

# Initial State in RHIC and Ground-State Properties of Nuclei

**Peter Filip**

Institute of Physics, Slovak Academy of Sciences, Dúbravská cesta 9, Bratislava, Slovakia

E-mail: [peter.filip@savba.sk](mailto:peter.filip@savba.sk)

**Abstract.** The influence of ground-state properties of nuclei on the initial state geometry of strongly interacting matter in relativistic heavy ion collisions is discussed. Self-orientation effect in very-high-multiplicity collisions of deformed nuclei is explained. Deformation and wave function of Au, Cu nuclei are discussed in connection to the initial eccentricity simulations. Suggestion for colliding selected isotopes of Sm, Zr and Ru nuclei is presented.

## 1. Introduction

Elliptic flow in Au+Au collisions measured by RHIC detectors at Brookhaven National Laboratory has become a very important quantity for studying properties of the hot strongly interacting matter created in relativistic interactions of nuclei. The detailed understanding of the elliptic flow phenomenon is thus of primary importance. Although the hydrodynamic picture of the partonic matter expansion in Au+Au collisions allows us to reproduce the elliptic flow data well, there still remain some issues to be understood.

For example, the elliptic flow strength measured in Cu+Cu collisions [1] at RHIC is 2x larger than predictions from our models (which reproduce the observables measured in Au+Au collisions). Is there something substantial in the initial state of dense partonic matter and its expansion in Cu+Cu collisions which we do not take properly into account?

In this contribution we discuss the influence of ground-state properties of nuclei (intrinsic deformation, and shape vibration) on the asymmetric geometry of the initial state, which is believed to be primarily responsible for the final strength of the measured elliptic flow.

## 2. Initial eccentricity in collisions of deformed nuclei

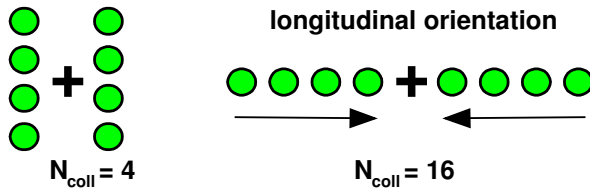
Motivation for studying deformation effects in relativistic collisions of heavy nuclei came partially from the suggestion [2], that a sample of central Au+Au collisions studied at RHIC/BNL contains a small admixture of events with anomalously large (single-event) elliptic flow values. Assuming deformation of  $^{197}\text{Au}$  nucleus, such events could be understood as originating from central collisions of suitably oriented non-spherical Au nuclei. A quantitative study was done [3] with the Optical Glauber Model (OGM) and also with full MC Glauber simulation [4] to investigate effects of deformation in heavy ion collisions. A short summary of these studies is given here and then we suggest the experimental verification of our understanding of the initial state geometry and the elliptic flow origin with carefully selected collision systems.

### 2.1. Collisions of Prolate nuclei

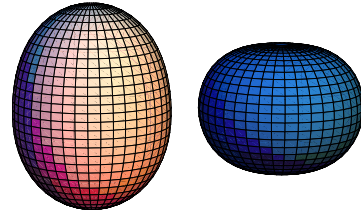
In collisions of nuclei with strong prolate ( $\beta_2 \approx 0.3$ ) deformation an effective *self-orientation* effect can take place in the sample of very-high-multiplicity (VHM) ultra-central collisions. The behaviour comes from binary (nucleon-nucleon) interaction contributions to secondary charged particles multiplicity  $N_{ch}$ . If one assumes that secondary particle multiplicity in relativistic collisions of nuclei at RHIC can be described by two-component model of particle production [5]

$$dN_{ch}/d\eta = (1 - x) \cdot n_{pp} \frac{N_{part}}{2} + x \cdot n_{pp} N_{coll} \quad (1)$$

then central collisions of longitudinally oriented prolate nuclei have significantly larger  $dN_{ch}/d\eta$  due to higher  $N_{coll}$  value if compared to other orientations of colliding nuclei (see Fig.1). Thus, in the sample of very-high-multiplicity (VHM) events, collisions of longitudinally oriented prolate nuclei will appear more frequently, and the effective self-orientation occurs. Longitudinal orientation of colliding prolate nuclei increases the achieved transverse energy density [6]. The overlap of longitudinally oriented nuclei in the transverse plane becomes more spherical at small impact parameters, which gives smaller eccentricity values. A sudden drop of the initial eccentricity in the sample of most central high-multiplicity collisions of prolate nuclei has been predicted [4]. This should be experimentally observable as a decrease (cusp) of elliptic flow strength  $v_2$ , if measured as a function of charged particles multiplicity ( $dN_{ch}/d\eta$ ). When the number of participants  $N_{part}$  is used for studying  $v_2$  dependence on centrality, all orientations of colliding deformed nuclei get mixed together in the most central bin, and self-orientation effects will not be observed via  $v_2$  behavior.



