Anisotropy of thermal dileptons

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The meaningful specific anisotropy in the angle distribution of leptons with respect to the three-momentum of pair is predicted as a feasibility signature of synchrotron-like mechanism resulting from the quarks interacting with a collective confining color field in the heavy ion collisions. The lepton pair production rate and the spectrum of pair invariant mass are presented for this new dilepton source that is apparently not taken into consideration in the available phenomenological estimates.

1. INTRODUCTION

The results of experimental studies of relativistic heavy ion collisions at LHC and RHIC in recent years have been summarized as an implication of creating hot (with high energy density) medium whose intrinsic degrees of freedom are the color quarks and gluons of standard quantum chromodynamics (QCD). Alongside the compelling evidence to make reference to such an environment as a quark-gluon plasma (QGP) still must be found\textsuperscript{1,2} and well elaborated. The electromagnetic probes (photons and dileptons), long been proposed with this goal\textsuperscript{3,4}, still remain one of the most informative, even when their momenta are not very large, because their weak electromagnetic interactions provide them with a mean free path inside medium essentially larger than the medium size. Photons and leptons are freely emitted from this excited region, practically without interaction with the color quarks and gluons, and their undistored spectra are carrying a direct information on the state of hot excited medium\textsuperscript{5,6}.

In this context the recent measurements by the PHENIX Collaboration which show the azimuthal anisotropy of produced direct photons very close to the hadron one\textsuperscript{7} are rather exciting. This result appears to be in a serious contradiction with expected dominance of photon production from QGP at an early stage of ion collision at the top RHIC and now available LHC energies. The observed temperature of “anomalous” photon radiation (about \(T_{\text{ave}} \approx 220\) Mev) is in accordance with the PHENIX Collaboration measurements\textsuperscript{8} at the energy \(\sqrt{s} = 200\) GeV of heavy ion collisions. This temperature magnitude being considered as a result of averaging over the entire evolution of the matter created in nuclear collisions is noticeably higher than the expected critical temperature\textsuperscript{9} and obviously supports the scenario of photon radiation from QGP. Clearly, such a situation is nontrivial for the phenomenological studies because the production rate of real and virtual (low mass dileptons) generated by a hot QGP is considered increasing like \(T^4\) and, hence, being very sensitive to the temperature of medium. Fortunately, the situation with improving a description of global photon data overall is gradually becoming more controlled\textsuperscript{10} (at least with one disadvantage which is a number of photon sources getting larger).

Recent interesting suggestions for photon and dilepton sources\textsuperscript{11} (thermal photons may have elliptic flow),\textsuperscript{12} (thermal radiation from semi-QGP), and\textsuperscript{13} (forming a gluon condensate that radiates the photons at the early stage of collisions) which are ideologically close to the scenario we develop in this letter declare pretty small photon azimuthal anisotropy\textsuperscript{14} and insufficient to explain the experimental data mentioned. There are many other phenomenological models under discussion (see, for example,\textsuperscript{15,16,17,18,19,20,21}) which are in different extent fairly successful at treating the experimental data quantitatively but sometimes with noticeable uncertainties. In our previous work\textsuperscript{22} we have suggested significantly alternative mechanism that contributes to the observed anisotropy of direct photons. The reference is to a "magnetic bremsstrahlung-like radiation" (or synchrotron radiation in present terminology) of quarks in the collective color field ensuring confinement. We have found that this boundary bremsstrahlung is intensive enough\textsuperscript{23,24,25} to develop the azimuthal anisotropy\textsuperscript{22} and is capable of resolving the "direct photons puzzle"\textsuperscript{7} still without appealing to the non-equilibrium dynamics of heavy ion collision process.

The main goal of our present letter is to show that the mechanism above predicts also the anisotropy of dileptons that now is considered\textsuperscript{26,27} as a good probe of QGP and effective instrument for resolving the discussed discrepancy between the experimentally observed dilepton spectra and the theoretical expecta-
In Sec. II we give the basic equations and estimates of the total number of lepton pairs and their spectra. The peculiarity in the angular dilepton distribution is discussed in Sec. III. In the conclusion we summarize the main results.

