Search for toroidal and bubble nuclei formed in the Au + Au reaction.

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Abstract

In this contribution the feasibility study for experimental observation of toroidal and bubble nuclei in the Au + Au reaction is presented. The beam time needed to accumulate a reasonable number of events with at least five heavy fragments is estimated.

Fifty years ago Wheeler suggested existence of nuclei with nonspherical shapes and investigated the stability of toroidal nuclei [1,2]. About 30 years ago Siemens and Bethe showed that spherical bubble nuclei with sufficiently large charge may be stable against a symmetry-preserving breathing deformation [3]. Nearly twenty years ago Wong pointed out that probability of existence of such nuclei should depend on temperature [4]. As the nuclear temperature increases the surface tension coefficient decreases and the Coulomb repulsion is pushing nuclear matter outward leading to the formation of toroidal and bubble nuclei. Moretto [5] showed that depletion of charge in the central cavity of nuclear bubbles stabilizes them against monopole oscillations. Such objects are however unstable with respect to quadruple and octupole distortions. The generalized rotating liquid drop model calculations are showing the minimum of the potential energy for toroidal shape even at zero angular momentum for heaviest nuclear systems with masses greater than 300 atomic mass units [6].

Toroidal-shaped objects are also common in hydrodynamical collisions [7]. Simulations of nuclear collisions by means of transport equations show the possibility of ring-, disk-, or bubble-shaped nuclear configurations formation in central collisions [8-13]. It was found that different values of the incompressibility of nuclear matter lead to different exotic objects [9].

Number of observables were suggested as the signatures of noncompact nuclear system configurations breakup:

(i) More of the intermediate mass fragments should be generated than would be expected for the decay of a compact object at the same temperature [8,14];

(ii) Enhanced similarity in the charges of large fragments. Theoretical models have quantitatively predicted that the formation of noncompact geometries will result in increased cross section for emission of fragments with nearly equal masses [12, 15];

(iii) Suppressed sphericity in the emission of heavy fragments [16];

(iv) Two-body observables of the intermediate mass fragments should disentangle the emission from spherical sources and from ring- and disc-shaped sources [17].

The experimental evidence for the decay of nuclear matter noncompact geometries up to now is very limited. The article of Stone et al. [16] presents a systematic study of experimental results for the ^{86}Kr + ^{93}Nb system for incident energies ranging from 35 to 95 MeV/nucleon. The authors noticed a 5% enhancement of the intermediate mass fragments emission and similarity of these fragment charges. They also observe a 5% suppression in the mean value of the sphericity and suppressed flow angles of IMF emission. These observations which indicate existence of exotic geometries appear for beam energies between 60 and 75 MeV/nucleon.

In this contribution we present the feasibility study for the experimental observation of toroidal and bubble nuclei. This search is based on data collected by the CHIMERA collaboration for the Au + Au reaction at 15 MeV/nucleon. The experiment was performed at INFN – LNS in Catania using the 4π CHIMERA multidetector [18].

In the first step of our analysis we have established the identification method of heavy fragments using raw (uncalibrated) experimental data. Fig.1 present the raw

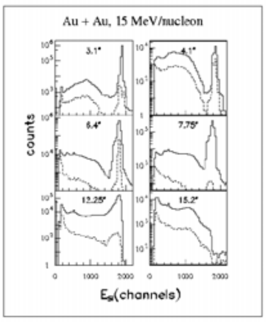

Fig. 1. Energy spectra for the Au + Au reaction (for details see text)

energy spectra observed at several angles for all particles and fragments detected by silicon detectors (solid lines). In each panel the ring polar angle is indicated. The dashed lines correspond to particles that lose only part of their energy in silicon detector and deposits the residual energy in adjacent CsI detector. Inspection of the solid lines at smaller observation angles shows relatively narrow peak related to elastic and quasielastic scattering and a broad maximum at lower energy. With increasing angle of observation the narrow peak disappears and the broad maximum is less visible. The similar spectra for the Au + C reaction at the same incident Au beam energy are shown in Fig. 2. For this reaction the cross section

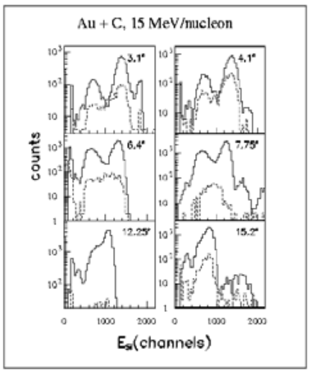

Fig. 2. Energy spectra for the Au + C reaction (for details see text)

is dominated by the fission of the Au-like nuclei after the inelastic collision with C target. Two fission fragments peaks are well visible in energy spectra while the elastic peak is here practically not visible due to very small grazing angle for this reaction.

In order to get an approximate identification of heavy fragments for the Au + Au reaction we applied following criteria: (i) energy deposited in a silicon detector is lower than energy of the quasielastic peak; (ii) particle is stopped in silicon detector and associated CsI signal is not observed. Comparison between the solid and dashed curves in Figs 1 and 2 shows that emission probability for light particles in both reaction is relatively small in comparison to the heavy fragments (notice logarithmic y axis scale on Figs. 1 and 2).

