Evidence for dynamical proton emission in peripheral Xe+Sn collisions at 50 MeV/u.

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Abstract: Relative angle correlation functions for mid-rapidity protons built up from 50 MeV/u Xe+Sn data recorded by the INDRA multidetector exhibit the characteristics of a non-equilibrated emission: they show an energy dependent anisotropy which cannot be accounted for by standard evaporation processes; a possible explanation lies in the dynamical origin of these protons as suggested by a Landau-Vlasov simulation.

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Particles emitted in intermediate energy (20-200 MeV/u) heavy ion collisions are known to have different

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origins. In the first stage of the reaction, they are emitted from the interaction zone, during the overlap time of the two colliding nuclei. Then the thermal emission by hot nuclei takes place.

It is then rather difficult to separate evaporative from non-equilibrium processes. Such a task calls for the use of 4π multidetectors on one hand and appropriate model descriptions on the other hand. Simulations of transport equations like LV [1], BUU [2], BNV [3] which are able to follow the time-dependent reaction process are then an essential tool to better understand the role of the dynamics in such heavy ion collisions. All these models agree on one point: the formation and decay of hot nuclei is preceded by an emission of particles generally referred to as pre-equilibrium emission. Among them some nucleons are preferentially observed in the mid-rapidity region [4]. The chemical and kinematical properties of mid-rapidity emission in Xe + Sn and Ar + Ni collisions have been recently studied [5, 6, 7, 8]. A possible interpretation of this early emission is provided by directed flow analyses [9, 10].

In order to sign the presence of non-equilibrium processes in intermediate energy heavy-ion collisions we present in the following a study of proton emission in Xe + Sn data recorded at GANIL with the INDRA multidetector. Its performances have been described in a specific paper [11]: let us only specify here that INDRA provides a 4π detection for IMF in central collisions and for particles whatever the reaction mechanism. Especially for the purpose of the present paper, protons are unambiguously identified above 3 MeV with an energy resolution less than 2 %.

Event selection was achieved in the following way:

i. Completion criterium as already used [12, 13, 14] in previous studies of the 50 MeV/u Xe+Sn reaction: it requires that the selected events carry out at least 80% of the total pseudo-initial parallel momentum, $Z_{proj}V_{proj}$.

ii. Violence of the collision using the transverse energy E_{t12} carried out by H and He isotopes. We then define peripheral ($E_{t12} < 240$ MeV) and central ($E_{t12} > 460$ MeV) regions, which can be respectively associated to geometrical impact parameters b $>$ 6 fm and b $<$ 2.5 fm [5].

Fig.1 shows an invariant plot $V_{longitudinal}(V_L)$-$V_{transverse}(V_T)$ for protons detected under the two tranverse energy domains we consider: in both cases one observes the expected emission from projectile-like and target-like sources. Moreover, a mid-rapidity component might contribute, especially in the bottom case which displays the central collisions pattern. Following [13], we define the mid-rapidity region of interest by a center-of-mass opening angle between 60^o and 120^o.

The correlation function technique is well suited for the study of low probability processes. Usually, azimuthal correlation functions [14-23] are used to explore the reaction dynamics. We choose here to study relative angle correlation functions between protons to get information on the emission pattern of those particles because they

combine the information of polar and azimuthal angles. The correlation function is defined as:

$$1 + R(\alpha) = \frac{N(\alpha)}{D(\alpha)} \quad with \quad \alpha = acos(\frac{\vec{p_1}\vec{p_2}}{|\vec{p_1}||\vec{p_2}|}) \tag{1}$$

where N stands for the correlated distribution of the two protons emitted with momentum $\vec{p_1}$ and $\vec{p_2}$ in a same event. The uncorrelated distribution (D) is constructed with the same batch of particles but taken each from different events.

A Monte-Carlo calculation has been performed in order to estimate the error in relative angle; this calculation accounts for both the polar/azimuthal granularity and energy resolution of the multidetector: it results that the α resolution remains always less than 12^o(FWMH), whatever the angles and energies of the correlated protons.

Fig.2 shows the relative angular correlation functions for two protons emitted in the mid-rapidity region as defined above for peripheral (top-left) and central (top-right) collisions. The correlation pattern is rather structureless, except if a specific sample of high energy protons is selected: in order to get a better insight on a possible out-of-equilibrium signal, we have applied a cut on the proton energy.

In fact, for $E_p > 20$ MeV and peripheral collisions, one observes a clear anisotropy of the relative angle correlation: the two protons are preferentially emitted either closely at $\alpha \simeq 0$ or back-to-back. Such a trend is confirmed by the set of various plots (fig. 3, top) which shows the α correlations for increasing energy cuts: one observes clearly an energy dependent anisotropy; the transverse momentum of the protons appears to be a leading parameter which emphasizes the correlation pattern.