2. DILEPTON SPECTRA

An existence of the boundary bremsstrahlung is based on three quite realistic assumptions: 1) the presence of relativistic light quarks (u and d quarks) in the hot medium; 2) the semiclassical nature of their motion; 3) confinement. Then as a result, each quark (antiquark) at the boundary of the system volume moves along a curve trajectory and (as any classical charge undergoes an acceleration) emits photons. Estimating the magnitude of this effect we have utilized \([23, 24, 25]\) the chromoelectric flux tube model \([28, 29, 30]\) in which the interaction between the volume of quark-gluon system and color object crossing over its boundary develops the constant force \(\sigma\) bringing a color object back. Apparently, this force is acting along the normal to the plasma surface. Quantitatively, an effect is rooted in the large magnitude of quark confining force \(\sigma \simeq 0.2\) GeV. It is easy to recognize that this mechanism could be an alternative one for generating the lepton pairs, too, as it has been argued in our old paper \([31]\), some results from that we reproduce below to be clear.

A large value of \(\sigma\) results in the large magnitude of characteristic parameter \(\chi = ((3/2)\sigma E/m^3)^{1/3}\) (where \(E\) and \(m\) are the energy and mass of the emitting particle, respectively) for u and d quarks (the strong-field case). In this regime the probability of emitting a "massive" photon is independent of the mass of the emitting particle and in the first order in inverse powers of the parameter \(\chi\) can be written as \([32]\)

\[
    dW_q(M^2)/dt = 1.56\alpha^2 \alpha (\sin \varphi)^{2/3} E^{-1/3},
\]

where \(\alpha = 1/137\) is the fine structure constant, \(\varphi\) is the quark charge in units of electron charge and \(\varphi\) is the angle between the quark velocity and the direction of quark confining force (the normal to the QGP surface in our case). Using the well-known relation between the cross sections for virtual-photon and lepton-pair production, from Eq. (1) we easily find the lepton-pair distribution in the invariant mass:

\[
    \frac{dN}{dt dM^2} = \frac{\alpha}{3\pi} f(M) \frac{dW_q(M^2)}{dt},
\]

\[
    f(M) = \frac{1}{M^2} \left( 1 + \frac{2\mu^2}{M^2} \right)^{3/2} \left( 1 - \frac{4\mu^2}{M^2} \right)^{1/2},
\]

\(2\mu \leq M \leq E\).

In this equation \(\mu\) and \(M\) stand for the lepton mass and the invariant mass of the pair, respectively. Both these equations are invalid only for the invariant masses \(M\) close to \(E\).

Further, in order to obtain the number of lepton pairs radiated per unit surface area of QGP per unit time in invariant mass interval \(M^2, M^2 + dM^2\), it is necessary to average Eq. (2) over the quark paths and to convolute it with the flux of quarks reaching the boundary of the QGP volume from within. This procedure does not differ from the analogous one performed in detail in Refs. \([24, 25]\) for photons spectra, so we present only the final result here:

\[
    \frac{dN}{dS dt dM^2} = A \alpha^2 \sigma^{-1/3} \int_1^\infty d\xi (\xi^{8/3} - 1) \exp \left( -\frac{M\xi}{T} \right),
\]

where

\[
    A = \frac{1.56}{2(2\pi)^3} \frac{\Gamma(4/3)\Gamma(1/2)}{\Gamma(11/6)} g(e_u^2 + e_d^2),
\]

