Negative Elliptic Flow from Anomaly Induced DCC Formation

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We discuss characteristic experimental signatures related to the mechanism of DCC formation triggered by the chiral U(1) anomaly in relativistic heavy ion collisions. We predict an enhancement of the fraction of neutral pions compared with all pions in the direction perpendicular to the scattering plane. To quantify the effect on the angular distribution of neutral pions, we compute the elliptic flow parameter $v_2$ as a function of the transverse momentum. We find values of order $-0.05$ at small momenta for neutral pions. We also compute the $v_2$ parameter for inclusive photons, which is easier to measure, and confirmed that the negative a few percent effect prevails in this observable.

1. Introduction

Some time ago we predicted that the chiral U(1) anomaly may provide an efficient trigger mechanism for the formation of coherent domains of pion fields, the disoriented chiral condensate (DCC), in relativistic heavy ion collisions \cite{1}. By implementing the anomaly effect into the linear sigma model simulation code developed by Asakawa et al. \cite{2}, we demonstrated that this mechanism indeed enhances the DCC formation \cite{3}.

In the following section, we present a compact summary of this idea. (Those who are familiar with our idea can skip the rest of the section and can go directly to the section 2.)

It is natural to suspect a possible significance of the electromagnetic interaction in DCC formation because it breaks isospin symmetry, and DCC is the phenomenon of formation of coherent domains with definite isospin. In relativistic heavy ion collisions there exist transient strong electromagnetic fields, which could affect the formation of chiral domains. This idea provided our starting point of the subsequent development.

We quickly recognized that a time-independent and spatially uniform electromagnetic fields do not affect the chiral orientation of the ground state of the linear sigma model at the one-loop level. Instead, we found that a coherent effect can arise from electromagnetism via the chiral anomaly \cite{1}.

We have formulated the anomaly effect as an initial “kick” to the $\pi^0$ fields, because the collision time scale is much shorter than the time required for DCC formation. In the framework of ref. \cite{1}, however, it was difficult to assess how effective the “kick” is; it is a small effect in magnitude, but it is a coherent effect which extends over the nuclear dimension. So we needed some powerful tool to analyze the intricate question of effectiveness of the kick. We found that the linear sigma model simulation is appropriate for this purpose. We have adopted the simulation code developed by Asakawa et al. \cite{2}, rather than the original one used by Rajagopal and Wilczek \cite{4}, because we wanted to

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be as realistic as possible. For example, the newer code takes into account the boost invariant longitudinal expansion of the hadronic debris.

We found, to our surprise, that the anomaly kick is efficient in triggering a coherent motion of the chiral order parameter and resulting in the formation of a domain of DCC [3]. The effect of the kick survives the non-linear evolution of the system and the coherent motion triggered by the kick continues until times of order \( \sim 10 \text{ fm} \) (see Figs. 10 and 11 of ref. [3]). We need to emphasize that the persistence of the kick effect may be, in part, due to the neglect of quantum dissipation in the classical simulation. We refer to ref. [3] for further details.

To facilitate the discussion of experimental signatures of the anomaly mechanism in the next section we note here the crucial characteristic property of the anomaly kick. That is, the kick is proportional to the angular momentum of the two ions in collision and depends on the momentum direction perpendicular to the scattering plane. It points into the \( I_3 \) direction in the isospin space. These properties derive from the vector structure of the anomaly \( \mathbf{E} \cdot \mathbf{B} \) produced by two colliding ions [3].

2. Experimental signatures

We now discuss possible characteristic experimental signatures of the anomaly-induced DCC formation in relativistic heavy ion collisions. We first summarize our work done previously, and then come to our new results. We examine three types of observables, which we discuss one by one below. They are: (1) number ratio of \( \pi^0 \) to all \( \pi \) [3], (2) azimuthal angle distribution of the ratio of the number of \( \pi^0 \) to all pions and photons [3], and (3) the elliptic flow parameters of \( \pi^0 \) and photons. We report (3) for the first time in this article. We have found that the latter two types of observables are particularly suitable for this purpose.

In calculating experimental observables we use three values of the anomaly kick parameter \( a_n = 0.05, 0.1, \) and \( 0.2 \), and employ the coherent state approximation to extract particle number from field configurations of linear sigma model fields. Based on our previous estimate of the kick parameter at RHIC [3], we focus on \( a_n = 0.1 \) to estimate the effect that would be seen in relativistic heavy ion collisions at RHIC. See [3] for the definition of the anomaly kick parameter \( a_n \) and more details of our calculational procedure.

