INVESTIGATION OF THE FREEZE-OUT CONFIGURATION IN THE ^{197}Au + ^{197}Au REACTION AT 23 A MeV*

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According to the model predictions, observation of toroidal objects is expected in collisions of heavy ion at low incident energies. Comparison between experimental data and model predictions which may indicate the formation of flat/toroidal nuclear systems is shown.

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1. Introduction

Nuclear dynamics studies have been performed by the BREAKUP group for the system ^{197}Au +^{197}Au at 23 A MeV 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 A MeV, in which a new reaction mechanism of violent collinear breakup of non-fusing colliding systems into three and/or four massive fragments was discovered [2].

The search for exotic nuclear configurations was inspired by Wheeler [3]. His idea was investigated by many authors who studied the stability of exotic nuclear shapes [4]. 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 $N > 500$ [5]. Recently, it was found that for nuclei with $Z > 140$, the global energy minimum corresponds to toroidal shapes [6]. In contrast to bubble nuclei, the synthesis of toroidal nuclei is experimentally available in collisions between stable isotopes.

2. Experiment details

The experiment for the Au + Au reaction was performed in March 2010 using the CHIMERA detector at INFN — LNS [7]. In order to identify fragments, two methods were applied: *(i)* the ΔE–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.

More details about experiment and data calibration procedures can be found in [8].

3. Data analysis

In order to investigate the reaction scenario responsible for events with five fragments, we have compared experimental data with ETNA (Expecting Toroidal Nuclear Agglomeration) [1] and QMD (Quantum Molecular Dynamics) [9] model predictions. The ETNA model allows to simulate the decay of nuclear systems with exotic shapes, while the QMD model simulates heavy-ion reactions preserving multi-body correlations and fluctuations.

We use dedicated observables sensitive to the shape of freeze-out configurations: δ and Δ^2. The δ variable is related to sphericity and coplanarity variables and measures the shape of events in momentum space, and the Δ^2 variable gives a measure of the event flatness in the velocity space [1, 8].

In conjecture with δ, Δ^2 parameters the θ_{flow} and θ_{plane} angles are defined, respectively. The θ_{flow} angle is an angle between the beam axis and the main axis of event, and the θ_{plane} angle defines the location of the event plane in respect to the reaction plane [8]. The dependence between $\theta_{\rm plane}$ and $\theta_{\rm flow}$ for Ball $8V_0$ (ball geometry with volume 8 times greater than normal nuclear volume V_0), Toroid 15 fm (fragments distributed on the ring with diameter 15 fm), QMD and experimental data is presented in Fig. 1. One can observe here that for experimental data, most of events are located in the region selected by conditions $\theta_{\rm flow} < 20^\circ$ and $\theta_{\rm plane} > 75^\circ$. The same behavior is observed in the case of QMD calculations. These observations indicate that such events correspond to non-central collisions. For the Ball $8V_0$ configuration, one observes the correlation between $\theta_{\rm flow}$ and $\theta_{\rm plane}$ angles. For toroidal configuration, the correlation between these angles is even stronger. Most of these events are located in the region defined by conditions $\theta_{\rm flow} > 20^\circ$ and $\theta_{\rm plane} < 75^\circ$.

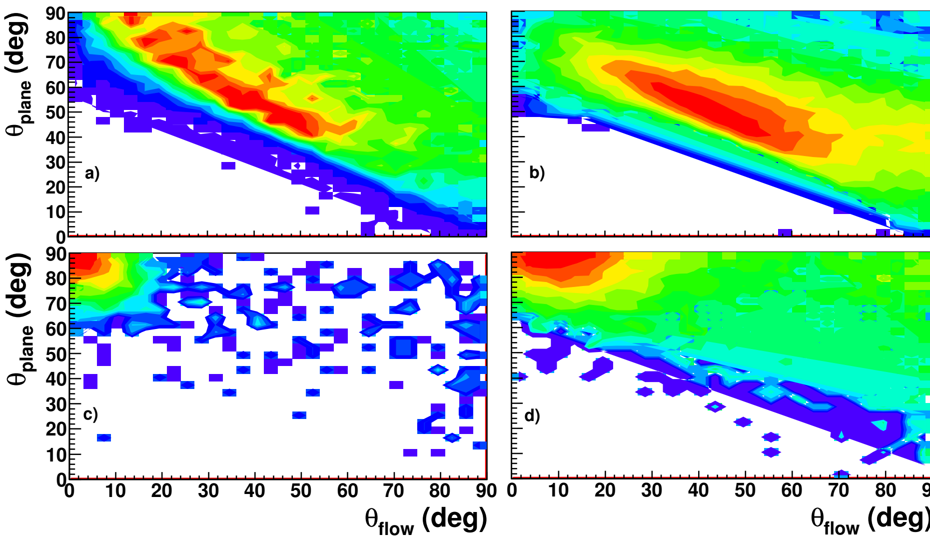

Fig. 1. The dependence between $\theta_{\rm plane}$ and $\theta_{\rm flow}$ for: (a) Ball $8V_0$, (b) Toroid 15 fm, (c) QMD, and (d) experimental data. All the distributions presented here are constructed using the condition $Z_{\rm frag} \geq 10$.

