PROCEEDINGS OF SCIENCE

Influence of Deformation and Vibration of Nuclei on the Elliptic Flow

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We investigate the influence of ground-state properties of nuclei on the initial state geometry in heavy ion collisions with the emphasis on the elliptic flow phenomenon. Deformation and ground-state vibration of Au and Cu nuclei is discussed. Effective self-orientation behavior of deformed nuclei in very-high-multiplicity (VHM) central collisions is explained. Prediction for the behavior of the elliptic flow strength in the highest multiplicity interactions of strongly deformed oblate and prolate nuclei is given. We also suggest to study collisions of specific nuclei in order to verify our understanding of the elliptic flow and partonic matter created in relativistic heavy ion collision experiments.

XXI International Baldin Seminar on High Energy Physics Problems,
September 10-15, 2012
JINR, Dubna, Russia

PoS(Baldin ISHEPP XXI)051

1. Introduction

In heavy ion collision experiments, ground-state deformation of nuclei is usually believed to be the unnecessary complication and spherical nuclei are preferred for such experiments. However, if the highest possible baryonic or energy densities are required, and when nuclei significantly heavier than ^{208}Pb are accelerated (collided), the prolate deformation has to be taken into account. Moreover, vast majority of nuclei are slightly deformed, including *Au* and *In* collided at RHIC/BNL and SPS/CERN and one can ask, how much the quantities (e.g. J/Ψ suppression) evaluated with the assumption of spherical shape of such nuclei can be affected.

Although the Elliptic flow in Au+Au collisions measured by RHIC detectors at Brookhaven National Laboratory seems to be well understood there still remain some issues to be explained. For example, strength of the elliptic flow measured in Cu+Cu collisions [1] at RHIC is 2x larger than predictions from our models. Is our understanding of in the initial state of QCD matter in Cu+Cu collision incomplete or is there some physics being neglected in our models of the partonic matter expansion?

In this contribution we discuss, why deformation and ground-state vibration of nuclei affects the initial eccentricity of the interaction volume. Possible influence of short-range-correlations (SRC) of nucleons in some nuclei is briefly skeched and specific collision systems are suggested.

2. Intrinsic deformation and vibration of nuclei

Majority of nuclei posess the intrinsic quadrupole deformation as a consequence of spontaneous symmetry breaking in the ground-state of rotationaly invariant hamiltonian [2]. Spectroscopic quadrupole moments $Q(s_z)$ of nuclei observed in NMR spectra are related to the intrinsic quadrupole moment Q_o via formula: $Q(s_z) = Q_o[3s_z^2 - J(J+1)]/[(J+1)(2J+3)]$, which gives e.g. $Q(1/2)>0$ while $Q_o < 0$ for ^{197}Au (J=3/2) nucleus and always yields $Q = 0$ for $J = 0$ nuclei. Indeed, it is well known, that ^{154}Sm and many other rare-earth nuclei [3] are strongly deformed $\beta_2 \approx 0.27$ while having zero spin $J = 0$ (see ^{150}Nd in Fig.2 and ^{154}Sm in Fig.6).

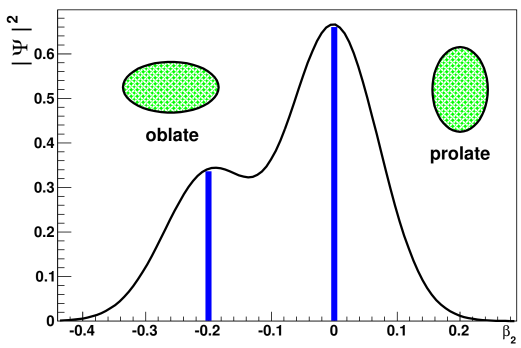

Figure 1: Probability of vibrating oblate nucleus to have deformation given by fluctuating β_2 parameter.