**Figure 1.** Number of nucleon-nucleon collisions for different orientations of two extremely prolate nuclei.



**Figure 2.**  $^{165}\text{Ho}$ ,  $^{116}\text{Cd}$  shapes.

We emphasize here, that the prediction of the effective self-orientation is dependent on the particle production mechanism used in Eq.(1). Additionally a Poissonian (or negative binomial) high-multiplicity fluctuation tail of more frequent collisions with lower average  $\langle N_{ch} \rangle$  values can significantly contaminate the sample of VHM collisions. Therefore, a sudden drop of  $v_2$  value for VHM collisions of prolate nuclei needs to be experimentally verified. Rare-earth elements (e.g.  $^{165}\text{Ho}$ ) or some nuclei heavier than  $^{208}\text{Pb}$  have suitably large  $\beta_2 \approx 0.3$  prolate deformation.

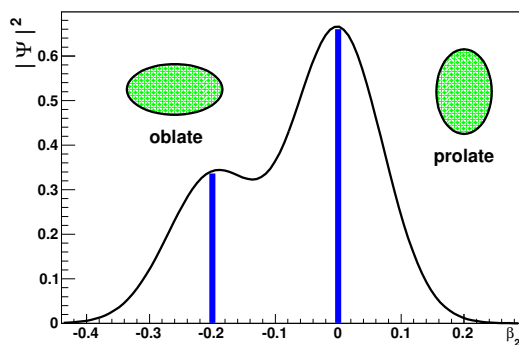
### 2.2. Collisions of Oblate nuclei

For nuclei with strong oblate deformation [7] ( $\beta_2 \approx -0.24$  for  $^{116}\text{Cd}$ ) the effective self-orientation can also happen. The highest binary collisions number  $N_{coll}$  and maximal multiplicities  $N_{ch}$  are achieved for oblate nuclei when oriented orthogonally to the beam. This configuration gives larger eccentricity than in other orientations, and therefore the increased elliptic flow is expected in VHM collisions of oblate nuclei. In optimal case (large static oblate deformation) a small rise of the elliptic flow strength  $v_2$  can be expected [4] for the VHM tail of e.g. Cd+Cd collisions.

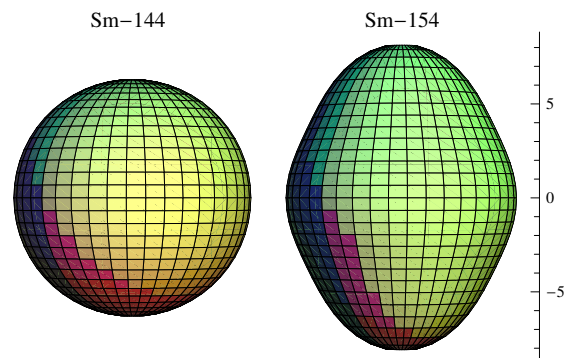
### 3. Ground-state of Au-197 nucleus

The spectroscopic quadrupole moment of Au nucleus  $Q=+0.58$  [8] confirms the non-sphericity of the charge distribution in  $^{197}\text{Au}$ . Theoretical calculations predict  $^{197}\text{Au}$  to be oblate [7] with  $\beta_2=-0.13$  and recent GDR measurements confirm this (see Refs in [4]). Positive sign of  $Q$  measured via muonic spectroscopy [8] may correspond to oblate  $J=3/2$  nucleus observed in quantum substate  $s_z=1/2$ . Indeed, known formula  $Q(s_z) = Q_o[3s_z^2 - J(J+1)]/[(J+1)(2J+3)]$  gives  $Q(1/2) > 0$  while  $Q_o < 0$ . However, an odd number of protons in a stable Au nucleus makes theoretical calculations complicated, and ground-state wave function of  $^{197}\text{Au}$  is not well known. Assuming that stable Pt and Hg nuclei behave similarly as  $^{197}\text{Au}$  one can speak about the probability distribution of Au nucleus to be found (observed) with positive or negative  $\beta_2$  value (shape coexistence is expected to occur in the region of Pt-Au-Hg nuclei).

Typical probability distribution of quadrupole deformation  $\beta_2$  calculated for ground-state wave function of  $^{196}\text{Hg}$  nucleus [9] is reproduced in Fig.3. Although the average deformation is oblate ( $\langle\beta_2\rangle < 0$ ) a significant probability of finding such nucleus in the prolate shape configuration exists. This type of behavior probably needs to be taken into account in initial eccentricity simulations of central Au+Au collisions at RHIC. Axial vibrations might also be significant.