\(\Gamma\) is the gamma-function, \(e_u\) and \(e_d\) are the u- and d-quark charges, \(g = \text{spin color} = 6\) is the number of quark degrees of freedom, \(T\) is the plasma temperature. Integrating Eq. (3) over \(dM^2\) one obtains the total number of lepton pairs emitted per unit time from unit surface area of QGP as

\[
    \frac{dN}{dS dt} = \frac{16}{3} A \alpha^2 \sigma^{-1/3} T^{11/3} \int_\beta^\infty dy e^{-y^{5/3}} \times \left\{ \ln \frac{y}{\beta} \left( 1 + \left( 1 - \frac{\beta^2}{y^2} \right)^{1/2} \right) - \frac{1}{6} \left( 1 - \frac{\beta^2}{y^2} \right)^{1/2} \left( 5 + \frac{\beta^2}{y^2} \right) \right\},
\]

where \(\beta = 2\mu/T\). At \(\beta \ll 1\) Eq. (4) is essentially simplified

\[
    \frac{dN}{dS dt} \simeq 2A \Gamma \left( \frac{11}{3} \right) \alpha^2 \sigma^{-1/3} T^{11/3} [\ln(T/2\mu) + a + O(\beta^2)],
\]

\[
    a = \ln 2 - 5/6 + \Gamma'(8/3)/\Gamma(8/3).
\]

This is a reasonable estimate of the total number of electron-positron pairs, since \(\mu_e \simeq 0.5\) MeV is considerably less than the minimal plasma temperature \(T \simeq 200\) MeV.
In the simplest case, if the plasma occupies a spherical volume of radius $R$ and does exist during the time $\tau$, then the total number of electron-positron pairs is easy estimated as

$$N = 4\pi R^2 \tau dN/d\sigma dt.$$  \hfill (6)

Of course, it is interesting to compare this result with the total number of electron-positron pairs produced by "standard" quark-antiquark annihilation processes in the QGP volume \[^3\,^4\,^6\,^33\]

$$N_{ann} = \frac{4}{3} \pi R^3 \tau B a^2 T^4, \quad B = 10/9 \pi^3,$$  \hfill (7)

which takes into account only the $u$- and $d$-quark contributions to the rate to make comparison adequately here. There are other QGP volume (and not QGP) contributions except the Born term (see, e.g., \[^34\,^35\]) which should be taken into consideration at detail analysis, especially for lower invariant masses. Then the relevant quantity is the ratio

$$\frac{N}{N_{ann}} = \frac{C}{RT^{1/3} \sigma^{1/3}} \left( \frac{\ln T}{2\mu} + a \right),$$  \hfill (8)

where $C = 6\Gamma(11/3)A/B \approx 11.8$. Numerically $N/N_{ann} \approx 40$ on setting $R = 1$ fm, and $N/N_{ann} \approx 4$ on setting $R = 10$ fm at $T \approx 200$ MeV. Therefore, for QGP systems of the expected size (5-10) fm, the mechanism outlined above contributes dominantly to the total number of electron-positron pairs produced by the plasma.

This result is still valid when the space-time plasma evolution has been included following \[^33\]. Indeed, the corresponding integration over $d\sigma dt$ and $d^4x$ can be performed as in Ref. \[^25\] if one neglects additional logarithmic dependence on the temperature in Eq. (3), taking $\ln(T_c/2\mu)$ ($T_c$ is the phase transition temperature) instead of $\ln(T/2\mu)$. Then, as for the photons \[^25\], the functional distinction between the proposed mechanism and the "standard" volumetric one is mainly determined by the parameter that is just the dimensionless combination as

$$(RT_c^{1/3} \sigma^{1/3})^{-1}$$

(note that it is $\approx 1$ on setting $R \approx 0.6$ fm) with a constant which is slightly different from $C[\ln(T_c/2\mu) + a]$ incoming in Eq. (3).

For muon pairs, the ratio $2\mu/T \approx 1$ and the integration over invariant mass cannot be performed analytically. However, on extracting the basis temperature dependence $T^{11/3}$, one can estimate numerically the remaining integral $I$ in Eq. (3) since it is a slowly varying function over the small temperature interval (in the models based on the scaling solution of hydrodynamical equations $T = 200 - 500$ MeV). Thus the ratio, analogous to Eq. (8) for the muon-pair production from the plasma of a spherical volume with no space-time evolution, is

$$(N/N_{ann})_{\mu\mu} = C_{\mu\mu}/RT^{1/3} \sigma^{1/3},$$  \hfill (9)

where $C_{\mu\mu} \approx 7.1$, demonstrating the significant contribution of the bremsstrahlung mechanism. The ratio of the invariant mass spectra is also analytically estimated in the regime $T \ll M$ \[^31\] with the similar conclusion.