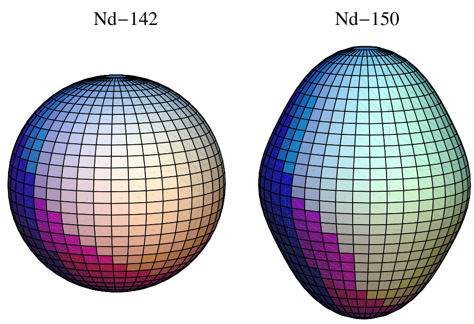

Figure 2: ^{142}Nd and ^{150}Nd nuclei.

Besides the static quadrupole intrinsic deformation, the shape of nuclei may vibrate in their lowest energy state due to the quantum zero-point vibartional energy [4]. In molecular physics, quantum vibrations are well understood and the amplitude of ground-state shape vibrations of C_{60} molecule was calculated [5]. Also, for muonic heavy hydrogen molecule, vibrational wave function of the ground state needs to be known for estimating the fusion probability [6] in such system.

If nuclear shape vibrations are large enough they can effectively generate *dynamical* quadrupole moment even for almost spherical $\beta_2 \approx 0$ nuclei [7]. In Fig.1 we show how large quadrupole vibrations we may expect in the ground state of ^{196}Hg nucleus according to [8]. Such dynamical deformation effects have not been taken into account in the initial eccentricity simullation [9].

Initial overlap time τ_i for relativistic collisions of nuclei is much shorter then period of zero-point shape vibrations $(1/\nu)$, and one can consider dynamic vibrational state to be frozen during the collision. All deformation values β_2 below the curve shown in Fig.1 have to be taken into account with the corresponding probability. In the next section we discuss how static deformation can influence the average eccentricity of the interaction zone in ultra-central collisions.

3. Eccentricity in collisions of deformed nuclei

Spatial orientation of deformed nuclei colliding at given impact parameter directly affects the total charge multiplicity $dN_{ch}/d\eta$ and initial eccentricity ε_2 of the interaction zone on event-by-event basis. Strongly exagerated effect is shown in Fig.3. Assuming two-component model for particle production [10]

$$dN_{ch}/d\eta = (1-x)\cdot n_{pp}\frac{N_{part}}{2} + x\cdot n_{pp}N_{coll} \tag{3.1}$$

one has larger multiplicity $dN_{ch}/d\eta$ due to significantly higher number of binary nucleon-nucleon collisions N_{coll} for longitudinaly oriented prolate nuclei colliding at zero impact parameter if compared to other possible orientations. Selecting central collisions of prolate nuclei with very-high-multiplicity (VHM) one effectively enhances the fraction of events with longitudinaly oriented nuclei in such data sample, which corresponds to the effective "self-orientation".

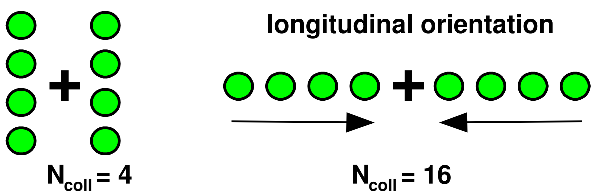

Figure 3: Number of nucleon-nucleon collisions for different orientations of two extremely prolate nuclei.

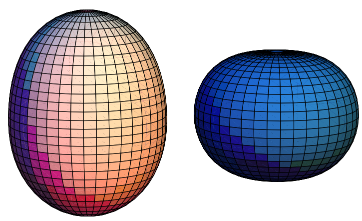

Figure 4: ^{165}Ho,^{116}Cd shapes.