At a first glance, such a signal, which appears for protons ejected with high transverse momentum, calls for pre-equilibrium emission: in fact, the production of fast particles is favoured at the beginning of the reaction, before thermal equilibrium. This may be assessed under simple arguments of phase-space availability at that early time. Nevertheless, more standard explanations have to be considered: the most plausible one is the evaporation of two protons by the projectile-like and/or target-like residue, and we already noticed from Fig. 1 that some mid-rapidity emission might also contribute: we probably deal with a two(three) source process in the peripheral case (top Fig. 1) we are concerned with.

Moreover, the observed anisotropy in a two-particle angular distribution claims for spin effects: such effects have obviously to be accounted for in the scenario. Finally, we have to rule out any misleading effect due to a possible detector bias.

Then, in order to justify the pre-equilibrium hypothesis, we have first to check it against the "trivial" scenario resulting from the combination of the above-mentioned effects; such a scenario has to be handled by an appropriate simulation procedure: the SIMON code [25] was used to provide an exhaustive description of the reaction process : at a given impact parameter, the collision is driven in the reaction plane of each event

according to a standard binary dissipative process. The resulting projectile/target-like nuclei then endeavour statistical decay allowing IMF and particle emission. Pre-equilibrium emission of nucleons, which is calculated by the code is not – of course – accounted for in the simulation. The calculation is integrated over the whole suitable impact parameter range. This scenario accounts for total angular momentum conservation, the latter being shared off upon the outgoing hot nuclei, in a scenario where each event is characterized by its proper reaction plane. Let us stress that this code calculates in the final state the trajectories of the outgoing decay particles in the Coulomb field [26].

The emitted particles were subjected to a software filter which reproduces the INDRA characteristics: geometrical efficiency, granularity, energy thresholds. It also accounts for the possible particle mis-identification due to multi-hits.

Fig. 3, bottom shows the relative angle distributions simulated by the SIMON code for the peripheral events, with and without the cuts performed in the experimental data: they are rather flat in every cases, and never exhibit the anisotropy observed in the data. In the upper range of impact parameter in which the phenomenon is observed, a three sources contribution (according to a possible participant/spectator scenario) is probably negligeable. Nevertheless such a scenario has been checked with a specific simulation: the α distribution remains also structureless, whatever the energy cut ([14]).

From this confrontation with SIMON, we might exclude any evaporative origin from thermalized projectile-like and target-like sources with correlative spin effects able to reproduce the specific shape observed in the data. The fact that the SIMON events were filtered according to the characteristics of INDRA including every misleading effect, rules out any possible detector bias which could artificially generate the specific observed shapes.

Another cause for the observed anisotropy could be the well-known resonance at 20 MeV/c observable in the p-p relative momentum correlation function: this effect has been ruled out [14] since the anisotropy remains when one eliminates the low relative momentum (q<50 MeV/c) contribution in the set of particles selected to built-up the correlation function.

Since one cannot explain the observed correlation neither by the decay of hot sources nor by resonance de-excitation, we conclude that high energy mid-rapidity protons have a non-equilibrium origin, in agreement with conclusions from directed flow studies of light particles on several systems at similar incident energies [9, 24]. We shall notice that such a shape of the function (fig.2 (bottom)) has already been observed in azimuthal correlation function for protons and light fragments at around 50 MeV/u reactions [21, 23] and was interpreted as probes of the reaction dynamics in terms of directed flow and rotational collective motion.

This observed anisotropy might be explained in the light of recent calculations done in the framework of the

Landau-Vlasov model [1]. It has been shown in reference [28, 29, 30] that binary dissipative collisions which dominate the reaction cross-section in this incident energy range are accompanied by an abundant dynamical emission of prompt particles (PRP) occurring before the separation time, i.e. before the birth of the two exit channel nuclei. This PRP emission includes pre-equilibrium and mid-rapidity components [28], the latter being much larger than the former. We present an analog simulation using the Landau-Vlasov equation solved for the momentum dependent Gogny D1-G1 force [31]. It was performed for the Xe+Sn system at 50 MeV/u for semi peripheral collisions (b=8fm). In this case, a separation time of about 100fm/c is found. To derive the phase space origin of the dynamically emitted particles, their trajectories were followed backward in time, down to 40 fm/c which is the time at which the emission of mid-rapidity particles begins. In fig. 4 are displayed equidistant density-profile contours projected on the reaction plane in both the geometrical (left) and the momentum space (right). Density profiles are shown for the PRP emission (bottom) and for the whole system (top), i.e. all the particles constituting the two initial nuclei.