Following the method proposed in Ref. [1], we select events corresponding to the toroidal-shape by the set of conditions:

$$\varDelta^2 < 0.001\ c^2 \quad \text{and} \quad \delta < 0.05\,. \tag{1}$$

As an efficiency measure of the above conditions, we take the ratio of number of events fulfilling the selection conditions to the number of events with five and more heavy fragments (EF, efficiency factor). The results of this procedure are presented in Fig. 2 for different regions of $\theta_{\rm flow}$ and $\theta_{\rm plane}$ angles. As one can see, the EF is very low for spherical freeze-out configurations with

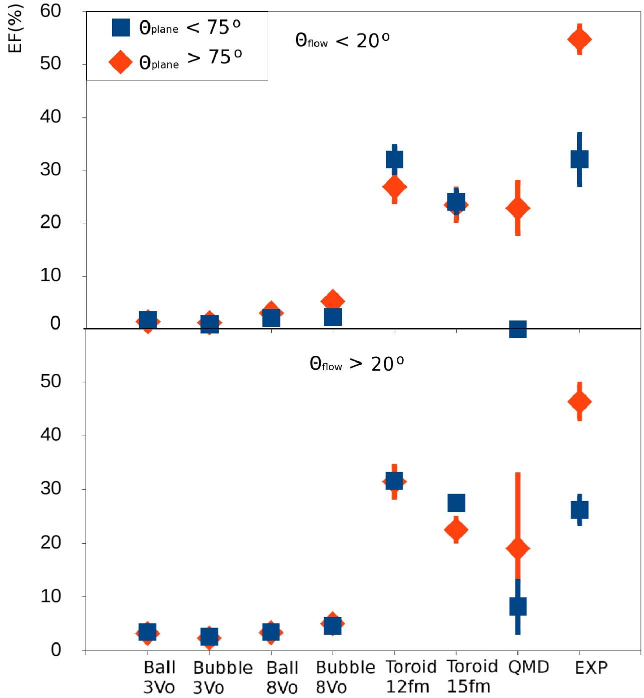

Fig. 2. The EF values for different windows of $\theta_{\rm plane}$ and $\theta_{\rm flow}$. The presented results were calculated using the condition $Z_{\rm frag} \geq 10$.

respect to the corresponding values for toroidal configurations. For QMD calculations, the value of the efficiency factor is strongly dependent on the $\theta_{\rm plane}$ range. For events selected by the condition $\theta_{\rm flow} < 20^\circ$, the EF drops to zero, when we consider events corresponding to small values of $\theta_{\rm plane}$. For experimental data, the value of the efficiency factor is about 50% for events located in the reaction plane ($\theta_{\rm plane} > 75^\circ$) and is reduced by factor of 2 for events perpendicular to the reaction plane.

Here, one can notice that the EF value for experimental data in the region, where according to ETNA predictions the toroidal configuration is expected, is very close to the model predictions for toroidal shapes. This observation may indicate the formation of toroidal/flat freeze-out configuration created in the Au + Au collisions at 23 MeV/nucleon.

4. Other observables

In order to get additional evidence to support the hypothesis that toroidal objects are created, the behavior of other observables was investigated. We consider here for each event separately:

— mass standard deviations σ_A of fragments;
— relative velocities of fragments pairs (v_{ij});
— relative angles of fragment pairs (θ_{ij});
— mean velocities of fragments as a function of their mass.

First, all these observables were constructed for events selected by conditions $\theta_{\rm flow} > 20°$ and $\theta_{\rm plane} < 75°$, where observation of toroidal freeze-out configurations is expected.