3. ANGULAR DISTRIBUTION

One of the most distinctive features of the proposed mechanism is a large degree of photon polarization \[^24\,^25\]. For a plasma of cylindrical symmetric volume with its axis along the collision axis, the bremsstrahlung photons are dominantly polarized along the normal to the plane spanned by the cylinder axis and the momentum of registered photons. The appearance of such a polarization is closely connected with the choice of direction of the collective field where quarks are moving and its value is virtually insensitive to the parameter regulating an intensity of bremsstrahlung. Consequently, these photons can also be polarized for other "nonideal" shapes of plasma surface possessing this decisive property. The corresponding calculations of the polarization degree in a lucid form can be very complicated.

We realize that the difficulties in registering photon polarization entail many problems for experimental search for this effect. But observing lepton-pair spectra resulting from the polarization of intermediate photon could be a potentially efficient probe of QGP \[^26\,^27\] if formed in collisions of ultrarelativistic ions.

Considering the decay of massive photons with the four-momentum $k$ into a lepton pair, the following expression gives the squared matrix element of this process:

$$|M|^2 = 4\pi\alpha S^2(p_1 + \mu)\gamma_\mu(p_2 - \mu)\gamma_\nu e_\mu^* e_\nu^*,$$

$$= 16\pi\alpha |k^2/2 + (p_1 e)(p_2 e^*) + (p_1 e^*)(p_2 e)|,$$  \hfill (10)

where $e$ is the polarization four-vector of the photon and $(ee^*) = -1$; $p_1$ and $p_2$ are the four-momenta of the lepton and antilepton, respectively.

Drawing the relevant phase space of the pair and taking into account the transversality condition $(ek) = 0$, the lepton distribution per unit time in the radiation angle reads as

\begin{align*}
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\end{align*}
\[
\frac{dW}{dtd\Omega_1} = \frac{\alpha}{2\pi k^0} \int \frac{p^2 dp}{p_1^0(k^0 - p_1^0)} \delta[f(p)] \\
\times [k^2/2 - 2(p_1 \epsilon)(p_1 \epsilon^*)],
\]

where

\[
f(p) = k^0 - p_1^0 - (\mu^2 + k^2 + p^2 - 2|k|p \cos \theta_1)^{1/2}.
\]

Here \( \theta_1 \) is the angle between the three-vectors \( k \) and \( p_1 \) and the condition \( f(p) = 0 \) determines the length of the three-vector \( p_1 \) as a function of \( \cos \theta_1 \).

If the initial photons are unpolarized, Eq. (11) has to be averaged over polarization and then it results to the lepton distribution independent of the radiation azimuthal angle \( \phi_1 \). This dependence exists at decay of the polarized photons. Defining \( n(1 + \delta)/3 \) as the photon number of the states with polarization vector \( e_1 \), \( n(1 - \delta)/3 \) as the photon number of the states with polarization vector \( e_2 \) and \( n/3 \) as the same with polarization vector \( e_3 \), and choosing the reference frame with the \( z \) axis directed along the three-vector \( k \) and the \( x \) and \( y \) axes tallying with the directions of \( e_1 \) and \( e_2 \), we have then

\[
e_1 = \{0, 1, 0, 0\}, \quad e_2 = \{0, 0, 1, 0\},
\]

\[
e_3 = \{|k|/\sqrt{k^2}, 0, 0, k^0/\sqrt{k^2}\}, \quad k = \{k^0, 0, 0, 0\}, \quad |k|,
\]

\[
p_1 = \{\sqrt{\mu^2 + p^2}, \sin \theta_1 \cos \phi_1, \sin \theta_1 \sin \phi_1, \cos \theta_1\}.
\]

