Asymmetry of in-medium $\rho$-mesons as a signature of Cherenkov effects

I.M. Dremin*, V.A. Nechitailo†

P.N. Lebedev Physics Institute RAS, 119991 Moscow, Russia

February 1, 2008

Abstract

Cherenkov gluons may be responsible for the asymmetry of dilepton mass spectra near $\rho$-meson observed in experiment. They can be produced only in the low-mass wing of the resonance. Therefore the dilepton mass spectra are flattened there and their peak is slightly shifted to lower masses compared with the in-vacuum $\rho$-meson mass. This feature must be common for all resonances.

PACS: 12.38Bx, 13.87.-a

There exist numerous experimental data [1, 2, 3, 4, 5, 6, 7, 8, 9] about the in-medium modification of widths and positions of prominent vector-meson resonances. They are mostly obtained from the shapes of dilepton mass and transverse momentum spectra in nucleus-nucleus collisions. Such in-medium effects were tied theoretically to chiral symmetry restoration a long time ago [10].

The dilepton mass spectra decrease approximately exponentially with increase of masses albeit with substantial declines from the average approximation of the general trend by the exponent in the low-mass region. A significant excess of low-mass dilepton pairs yield over expectations from hadronic decays is observed in experiment. The shape of the excess mass spectra shown in [1, 2, 3] is dominated by $\rho$-mesons. Their ratio to other vector meson resonances can be estimated as $\rho : \omega : \phi = 10:1:2$.

*email: dremin@lpi.ru
†email: nechit@lpi.ru
Several approaches have been advocated for explanation of the excess. Strong dependence of the parameters of the effective Lagrangian on the temperature and the chemical potential was assumed in [11, 12]. The hydrodynamical evolution was incorporated in [13] to describe the spectra. The QCD sum rules and dispersion relations have been used [14, 15] to show that condensates decrease in the medium leads to both broadening and slight downward mass shift of resonances. The similar conclusions have been obtained from more traditional attempts using either the empirical scattering amplitudes with parton-hadron duality [16, 17] or the hadronic many-body theory [18, 19, 20].

In the latest approach, which pretends on the best description of experimental plots, the in-medium V-meson spectral functions are evaluated. The excess of dilepton pairs below \( \rho \)-mass is ascribed to anti-/baryonic effects. This conclusion is the alternative to more common ideas about the chiral restoration at high energies. It asks for some empirical constraints to fit the observed excess.

In this paper we propose another possible source of low-mass lepton pairs. Namely, the emission of Cherenkov gluons may provide a substantial contribution to the low mass region.

Considered first for processes at very high energies [21], the idea about Cherenkov gluons was extended to resonance production [22, 23]. For Cherenkov effects to be pronounced in ordinary or nuclear matter, the (either electromagnetic or nuclear) index of refraction of the medium \( n \) should be larger than 1. Qualitatively, the observed low mass excess of lepton pairs is easy to ascribe to the gluonic Cherenkov effect if one reminds that the index of refraction of any medium exceeds 1 within the lower wing of any resonance (the \( \rho \)-meson, in particular).

This feature is well known in electrodynamics (see, e.g., Fig. 31-5 in [24]) where the atoms behaving as oscillators emit as Breit-Wigner resonances when get excited. This results in the indices of refraction larger than 1 within their low-energy wings. In QCD, one can imagine that the nuclear index of refraction for gluons in the hadronic medium behaves in a similar way in the resonance regions. This statement is more general and can be valid also at other energies if the relation (see, e.g., [25]) between the index of refraction and the forward scattering amplitude \( F(E, 0^\circ) \) is fulfilled not only for photons but for gluons as well:

\[
\Delta n = Rn - 1 \propto \text{Re}F(E, 0^\circ)/E. \tag{1}
\]

Here \( E \) is the photon (gluon) energy. In classical electrodynamics, it is the dipole excitation of atoms in the medium by light which results in the Breit-Wigner shape of the amplitude \( F(E, 0^\circ) \). In hadronic medium, there should
be some modes (quarks, gluons or their preconfined bound states, condensates, blobs of hot matter...?) which can get excited by the impinging parton, radiate coherently if \( n > 1 \) and hadronize at the final stage as hadronic resonances \([22, 23]\). The hadronic Cherenkov effect can provide insight into the substructure of the medium formed in nucleus-nucleus collisions. The resonance amplitudes are chosen for \( F(E, 0^o) \) at comparatively low energies.

The scenario, we have in mind, is as follows. The initial parton, belonging to a colliding nucleus, emits a gluon which traverses the nuclear medium. On its way, it collides with some internal modes. Therefore it affects the medium as an "effective" wave which accounts also for the waves emitted by other scattering centers (see, e.g., \([25]\)). Beside incoherent scattering, there are processes which can be described as the refraction of the initial wave along the path of the coherent wave. The Cherenkov effect is the induced coherent radiation by a set of scattering centers placed on the way of propagation of a gluon. That is why the forward scattering amplitude plays such a crucial role in formation of the index of refraction. At low energies its excess over 1 is related to the resonance peaks as dictated by the Breit-Wigner shapes of the amplitudes. In experiment, usual resonances are formed during the color neutralization process. However, only those gluons whose energies are within the left-wing resonance region of \( n > 1 \) give rise also to collective Cherenkov effect proportional to \( \Delta n \).