It has been speculated [11] that sample of central Au+Au collisions studied at RHIC/BNL may contain a small admixture of events with anomalously large (single-event) elliptic flow values. Such events could be understood as central collisions of suitably oriented non-spherical Au nuclei. Indeed, spectroscopic quadrupole moment of Au nucleus Q=+0.58 [12] confirms the non-sphericity of ^{197}Au charge distribution. Also theoretical calculations [3] predict ^{197}Au to be have oblate deformation ($\beta_2 = -0.13$), which has been confirmed by recent GDR measurements [13]. Strongly deformed oblate nucleus ^{116}Cd with $\beta_2 = -0.24$ [3] is shown in Fig.4 next to the prolate nucleus ^{165}Ho. It is clear, that for collisions of oblate nuclei the highest multiplicity is obtained when the main symmetry axis of nuclei is oriented orthogonally to the beam and parallel to each other. Number of binary nucleon-nucleon collisions N_{coll} is the highest in this case, giving the largest multiplicity of produced particles (see Eq.3.1). At the same time initial eccentricity ε_2 in such collisions is rising proportionaly to the strength of the oblate deformation $\beta_2 < 0$. Thus oblateness of Au nucleus could explain admixture of events with anomalously large elliptic flow values in the sample of central Au+Au collisions. Ground state wave function of ^{197}Au nucleus is however not precisely known, due to the odd number of protons $Z = 79$. It is not clear how much ^{197}Au nucleus vibrates in its ground state compared to ^{196}Hg (see Fig.1).

For collisions of prolate nuclei a sudden drop (cusp) in the initial eccentricity for the highest multiplicity (VHM) collisions has been predicted [9]. Indeed, the initial eccentricity suddenly decreases if prolate nuclei oriented longitudinally collide at very small impact parameters. This prediction [9] is based on the model of charged particle multiplicity production [10] (see Eq.3.1), which may be slightly different from the real particle production mechanism. Additionally, a high multiplicity tail of Poissonian (or negative-binomial) distribution from the more frequent randomly oriented collisions with smaller average $\langle dN_{ch}/d\eta \rangle$ can contaminate substantially the sample of VHM collisions. Therefore, anticipated cusp-like decrease of the elliptic flow value at high-multiplicity tail of central collisions of prolate nuclei [9] needs to be verified experimentally.

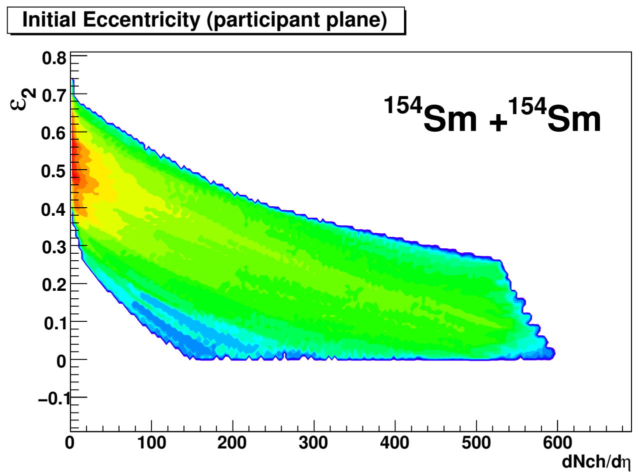

Figure 5: Eccentricity[Nch] plot for ^{154}Sm +^{154}Sm collisions obtained from the Optical Glauber Model [14] simulation.

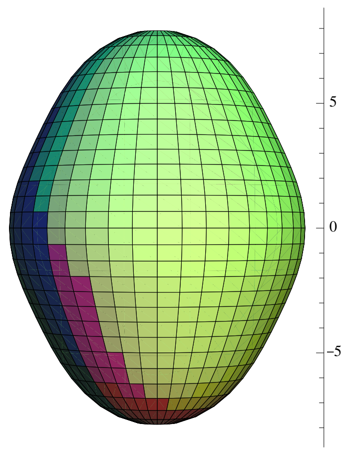

Figure 6: ^{154}Sm nucleus.

