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Evolution of electro-magnetic fields in relativistic heavy-ion collisions from the HSD transport approach

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Retarded electromagnetic fields – as emerging from the charge four-currents – have been calculated in the Hadron String Dynamics (HSD) model. The creation and evolution of the fields as well as their influence on the quasiparticle propagation were studied in detail for non-central Au+Au collisions at the top RHIC energy. It is shown that the created magnetic field is highly inhomogeneous but in the central region of the overlapping nuclei it changes relatively weakly in the transverse direction. We find that at any time the location of the maximum in the distribution of magnetic field strength correlates with that of the energy density of the created particles. Our actual calculations show no noticeable influence of the electromagnetic fields - created in heavy-ion collisions - on the effect of the electric charge separation with respect to the reaction plane.

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1. Introduction

In the last few years, particular attention has been paid to the Chiral Magnetic Effect (CME) manifesting local P and CP symmetry violation in strong interactions as suggested in Ref [1] and widely discussed in Refs. [2, 3]. This effect originates from the existence of nontrivial topological configurations of gauge fields and their interplay with the chiral anomaly which results in an asymmetry between left- and right-handed quarks. Such a chiral asymmetry, when coupled to a strong magnetic field as created by colliding nuclei perpendicularly to the reaction plane, induces an electric charge current along the direction of a magnetic field thereby separating particles of opposite charges with respect to the reaction plane. Thus, such topological effects in QCD might be observed in heavy-ion collisions directly in the presence of very intense external electromagnetic fields due to the CME as a manifestation of the CP symmetry violation. Indeed, the electric charge asymmetry of produced particles with respect to the reaction plane has been recently measured by the STAR Collaboration [4].

Here we present our study [5] of the space-time evolution of electro-magnetic fields formed in relativistic heavy-ion collisions. The Hadron String Dynamics (HSD) transport model [6] is used as a basis of our considerations. In our approach the dynamical formation of the electromagnetic field, its evolution during a collision and influence on the quasiparticle dynamics as well as the interplay of the created magnetic and electric fields and back-reaction effects are included simultaneously.

2. Space-time evolution of electric and magnetic fields

The time evolution of the magnetic field component $eB_y(x, y = 0, z)$ for Au+Au collisions for the collision energy $\sqrt{s_{NN}} = 200$ GeV at the impact parameter $b = 10$ fm is shown in Fig. 1. If the impact parameter direction is taken as the x axis (as in the present calculations), then the magnetic field will be directed along the y-axis perpendicularly to the reaction plane $(z-x)$. The geometry of the colliding system at the moment considered is demonstrated by points in the $(z-x)$ plane where every point corresponds to a spectator nucleon. It is seen that the largest values of $eB_y \sim 5m_\pi^2$ are reached in the beginning of a collision for a very short time corresponding to the maximal overlap of the colliding ions. Note that this is an extremely high magnetic field, since $m_\pi^2 \approx 10^{18}$gauss. The first panel in Fig. 1 is taken at a very early compression stage for $t = 0.01$ fm/c. The time $t =$ 0.05 fm/c is close to the maximal overlapping and the magnetic field here is maximal. Then, the system expands (note the different z-scales in the different panels of Fig. 1) and the magnetic field decreases. For $b = 0$ the overlapping time is maximal and roughly given by $2R/\gamma_c$ which for our case is about 0.15 fm/c. For more peripheral collisions this time is even shorter.

The possibility of attaining extremely high magnetic fields in heavy-ion collisions was pointed out 30 years ago [7] but there have been only two real attempts to estimate the magnetic field for relativistic heavy-ion collisions [3, 8]. In Ref. [3] the colliding ions were treated as infinitely thin layers (pancake-like), and the results in the center of a Au-Au collision $eB_y(0,0,z)$ could be presented in a semi-analytical form. In Fig. 2 these estimates are confronted with our results. It is clearly seen that the magnetic field in our transport model for $b = 10$ fm is lower than the estimate from Ref. [3] for both $b = 12$ and 8 fm. This difference originates mainly from the fact that to simulate rapidity degradation of pancake-like nuclei, a heuristic function was assumed

