Quest for toroidal freeze-out configuration in the central $^{197}Au + ^{197}Au$ collisions at 23 AMeV

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Abstract

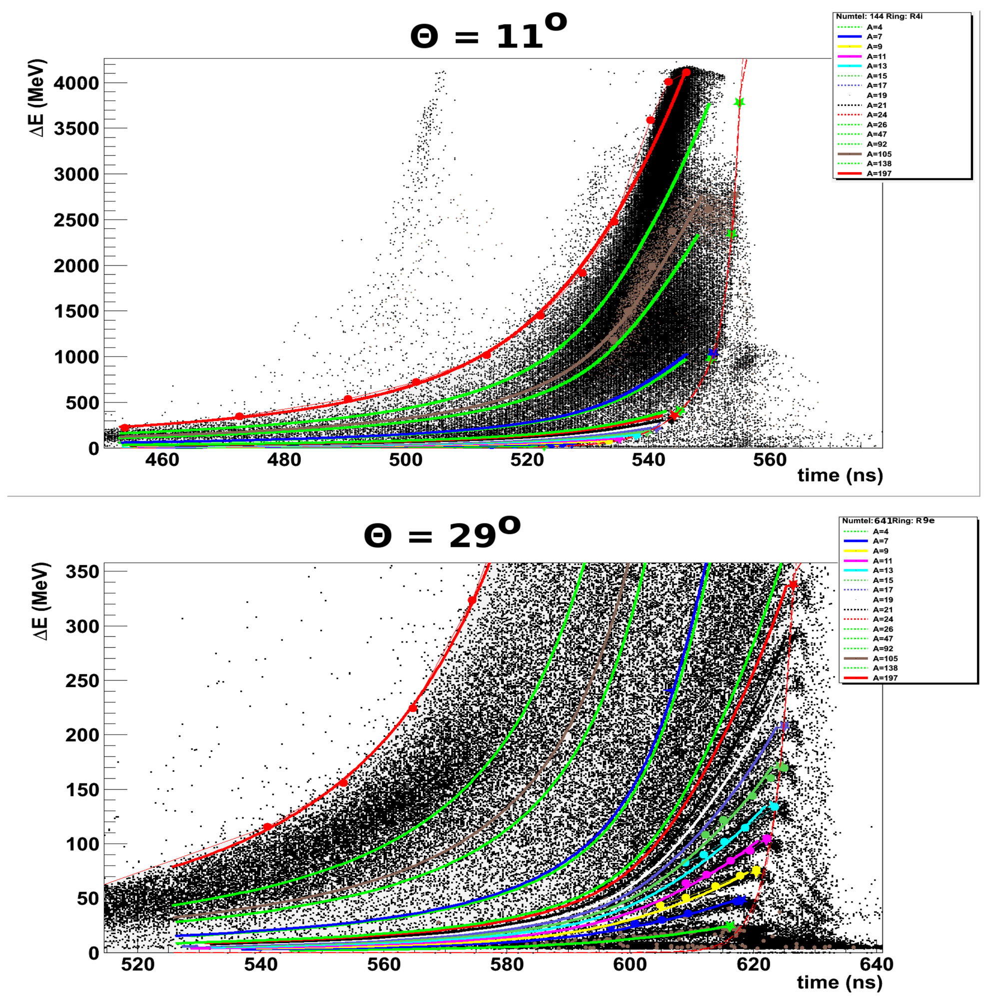
The results of the experiment performed by the BREAKUP collaboration with the CHIMERA array, for the system $^{197}Au + ^{197}Au$ at 23 AMeV are presented. Conclusions related to the shape of the freeze-out configuration are shown.

