STATISTICAL MULTIFRAGMENTATION OF NON-SPHERICAL EXPANDING SOURCES

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Abstract

We study the anisotropy effects measured with INDRA at GSI in central collisions of ^{129}Xe+^{nat}Sn and ^{197}Au+^{197}Au between 50 and 100 A MeV incident energy. The microcanonical multifragmentation model with non-spherical sources is used to simulate an incomplete shape relaxation of the multifragmenting system. It allows to interpret observed anisotropic distributions in the fragment size and mean kinetic energy. The data can be well reproduced if an expanding prolate source aligned along the beam direction is assumed. In order to improve the shape characterization of the source, we have constructed directional correlations functions in fragment relative velocity. By employing projected relative velocities, a high sensitivity to the source geometry (volume and shape) is obtained, and the source elongations deduced from the statistical approach are confirmed.

1 INTRODUCTION

In central heavy-ion collisions at intermediate energies, many experimental results (see e.g. [1]) have revealed anisotropies in fragment emissions. They suggest a non-complete shape relaxation of sources formed in heavy-ion central collisions at intermediate energies, which may originate from nuclear transparency. This implies that the statistical description requires the partition space being filled in an expanding and non-spherical volume. The Berlin statistical multifragmentation model MMMC [2] extended to the case of non-spherical nuclei [3, 4], has shown that it is possible to describe the observed anisotropies. Within this model, they are explained by the non-sphericity of the source in coordinate space, at the low-density freeze-out stage.

2 THE FRAGMENT ANISOTROPIES AND THE STATISTICAL APPROACH

From the results of the INDRA experiments at GSI, we have found that central collisions of heavy symmetric systems lead to the formation of a heavy, hot and expanding composite nucleus. It exhibits pronounced anisotropies in the fragment yields and kinetic energies, as observed in the ^{197}Au+^{197}Au and ^{129}Xe+^{nat}Sn systems studied in the energy range of 40 to 150 A.MeV [5]. As an illustration of the good agreement that we have obtained [4] with the MMMC-NS (for "Non Spherical") predictions, we present in Fig. 1 comparisons with the experimental data of central ^{197}Au+^{197}Au at

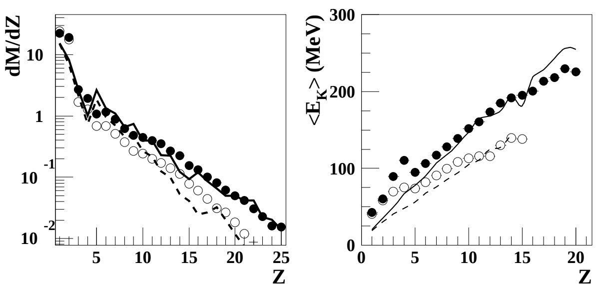

Figure 1: Left: Mean multiplicities of fragment charges normalized to the total solid angle. The circles represent the experimental data (^{197}Au+^{197}Au at 60 $A.MeV$, central collisions), and the lines are the MMMC-NS model prediction obtained with the prolate source described in the text; the full circle and solid line account for forward angles (below 60^o around the beam in the center of mass); the open circle and the dashed line are for sideward angles (between 60^o and 120^o). Right: Mean kinetic energy of fragments as a function of Z in the center of mass, with the same notation as the left panel.

60 A.MeV, in charge distributions and mean kinetic energies of fragments, for two separate angular regions. The model predictions have been obtained with a source having a prolate shape in the coordinate space, elongated along the beam axis, with a longitudinal-to-transversal elongation ratio $\mathcal{R} = (1 : 0.7)$ [4]. The observed anisotropies indicate that fragments emitted along the beam direction are more numerous and bigger than sidewards, and that they have much more kinetic energy.

We have performed the same analysis for the ^{197}Au+^{197}Au central collisions at other beam energies, and for ^{129}Xe+^{nat}Sn at 50 A.MeV. We have deduced similar prolate deformations of the source in the coordinate space along the beam axis. We have observed that the elongation ratio $\mathcal{R}$ remains remarkably stable with the change in system size and beam energy, up to 80 A.MeV, while the size of the source, its excitation energy, and in particular its collective energy get strongly modified, as illustrated by Fig. 2. It is only at 100 A.MeV that a more compact source is observed, with $\mathcal{R} = (1 : 0.76)$, which may indicate a decrease of the nuclear transparency around this energy.

