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Source shape determination with directional fragment–fragment velocity correlations

INDRA and ALADIN Collaborations

A. Le Fèvre [a], C. Schwarz [a], G. Auger [b], M.L. Begemann-Blaich [a], N. Bellaize [c], R. Bittiger [a], F. Bocage [c], B. Borderie [d], R. Bougault [c], B. Bouriquet [b], J.L. Charvet [e], A. Chbihi [b], R. Dayras [e], D. Durand [c], J.D. Frankland [b], E. Galichet [d,k], D. Gourio [a], D. Guinet [f], S. Hudan [b], P. Lautesse [f], F. Lavaud [d], R. Legrain [e,✠], O. Lopez [c], J. Łukasik [a,j], U. Lynen [a], W.F.J. Müller [a], L. Nalpas [e], H. Orth [a], E. Plagnol [d], E. Rosato [g], A. Saija [h], C. Sfienti [a], B. Tamain [c], W. Trautmann [a,*], A. Trzciński [i], K. Turzó [a], E. Vient [c], M. Vigilante [g], C. Volant [e], B. Zwiegliński [i]

[a] *Gesellschaft für Schwerionenforschung mbH, D-64291 Darmstadt, Germany*
[b] *GANIL, CEA et IN2P3-CNRS, F-14076 Caen, France*
[c] *LPC Caen, ENSICAEN, Université de Caen, CNRS/IN2P3, F-14050 Caen, France*
[d] *Institut de Physique Nucléaire, IN2P3-CNRS et Université, F-91406 Orsay, France*
[e] *DAPNIA/SPhN, CEA/Saclay, F-91191 Gif-sur-Yvette, France*
[f] *Institut de Physique Nucléaire, IN2P3-CNRS et Université, F-69622 Villeurbanne, France*
[g] *Dipartimento di Scienze Fisiche e Sezione INFN, Università Federico II, I-80126 Napoli, Italy*
[h] *Dipartimento di Fisica dell'Università and INFN, I-95129 Catania, Italy*
[i] *A. Sołtan Institute for Nuclear Studies, Pl-00681 Warsaw, Poland*
[j] *H. Niewodniczański Institute of Nuclear Physics, Pl-31342 Kraków, Poland*
[k] *Conservatoire National des Arts et Métiers, F75141 Paris cedex 03, France*

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Abstract

Correlation functions, constructed from directional projections of the relative velocities of fragments, are used to determine the shape of the breakup volume in coordinate space. For central collisions of ^{129}Xe + ^{nat}Sn at 50 MeV per nucleon incident energy, measured with the 4π multidetector INDRA at GSI, a prolate shape aligned along the beam direction with an axis ratio of 1 : 0.7 is deduced. The sensitivity of the method is discussed in comparison with conventional fragment–fragment velocity correlations.

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Keywords: Heavy ion collisions; Multifragmentation; Breakup state; Correlation functions

A recent study of central ^{129}Xe + ^{nat}Sn and ^{197}Au + ^{197}Au collisions at bombarding energies between 50 and 100 MeV per nucleon has shown that a good statistical description of the measured fragment yields and kinetic energies can be obtained provided that a prolate source deformation and a superimposed collective motion are included [1]. The experimental data had been collected with the 4π INDRA multidetector [2] at the GSI laboratory. The statistical model employed in this study was the Metropolis Multifragmentation Monte

* Corresponding author.
E-mail address: w.trautmann@gsi.de (W. Trautmann).
✠ Deceased.

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Carlo (MMMC) model [3] which had been extended to non-spherical (NS) sources [4], a version referred to in the following as MMMC-NS model. The MMMC Statistical Model is based on the microcanonical ensemble and has found many applications in nuclear multifragmentation (see, e.g., [3,5–8]).

A prolate deformation of the emitting source along the direction of the incident beam was indicated by the observed anisotropies of the fragment production. The element spectra were found to extend to larger atomic numbers Z at forward and backward emission angles than at sideward angles. The largest fragment within an event is preferentially emitted toward forward or backward angles. If emitted sidewards, its mean Z decreases, e.g., from $Z \approx 18$ at $\theta_{\mathrm{cm}} = 0°$ to $Z \approx 14$ at $\theta_{\mathrm{cm}} = 90°$ for the 1% most central collisions of $^{129}\mathrm{Xe} + {}^{\mathrm{nat}}\mathrm{Sn}$ at 50 MeV per nucleon, selected on the basis of the measured charged-particle multiplicity or the transverse energy of light charged particles [1].

In the model description, an important role is played by the Coulomb interaction which favours large separations between heavy fragments in order to minimize the Coulomb energy. Heavy fragments are, therefore, preferentially placed in the tips of a prolate source. Coulomb repulsion and the superimposed radial flow transform these spatial correlations into correlations in momentum space which produces the observed maxima in the yields and kinetic energies of the heaviest fragments at forward and backward directions. The orientation along the beam axis is clearly of a dynamical origin. The question, therefore, arises whether the deformation of the model source, besides the superimposed flow, is mainly required for simulating the observed anisotropies in momentum space or whether it actually reflects the source shape at breakup as caused by the reaction dynamics.

