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PARTICLE POLARIZATION AS A SIGNAL OF PLASMA FORMATION

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A B S T R A C T

Heavy ion collisions leading to the formation of a quark-gluon plasma are characterized by an isotropic distribution of the parton momenta in the plasma rest frame. We discuss the restrictions that this isotropy imposes on the polarizations of plasma produced virtual photons, hyperons and hadronic resonances.

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A central feature of quark-gluon plasma formation in heavy ion collisions is the thermalization of (part of) the kinetic energy¹⁾. Thus, in the (local) plasma rest frame there is no preferred direction, and in particular, the direction of the incoming nuclei is "forgotten". In this note we wish to point out the restrictions that this isotropy implies for the polarization of particles produced from the plasma.

Our considerations rely solely on symmetry arguments and as such are model independent. An application of these ideas to data on heavy ion collisions will involve uncertainties due to the determination of the plasma rest frame and the possibility of particle production from non-thermalized quarks and gluons. We begin our discussion of polarization effects assuming a perfect plasma at rest.

We may distinguish three cases in which the polarization of produced particles can be readily measured:

(a) Virtual photons, i.e., lepton pair production. The $q\bar{q} \rightarrow \gamma^* \rightarrow \ell\bar{\ell}$ process is of central interest in heavy ion experiments as it is a direct probe of the quark motion²⁾. The characteristics of lepton pair production from a quark-gluon plasma have been studied in detail, and compared³⁾ to competing production processes like the ordinary Drell-Yan mechanism and resonance decays. It is expected^{2,3)} that plasma formation will be indicated by an enhanced lepton pair rate in the intermediate mass region ($m_\rho \lesssim M_{\ell\ell} \lesssim m_\phi$), with a characteristic dependence on the transverse and longitudinal momenta of the pairs.

Here we propose to use the decay angular distribution of the virtual photon as an additional check that the enhanced lepton pair rate is indeed due to plasma formation and not, e.g., the result of a pre-equilibrium production process⁴⁾. The virtual photon is always transversely polarized with respect to the momenta of the annihilating quarks. In a true plasma the quarks are moving in random directions and so the photon must be unpolarized. Hence, the angular distribution of the leptons in the pair rest frame is isotropic. This is strictly true only for lepton pairs whose rest frame coincides with that of the plasma. Otherwise, we may expect a $1 + \alpha \cos^2\theta$ distribution of the leptons with respect to the pair momentum, with the coefficient α depending on the plasma temperature and the mass and momentum of the pair. This follows because the annihilating quarks tend to be aligned along the direction of motion of the virtual photon. For lepton pair momenta small compared to the plasma temperature this effect should be negligible ($\alpha \approx 0$). Furthermore, symmetry arguments require that the decay

distribution always be independent of the azimuthal angle around the virtual photon direction.

The decay angular distribution of virtual photons produced in ordinary hadron collisions, as well as in pre-equilibrium processes of heavy ion collisions⁴⁾, should have a $1 + \cos^2\theta^*$ dependence on the angle θ^* of the lepton with respect to the beam direction, because of the predominantly longitudinal motion of the quarks. This is in agreement with data on $\pi^\pm A \rightarrow \mu^+\mu^- + X$ both in the high mass ($M_{\mu\mu} > 4 \text{ GeV}$)^{5,6)} and intermediate mass ($2 \text{ GeV} < M_{\mu\mu} < 3 \text{ GeV}$)⁷⁾ regions. The hadronically produced $\phi(3100)$ has, in contrast, an isotropic decay distribution⁵⁾. The angular distribution in the $M_{\mu\mu} < 2 \text{ GeV}$ region is not established experimentally.

(b) Hyperons. The hyperons (Λ, Σ, Ξ) can be produced with a polarization perpendicular to the scattering plane, which is measurable due to their parity violating decay. The polarization is sizeable experimentally in hadron collisions, for both proton and nuclear targets⁸⁾.

Considerable hyperon production is expected from quark-gluon plasmas due to the abundance of baryon number and strange quarks⁹⁾. Just as for virtual photons, the only relevant direction is that of the hyperon momentum with respect to the plasma. Parity conservation in the production process forbids a polarization along the hyperon momentum, however. Hence, the hyperons produced from a plasma must be unpolarized.

(c) Resonances. The polarization of hadronic resonances such as $\rho, \omega, K^*, \phi, \dots; \Delta, Y^*, \dots$ can be reconstructed from their decay angular distributions. When produced at rest in the (local) plasma frame they must be totally unpolarized. Otherwise, the decay distributions may have a dependence on the polar angle with respect to the resonance direction of motion. The dependence on the azimuthal angle must always vanish.

The usefulness of the resonance polarization as a plasma signal will depend on the degree of polarization observed in collisions without plasma formation. The scant data available on decay distributions suggests little polarization for inclusively produced ρ, ω and K^* in pp collisions¹⁰⁾.

We end with some comments on the analysis of heavy ion collisions. The plasma may be produced with considerable longitudinal motion in the overall CM

system. This is especially the case if the plasma forms in the fragmentation region of one of the colliding nuclei. Unless the plasma motion can be independently determined (from the overall event structure) the best estimate for the (local) plasma rest frame would seem to be the longitudinal momentum of the particle (virtual photon, hyperon, resonance) under study³⁾. This neglects the (small) longitudinal motion imparted to the particle by the plasma itself. However, in an average polarization measurement this effect will cancel out. Hence, the relative motion of particle and plasma can be determined only in the transverse direction (with respect to the beam). For example, in the case of the virtual photon this means that a $1 + \alpha \cos^2\theta$ distribution is possible along an axis in the transverse direction only. This is orthogonal to the standard Drell-Yan case, where the beam provides the reference axis.

As has been repeatedly stressed^{1,11)} evidence for the formation of a quark-gluon plasma must be based on a combination of several indicators. The polarization measurements we have advocated here are in any case only a necessary, not a sufficient condition for plasma formation. Its credibility can be enhanced by comparing, in the same experiment, the decay distributions in events which are unlikely to form a plasma (e.g., peripheral collisions) with the decay distributions in events that may have had a plasma (central collisions).

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