As in [28], the following conclusions can be drawn from this figure: the PRP emission contribution comes mainly from the overlapping zone between the two incoming nuclei and is maximum at mid-rapidity. Moreover, at such a large impact parameter, two components in the momentum space can be observed in PRP emission as previously seen for the Ar + Al system [29]. This effect is a clear signature of a non-global equilibrium in the interaction zone as appears when PRP alone is compared to the whole system (fig. 4, bottom and top).

These two components might explain the behaviour of the experimental proton-proton correlations as they favour correlations at small and large angles. Another strong argument in favour of this interpretation is that such a pattern disappears in central collisions, either in experimental data or in the simulation. A possible explanation could be the following: in central collisions, the interaction zone increases. So the nucleons have to cross a more dense nuclear matter, that favours a larger and larger number of nucleon-nucleon collisions inside the interaction zone, preventing the direct emission of high energy particles (i.e. first chance collision ones). This implies a quasi complete mixing of nucleons belonging initially to the projectile and to the target respectively. The separation time is then longer, leading the system to loose the memory of the entrance channel.

In conclusion, an evidence for a dynamical process emission has been found in peripheral Xe+Sn collisions in the mid-rapidity region. This signal appears clearly when an energy cut is imposed reducing the thermal contributions. The relative angular correlations together with appropriate dynamical simulations, then appear to be a very suitable tool to search for dynamical and primordial processes.

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Figure Caption

Figure 1: Center-of-Mass V_L-V_T plot for protons emitted in Xe + Sn peripheral (top) and central (bottom) collisions at 50 MeV/u. The lines are the limits of the mid-rapidity region considered. The arcs correspond to a proton energy in the center of mass: E_p(cm) = 20 MeV. The arrows correspond to the projectile and the target velocities.

Figure 2: Correlation functions in relative angle between protons emitted in the mid-rapidity region. Top: without any selection of the proton energies, bottom: $E_p > 20MeV$ in the center of mass of the reaction.

Figure 3: Correlation functions in relative angle between protons emitted at mid-rapidity in peripheral collisions (top) with different cuts on proton energy, and simulated correlation function with SIMON (bottom). The one with a proton energy cut of 20 MeV is not presented here because of a lack of statistics.

Figure 4: Landau-Vlasov density profiles in space coordinates (left) and momentum coordinates (right) of Xe+Sn at 50 MeV/u and b = 8 fm. For further details, see text.