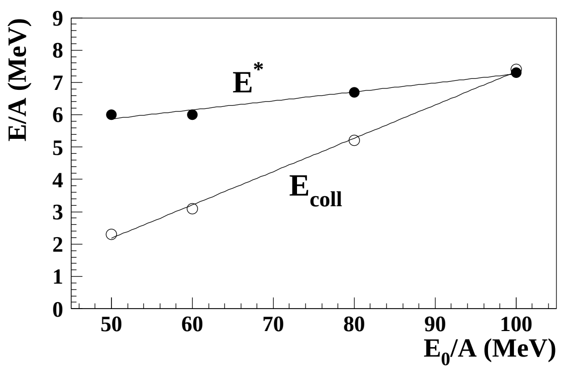

Figure 2: Mean thermal excitation energy (full circles) and collective flow energy (open circles) at freeze-out, extracted by means of the MMMC-NS model, as a function of the incident energy E_0/A for central collisions of ^{129}Xe+^{nat}Sn at 50 A MeV and ^{197}Au+^{197}Au at 60, 80 and 100 A MeV. The lines are linear fits, meant to guide the eye.

In the MMMC-NS approach, the strong forward-backward focusing of the heaviest fragments originates from their particular location in the freeze-out volume, as illustrated in Fig. 3. It shows that heavy fragments are emitted predominantly from the tips of the ellipsoidal shape, not far from the boundary surface. On the other hand, the model predicts that light fragments are more compactly distributed inside the source, and light charged particles (Z=1,2) are homogeneously spread. Since the radial flow is correlated to the distance to the center of the source, these distributions are replicated in the velocity space, making heavy fragments being predominantly emitted forward, at higher velocities.

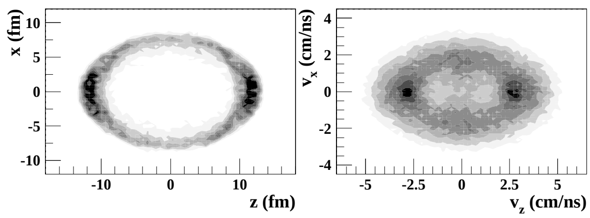

Figure 3: Two-dimensional distributions of heavy fragments with $Z > 4$ obtained with a MMMC-NS prolate source with radial flow (see [4]). Projections of longitudinal and centered slices, in coordinate (left panel) and velocity space (right panel), respectively. The z-axis follows the beam, x is perpendicular to the beam. The shading scale is linear.

In the framework of MMMC-NS, this correlation between the size of a fragment and its location in coordinate space is the consequence of the minimization of the Coulomb energy on the event-by-event basis.

3 COMPARISON OF TWO METHODS OF DIRECTIONAL CORRELATIONS

In order to obtain additional evidence for the geometrical properties of the composite system, we have get use of directional correlation functions in fragment relative velocity, which have been used to gain access to the space-time geometry of the final freeze-out stage [6-8]. For the source evolution, we assume that all fragments are emitted at the same time. This implies that the extracted radii reflect the mean distance between the fragments at their last collision.

3.1 Directional cuts

This first type of correlation function is based on cuts on the angle ψ between the beam direction and the relative velocity of the particle pairs. Angular cuts have been suggested in [9] in order to study correlations between protons emitted with nearly equal momenta, for determining the size, velocity, and lifetime of the collision volume in heavy ion collisions at high energy. Instead of hard angular cuts, we have applied a harmonic *angular weight* for each event [7]. We employed $cos^2(\psi)$ and $sin^2(\psi)$ as weights for the longitudinal and transversal correlation functions respectively. The correlation functions are constructed dividing the spectrum of reduced velocities of two coincident fragments by the spectrum of pairs from different events. The reduced velocity is defined as $v_{red} = v_{rel}/\sqrt{Z_1 + Z_2}$, where v_{rel}, Z_1 and Z_2 are the relative velocity and the charges of the two fragments, respectively. In Fig. 4, MMMC-NS predictions with three different source elongations are presented: prolate, oblate – i.e. elongated/compressed along the beam with axis ratios 1:0.70 and 1:1.67 – and spherical, with a size Z=79, 6 A.MeV excitation energy and 2.3 A.MeV collective flow. The sensitivity of both directional correlation functions to the source elongation is seen on the width of their depletion at small v_{red}.

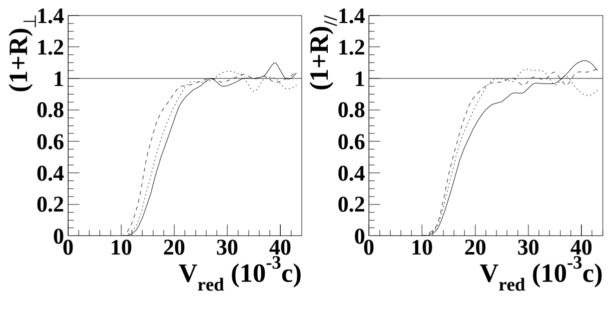

Figure 4: Correlation functions in reduced velocity between the two biggest fragments in an event. Left and right panels correspond to the longitudinal and transversal correlation functions respectively, made by means of directional weights. The solid, dashed and dotted lines are the predictions of the MMMC-NS model for the prolate, oblate and spherical sources respectively.