It is the aim of the present work to confirm the indicated source deformations in coordinate space by applying interferometric methods to the same data, here at first only for the case of $^{129}\mathrm{Xe} + {}^{\mathrm{nat}}\mathrm{Sn}$ at 50 MeV per nucleon. Interferometry has become a standard tool for investigating the space–time properties of the breakup state in heavy-ion reactions [9–11]. The spatial dimensions or space and time are usually separated by exploiting the effects of quantum statistics in proton–proton, neutron–neutron, or pion–pion correlation functions [10,12–16]. Particle pairs are selected according to the orientation of their relative velocity with respect to the chosen coordinate axes, and separate correlation functions are generated as, e.g., for longitudinal and transverse orientations. In fragmentation reactions, the mutual Coulomb repulsion between fragment pairs has been used to derive time scales for the emission process from fragment–fragment correlation functions [17–21]. Glasmacher et al. have shown that also information on the source geometry can be obtained if directional cuts are applied and correlation functions are generated for fragment pairs with relative velocities parallel or perpendicular to the symmetry axis [22,23]. The dependence on the source geometry was small, even though nuclei with the unusual shapes of flat disks or toroids were included in these studies. It will be shown in the following that the sensitivity to the source geometry is significantly enhanced with the proposed new kind of correlation functions of projections.

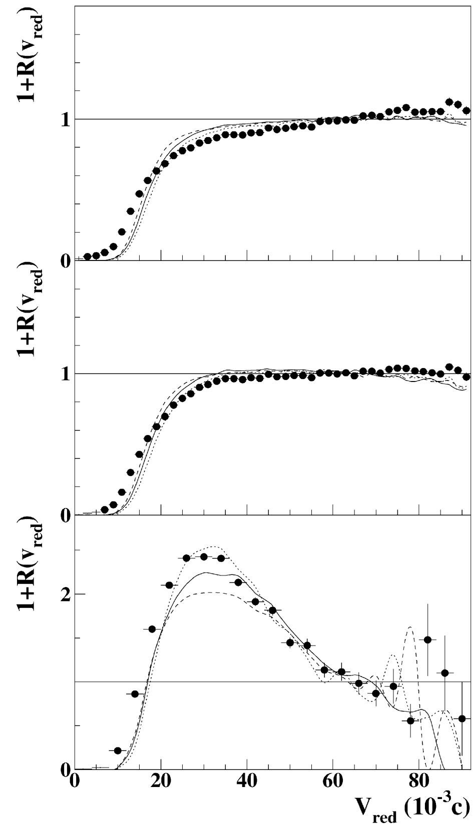

Fig. 1. Fragment–fragment velocity correlations as a function of the reduced velocity v_{red} (in units of $10^{-3}c$) of fragment pairs with $3 \leqslant Z \leqslant 30$ (top and middle panels) and of the two fragments with the largest Z within an event (bottom panel) for central collisions of $^{129}\mathrm{Xe} + {}^{\mathrm{nat}}\mathrm{Sn}$ at 50 MeV per nucleon (dots). Solid, dashed and dotted lines represent the filtered predictions of the MMMC-NS model for the prolate, oblate and spherical sources, respectively. The uncorrelated denominator was generated after azimuthal event alignment for the top panel and after polar event alignment for the middle and bottom panels (see text). The interval 50–100 $\times\, 10^{-3}c$ is chosen for normalization.

The new correlation functions are constructed from the relative velocities of fragment pairs by not using their modulus, as for conventional fragment–fragment correlations, but rather their longitudinal and transverse components with respect to the direction of orientation which here is the beam axis. To correct, in first order, for the variation of the Coulomb repulsion with the fragment Z, the reduced velocity $v_{\mathrm{red}} = v_{\mathrm{rel}}/\sqrt{Z_i + Z_j}$ is used, where v_{rel}, Z_i and Z_j are the relative velocity and the atomic numbers of the two fragments, respectively [24]. With the help of model calculations, it will be shown that these projected correlations are particularly sensitive to a deformation of the source. This will be done in comparison to conventional correlation functions generated not with directional cuts but with directional weights, proportional to $\sin^2\theta$ and $\cos^2\theta$ where θ is the polar angle of the relative velocity vector with respect to the beam axis [16]. The method will then be applied to the experimental data for the $^{129}\mathrm{Xe} + {}^{\mathrm{nat}}\mathrm{Sn}$ reaction at 50 MeV per nucleon.

Experimental details of these measurements, performed at the GSI laboratory in 1998 and 1999, and of the analysis and calibration procedures may be found in [1,25–27]. Natural Sn