To verify the quality of the heavy fragment identification procedure the azimuthal correlation function, $\Delta\Phi_{ij}$, was studied. Such correlation functions are show in Fig. 3 for Au + Au reaction (upper panels) and for Au + C system (lower panels). When

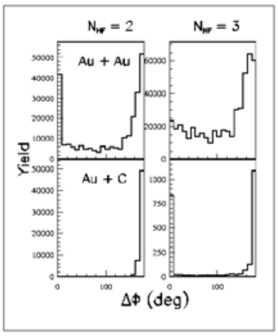

Fig. 3. Azimuthal correlation function for Au + Au (upper panels) and Au + C (lower panels) reactions

events with only two heavy fragments are considered (N_{HF}=2) for the Au + C we observe a peak at 180^0 corresponding to fission fragments of Au-like nuclei. In the case of Au + Au reaction additionally to the peak at 180^0 we observe a peak at 0^0 and some events with $\Delta\Phi_{ij}$ angles in between. These $\Delta\Phi_{ij}$ values are more abundant for the class of events with three heavy fragments.

The multiplicity distributions of heavy fragments for both reactions are presented in Fig. 4. This distribution is limited to multiplicities smaller than 4 and has a maximum at multiplicity 2 for the Au + C system. The distribution is much broader for the Au +Au reaction.

In order to distinguish between different nuclear system geometries we need to accumulate a reasonable number of events with many heavy fragments. The beam time

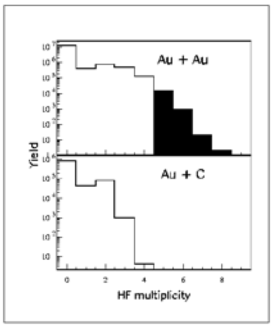

Fig. 4. The multiplicity of heavy fragments distributions for Au + Au and Au + C reactions (black area correspond to events with at least five heavy fragments).

needed to achieve this goal is calculated for events with at least 5 heavy fragments. We found that the fraction of such events among the accumulated data is equal to $8*10^{-4}$. Assuming the Au beam intensity 0.03 pnA and target thickness equals 0.3 mg/cm^2 we estimated that 450 hours of beam time is needed to record 10^6 multifragment events.

In order to test the applicability of CHIMERA multidetector for recognition of noncompact nuclear geometries we have developed a Monte Carlo simulation program ETNA (Expecting Toroidal Nuclear Agglomerations). This code allows to simulate the decay of ball, disk, toroidal and rod-like shapes of the compound nucleus. For each geometry the volume of the system is determined by assuming an average nuclear density $\rho = 0.3\ \rho_0$, where ρ_0 denotes the density of normal nuclear matter. Charged fragments are randomly distributed into the assumed system volume according to a uniform probability distribution constrained by the requirement that any two particles are separated by more than the sum of their radii. In this simple simulation we assume the complete fusion process for the Au + Au reaction at 15 MeV/nucleon. Mass distribution of the fragments is obtained through random breaking of the system. In each step of the breaking procedure the probability of cracking of a given fragment is proportional to its mass and the resulting sub-fragments mass distribution is determined from a bell curve. In the first step the probability for decay of the total system is one. The system disintegrates and the fragments move along the Coulomb trajectories. As an example of simulation predictions we plot angular distributions of IMFs in the laboratory system (Fig. 5). Here different lines correspond to different geometries of the decaying system. The differences between different geometries are visible.

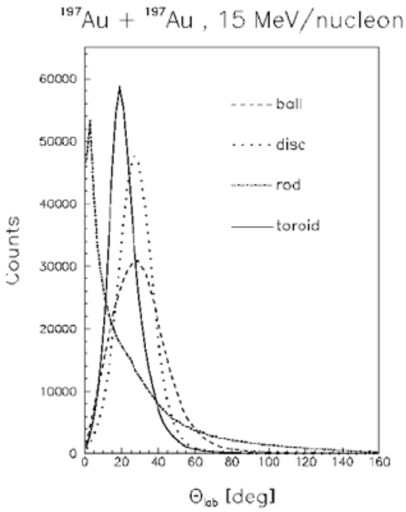

Fig. 5. The angular distributions for heavy fragments in the laboratory system for different geometries of the decaying system.

In this contribution the feasibility study of experimental observation of toroidal and bubble nuclei in the Au + Au reaction is presented. The beam time needed to accumulate a reasonable number of events with at least five heavy fragments is estimated. Present status of the Monte Carlo simulation predictions is shortly discussed.

REFERENCES

[1] J.A.Wheeler, “Nucleonic Notebook”, 1950 (unpublished).
[2] R.E.Euwema and J.A.Wheeler, unpublished.
[3] P.J.Siemens and H.Bethe, Phys. Rev. Lett. 18 (1967) 704.
[4] C.Y.Wong, Phys. Rev. Lett. 55 (1985)1937.
[5] L.G.Moretto et al., Phys. Rev. Lett. 78 (1997) 824.
[6] C.Fauchard and G.Royer, Nucl. Phys. A598 (1996) 125.
[7] R. Adams et al. Appl. Phys. 39 (1968) 5173.
[8] W.Bauer et al., Phys. Rev. Lett. 69 (1992) 1888.
[9] L.G.Moretto et al., Phys. Rev. Lett. 69 (1992) 1884.
[10] S.R.Souza and C.Ngo, Phys. Rev. C48 (1993) R2555.
[11] B.Borderie et al., Phys. Lett. B302 (1993) 15.
[12] H.M.Xu et al., Phys. Rev. C49 (1994) R1778.
[13] D.O.Handzy et al., Phys. Rev. C51 (1995) 2237.
[14] L.Phair et al., Phys. Lett. 314 (1993) 271.
[15] C.Y.Wong, Ann.Phys. (N.Y.) 77 (1973) 279.
[16] N.T.B.Stone et al., Phys. Rev. Lett. 78 (1997) 2084.
[17] T.Glasmacher et al., Phys. Lett. B314 (1993) 265.
[18] A.Aiello et al., Nucl. Phys. A583 (1995) 461.