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Discussing the possibility of observation of parity violation in heavy ion collisions

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It was recently argued that in heavy ion collisions the parity could be broken. This paper addresses the question of the possibility of the experimental detection of the effect. We discuss how parity violating effects would modify the final particle distributions and how one could construct variables sensitive to the effect, and which measurement would be the (most) conclusive. Discussing different observables we also discuss the question of whether the ''signals'' can be faked by ''conventional'' effects (such as anisotropic flow, etc.) and make estimates of the signals.

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I. INTRODUCTION

Kharzeev, Pisarski, and Tytgat [1] argue that during the evolution of the hot [quark gluon plasma (QGP)] fireball created in heavy ion collisions metastable parity-odd bubbles can be created. Such bubbles would have a nonzero expectation value of $\langle \mathbf{B}\cdot\mathbf{E}\rangle \neq 0$, where **B** and **E** are the chromomagnetic and chromoelectric fields. The expectation value $\langle \mathbf{B}\cdot\mathbf{E}\rangle$ is not sign definite and would take positive and negative values with equal probabilities. Originally [1] it was proposed to look for the effect by detecting the nonstatistical fluctuations in the variable

$$J=\sum_{\pi^+,\pi^-}\frac{(\vec{p}_{\pi^+}\times\vec{p}_{\pi^-})_z}{p_{\pi^+}p_{\pi^-}}. \tag{1}$$

Later, Gyulassy [2] proposed to use for this purpose the so-called twist tensor

$$T_{ij}=\sum_{\pi^+,\pi^-}(\vec{p}_{\pi^+}\times\vec{p}_{\pi^-})_i(\vec{p}_{\pi^+}-\vec{p}_{\pi^-})_j\,. \tag{2}$$

Other observables as well as relations between them were also discussed in [3,4]. The purpose of the current paper is not to discuss and compare all different P- and/or CP-odd variables (though we do discuss some of them), but instead concentrate on the general approaches to the question of the experimental detection of the hypothetical bubbles with parallel electric and magnetic fields. This problem clearly belongs to what now is usually called event-by-event (EbyE) physics. The parity violating effects modify the particle distributions on the EbyE basis and we try to apply EbyE techniques to detect the signal. We also show that sometimes the effect of parity violation can be confused with other effects (having nothing to do with parity violation) such as anisotropic flow, and caution should be used analyzing different signals.

In our discussion we adopt the idea of Chikanian and Sandweiss [5], who for simplicity proposed to simulate the effect of parity-odd bubbles by bubbles with parallel (real) magnetic and electric fields randomly oriented in space. Note that the real effect caused by color fields is *not* necessarily opposite for positive and negative pions as it is for real electric and magnetic fields. Thus it is very important whenever possible to measure the effect separately for each particle species including baryons and antibaryons. The observables discussed in this paper provide such a possibility.

The paper is organized as follows. The discussion of the effect of parity-odd bubbles on particle momentum distributions we split into two parts. The effects related to the transverse field component and due to the longitudinal component are discussed separately. Then based on the picture we get, we discuss how the effect can be observed experimentally. There exist two classes of possible observables, being sensitive only to one of the fields or to both of them. We discuss both classes. Finally we make simple statistical estimates of the signal (and background).

In our discussion we often assume that the parity-odd bubble is located at midrapidity, and we consider the effect of particle distribution modification separately in the forward and backward hemispheres. In principle the bubble can be produced anywhere in rapidity, and the corresponding splitting of the entire rapidity space into two parts can be done at any rapidity point.

II. EFFECT OF THE TRANSVERSE FIELD COMPONENTS

We start with the case of the nonzero transverse component of the electric and magnetic fields. We choose the coordinate system such that the magnetic field points in the y direction. The electric field would point either in the same or in the opposite direction. The effect of the fields on the particle distribution is the following. First, the magnetic field ''rotates'' the distribution about the y axis. Figure 1(a) shows qualitatively such a rotation for positively charged particles. Next, the electric field ''shifts'' the entire distribution along the y axis either in the positive or negative direction based on the orientation of the field and charge of the particle [Fig. 1(b)].