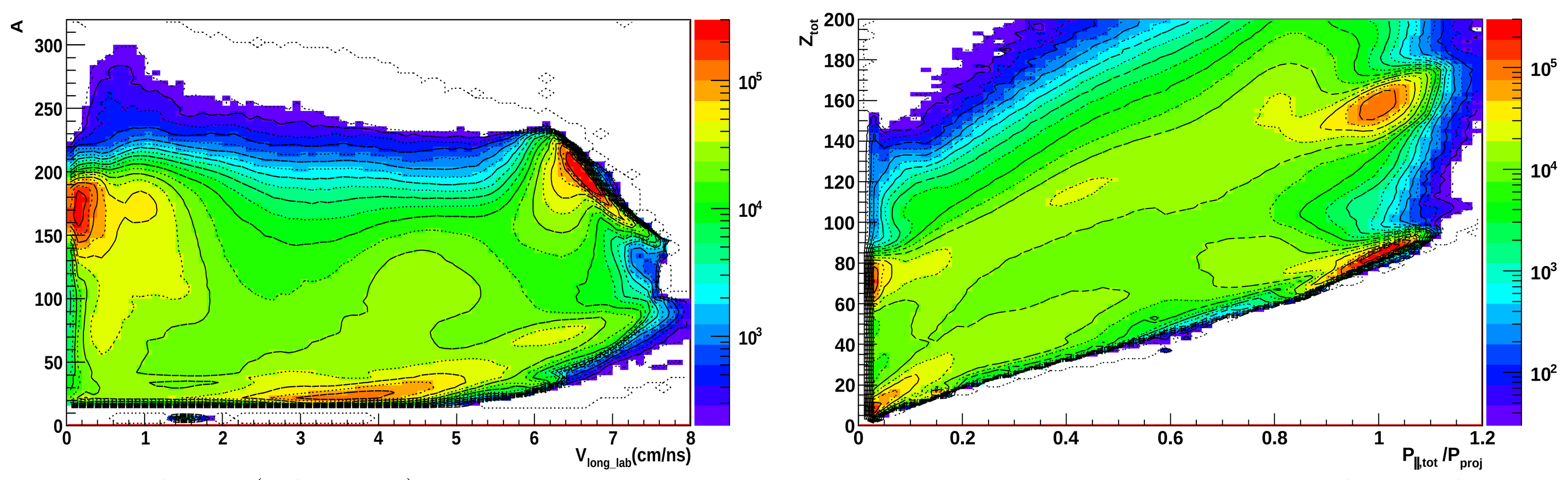
Motivation

Nuclear dynamics studies have been performed by the BREAKUP group for the system $^{197}Au + ^{197}Au$ at 23 AMeV with two goals: (i) a search for toroidal freeze-out configurations predicted to be formed for this heavy system [1]; (ii) an extension of an earlier study carried out at the lower energy of 15 AMeV, in which a new reaction mechanism of violent collinear breakup of non-fusing colliding systems into 3 and/or four massive fragments was discovered [2], [3], [4].
The search for exotic nuclear configurations was inspired by J.A.Wheeler [5]. His idea was investigated by many authors who studied the stability of exotic nuclear shapes (see e.g. [6]). Theoretical investigations related to the synthesis of long-living nuclei beyond the island of stability have shown that they can be reached only if non-compact shapes are taken into account. Calculations for bubble structures showed that such nuclei can be stable for $Z > 240$ and $N > 500$ (see e.g. [7]). Recently it was found that for nuclei with $Z > 140$ the global energy minimum corresponds to toroidal shapes [8]. In contrast to bubble nuclei, the synthesis of toroidal nuclei is experimentally available in collisions between stable isotopes.

Experiment and data analysis

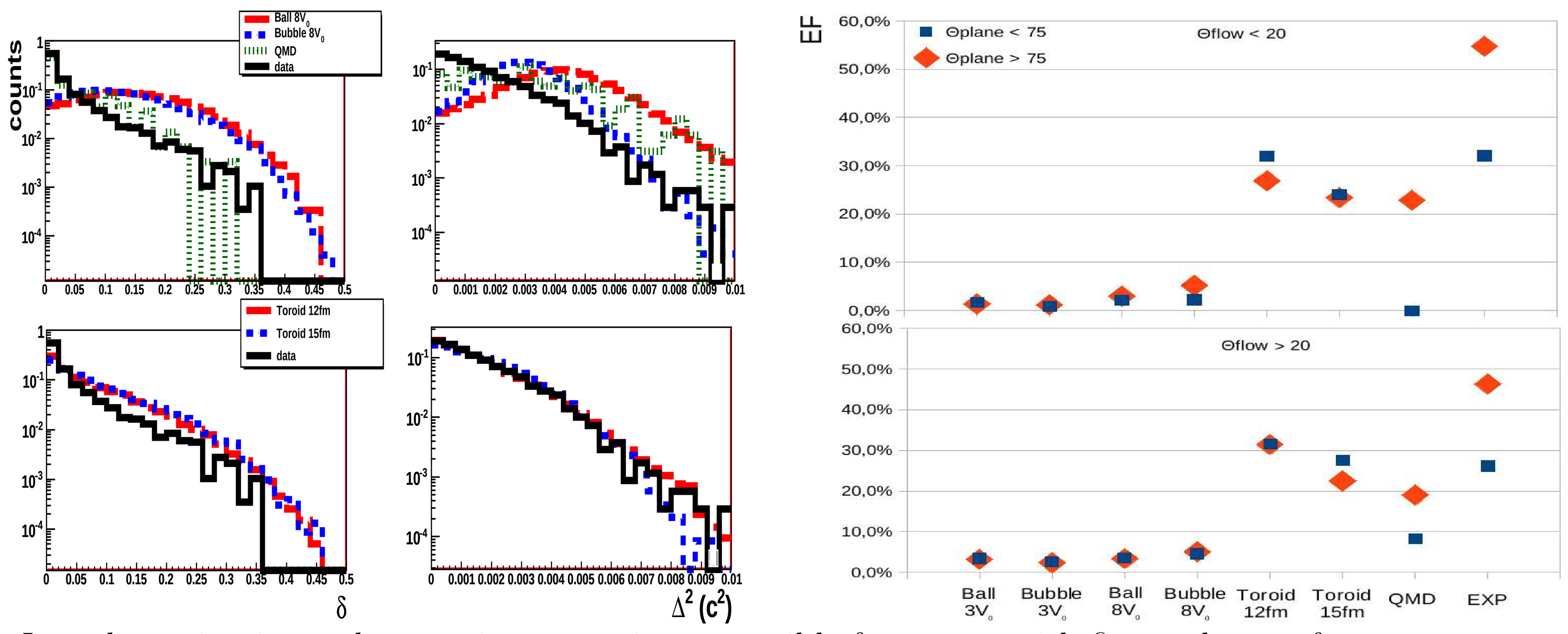
The experiment for the Au + Au reaction was performed in March 2010 using the CHIMERA detector at INFN-LNS [9]. In order to identify fragments two methods were applied: (i) the $\Delta E - E$ technique for fragments punching through the silicon detectors; (ii) the time of flight (TOF) method for the class of fragments stopped in Si detectors (see figures below).





