of the primary QP, and including those being in the forward hemisphere of the QP, are exposed to the Coulomb repulsion of the QP. Their emission pattern is so much distorted by the Coulomb field that, although genuinely emitted from the overlapping zone, they appear asymptotically to originate in the QP (see figs. 6 and 9 in [15]). *At the end of the reaction the DE particles in the QP frame are characterized by the energy spectra analogous to those originating from a thermalized source* (see fig. 3 a)). *Such behavior has led a number of experimentalists to consider all particles emitted forward to the QP as being truly emitted by the thermally equilibrated primary QP.*

From a simple glance at figs. 1 and 3 it is obvious that DE regularly and strongly increases with collision centrality whereas the amount of SE particles is roughly b independent (see also [15]). A detailed study of DE for several systems has shown a similar strong and regular increase of DE with energy and centrality [17]. Thus, *an important portion of available system energy is in central collisions evacuated by DE.*

The slope parameter S extracted by the fitting procedure is indicated in each spectrum. The S values are shown in fig. 4 for the DE (open squares), SE (open triangles), and DE + SE (filled circles) components. For comparison, the values extracted using the same kind of fitting procedure carried out for two sets of experimental data for $Z = 2$ species are displayed by the grey zone in fig. 4. The lower edge of the grey zone corresponds to the results of ref. [6] and the upper one to those of ref. [2]. The difference between these two sets of data comes mainly from the fact that two different methods for the determination of b and the source velocity were used. The largeness of the grey zone, in particular for small impact parameters, indicates problems that an experimental analysis has to face. Because of this uncertainty in the extraction of S as well as the fact that the experimental results on protons are not available in the literature we limit ourselves to a qualitative comparison of our and experimental results. A common feature of both experimental sets is a steady rise of S with centrality. Similar behavior is observed for the slopes of calculated energy spectra for the total emission forward to the QP (filled circles). Moreover, S values for the DE + SE lay well within the grey zone. However, when the dynamical component is discarded from the analysis, the slope of the genuine QP emission energy spectra does not increase with increasing violence of the collision (SE; open triangles). It displays a large maximum around $S \sim 5$ MeV for semicentral collisions, demonstrating that the hottest primary QP is not formed in the most central collisions as it was up to now commonly considered. This apparently striking result is not unexpected when one takes into account the ever rising energetic DE component with collision centrality [15,17].

4 Conclusions

To summarize, during the short but violent dynamical stage of the emission a large fraction of the available energy is evacuated [15,17,19]. Therefore, the primary QP and QT are not very hot. Owing to the features of dynamical emission the slope of the energy spectra of the QP emission displays the following behavior:
1. The apparent temperature of the genuine QP emission displays a weak dependence on the impact parameter.
2. The hottest primary QP is not formed in the most violent collisions.
3. The apparent temperature of the particles emitted by the QP does not exceed about 5 MeV.
In the light of these results it would be important to investigate the role which the reaction dynamics plays in the QP temperature as a function of incident energy and system size and symmetry since the large discrepancies in the value of the nuclear temperature obtained by means of different temperature-dependent observables [4,23] may probably be accounted for by these dynamical effects on the QP properties. If the predictions of our simulations are correct, the properties of hot nuclei deduced up to now in many experimental studies are questionable.

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