How can these changes in the distribution be detected? The ''cleanest'' (and the most robust) observable for the effect would be the one which is sensitive to both fields. One of the simplest observables of this kind is the so-called V variable. It is also important that this variable can be constructed using only one kind of particle (e.g., positive pions, protons, antinucleons, etc.). It uses the average transverse momenta of particles with positive and negative rapidities (or pseudorapidities), $\langle \mathbf{p}_t\rangle_{\eta>\eta_c}=(1/N_{\eta>\eta_c})\Sigma_{\eta>\eta_c}\mathbf{p}_t$ and

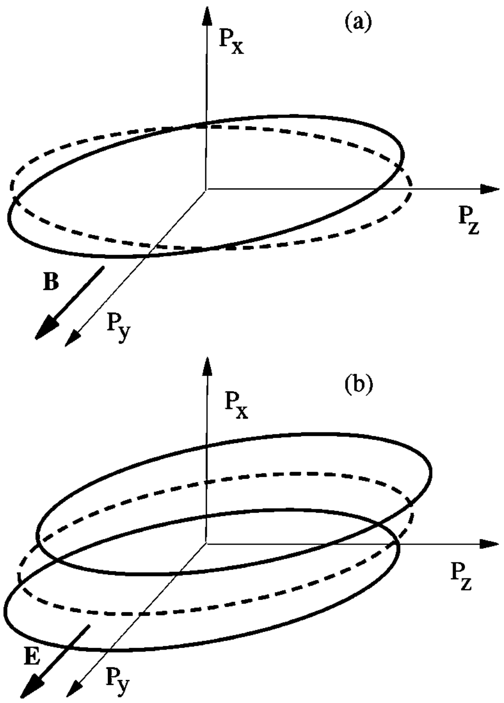

FIG. 1. (a) The rotation of the (positive) particle distribution due to the magnetic field. (b) The shifts of the distributions of positive and negative particles in the opposite directions due to electric field.

$\langle \mathbf{p}_t \rangle_{\eta<\eta_c} = (1/N_{\eta<\eta_c})\Sigma_{\eta<\eta_c}\mathbf{p}_t$, where the sums run over all particles in the rapidity interval. $N_{\eta>\eta_c}$ and $N_{\eta<\eta_c}$ are the corresponding multiplicities. The result of the rotation of the distribution due to magnetic field on $\langle \mathbf{p}_t \rangle$ is opposite in the forward and backward hemispheres. Then the quantity $(\langle \mathbf{p}_t \rangle_{\eta>\eta_c} - \langle \mathbf{p}_t \rangle_{\eta<\eta_c})$ would be a good measure of the strength of the magnetic field (depending on how it is constructed this quantity on average has a nonzero x component, positive in Fig. 1). (If it were a real magnetic field, it could be better to weight each particle with its longitudinal momentum. We do not discuss possible weights at this moment.)

The effect of the electric field is on the contrary similar in both hemispheres. To ''feel'' the electric field we use the quantity $(\langle \mathbf{p}_t \rangle_{\eta>\eta_c} + \langle \mathbf{p}_t \rangle_{\eta<\eta_c})$ (oriented along the y axis in our example if one considers positive particles). Finally we construct the variable

$$V = \{(\langle \mathbf{p}_t \rangle_{\eta>\eta_c} - \langle \mathbf{p}_t \rangle_{\eta<\eta_c}) \times (\langle \mathbf{p}_t \rangle_{\eta>\eta_c} + \langle \mathbf{p}_t \rangle_{\eta<\eta_c})\}_z . \tag{3}$$

The value of V is directly proportional to $\langle \mathbf{B} \cdot \mathbf{E} \rangle$ and thus directly measures the effect. V depends on both electric and magnetic fields and thus is quadratic in the field strengths. Because of this, the effect may be small in magnitude. We leave the numeric estimates for the last section of the paper. As was already mentioned the electric field can be either parallel or antiparallel to the magnetic field. It means that V would have both positive and negative values. The nonzero effect would manifest itself by nonstatistical fluctuations in V. It could be measured, for example, by the subevent method (see section on estimates, Sec. IV, and [6] for a description of the method).

If the strength of the signal permits, the best thing would be to correlate the magnitude of $(\langle \mathbf{p}_t \rangle_{\eta>\eta_c} + \langle \mathbf{p}_t \rangle_{\eta<\eta_c})$ to the component of $(\langle \mathbf{p}_t \rangle_{\eta>\eta_c} - \langle \mathbf{p}_t \rangle_{\eta<\eta_c})$ perpendicular to it in order to prove that **B** and **E** fields are correlated or check that the electric and magnetic fields are indeed aligned, that is, to check if $(\langle \mathbf{p}_t \rangle_{\eta>\eta_c} + \langle \mathbf{p}_t \rangle_{\eta<\eta_c})$ is perpendicular to $(\langle \mathbf{p}_t \rangle_{\eta>\eta_c} - \langle \mathbf{p}_t \rangle_{\eta<\eta_c})$.