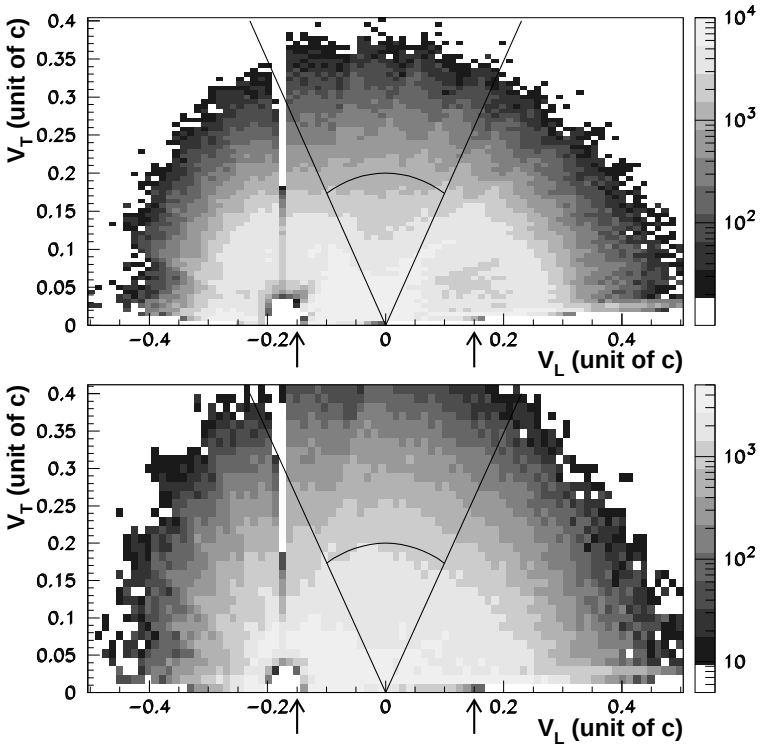

Figure 1

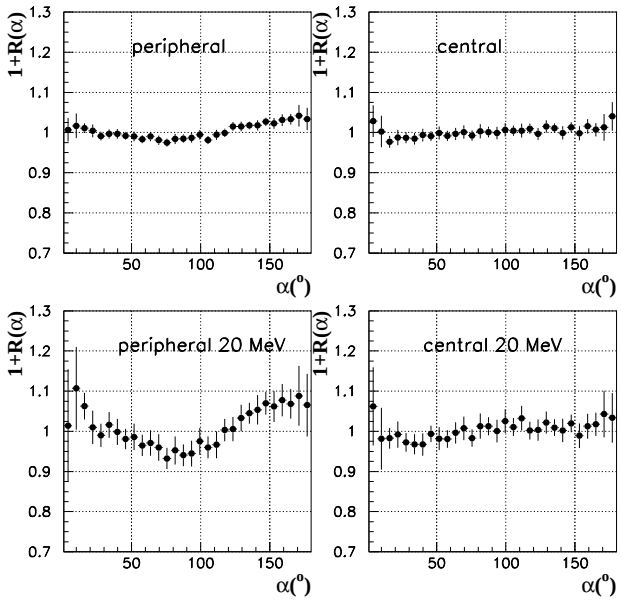

Figure 2

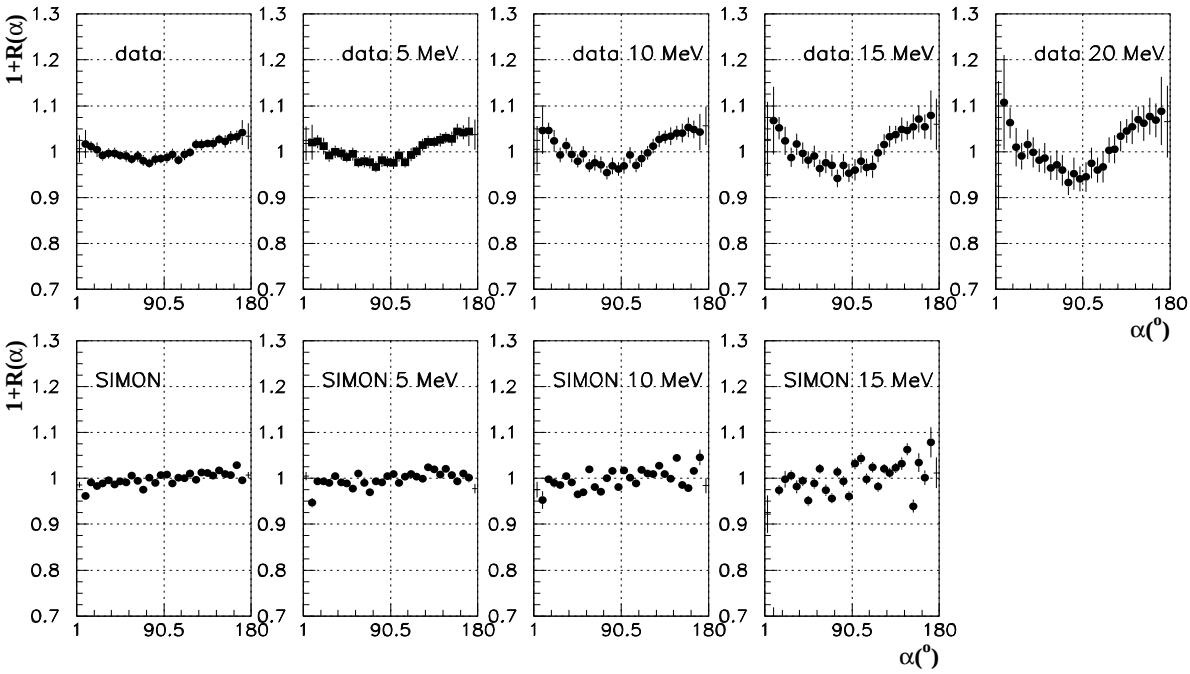

Figure 3

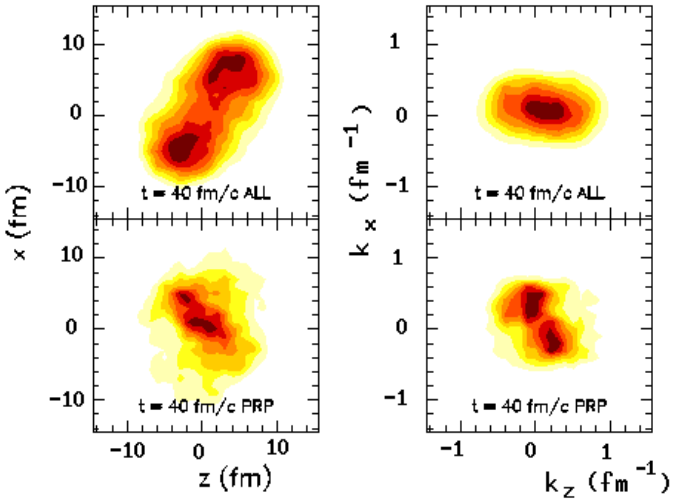

Figure 4