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Effect of giant resonances on fluctuations of electromagnetic fields in heavy ion collisions

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A very strong magnetic field can be generated in heavy ion collisions at RHIC and LHC energies: $eB \sim 3m_\pi^2$ for RHIC ($\sqrt{s} = 0.2$ TeV) and $eB \sim 45m_\pi^2$ for LHC ($\sqrt{s} = 2.76$ TeV) [1–4]. In the last years effect of the magnetic field on the processes in the quark-gluon plasma produced in AA collisions attracted much attention (e.g., the charge separation along the magnetic field direction due to the anomalous current $\propto \mathbf{B}$ (the chiral magnetic effect) [1, 5], the synchrotron photon emission [6, 7], anisotropy in the heavy quark diffusion [8, 9], the magnetohydrodynamic flow effects [10, 11]). To a good approximation [4], the initial fields after intersection of the Lorentz contracted nuclei are determined by a sum of the fields generated by the colliding nuclei. But at later times the plasma response can modify them [4]. If one neglects it, the average electric, $\langle\mathbf{E}\rangle$, and magnetic, $\langle\mathbf{B}\rangle$, fields of each nucleus are simply given by the Lorentz transformation of its Coulomb field in the nucleus rest frame. The average magnetic field, in the center of mass system of the nucleus-nucleus collision, at $y = 0$ (here y is the axis transversal to the reaction plane) turns out to be transversal to the reaction plane. However, the field fluctuations can generate nonzero reaction plane components, $\delta B_{x,z}$. Usually, in the literature (see, e.g., [12–15]) fluctuations of the electromagnetic fields in AA collisions are treated using the classical Lienard–Weichert potentials of the protons within the Monte-Carlo simulation with the Woods–Saxon (WS) nuclear distributions. This approach gives rather strong event-by-event fluctuations of the magnetic field. However, the classical treatment has no serious theoretical justification. The deviations from the classical approach may come both from the dynamical quantum effects in the colliding nuclei and from the quantum effects for the electromagnetic fields. Indeed, the field fluctuations should be most sensitive to the large scale fluctuation of the electric charge density in the colliding nuclei. They are dominated by the collective giant resonances (see, e.g., [16, 17, 18]). The potentially important collective excitations are the isovector giant dipole resonance (IV-GDR) and isoscalar/isovector giant quadrupole resonances (IS/IV-GQRs) with the excitation energy $\omega_R \sim 10-25$ MeV [18]. But the factorized WS nuclear distribution ignores the collective quantum effects. From the side of the electromagnetic field the classical treatment should be invalid when the distance from the nucleus, R, in the nucleus rest frame, becomes bigger than $1/\omega_R$.

The quantum calculation of the electromagnetic field fluctuations can be performed using the general formulas of the fluctuation-dissipation theorem [19] for the electromagnetic fluctuations given in [20]. In the case of interest the field fluctuations can be expressed via the nuclear dipole and quadruple polarizabilities. The contribution of the dipole mode have been addressed in [21]. In the present letter we address the field fluctuations accounting for both the GDR and GQRs.

We consider the spherically symmetrical even-even ^{208}Pb nucleus. In this case the dipole and quadrupole polarization tensors can be written in terms of two scalar polarizabilities α_d and α_q. We parametrize them by a single Lorentzian form

$$\alpha_i(\omega) = c_i \left[\frac{1}{\omega_i - \omega - i\Gamma_i/2} + \frac{1}{\omega_i + \omega + i\Gamma_i/2}\right].$$

The parameters ω_d, Γ_d, c_d for the GDR have been obtained in [21] from the data on the photoabsorption cross section [22]. In the present analysis we obtained ω_q, Γ_q for the IS-GQR and IV-GQR from the parameters of the GQRs obtained in [23, 24], and the normalization constants c_q for the IS and IV modes have been obtained from the exhaustion of the energy weighted sum rule (100 % [23] and 56 % [24]).