In above figure (left panel) two dimensional mass distribution versus parallel velocity of identified fragments is shown. Location of quasielastic Au peak is visible at mass around 200 and velocities close to the beam velocity. Peak corresponding to Au recoil fragments can be found at velocities close to zero. At velocities between these two limits fragments originating from fission of the Au-like nuclei are located. One can also identify a separated region located at low masses and velocity close to center of mass velocity. This region correspond to the intermediate velocity source.

For the identified fragments we have constructed the plot presenting the dependence between the total charge of identified fragments, Z_{tot}, versus total parallel momentum of those fragments normalized to the beam momentum, $p_{\parallel,tot}/p_{proj}$ (right panel). Region where the total detected charge is close to total charge of the system and total parallel linear momentun is close to linear momentum of the projectile can be called as region of well defined events. In our present analysis this region is described by conditions: $120 < Z_{tot} < 180$ and $0.8 < p_{\parallel,tot}/p_{proj} < 1.1$.



In order to instigate the reaction scenario responsible for events with five and more fragments we have compared experimental data with ETNA and QMD model predictions. The ETNA model can simulate the decay of nuclear system assuming compact and noncompact freeze-out configurations [1].

In our analysis several observables sensitive to the freeze-out configuration were investigated. As a most suitable δ, Δ^2 observables were proposed [1]. The δ variable is related to sphericity and coplanarity variables. The Δ^2 gives a measure of the event flatness in the velocity space. In conjecture with δ, Δ^2 parameters the θ_{flow} and θ_{plane} angles are defined, respectively. In figure above (left panel) the δ, Δ^2 distributions generated for Ball $8V_0$, Bubble $8V_0$, Toroid 12 fm, Toroid 15 fm freeze-out configurations and QMD model are compared with the experimental distributions.

Following the method proposed [1] we select events corresponding to toroidal/flat freeze-out configuration by conditions: $\Delta^2 < 0.001c^2$, $\delta < 0.05$. As an efficiency measure of the above conditions we take ratio of number of events fulfilling the selection conditions to the number of events with 5 and more heavy fragments (efficiency factor, EF). The results of this procedure are presented in the figure above (right panels) for different regions of θ_{flow} and θ_{plane} angles. The region selected by the condition $\theta_{flow} > 20^o$ corresponds to more central collisions. The condition $\theta_{plane} > 75^o$ indicate that for toroidal/flat events the reaction fragments are located close to the reaction plane. In opposite case for flat events the reaction fragments are locate in the plane perpendicular to the reaction plane.

As one can see the EF is very low for spherical freeze-out configurations with respect to the corresponding values for experimental data. For experimental data the efficiency factor is about 50% for events located in the reaction plane ($\theta_{plane} > 75^o$) and is reduced by factor of 2 for events perpendicular to the reaction plane.
For QMD calculations the value of the efficiency factor is strongly dependent on the θ_{plane} range. For events selected by the condition $\theta_{flow} < 20^o$ the EF drops to zero, when we consider events corresponding to small values of θ_{plane}.
For the class of events when particles are located in the plane perpendicular to the reaction plane ($\theta_{plane} < 75^o$) the EF value for experimental data is similar to the model predictions for toroidal configurations. This observation may indicate the formation of toroidal/flat freeze-out configuration created in the Au + Au collisions at 23 MeV/nucleon. The latest observations needs to be confirmed by more detailed analysis. This analysis is in progress.
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