Let us now discuss the possibility to observe *first order effects*, namely, the effects due to only magnetic or only electric fields. We start with a *magnetic* field. As can be seen directly from Fig. 1 the effect of the magnetic field (rotation about the y axis and predominant particle emission in one of the transverse directions for particles in the forward hemisphere and in the opposite direction in the backward hemisphere) is indistinguishable from the effect of directed flow (which can be small but not negligible even for very central collisions). One can argue that the parity violation effect should be different for positive and negative pions, but the same could be true for directed flow. Taking into account that the effect of P- and CP-odd bubbles is expected to be rather small (some estimates are given below) it would be extremely difficult to disentangle it from the effect of ''conventional'' directed flow. Even if the effect is large, one would have to prove that the observed effect is due to the parity violation and not to anomalously large directed flow.

At this point one can ask why the effects are so similar, while directed flow obviously does not violate parity. The answer to this question is that the directed flow can ''rotate'' the distribution only in the reaction plane. Any rotation in any other plane would constitute the parity violation. Unfortunately, in reality we do not know the real reaction plane orientation, and the particle azimuthal distribution itself is used to determine the plane. Then it is not at all clear what is the cause for the observed anisotropy in the azimuthal particle distribution. The variable V discussed above (as any other variable sensitive to both fields, e.g., the twist tensor) correlates the effects due to magnetic and electric fields and thus is not confused by the anisotropic flow.

The effect of the *electric* field (shifts of the positive and negative pion distributions in opposite directions) in principle should be also possible to observe, but once more one has to prove that is not due to Coulomb interactions and/or resonance decays, etc.

III. LONGITUDINAL FIELD COMPONENTS

Now we move on to the discussion of the effect of the longitudinal components of the electric and magnetic fields. The electric field ''shifts'' positive particles along the z axis (read rapidity) while shifting negative particles in the opposite direction. The magnetic field would ''rotate'' the particle distribution about the z axis. In principle the magnitude of the ''shift'' due to the electric field could be correlated with the change in particle distribution due to the magnetic field (a correlation similar to the one discussed in the previous

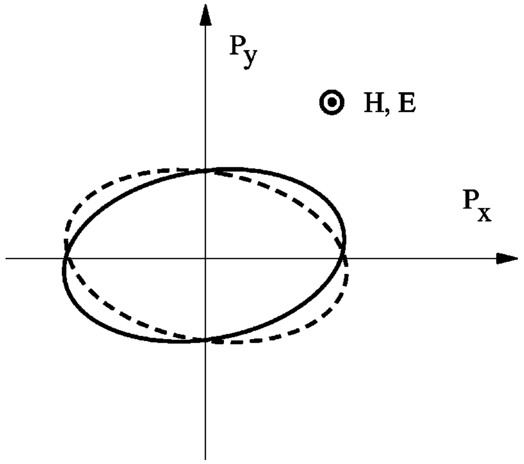

FIG. 2. The rotation of the distribution due to the longitudinal component of the magnetic field. Positive and negative particles exhibit opposite effects.

section), but as is shown below the effect of magnetic field itself would be an unambiguous signal of parity violation. Thus we concentrate in this section on effects sensitive to only electric or magnetic fields.

The *electric* field effect (relative shift of the rapidity distribution of positive and negative particles) from our point of view can be confused with the effects due to Coulomb interactions and/or resonance decays, unless the electric field effect happen to be extremely strong. The hope here would be to observe strong EbyE fluctuations in the shift, but once more one would have to calculate the possible fluctuations in Coulomb fields. A much ‘‘cleaner’’ signal could be the one based on the effect of the *magnetic* field, which presumably ‘‘rotates’’ the initial distribution about the z axis in opposite directions for positive and negative particles. If the initial distribution is azimuthally symmetric, such a rotation obviously does not produce any noticeable effect and is not detectable (as was already noticed in [5]). But in the real collisions the distribution is not expected to be azimuthally symmetric due to directed and/or elliptic flow. Then the magnetic field effect becomes observable.

The direction of the rotation of the distribution is different for positive and negative particles as shown in Fig. 2.

Such rotations would lead to the difference in the reaction planes reconstructed separately using positive or negative particles.[1] One should have in mind that the final observable effect is a product of two effects, anisotropic flow and parity violation (magnetic field), and can be small. Expressed as the mean sine of the azimuthal angle difference between positive and negative particles in a given event the effect is

$$\langle \sin(\phi_{\pi^+}-\phi_{\pi^-})\rangle \approx 2v_n\langle \Delta\phi_H\rangle, \tag{4}$$

where $v_n(n=1,2)$ is the anisotropic flow parameter (nth Fourier coefficient in the particle azimuthal angle distribution with respect to the reaction plane; for a definition see, for example, [7]) and $\langle \Delta\phi_H\rangle$ is the mean (over all particles in a given event) rotation angle due to the magnetic field. $\langle \Delta\phi_H\rangle$ can be positive or negative depending on the orientation of the field and thus one has to study the nonstatistical fluctuations in this quantity, $\sigma_{\sin(\Delta\phi),nonstat}$.