In Fig.5 we show the result of Optical Glauber simulation [14] for the initial eccentricity ε_2 as a function of charged multiplicity for collisions of strongly deformed ^{154}Sm nuclei. The cusp-like decrease of the *average* initial eccentricity is located in the multiplicity region $500 < dN_{ch}/d\eta < 600$ where effective orientation of prolate nuclei happens. It is also clear, that eccentricity fluctuations are large at given $dN_{ch}/d\eta$ due to deformation. For spherical ^{144}Sm+^{144}Sm collisions the Optical Glauber Model [14] gives just a single value of eccentricity ε_2 at given $dN_{ch}/d\eta$. Full Monte Carlo Glauber simulation [9] generates fluctuating eccentricities even for spherical nuclei.

In collisions of deformed nuclei, width σ_{v_2} of the elliptic flow fluctuation should increase as $\sigma_{v_2} \approx \lambda \cdot \sqrt{\tilde{\sigma}_\varepsilon^2 + \sigma_\beta^2}$, where $\tilde{\sigma}_\varepsilon$ is the eccentricity fluctuation present also for spherical nuclei collisions (originating from all other sources exept a static deformation), and σ_β denotes the eccentricity fluctuation width due to β_2 deformation of nuclei. Factor $\lambda \approx 0.2$ comes from the hydrodynamic simulations of the partonic matter expansion. Experimental verification of the above mentioned effects would convince heavy ion community, that our understanding of the initial eccentricity and the elliptic flow phenomenon are correct. In the next section we suggest carefuly selected collision systems, which may allow one to disentangle deformation effects from other physics observables of interest and verify our models of partonic matter behavior during the expansion.

4. 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}Sm+^{144}Sm and ^{154}Sm+^{154}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. Another element providing us with the same possibility is Neodymium (see Fig.2). Static shape of pherical ^{144}Sm and prolate ^{154}Sm isotopes (both stable) is shown in Fig.7. Cusp-like decrease of v_2 strength in VHM central collisions of heavy ^{154}Sm nuclei should be observable at ultra-relativistic energies on LHC and RHIC colliders if our understanding of the mechanism of charged multiplicity generation (see Eq.3.1) are indeed correct.

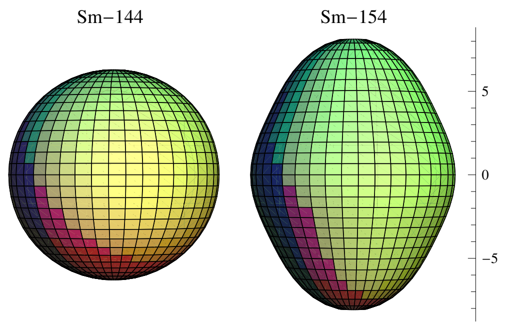

Figure 7: Shape of ^{144}Sm and ^{154}Sm nuclei.

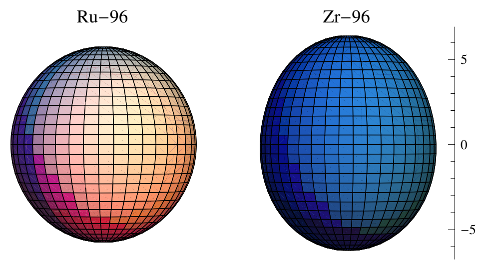

Figure 8: Shape of ^{96}Ru and ^{96}Zr nuclei.

Another important possibility is to compare collisions of ^{96}Zr+^{96}Zr and ^{96}Ru+^{96}Ru nuclei which have the same mass number but their charge (proton number) differs by 10%. Different charge of these nuclei allows one to perfome testing of the sensitivity of various measurable quantities (also the elliptic flow) on the extreme (B$>10^{14}$T) magnetic fields created for a short time by charged spectators in non-central collisions. One has to keep in mind however, that ^{96}Ru nucleus is almost spherical ($\beta_2 = 0.05$) while ^{96}Zr is prolate ($\beta_2 = 0.22$) [3]. It is therefore important to understand and subtract deformation effects (observed e.g. in ^{154}Sm+^{154}Sm collisions), from ^{96}Zr+^{96}Zr observables before chiral magnetic effect [15] (strong Parity violation) or initial-state isospin-dependent phenomena are claimed. Collisions of Zr+Zr and Ru+Ru nuclei have been studied succesfully by FOPI collaboration [16] at GSI.

