QUEST FOR HYPERHEAVY TOROIDAL NUCLEI*

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We investigate the possibility of observing toroidal breakup configurations in Au+Au collisions using the CHIMERA multidetector system. BUU simulations indicate that the threshold energy for toroidal configuration formation is around 23 MeV/nucleon. The simulations of the decay process using the static model code ETNA indicate the sensitivity of some observables to different studied break-up geometries.

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The existence of nuclei with non-spherical shapes was first suggested by Wheeler [1]. This idea was investigated by many authors who studied the stability of exotic nuclear shapes (see *e.g.* [2–4]) and examined the possibility of their realization in nuclear collisions with dynamical model calculations (see *e.g.* [5–7]).

Theoretical investigations related with 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 (see *e.g.* [8–10]). Recently it was found that for nuclei with $Z > 140$ the global energy minimum corresponds to toroidal shapes [11]. In contrast to bubble nuclei, the synthesis of toroidal nuclei is experimentally available in collisions between stable isotopes.

To address this issue we have performed simulations for Au+Au collisions in a wide range of incident energies [12] using the BUU code developed by Bao An Li [7]. These calculations indicate that the threshold energy for the formation of toroidal nuclear shapes is located around 23 MeV/nucleon. These calculations indicate that toroidal structures can be also formed for semicentral collisions.

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In order to test the applicability of the CHIMERA multidetector [13] for the detection of noncompact nuclear geometries we developed the Monte Carlo simulation code ETNA (Expecting Toroidal Nuclear Agglomerations) [14]. This code allows us to simulate the decay of the nuclear system assuming exotic break-up geometries. Fragment charges are drawn from a Gaussian distribution centered at the total charge of the system divided by the number of fragments. Results presented are calculated assuming a number of fragments is equal to 5. In this model three freeze out configurations are considered: *(i)* ball geometry with a volume 3 and 8 times greater than normal nuclear volume V_0 (fragments uniformly distributed inside the sphere); *(ii)* fragments distributed on the surface of the spheres mentioned above (bubble configuration); *(iii)* fragments distributed on the ring with diameter 12 fm (toroid 12 fm) and ring with diameter 15 fm. The third geometry corresponds to the theoretical predictions of Ref. [11]. The angular momenta of the created systems are drawn up to a limiting value corresponding to the impact parameter of 3 fm. The excess energy is distributed between the excitation energy of fragments and their thermal motion assuming equal temperature limit.

In order to simulate the contribution from noncentral collisions to the production of "exotic" events the QMD calculations [15] were performed for Au+Au at 23 MeV/nucleon in the full impact parameter range 0–12 fm.

The decay of hot fragments generated by ETNA and QMD calculations was simulated with a dynamical version of GEMINI code [16, 17]. In the next step, the Monte Carlo events are filtered by the software replica of the CHIMERA detector [18], which takes into account the granularity of the detector. We assume that fragments are detected with charge resolution equal to 0.6 charge unit. Masses of detected fragments are assumed to be $2.08\,Z$ (GEMINI prediction). We also require that the kinetic energy of the detected fragments is greater than 1 AMeV.

In order to disentangle between different break up geometries several observables were tested. In the construction of these observables only heavy fragments ($Z \geq 15$) were considered. Only events with at least 5 fragments were taken into account both for ETNA and QMD calculations. As a first test, we consider the shape of events in the momentum space. Here we use the sphericity, s, and coplanarity, c, variables [19]. In the (s,c) plane all events are located inside a triangle defined by points $(0,0)$, $(\frac{3}{4},\frac{\sqrt{3}}{4})$, and $(1,0)$. In the case of ball and bubble geometries the maxima of the corresponding distributions are located in the centre of the triangle. For toroidal configurations the distributions are located closer to the line $(0,0)$, $(\frac{3}{4},\frac{\sqrt{3}}{4})$. Therefore we introduce a new variable, δ which measures the distance between a given point and the above line. In Fig. 1 the δ distributions are presented for considered freeze-out geometries at 15, 23, and 40 MeV/nucleon incident energies. One can see here that the δ distributions for the ball and bubble configurations are very similar and different from the distributions corresponding to toroidal configurations. One can also notice that the difference decreases with increasing incident energy.