In the analysis, especially if one studies elliptic flow, it could be more convenient to use the reconstructed reaction planes, not the azimuthal angles of the individual particles. Then for a weak signal one gets

$$\langle \sin(\Psi_{RP,\pi^+}-\Psi_{RP,\pi^-})\rangle \approx \sqrt{N_{\pi^+}N_{\pi^-}}\langle \sin(\phi_{\pi^+}-\phi_{\pi^-})\rangle. \tag{5}$$

Such a kind of analysis was done by the NA49 Collaboration [8,9] for Pb+Pb collisions at CERN SPS energies. In that analysis the nonstatistical fluctuations in the azimuthal angle between positive and negative pions have been measured. The results are presented as an upper limit on $\sigma_{\sin(\Delta\phi),nonstat}<10^{-3}$, the variance of the angle difference. According to the discussion above, one has to divide this quantity by the flow signal (in that case v_1) typically of a few percent in order to get the limit on the rotational angle due to the bubble magnetic field.

IV. NUMERIC ESTIMATES

The impulse that acts on the particle crossing the bubble is estimated [10] to be about 30 MeV. It is similar for both electric and magnetic fields. Not all particles in the collision cross the bubble boundaries. The fraction would obviously depend on the bubble volume. In our estimates we will use that the mean impulse due to either field is $\Delta p \approx \alpha \times 30$ MeV. Then α would be the fraction of all particles (in the acceptance) suffering a collision with the bubble boundary. In the STAR acceptance for central Au+Au collisions we expect about 2000 charged particles. In our analysis one often has to subdivide this number into two parts (e.g., forward and backward hemispheres), which gives about 1000 particles in each part. We also use an estimate (which comes from RQMD) for $\langle p_x^2\rangle \approx (350\ \text{MeV})^2$. Then the ‘‘signal to background’’ ratio in a quantity like $\langle p_x\rangle_{\eta>\eta_c}$ would be of the order of $(\alpha\times 30/\sqrt{3})/(350/\sqrt{1000})\approx 1.5\alpha$, where we divided the impulse by a factor of $\sqrt{3}$, taking into account that the direction of the corresponding field is not fixed.

All quantities discussed as a signal of parity violation are not sign definite and one has to look for nonstatistical fluctuations in such quantities. The subevent method is probably one of the best for this purpose. This technique involves the subdivision of all particles in a given event into two groups[2] with subsequent correlation of the signals in each of the groups (called subevents). The number of particles in a subevent is about half of that of the event, and signal to background ratio would drop to $S/B \approx \alpha$. Having in mind that one needs to correlate the subevents we get in the correlation

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[1] The procedure of the reaction plane reconstruction now is quite well established [7].

[2] This can be done in many ways, each of them having its own advantages and disadvantages; for a discussion see [6].

function $S/B \approx \alpha^2$. The last step in this direction would be to take into account the event statistics. Then $S/B \approx \alpha^2 \sqrt{N_{events}}$.

The above estimates are relevant mostly for a variable such as V. For the correlation of the reaction planes the relevant quantity would be

$$\langle \theta_H \rangle \approx \Delta p/\sqrt{3}/\langle p_t \rangle \approx \alpha \times 30/\sqrt{3}/(\sqrt{2}\times 350) \approx 0.05\alpha. \tag{6}$$

The anisotropic flow parameters are (at SPS) of the order of $v_n \approx 0.02$–0.06. Then for $\sigma_{\sin(\Delta\phi),nonstat}$ one would expect values about

$$\sigma_{\sin(\Delta\phi),nonstat} \approx \alpha(1-3)\times 10^{-3}. \tag{7}$$

Remember that the NA49 preliminary limit on this quantity is $<10^{-3}$.

V. CONCLUSION

Parity violation in strong interactions is a question of a fundamental value. The experimental detection of the effect is a challenge and a perfect example of a problem of event-by-event physics. The search is expected to be difficult, but as discussed in this paper as well as in [4,5] it is not hopeless in the sense that results valuable for theory can be obtained.

We should probably also mention here a ‘‘homework’’ for theorists. In the case the effect were an experimentally observed one would have to prove that it is not due to large fluctuations of the real electric and magnetic fields. Theoretical estimates of such fluctuations in the volume of the fireball created in heavy ion collisions are highly desirable.

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