Finally, the lepton distribution in the radiation angle takes the form

\[
\frac{dN}{dtd\Omega_1} = \frac{\alpha m}{2\pi k^0} \int \frac{p^2 dp}{p_1^0(k^0 - p_1^0)} \delta[f(p)] \\
\times \left[\frac{k^2 + 2\mu^2}{3} - \frac{2}{3} \delta p^2 \sin^2 \theta_1 \cos 2\phi_1\right].
\]

It follows from Eq. (12) that the angular lepton distribution has a characteristic dependence on the azimuthal angle \( \phi_1 \) of a massive photon that has transverse (in the three-dimensional space) polarization (\( \delta = 0 \) is not zero). When the photons are unpolarized or have longitudinal polarization (along the vector \( e_3 \)) this dependence disappears. Thus the azimuthal anisotropy of the radiation angle distribution of leptons certainly indicates that the intermediate ("massive") photon has a transverse polarization. We may argue this effect as a highly feasible to be experimentally measured and considered as a probe of QGP events just in accordance with the recent consideration [26, 27].

Indeed, it was shown [25] that for a plasma with a cylindrically symmetric volume the value of \( \delta \) can be calculated as about 20\%. In our case, the intermediate photons (as we have a strong field regime) could be considered up to the masses \( \sqrt{k^2} \approx \sqrt{\sigma} = 0.45 \text{ GeV} \) as having a small virtuality and their properties are quite close to real photons [32]. It means these photons are transversely polarized with practically the same degree of polarization \( \delta \). Since as the proposed mechanism contributes noticeably to the total yield of lepton pairs from QGP, the "bremsstrahlung" leptons could be identified by measuring their angle anisotropy that is absent in the Drell-Yan mechanism and the "standard" volumetric mechanism.

4. CONCLUSIONS

Our analysis shows that the interaction of quarks with the collective color field confining them results in an intensive radiation of the magnetic bremsstrahlung type (synchrotron radiation). The intensity of such a radiation for the hot medium of size 1-10 fm that is expected in ultrarelativistic collisions of heavy ions is comparable with that of the volume mechanism of photon and dilepton production in the temperature range of \( T \approx 200 - 500 \text{ MeV} \). Quantitatively a relative effect is regulated by the three basic parameters: the characteristic medium (QGP) size \( R \), the QGP temperature \( T \), and the confining force \( \sigma \), which are firmly fixed. Possible uncertainties come mainly from the simple modeling of confinement and simplification of the QGP geometry what allow us to obtain estimates in transparent analytical form.

The most striking feature of magnetic bremsstrahlung is the high degree (\( \sim 20\%) \) of polarization of both real and "massive" (virtual) photons that is mainly determined by the medium (QGP) geometry. The virtual photons develop the noticeable specific anisotropy in the angle distribution of leptons with respect to the three-momentum of pair. The origin of this anisotropy is rooted in the existence of a characteristic direction in the field where the quarks are moving. Besides the synchrotron radiation will be nonisotropic [22] for the noncentral collisions because the photons are dominantly emitted around the direction fixed by a surface normal. As result the coefficient of elliptic anisotropy for dilepton pairs (the study of which was suggested in Ref. [14]) will be also proportional to the eccentricity of QGP system as it takes place for the bremsstrahlung real photons and can be experimentally measured.

Indeed, in order to draw a more definite conclusion, further investigations are necessary including, in particularly, a proper comparison with other sources of photons and dileptons.
The papers by G. Baym in this field were quite instructive and imaginative for us since the first discussion of one of us (GMZ) with him at the 6th Quark Matter in Nordkirchen (1987). Critical remarks by B. Zakharov were quite instructive. Several comprehensive discussions of these results with V. Toneev are gratefully acknowledged. The paper was partially supported by the Goal-Oriented Program of Cooperation between CERN, JINR and National Academy of Science of Ukraine "Nuclear Matter under Extreme Conditions".

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