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Collective nuclear vibrations and initial state shape fluctuations in central Pb + Pb collisions: resolving the v_2 to v_3 puzzle

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The results of experiments on the heavy ion collisions at RHIC and LHC give a lot of evidences for formation of the quark-gluon plasma (QGP) in the initial stage of nuclear collisions (at the proper time $\tau_0 \sim 0.5{-}1\,\mathrm{fm}$) which flows as an almost ideal fluid. The most effective constraints on the QGP viscosity come from the hydrodynamic analysis of the azimuthal dependence of the hadron spectra which is characterized by the Fourier coefficients v_n

$$\frac{dN}{d\phi} = \frac{N}{2\pi}\left\{1+\sum_{n=1}^{\infty} 2v_n \cos\left[n\left(\phi-\Psi_n\right)\right]\right\}, \qquad (1)$$

where N is hadron multiplicity in a certain p_T and rapidity bin, Ψ_n are the event reaction plane angles. For smooth initial conditions at midrapidity ($y = 0$) in the Fourier series (1) only the terms with $n = 2k$ survive. And the azimuthal anisotropy appears only for noncentral collisions due to the almond shape of the overlap region of the colliding nuclei in the transverse plane. The event plane (for each n) in this case coincides with the true reaction plane and $\Psi_n = 0$. In the presence of fluctuations of the initial QGP entropy, all the flow coefficients v_n become nonzero. The fluctuations of the initial fireball entropy is a combined effect of the fluctuations of the nucleon positions in the colliding nuclei and fluctuations of the entropy production for a given geometry of the nuclear positions. The most popular method for evaluation of the initial entropy distribution for event-by-event simulation of AA-collisions is the Monte-Carlo (MC) wounded nucleon Glauber model [1 and references therein]. The even-by-event hydrodynamic modeling with the MC Glauber (MCG) model initial conditions has been quite successful in description of a vast body of experimental data on the flow coefficients in AA-collisions obtained at RHIC and LHC. However, in the last years it was found that the hydrodynamical models fail to describe simultaneously v_2 and v_2 flow coefficients in the ultra-central ($b \to 0$) Pb + Pb collisions at the LHC energies. For central collisions, at $b = 0$, the anisotropy of the initial fireball geometry originates completely from the fluctuations. The hydrodynamic calculations show [3, 2] that for small centralities in each event the v_n for $n \le 3$ to good accuracy satisfy the linear response relation

$$v_n \approx k_n \epsilon_n, \qquad (2)$$

where ϵ_n are the Fourier coefficients characterizing the anisotropy of the initial fireball entropy distribution, $\rho_s(\boldsymbol{\rho})$, in the transverse plane defined as [4]

$$\epsilon_n = \frac{\left|\int d\boldsymbol{\rho}\rho^n e^{in\phi}\rho_s(\boldsymbol{\rho})\right|}{\int d\boldsymbol{\rho}\rho^n \rho_s(\boldsymbol{\rho})}. \qquad (3)$$

Here it is assumed that the transverse vector $\boldsymbol{\rho}$ is calculated in the tranverse c.m. frame, i.e., $\int d\boldsymbol{\rho}\boldsymbol{\rho}\rho_s(\boldsymbol{\rho}) = 0$. The hydrodynamic calculations give $k_2/k_3 > 1$, and this ratio grows with increase of the QGP viscosity. On the other hand, the MCG calculations show that at $b = 0$ ϵ_2 and ϵ_3 are close to each other (and are ~ 0.1 for Pb + Pb collisions). This leads to prediction that $v_2/v_3 > 1$. But experimentally it was observed that v_2 is close to v_3 in the ultra-central 2.76 and 5.02 TeV Pb + Pb collisions [5, 6]. Since the hydrodynamic prediction for k_2/k_3 seems to be very reliable, this situation looks very puzzling (it is called in the literature v_2-to-v_2 puzzle). This leads to a serious tension for the hydrodynamic paradigm of heavy ion collisions.

There were several attempts to resolve the v_2-to-v_2 puzzle by modifying: the initial conditions [7, 8], the viscosity coefficients [9], and the QGP equation of state of [10]. However, these attempts have not been successful. The common feature of all previous analyses devoted to the v_2-to-v_2 puzzle is the use of the Woods–Saxon (WS) nuclear distribution for sampling the nucleon positions in the MC simulations of Pb + Pb collisions. In fact, this is an universal choice in the physics of high-energy

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heavy ion collisions. However, the MC sampling of nucleon positions with the WS distribution completely ignores the collective nature of the long range fluctuations of the nucleon positions. It is well known that the long range 3D fluctuations of the nuclear density have a collective nature and are closely related to the giant nuclear resonances [11] (for more recent reviews see [12, 13]). The major vibration mode of the spherical ^{208}Pb nucleus corresponds to excitation of the isoscalar giant quadrupole resonance [11]. These collective quantum effects are completely lost if one samples the nuclear configurations with the WS distribution. It is clear that an inappropriate description of the 3D long range fluctuation of the nucleon positions in the colliding nuclei will translate into incorrect long range fluctuations of the 2D initial fireball entropy density, which are crucial for $\epsilon_{2,3}$ in the central AA-collisions, when they are driven by fluctuations.

With the help the energy weighted sum rule (EWSR) (for a review, see [14]), we demonstrated that the WS distribution overestimates considerably the mean square nuclear quadrupole moment of the ^{208}Pb nucleus as compared to that obtained in the quantum treatment of the quadrupole vibrations. From EWSR we obtained for the ratio of the classical to the quantum mean square isoscalar L-multipole operator $F_L = \sum_{i=1}^{A} r_i^L Y_{Lm}(\hat{\boldsymbol{\rho}}_i)$ (here $\hat{\boldsymbol{\rho}}_i = \boldsymbol{\rho}/|\boldsymbol{\rho}|$) a simple formula

$$r = \frac{\langle 0|F_L^+ F_L|0\rangle_c}{\langle 0|F_L^+ F_L|0\rangle_q} = \frac{2m_N E_c \langle r^{2L}\rangle}{L(2L+1)\langle r^{2L-2}\rangle}, \tag{4}$$

where E_c is the centroid excitation energy for the L-mode. For the isoscalar $L = 2$ operator the EWSR is exhausted by the isoscalar giant quadrupole resonance with $\omega_q \approx 10.89\,\mathrm{MeV}$ and $\Gamma_q \approx 3\,\mathrm{MeV}$ [15]. Calculation with the Breit–Wigner parametrization of the quadrupole strength function gives the centroid energy $E_c \approx 11.9\,\mathrm{MeV}$. Using this centroid energy, we obtained for the quadrupole mode $r \approx 2.2$.

We calculated the azimuthal anisotropy coefficients $\epsilon_{2,3}$ in Pb + Pb collisions in the MCG model of [16] by sampling the nuclear configurations for ordinary WS distribution and a modified one which reproduces the quantum mean square nuclear quadrupole moment of the ^{208}Pb nucleus. Our results show that for the quantum version the ratio ϵ_2/ϵ_3 becomes substantially smaller than that for ordinary WS distribution. The magnitude of the obtained ϵ_2/ϵ_3 is small enough to resolve the v_2-to-v_2 puzzle.

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