For completeness, we mention here also ^{116}Cd+^{116}Cd collisions as an interesting system, for studying the oblate deformation effects (rising of the elliptic flow in central VHM collisions).

In principle, once Equation of State of hot QCD matter is known well enough, one can consider (and use) relativistic collisions of nuclei as a tool for studying of the ground-state properties (e.g. intrinsic deformation) of selected nuclei, using the observables (e.g. elliptic flow) which are sensitive to the initial state.

5. Unknown initial state effect or pre-equilibrium flow ?

What kind of phenomenon is reponsible for too strong elliptic flow observed [1] in RHIC experiments with ^{63}Cu+^{63}Cu collisions? According to theoretical calculation [3] static deformation of ^{63}Cu is $\beta_2 \approx 0.16$ (prolate) while ^{65}Cu is predicted to be oblate ($\beta_2 \approx -0.15$). Such deformation most likely cannot generate 2x higher eccentricity (elliptic flow) values than are expected when spherical shape of Cu nuclei is assumed in the simulations. In general, amplitude of zero point vibrations is larger for lighter systems (molecules) and thus vibrations of Cu nuclei may be stronger then the vibration of ^{196}Hg nuclei (see Fig.1). However, even the shape coexistence phenomenom (superposition of obalte and prolate shapes in the ground state of nucleus) does not seem to be capable of enhancing initial eccentricities by factor 2x in the centrality region studied in [1].

In fusion experiments with ^{16}O+^{63,65}Cu system [17] significant anomalies were observed for ^{63}Cu which do not appear for ^{65}Cu. Is there something in the ^{63}Cu ground state which is not understood? Besides the vibrational properties of nuclei (which we have discussed), there exists a phenomenon of the short-range-correlation (SRC) of p-n pairs in nuclei [18], which might influence the initial state. In ^{12}C the fraction of SRC pairs [18] is estimated to be 12%. Also cumulative effects studied 30 years ago [19] indicated that wave function of ^{12}C nucleus and other nuclei (including Cu) contains an admixture of very dense multi-nucleon spots (fluctuons) with unusually high momenta. Such "hot spots" and pre-equilibrium flow phenomena originating from large (antiparallel) transverse momenta of correlated SRC nucleon-nucleon pairs [18] might possibly influence the azimuthal asymmetry of particle production in momentum space (the elliptic flow). At present, it is not clear, how to resolve the observed strength of elliptic flow v_2 in ^{63}Cu+^{63}Cu collisions at RHIC [1].

6. Conclusions

MC Glauber simulation [9] suggests, that interesting deformation effects can be expected mainly in central (very-high-multiplicity) collisions of strongly deformed nuclei. Central collisions of deformed nuclei may be of special interest, since energy density reaches the highest values in such collisions and also because the extreme magnetic fields (B$\approx 10^{14}$T) disappear for very small impact parameters. It is known, that critical temperature of chiral and deconfinement QCD phase transitions may be influenced by strong magnetic fields [20]. Properties of the hot QCD partonic matter created in the most central collisions can thus be different from that observed in non-central collisions, where strong magnetic fields are present. Collisions of carefully selected Cd, Sm, Zr, Ru and Cf nuclei at relativistic collider facilities (LHC, RHIC and also NICA) might verify our understanding of the elliptic flow, and possibly reveal new behavior or phases of dense hadronic/partonic matter created.

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Acknowledgements: This work has been supported by Grant agency VEGA(1/0171/11) and APVV-0177-11 of Slovakia.

Author thanks the organizers for kind invitation to attend the XXI International Baldin Seminar on High Energy Physics Problems "Relativistic Nuclear Physics and Quantum Chromodynamics".

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