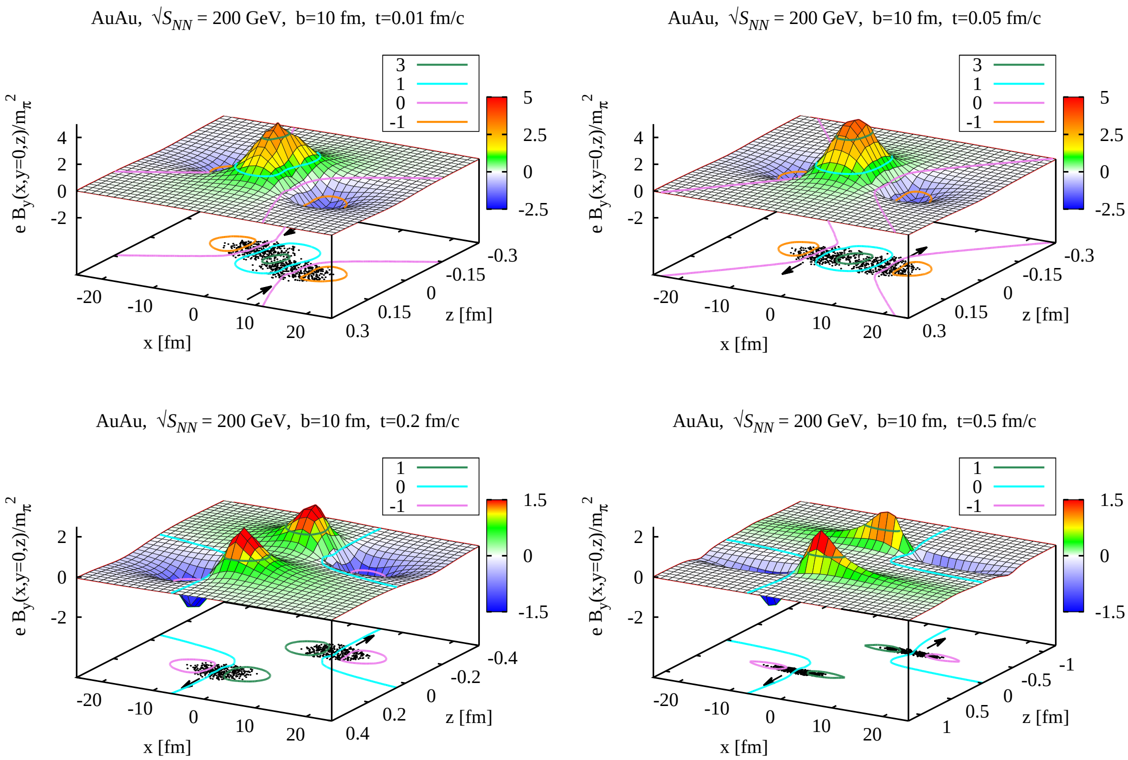

Figure 1: Time dependence of the spatial distribution of the magnetic field B_y at times t created in Au+Au ($\sqrt{s} = 200$ GeV) collisions with the impact parameter $b = 10$ fm. The location of spectator protons is shown by dots in the $(x-z)$-plane. The level $B_y = 0$ and the projection of its location on the $(x-z)$ plane are shown by the solid lines.

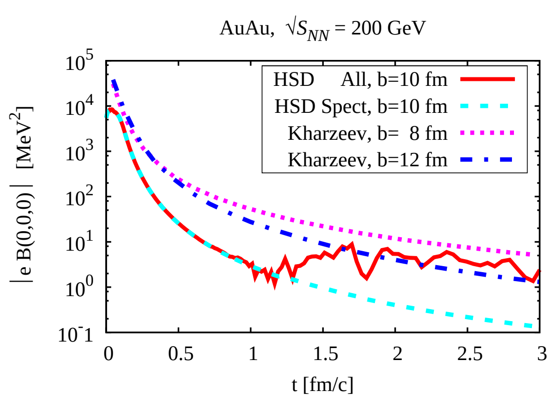

Figure 2: Time dependence of the $|eB|$ field in the center of the nuclear overlap region for Au+Au($\sqrt{s}$= 200 GeV) collisions from the HSD calculations. The dotted and dot-dashed curves are from Ref. [3] at the impact parameters $b = 8$ and 12 fm, respectively.

with making no difference between surviving baryons and new created particles [3] whereas in our case the dynamical hadron-string model is used for both primary and subsequent interactions while keeping track of the electric and baryonic charges and energy-momentum conservation [6].

The approximation of Ref. [3] is reasonable for first collisions but gets progressively worse with interaction time as seen in Fig. 2. The difference in the shape of the time dependence of the magnetic field for early times is due to neglecting the finite size of the colliding nuclei in Ref. [3].

It is of interest to note that in our transport model the spectator contribution to the magnetic field is practically vanishing at $t \approx 1$ fm/c (see Fig. 2). In subsequent times the magnetic field eB_y is formed essentially due to produced participants with roughly equal number of negative and positive charges which approximately compensate each other. The visible effect in our approach is by an order of magnitude lower than that in the estimate [3] which demonstrates the essential role of the retardation in this interaction phase.

We also studied [5] the background electric field which, being orthogonal to the magnetic one, is directed along the x axis. Similar to the case of the magnetic field, the $eE_x(x, y=0, z)$ distribution is also inhomogeneous and closely correlates with geometry.

Along with a high magnetic field, the presence of a quark-gluon phase is a necessary condition for a manifestation of the chiral magnetic effect according to Refs. [1, 2, 3]. The phase structure of excited matter is essentially defined by the energy density (cf. Refs. [9]). One can expect that for energy densities $\varepsilon > 1$ GeV/fm^3 the system is in a deconfined phase. Our calculation in Ref. [5] shows that even at the time $t \sim 0.5$ fm/c the local energy density is seen to be above the effective threshold of a quark-gluon phase transition $\varepsilon > 1$ GeV/fm^3.