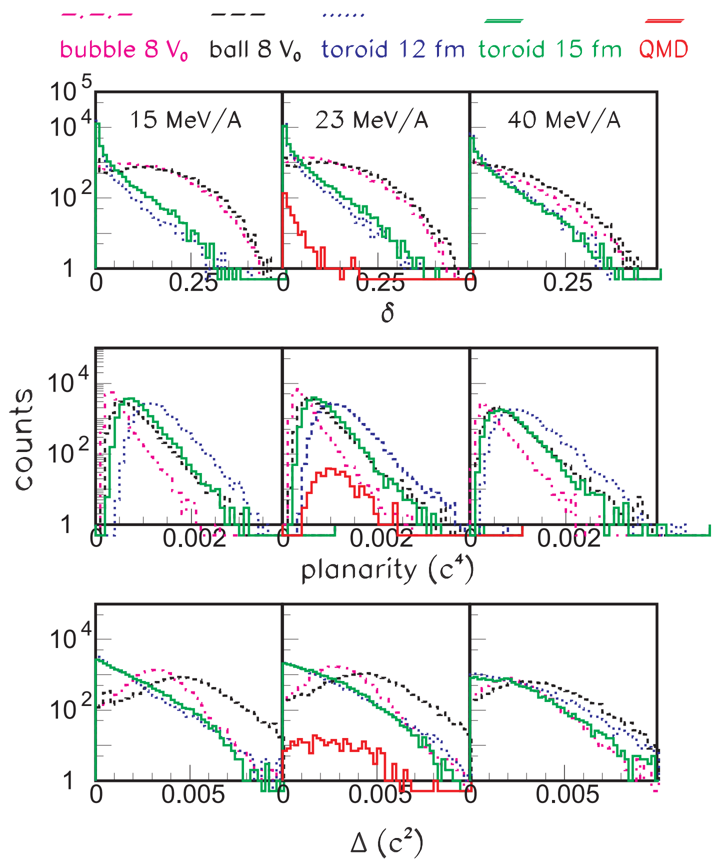

Fig. 1. (Color online.) The δ (upper panels), planarity, Δ parameter distributions for the investigated geometries at 15, 23, and 40 MeV/nucleon. Ball ($8V_0$) (dashed), bubble ($8V_0$) (dot-dashed), toroid 12 (dotted), toroid 15 (solid line). Additionally for 23 MeV/nucleon QMD predictions are presented by solid lines located lower other distributions.

The *planarity* variable introduced in our analysis gives a measure of events flatness and is defined as:

$$\frac{1}{8} \sum_{(i,j)(k,l);i\neq j\neq k\neq l} |(\vec{v_i} \times \vec{v_j}) \circ (\vec{v_k} \times \vec{v_l})| \,, \tag{1}$$

where $\vec{v_i}$ are the CM velocities of the detected fragments. The corresponding distributions are also shown in Fig. 1.

The third variable introduced here measure also the flatness of events. For each event we are establishing the plane in the velocity space. The parameters of this plane are selected in the way that the sum of squares of distances between the plane and the endpoints of velocity vectors reach the minimum value. This last quantity is called the Δ parameter. The distributions of this quantity are given in the bottom panels of Fig. 1.

In order to find the best conditions for selection of events corresponding to toroidal structures we have applied following procedure. In the first step we plot events corresponding to each considered configuration in δ *versus planarity* and Δ *versus planarity* planes. In the next step we divide the distributions corresponding to the toroidal configuration by the distributions for other configurations. We have found the region where events corresponding to toroidal shape dominate over events related to other configurations. Borders of this region are given by following selection conditions: $\Delta < 0.001c^2$, *planarity* $> 0.0008c^4$ and $\delta < 0.05$.

The above conditions however do not suppress sufficiently the contribution of QMD events corresponding to midcentral collisions. This is due to the fact that for these collisions events with 5 fragments originating mostly from fission of target-like and projectile-like fragments with additional production of intermediate fragment. Due to the large entrance channel angular momentum all fragments are located almost in the reaction plane and such configurations are similar to the toroidal ones. The only difference between these two classes of events is the orientation of the plane related to the Δ parameter. In the case of toroidal configuration the angle defined by the beam axis and vector normal to that plane is relatively small. For the QMD events this angle is close to 90°. In order to suppress the QMD events contribution we set additional condition that the above defined angle should be smaller than 75°.

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 5 heavy fragments (efficiency factor). The results of this procedure are listed in Table I.

For collision at 23 MeV/nucleon we investigate influence of noncentral collisions on our results using the prediction of QMD calculation. Assuming that exotic objects are formed for impact parameter range 0–1 fm (σ = 126 mb) we have calculated the corrected values of efficiency factor taking into account QMD events fulfilling the selection conditions (values in brackets). We see that a significant difference between the predictions for toroidal and other configurations is also present for the corrected values.

In the experiment the situation may be more complicated. In the region of central collisions (*e.g.* 0–1 fm) we can have a mixture of starting configurations. Let consider a simple model of such mixture where we have x% of

TABLE I

The efficiency factor at incident energies 15, 23, and 40 MeV/nucleon. In brackets the corrected values are given for 23 MeV/nucleon.

	Efficiency factor (%)		
Configuration	15 MeV/nucleon	23 MeV/nucleon	40 MeV/nucleon
ball $3V_0$	3.38	4.16 (3.2)	4.71
bubble $3V_0$	2.63	2.30 (1.9)	3.07
ball $8V_0$	2.20	2.50 (2.1)	3.38
bubble $8V_0$	0.68	0.6 (0.8)	1.26
toroid 12 fm	53.98	39.7 (29.5)	23.82
toroid 15 fm	29.18	21.2 (16.3)	14.10
QMD	—	1.07	—

toroid 12 events and $(100-x)\%$ of ball $3V_0$ (not exotic configuration) events. We can easily calculate that the corrected efficiency factor of the order of 15% will correspond to the 43% contribution of toroidal 12 fm configuration. The last value of corrected efficiency factor is significantly greater than the values of efficiency factor for all spherical configurations listed in Table I.

In this paper the efficiency factor is proposed as a signature of toroidal structure formation. Statistical analysis is necessary to calculate the lowest limit for toroidal configuration contribution which can be recognize. This analysis is in progress.

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