3.2 Directional projections

As a second type of correlation function, we have applied a new method. The correlation functions are generated for the longitudinal and the transversal *projections* – with regard to the beam axis – of the reduced velocity, i.e. $v_{red//} = v_{red} \cdot cos(\psi)$ and $v_{red\perp} = v_{red} \cdot sin(\psi)$ respectively. In Fig. 5, MMMC-NS predictions with the same three different source elongations as in Fig. 4 are shown. We observe that these functions exhibit a strong sensitivity to the source deformation, in the magnitude of their depletion at small v_{red}. The comparison to the experimental data of ^{129}Xe+^{nat}Sn central collisions at 50 A.MeV shows, in both longitudinal and transversal projections, a good agreement with the prolate deformation that had been derived from the study of the fragment anisotropies in yields and kinetic energies.

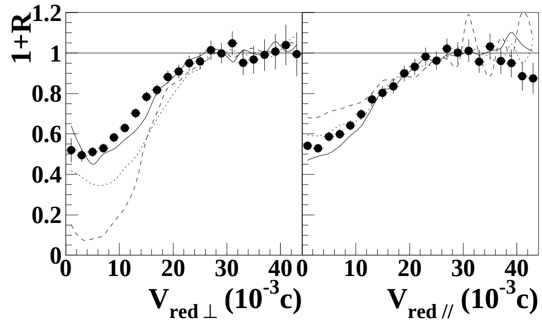

Figure 5: Correlation functions in projected reduced velocity between the two biggest fragments. Left and right panels correspond to the longitudinal and transversal projections of the reduced velocity respectively. The lines are chosen like in Fig. 4. The symbols represent the experimental data of central ^{129}Xe+^{nat}Sn at 50 A.MeV.

3.3 Comparison of the two methods

In order to quantify the sensitivity of both types of directional correlation functions with the geometry of the source, we have simulated various volumes and deformations of ellipsoidal sources, following a simple model. The fragments are sampled according to the experimental distributions in yield and kinetic energy – including the angular dependences –

and placed randomly without overlap into the ellipsoidal "freeze-out" volume. The subsequent time evolution was modeled with N-body Coulomb trajectories. For each simulated source geometry, we have calculated the χ^2 corresponding to the comparison of the directional correlation functions with the experiment. Fig. 6 shows the resulting two-dimensional χ^2 distributions in the plane of the longitudinal and transversal extension of the source, obtained with fragments of $Z = 5-7$, compared to the data of central ^{129}Xe+^{nat}Sn at 50 A.MeV, for both angular cut and projection methods. With the directional cut method, we observe a fairly narrow valley of minimum χ^2 at constant volume, indicating a good sensitivity to the density of the source, but a weak sensitivity to the longitudinal to transversal radius ratio, i.e. to the elongation of the source in coordinate space. With the projection method, we observe a well defined and narrow χ^2 minimum that indicates a good sensitivity to both source density and shape in coordinate space. This minimum corresponds to a prolate source having a size ratio $(1 : 0.6 \pm 0.1)$ which is remarkably close to the MMMC-NS deduction for this reaction (see Section 2).

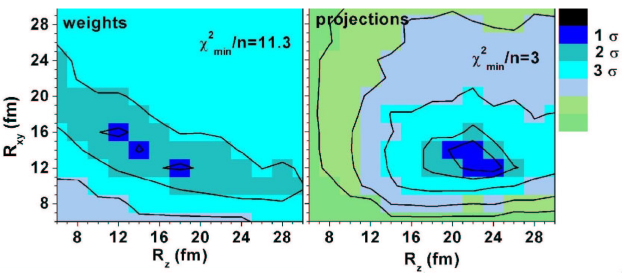

Figure 6: Contour plot (in units of the standard deviation σ) of the two-dimensional χ^2 distribution in the plane of the longitudinal (z) and transversal (xy) extension of the source, as obtained for the comparison of the directional correlation functions with fragments with $Z = 5-7$, from the experiment and from the N-body Coulomb trajectory calculations. The left panel corresponds to the correlations with directional weights, and the right panel to the correlations in projected reduced velocities.

4 SUMMARY AND OUTLOOK

We have observed that in central collisions at intermediate energies, multifragmentation sources are formed that exhibit anisotropies in fragment sizes and kinetic energies. The statistical approach can describe them, along with their anisotropies, assuming non-spherical expanding sources. Projected correlation functions in fragment reduced velocities, which yield at the same time information on volume – density – and elongation, confirm these predictions. We can interpret the observed sources elongations as the result of an incomplete stopping – i.e. transparency – of the colliding heavy ions, that has been observed at higher energies [10]. In particular, a recent study [11] as shown evidence for a strong increase of the nuclear stopping from 100 A.MeV to 400 A.MeV bombarding energy. The study of ^{197}Au+^{197}Au central collisions measured with INDRA at GSI indicates that this evolution prolongates down to the lower Fermi energy domain. The directional correlation functions seem to be an efficient tool to confirm and precise these findings.

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