3. Electric charge separation

The HSD model quite successfully describes many observables in a large range of the collision energy [6, 10]. We have investigated in detail that the electromagnetic field – incorporated in the HSD approach – only very slightly affects observables like the transverse mass m_t-spectra, rapidity y-distribution or elliptic flow v_2 [5].

As a signal of possible local *CP* violations in relativistic heavy-ion collisions, it was proposed in Ref. [11] to measure the two-particle angular correlation $\langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP}) \rangle$, where Ψ_{RP} is the azimuthal angle of the reaction plane defined by the beam axis and the line joining the centers of colliding nuclei. The correlator is calculated on an event-by-event basis with subsequent averaging over the whole event ensemble. The experimental data from the STAR Collaboration [4] and the results of HSD calculations are presented in Fig. 3. The expected CME stems from the interplay of topological effects of the excited vacuum and the chiral anomaly in the presence of a strong magnetic field [2, 3]. One can see that the calculated background - taking into account hadron string interaction dynamics and evolution of the electromagnetic field - is not able to describe the measured distribution especially for pions of the same charge. One should mention that our results are rather close to the background estimates within the UrQMD model in the experimental works [4].

4. Summary

We have extended the HSD model to describe the formation of the retarded electromagnetic field, its evolution during a nuclear collision and the effect of this field on particle propagation. The case of Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV for $b = 10$ fm is considered in particular detail.

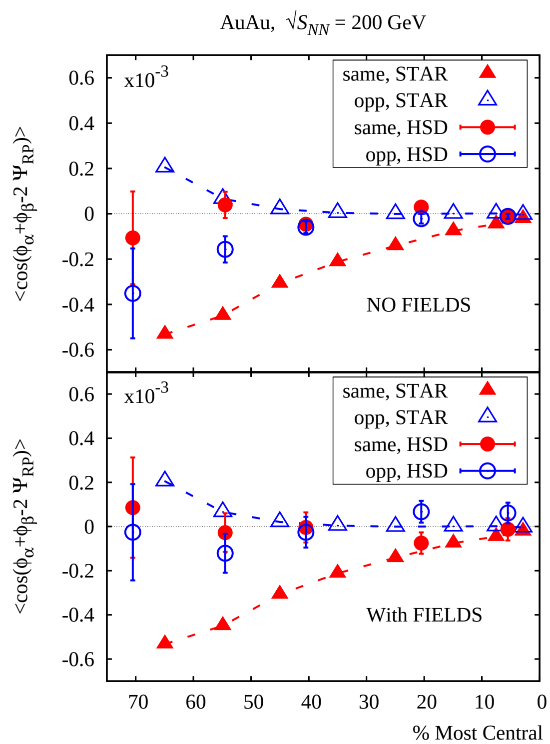

Figure 3: Azimuthal correlation in the transverse plane as a function of centrality for like and unlike charged pions from Au+Au ($\sqrt{s_{NN}} = 200$ GeV) collisions. The experimental points (with lines) are taken from [4].

It is quite important to understand the interplay of strong and electromagnetic interactions in this case since it provides a point which is decisive in the CME measurements at RHIC as a function of centrality [4]. It is shown that the most intensive magnetic field oriented perpendicularly to the reaction plane is formed during the time when the Lorentz-contracted nuclei are passing through each other, $t < 0.2$ fm/c. The maximal strength of the magnetic field here attains very high values, $eB_y/m_\pi^2 \sim 5$.

This maximal strength of the magnetic field is created predominantly by spectators. When target and projectile remainders are separated, the spectator contribution goes sharply down and for $t \sim 1$ fm/c decreases by more than three orders of magnitude. In subsequent times the charged participants come into the game, but their contributions are small due to the mutual compensation of approximately equal number of positive and negative charges as well as to the suppressive role of the relativistic retardation effect.

The important accompanying quantity is the energy density ε of the created particles. The location of the maximum in the field strength eB_y and the energy density ε nicely correlate with each other. Both, strong magnetic field and large energy density, are necessary conditions for the CME. We find that the energy density decreases faster than the magnetic field, but stays long enough at values $\varepsilon > 1$ GeV/fm^3 needed for the matter to be in the quark-gluon phase. Certainly, the issue of thermalization remains open in this consideration.

Our analysis of the angular correlators – specific for the CME – shows that the calculated HSD background is very small and not able to describe the STAR measurements [4]. The consideration of in-plane and out-of-plane projection components of this correlator does not allow us to clarify the picture and rises new questions related to the experiment [12]. In this respect it is of great interest to include quark-gluon degrees of freedom directly in our approach. In particular, the partonic generalization of the HSD model (PHSD) [9] is highly suited for this aim. Another way to approach the CME is to simulate an induced chromoelectric field which is assumed to be the source of the observed electric charge separation of pion pairs relative to the reaction plane.

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