**Figure 3.** Probability of vibrating oblate nucleus to have deformation with given  $\beta_2$ .



**Figure 4.**  $^{144}\text{Sm}$  and  $^{154}\text{Sm}$  nuclei.

### 4. Ground-state vibration

Even for spherical nuclei with zero static quadrupole deformation, one should consider a possibility of significant shape vibrations yielding average *dynamic* quadrupole moment to be important for the initial-state geometry in VHM collisions. In molecular physics, quantum vibrations are well understood and the amplitude of ground-state shape vibrations of  $\text{C}_{60}$  molecule was calculated [10]. Also, for muonic heavy hydrogen molecule the vibrational wave function needs to be known for estimating the fusion probability [11] in such system. Since the zero-point-energy (and amplitude) of molecular vibrations is more significant for lighter molecules, some lighter nuclei (e.g.  $^{63}\text{Cu}$ ) may vibrate more significantly than heavier ones.

### 5. Suggested collision systems

Verification of our understanding of the relation between initial eccentricity and observed elliptic flow strength (and fluctuations) can be done using collisions of carefully selected nuclei with known properties. Very interesting might be a comparison of  $^{144}\text{Sm}+^{144}\text{Sm}$  and  $^{154}\text{Sm}+^{154}\text{Sm}$  collisions. Samarium element allows one to study collisions of spherical and strongly deformed nuclei in a relativistic collider using the same setup of the ion source. Shape of spherical  $^{144}\text{Sm}$

and prolate  $^{154}\text{Sm}$  isotopes (both stable) is shown in Fig.4. Fluctuations of the initial eccentricity and elliptic flow  $v_2$  should significantly increase at given centrality ( $dN_{ch}/d\eta$ ) if strongly deformed  $^{154}\text{Sm}$  nuclei are collided instead of  $^{144}\text{Sm}$ . The expected increase of the elliptic flow fluctuation width  $\sigma_{v_2}$  for collisions of strongly deformed nuclei can be estimated as  $\sigma_{v_2} \approx \lambda \cdot \sqrt{\tilde{\sigma}_\varepsilon^2 + \sigma_\beta^2}$  where  $\tilde{\sigma}_\varepsilon$  is the eccentricity fluctuation for spherical nuclei collisions originating from all other sources except a deformation, and  $\sigma_\beta$  denotes the eccentricity fluctuation width due to deformation  $\beta_2$  of nuclei. Factor  $\lambda \approx 0.2$  comes from hydrodynamic simulations of the partonic matter expansion.

Also, cusp-like decrease of  $v_2$  strength in VHM central collisions of  $^{154}\text{Sm}$  nuclei and slight increase of  $v_2$  in VHM collisions of  $^{116}\text{Cd}$  nuclei should be observable, if our understanding of the elliptic flow origin, charged multiplicity generation and of the initial eccentricity are correct.

Another interesting possibility is to compare collisions of  $^{96}\text{Zr}+^{96}\text{Zr}$  and  $^{96}\text{Ru}+^{96}\text{Ru}$  nuclei (proton number differs by 10%). Dependence of various observables on the magnetic field strength (created by the charge of spectators) can be studied using these nuclei. One has to keep in mind, however, that  $^{96}\text{Ru}$  nucleus is almost spherical ( $\beta_2 = 0.05$ ) while  $^{96}\text{Zr}$  is prolate ( $\beta_2 = 0.22$ ) [7]. It is therefore important to understand and subtract deformation effects from the relevant observables studied in  $^{96}\text{Zr}+^{96}\text{Zr}$  system (in comparison with  $^{96}\text{Ru}+^{96}\text{Ru}$  collisions) before chiral magnetic effect [12] or other isospin-dependent phenomena are claimed to exist. Collisions of Zr+Zr and Ru+Ru nuclei have been studied by FOPI collaboration [13] at GSI.

## 6. Conclusions

For a detailed understanding of the initial eccentricity and the elliptic flow in central collisions of Au and U nuclei, one needs to take into account their static deformation and ground-state vibrational wave function. The explanation of the elliptic flow strength in Cu+Cu collisions [1] at RHIC is still awaited. We suggest ground-state properties (e.g. strong shape vibrations) in  $^{63}\text{Cu}$  nucleus might partially explain the observed discrepancy with theoretical models.

Experimental study of the relativistic collisions of carefully selected nuclei ( $^{96}\text{Zr}$ ,  $^{96}\text{Ru}$ ,  $^{144}\text{Sm}$  and  $^{154}\text{Sm}$ ) at RHIC and LHC colliders as well as on SPS at CERN and future facilities NICA, FAIR could allow us to verify and improve our understanding the elliptic flow phenomenon.

Deformation effects we have discussed here are expected to occur mainly in very central (VHM) collisions. We suggest that detailed understanding of such collisions is important. Theoretical calculations predict that extreme magnetic fields ( $B > 10^{14}\text{T}$ ) created in non-central collisions of nuclei may influence the critical temperature  $T_c$  of QCD phase transitions [14]. It can thus happen, that in the most central collisions ( $B \approx 0$ ) the hot partonic matter created may have different properties (Equation of State) than observed in non-central collisions.

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