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Magnetohydrodynamics and charged flow in heavy ion collisions

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Abstract

Strong magnetic fields are generated in any heavy ion collision with a nonzero impact parameter. These magnetic fields induce electric currents in the hot QCD matter produced in these collisions on the reaction plane. We study the imprint of these electric currents on the azimuthal distributions and correlations of the produced charged hadrons. In particular we find that these currents result in a charge-dependent directed flow v_1 that is odd in rapidity and odd under charge exchange and a charge-dependent elliptic flow v_2 that is even in rapidity. They can be detected by measuring correlations between the directed flow of charged hadrons at different rapidities, $\langle v_n^{\pm}(y_1)v_n^{\pm}(y_2)\rangle$.

Keywords: Magnetohydrodynamics, Quark Gluon Plasma, Heavy Ion Collisions

1. Introduction

Magnetic fields $\vec{B}$ are produced in all heavy ion collisions with nonzero impact parameter b by the charged spectators. Estimates obtained via application of the Biot-Savart law to heavy ion collisions with $b = 4$ fm yield $e|\vec{B}|/m_\pi^2 \approx$ 1-3 about 0.1-0.2 fm/c after a RHIC collision with $\sqrt{s} = 200$ AGeV and $e|\vec{B}|/m_\pi^2 \approx$ 10-15 at some even earlier time after an LHC collision with $\sqrt{s} = 2.76$ ATeV [1, 2, 3, 4, 5, 6, 7].

The most direct effect of magnetic fields [8] is induction of electric currents carried by the charged quarks and antiquarks in the quark-gluon plasma (QGP) and, later, by the charged hadrons. These charged currents may be generated in two ways, see fig 1. Firstly, decay in the magnitude of $\vec{B}$ in time generates a circular electric current in the reaction plane as a result of Faraday's law. Secondly, expansion of the plasma in the presence of $\vec{B}$ results in an electric field in the rest frame of a unit cell in the plasma, similar to the classical Hall effect. Fig. 1 serves to orient the reader as to the directions of $\vec{B}$ and the plasma velocity $\vec{u}$, and the electric currents induced by the Faraday and Hall effects. As demonstrated in this figure, the electric fields produced by these two mechanisms are in opposite directions. The total electric field is given by the sum of the two. Finally, this electric field results in a charge current in a medium with non-trivial conductivity, such as the QGP.

We want to study the effect of these charged currents on the charged hadron spectra. One can do this by applying the Cooper-Frye analysis at the freezout. The basic ingredient that enters this calculation is the 4-velocity field of the plasma V^μ. In the lab frame this total 4-velocity field includes both the expansion velocity of the plasma $\vec{u}$ and the additional velocities produced by the electromagnetic sources as a result of the aforementioned mechanisms. We follow a perturbative approach by ignoring the backreaction of the electromagnetic forces on the expansion velocity $\vec{u}$, that is valid when $|\vec{V} - \vec{u}|/|\vec{u}| \ll 1$ (justified a posteriori). To model the expanding medium we use the analytic solution

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to relativistic viscous hydrodynamics for a conformal fluid with the shear viscosity to entropy density ratio given by $\eta/s = 1/(4\pi)$ found by Gubser in 2010 [10]. The solution describes a finite size plasma produced in a *central* collision that is obtained from conformal hydrodynamics by demanding boost invariance along the beam (i.e. z) direction, rotational invariance around z, and two special conformal invariances perpendicular to z. As demonstrated in [8], we can choose parameters such that Gubser's solution yields a reasonable facsimile of the pion and proton transverse momentum spectra observed in RHIC and LHC collisions with 20 − 30% centrality, corresponding to collisions with a mean impact parameter between 7 and 8 fm, see e.g. [11, 12]. We denote the velocity of Gubser's solution as $\vec{u}$. To obtain the additional velocity field $\vec{v}$ we first boost by $-\vec{u}$ to a local rest frame in the plasma. We then obtain stationary currents in this frame by solving the equation of motion for a charged fluid element with mass m using the Lorentz force law:

$$m\frac{d\vec{v}}{dt} = q\vec{v}\times\vec{B}' + q\vec{E}' - \mu m\vec{v} = 0\,, \tag{1}$$

where E' and B' are the electric and magnetic fields in the rest frame. The last term describes the drag force on a fluid element with mass m on which some external (in this case electromagnetic) force is being exerted, with μ being the drag coefficient. The nonrelativistic form of (1) is justified by the aforementioned assumption. For the purpose of our order-of-magnitude estimate, we use the $\mathcal{N} = 4$ SYM value [13, 14, 15] $\mu m = 6.8T^2$, for a 't Hooft coupling $\lambda = 6\pi$ and $T = 255$ MeV. Finally, we boost back to the original center-of-mass frame to obtain the total velocity $\vec{V}$. The magnetic and electric fields $\vec{B}$ and $\vec{E}$ in the center-of-mass frame (the frame illustrated in Fig. 1) are obtained by solving Maxwell's equations with a single point-like charge moving with a velocity $\vec{\beta}$ in a medium with constant (our first simplifying assumption) conductivity σ [8]. The total field is obtained by integrating this over the entire distribution of all the protons in the two colliding nuclei. We also make the simplifying assumption that the protons in a nucleus are uniformly distributed within a sphere of radius R, with the centers of the spheres located at $x = \pm b/2$, $y = 0$ and moving along the $+z$ and $-z$ directions. For the participants we use the empirical distribution [1, 9]. We find [8] that, as other authors have shown previously [2, 3, 4, 5, 6, 7], the presence of the conducting medium delays the decrease in the magnetic field.

2. Results

Our goal in Ref. [8] is to make an estimate of the order of magnitude of the resulting charge-dependent v_n in the final state pions and protons. The theoretical estimations we make here are based on the basic assumption that the electromagnetic interactions can be treated classically. We checked this by comparing the total magnetic energy in the medium to the energy of a single photon with wavelength comparable to the size of the medium and showing that the former is larger roughly by a factor that varies from ~ 1000 to ~ 50 as τ increases from 0.3 fm to 0.8 fm.

We apply the standard prescription to obtain the hadron spectra from a hydrodynamic flow assuming sudden freezeout when the fluid cools to a specified freezeout temperature T_f, developed by Cooper and Frye [16]. We shall take $T_f = 130$ MeV for heavy ion collisions at both the LHC and RHIC. The hadron spectrum for particles of species i with mass m_i will depend on transverse momentum p_T, momentum space rapidity Y and the azimuthal angle in momentum space ϕ_p. The dependence of the hadron spectrum on ϕ_p can be expanded as

$$S_i \equiv p^0\frac{d^3N_i}{dp^3} = \frac{d^3N_i}{p_T dY dp_T d\phi_p} = v_0\left(1 + 2\,v_1\cos(\phi_p - \pi) + 2\,v_2\cos 2\phi_p + \cdots\right), \tag{2}$$

where in general the v_n will depend on Y and p_T.

Once we obtained the electromagnetic field, fixed the parameters of the hydrodynamic flow and calculated the total velocity $V^{\pm\mu}$ as explained in the previous section, we can finally use the freezeout procedure to calculate the hadron spectra, including electromagnetic effects. Figure 2 shows v_1 for positively and negatively charged protons (see [8] for analogous results for the positive and negatively charged pions) as a function of momentum-space rapidity Y at transverse momenta $p_T = 0.5$, 1, and 2 GeV. We have chosen the initial magnetic field created by the spectators with beam rapidity $\pm Y_0 = \pm 8$ (LHC), $\pm Y_0 = \pm 5.4$ (RHIC) and the participants, we have chosen the electric conductivity $\sigma = 0.023\ \mathrm{fm}^{-1}$ and the drag parameter μm in (1) as above and we have set the freezeout temperature to $T_f = 130$ MeV.