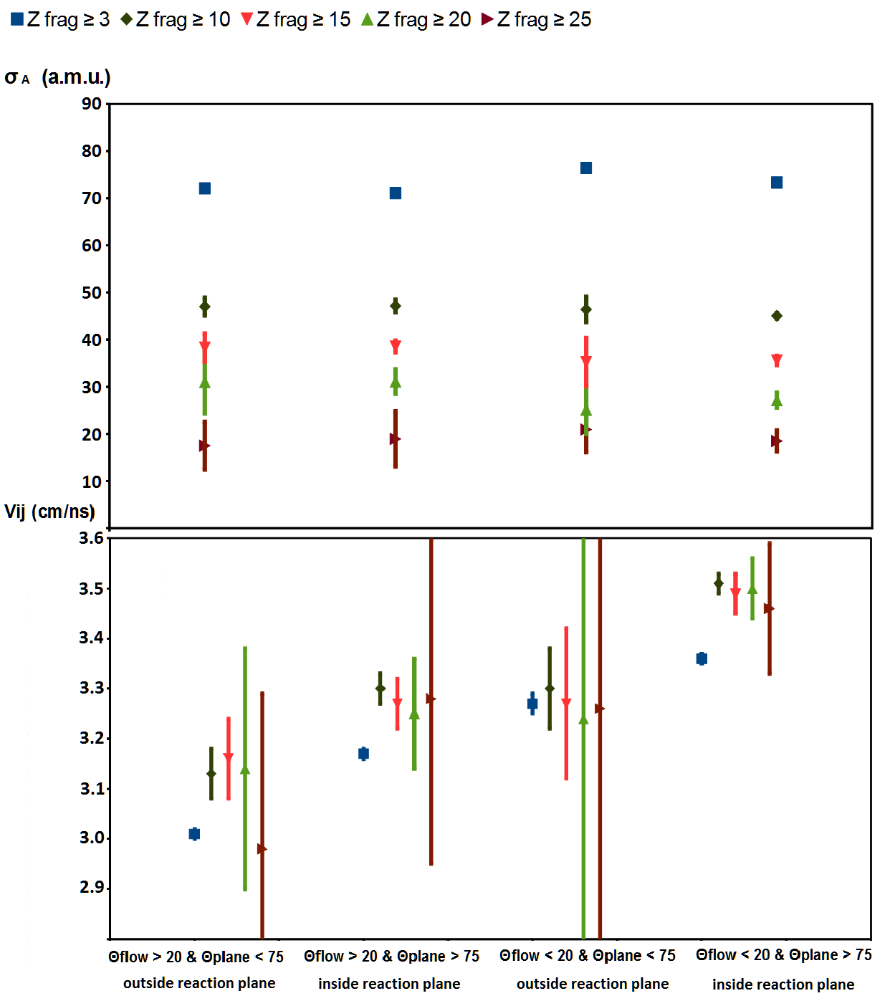

Fig. 3. The distribution of mean values of mass standard deviation of the fragments (top panel) and of relative velocities v_{ij} of fragments pairs (bottom panel) in different windows of $\theta_{\rm flow}$ and $\theta_{\rm plane}$ angles for a given threshold value of the fragment charge.

We can notice here that the corresponding mean values of the distribution of σ_A are similar for all $\theta_{\rm flow}$ and $\theta_{\rm plane}$ windows for a given threshold value of the fragment charge $Z_{\rm frag}$ (see Fig. 3, top panel). Such observation shows us that information carried by σ_A cannot be used as an indication of toroidal objects formation. For v_{ij} distributions (see Fig. 3, bottom panel), one observes that the mean values for class of events located outside the reaction plane are smaller in comparison to the case of events located in the reaction plane. The smallest mean values are seen for the region, where observation of toroidal freeze-out configurations are expected. This observation may be used as an indication that for events located outside the reaction plane freeze-out configuration is more extended in comparison with that for events located inside reaction plane.

Results obtained for the considered observables suggest that the formation of toroidal configurations can be related to a fraction of flat events tilted with respect to the reaction plane ($\theta_{\rm plane} < 75^{\circ}$). The probability for these events is much greater than the prediction of the QMD model. The nature of these events should be investigated.

5. Summary

The possibility of formation of toroidal-shape nuclei was demonstrated by the efficiency factor. The efficiency factor for Ball $8V_0$, Bubble $8V_0$, Toroid 12 fm, Toroid 15 fm and QMD was calculated and compared with that for experimental data. Proximity of efficiency factor values for experimental data and toroidal freeze-out configurations may be used as an indication of the formation of an exotic freeze-out configuration. The juxtaposition of the standard deviation of fragment mass values for class events located outside and inside the reaction do not support the hypothesis of toroidal freeze-out configuration formation. Comparison of distributions of relative velocities for event with different orientation in respect to reaction plane gives evidence that the freeze-out configuration is more extended for class events located outside reaction plane. The behavior of mean velocities of fragments as a function of their mass for flat and non-flat events gives an indication that toroidal configuration may be created for some subclass of flat events. The probability of appearance of this flat events is much greater than the prediction of the QMD model. The nature of flat events tilted with respect to the reaction plane should be investigated. The related analysis is in progress.

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