In Figure 1 we show our results for t-dependence of the ratio $\langle\delta B_x^2\rangle^{1/2}/\langle B_y\rangle$ (which gives the typical angle between the magnetic field and the perpendicular to the reaction plane) at $\mathbf{r} = 0$ for the impact parameters $b = 3$, 6 and 9 fm for RHIC energy $\sqrt{s} = 0.2$ and LHC energy $\sqrt{s} = 2.76$ TeV. For comparison we also show predictions of the classical Monte-Carlo calculations for the WS nuclear density. Figure 1 shows that in the quantum picture $\langle\delta B_x^2\rangle^{1/2}/\langle B_y\rangle$ is considerably smaller than in the classical one. One can see that the relative quadrupole contribution falls steeply with in-

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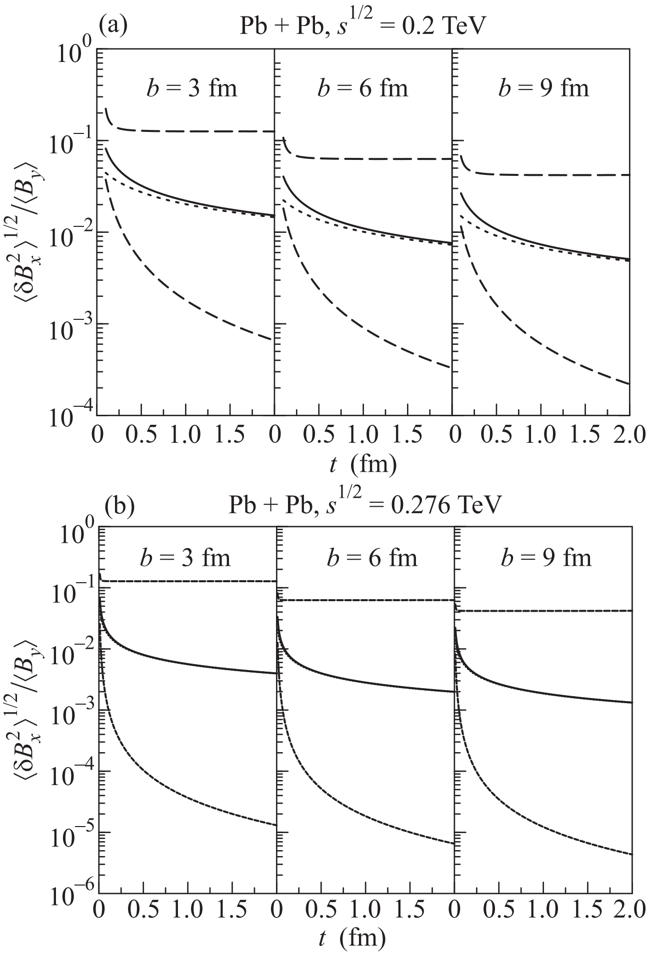

Fig. 1. Ratio $\langle \delta B_x^2 \rangle^{1/2} / \langle B_y \rangle$ versus t at $\mathbf{r} = 0$ for Pb + Pb collisions at $\sqrt{s} = 0.2$ (upper) and $\sqrt{s} = 2.76$ (lower) TeV for impact parameters $b = 3$, 6 and 9 fm. Results of quantum calculations: solid line is for the total contribution of the GDR, IS-GQR and IV-GQR, dotted line is for the contribution of the GDR, dashed line is for sum of the contributions of the IS-GQR and IV-GQR. Long-dashed lines show results of the classical Monte-Carlo calculation with the WS nuclear density

crease of t. The reduction of the field fluctuations in the quantum picture comes partly from smaller fluctuations of the dipole and quadrupole moments and partly from the dynamical quantum effects in the electromagnetic fields. The latter lead to an increase of the difference between the quantum and the classical models with increasing t. The fact the classical treatment based on the WS nuclear density overestimates the fluctuations of the dipole and quadrupole moments means that it overestimates the ellipsoidal fluctuations of the nuclear density. This may be very important for the event-by-event hydrodynamic simulations of AA collision that presently ignore possible collective effects in the nuclear distributions.

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