2.1. Number ratio of \( \pi^0 \) to all \( \pi \)

Since the anomaly kick acts only on the \( \pi^0 \) field, it is natural to expect that neutral pions behave differently from charged pions in our mechanism. Therefore, we first computed the number ratio \( n(\pi^0)/n(\text{all } \pi's) \) and found that the ratio exceeds 1/3 (the value expected by isospin invariance) by about 13% at low momenta, \( |\vec{k}| \leq 250 \text{ MeV} \) [3].

2.2. Azimuthal angle distributions of number ratio of \( \pi^0 \) to all \( \pi \) and photons

We then searched for other, clearer signatures, which would unambiguously indicate the anomaly-induced DCC formation. Since the characteristic feature of the kick is that it has a momentum dependence perpendicular to the scattering plane, it is natural to study whether the number ratio of \( \pi^0 \) to all \( \pi \) exhibits an angular dependence correlated with the scattering plane. Thus, we examined the azimuthal angle distribution of number ratio of \( \pi^0 \) to all \( \pi \). We found that the number ratio of \( \pi^0 \) to all \( \pi \) shows a large variation with azimuthal angle, peaking in the direction perpendicular to the scattering plane. See Fig. 1. (Fig.3 of [3])

An important question is whether this azimuthal asymmetry persists in the inclusive photon distribution, which is much easier to measure. We have examined this possibility and obtained a very encouraging result: photons exhibit an azimuthal angle variation of about 10%, even if we include a rather wide range of photon transverse momenta \( k_T \leq 500 \text{ MeV} \). See Fig. 2 (Fig.4 of [3]). If it exists, the effect should be observable in the RHIC...
experiments.

2.3. Elliptic flow parameter of $\pi^0$ and photons

It has become an industry to measure the elliptic flow parameter $v_2$ in heavy ion collisions. Of course, the main motivation for the enthusiasm comes from elucidating hydrodynamical behavior of the hadronic matter. But since our anomaly-induced mechanism of DCC formation also predicts an anisotropic flow of $\pi^0$, it is quite natural to convert our prediction into the language of elliptic flow.

We have run a Monte-Carlo code coupled with the Asakawa et al. sigma model simulation code to compute the elliptic flow parameter $v_2$ for neutral pions and inclusive photons from $\pi^0$ decay. Since the computation of the photon distribution is rather time consuming, we define an approximate $v_2$ as follows:

$$v_2^{app}(k_T) = \frac{(n_\parallel - n_\perp)}{\frac{2}{n_\parallel} + n_\perp},$$

(1)

where, $n_\parallel$ denotes the number of $\pi^0$ or gammas emitted with azimuthal angle $\phi$ measured from the reaction plane in the range $-45\,\text{deg} \leq \phi < 45\,\text{deg}$, or $135\,\text{deg} \leq \phi < 225\,\text{deg}$, and $n_\perp$ the number of $\pi^0$ or gammas in the range $45\,\text{deg} \leq \phi < 135\,\text{deg}$, or $225\,\text{deg} \leq \phi < 315\,\text{deg}$. This definition of $v_2$ is exact when the azimuthal asymmetry has solely a quadrupole contribution.

We present in Fig. 3 the result of our computation of the approximate $v_2$ for $\pi^0$ and photons. The value of $v_2^{app}$ is $\sim 4 - 5\%$ for $\pi^0$ and $\sim 1\%$ for photons. In the absence of other effects generating an elliptic flow, $v_2^{app}$ approaches unity at high momenta. The relativistic kinematics of $\pi^0 \rightarrow 2\gamma$ decay is taken into account in the Monte-Carlo code and it is essential to produce this behavior.
As we see in Fig. 3, $v_2^{app}$ for both $\pi^0$ and photons are negative at low $k_T$, the behavior quite opposite to the one commonly observed. The latter behavior is usually attributed to the hydrodynamical expansion of hadronic debris. It would be interesting to see such a peculiar feature as negative $v_2$ in either $\pi^0$ or gamma distributions in heavy ion collisions. It may be the unique signature of DCC formation due to the anomaly mechanism.

Although they are small effects, we suspect that at least the photon $v_2$ is measurable. It may be difficult to measure $v_2$ for $\pi^0$, because one needs event-by-event reconstruction of $\pi^0$. But for photons, measurement of either the inclusive single particle distribution with identification of the scattering plane, or the two particle azimuthal correlation would be enough. Therefore, we urge RHIC experimentalists to try to measure the photon $v_2$ at low transverse momenta.

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