Thus, apart from the ordinary Breit-Wigner shape of the cross section for resonance production, the dilepton mass spectrum would acquire the additional term proportional to \( \Delta n \) at masses below the resonance peak. Therefore its excess near the \( \rho \)-meson can be described by the following formula\(^1\)

\[
\frac{dN_{ll}}{dM} = \frac{A}{(m_{\rho}^2 - M^2)^2 + M^2 \Gamma^2} \left( 1 + \frac{m_{\rho}^2 - M^2}{M^2} \theta(m_{\rho} - M) \right)
\]

(2)

Here \( M \) is the total c.m.s. energy of two colliding objects (the dilepton mass), \( m_{\rho} = 775 \text{ MeV} \) is the in-vacuum \( \rho \)-meson mass. The first term corresponds to the Breit-Wigner cross section. According to the optical theorem it is proportional to the imaginary part of the forward scattering amplitude. The second term is proportional to \( \Delta n \) where it is taken into account that the ratio of real to imaginary parts of Breit-Wigner amplitudes is

\[
\frac{\text{Re} F(M, 0^o)}{\text{Im} F(M, 0^o)} = \frac{m_{\rho}^2 - M^2}{M \Gamma}.
\]

\(^1\)We consider only \( \rho \)-mesons here. To include other mesons, one should evaluate the corresponding sum of similar expressions.
This term vanishes for $M > m_\rho$ because only positive $\Delta n$ lead to the Cherenkov effect. Namely it describes the distribution of masses of Cherenkov states. In these formulas, one should take into account the in-medium modification of the height of the peak and its width. In principle, one could consider $m_\rho$ as a free in-medium parameter as well. We rely on experimental findings that its shift in the medium is small. All this asks for some dynamics to be known. In our approach, it is not determined. Therefore, first of all, we just fit the parameters $A$ and $\Gamma$ by describing the shape of the mass spectrum at $0.75 < M < 0.9$ GeV measured in [3] and shown in Fig. 1. In this way we avoid any strong influence of the $\phi$-meson. Let us note that $w$ is not used in this procedure. The values $A=104$ GeV$^3$ and $\Gamma = 0.354$ GeV were obtained. The width of the in-medium peak is larger than the in-vacuum $\rho$-meson width equal to 150 MeV.

Thus the low mass spectrum at $M < m_\rho$ depends only on a single parameter $w$ which is determined by the relative role of Cherenkov effects and ordinary mechanism of resonance production. It is clearly seen from Eq. (2) that the role of the second term in the brackets increases for smaller masses $M$. The excess spectrum in the mass region from 0.4 GeV to 0.75 GeV has been fitted by $w = 0.19$. The slight downward shift about 40 MeV of the peak of the distribution compared with $m_\rho$ may be estimated from Eq. (2) at these values of the parameters. This agrees with the above statement about small shift compared to $m_\rho$. The total mass spectrum (the dashed line) and its widened Breit-Wigner component (the solid line) according to Eq. (2) with the chosen parameters are shown in Fig. 1. The overall description of experimental points seems quite satisfactory. The contribution of Cherenkov gluons (the excess of the dashed line over the solid one) constitutes the noticeable part at low masses. The formula (2) must be valid in the vicinity of the resonance peak. Thus we use it for masses larger than 0.4 GeV only.

The experimental data plotted in Fig. 1 have not been corrected for the acceptance of the experiment, which strongly depends on mass and transverse momentum of the muon pairs. However, due to an approximate cancellation between the variations of the thermal radiation mediated by the rho and those of the acceptance, the data as shown can roughly be interpreted as spectral function of the rho, averaged over momenta and the complete space-time evolution of nuclear collision [3]. To use these data without further corrections is therefore justified as long as the $p_T$ spectra of the radiation and those of the Cherenkov process are not dramatically different. From general principles one would expect slightly lower $p_T$ for low-mass dilepton pairs from coherent Cherenkov processes than for incoherent scattering. Qualitatively, this conclusion is supported by experiment [3]. The Cherenkov dominance region of masses from 400 MeV to 600 MeV below the $\rho$-resonance has softer
Figure 1: Excess dilepton mass spectrum in semi-central In(158 AGeV)-In of NA60 (dots) compared to the in-medium $\rho$-meson peak with additional Cherenkov effect (dashed line).

$p_T$-distribution compared to the resonance region from 600 MeV to 900 MeV filled in by usual incoherent scattering. More accurate statements can be obtained after the microscopic theory of Cherenkov gluons developed.

We should mention that the expression (2) may be applied for $\Delta n \ll 1$. The RHIC experiments revealed rather large $\Delta n \approx 2$. If the same values are typical at lower energies of SPS then the more general formulas (see [23]) should be used. The qualitative conclusions stay valid.

Whether the in-medium Cherenkov gluonic effect is as strong as shown in Fig. 1 can be verified by measuring the angular distribution of the lepton pairs with different masses. The trigger-jet experiments similar to that at RHIC are necessary to check this prediction. One should measure the angles between the companion jet axis and the total momentum of the lepton pair. The Cherenkov pairs with masses between 0.4 GeV and 0.7 GeV should tend
to fill in the rings around the jet axis. The angular radius $\theta$ of the ring is determined by the usual condition

$$\cos \theta = \frac{1}{n}$$

as discussed in more detail in [22].

Another way to demonstrate it is to measure the average mass of lepton pairs as a function of their polar emission angle (pseudorapidity) with the companion jet direction chosen as $z$-axis. Some excess of low-mass pairs may be observed at the angle $\theta$. Baryon-antibaryon effects can not possess signatures similar to these ones.

In practice, these procedures can be quite complicated at comparatively low energies if the momenta of decay products are comparable to the transverse momentum of the resonance. It can be a hard task to pair leptons in reliable combinations. The Monte Carlo models could be of some help.

In non-trigger experiments like that of NA60 there is another obstacle. Everything is averaged over directions of initial partons. Different partons are moving in different directions. The angle $\theta$, measured from the direction of their initial momenta, is the same but the total angles are different, correspondingly. The averaging procedure would shift the maxima and give rise to more smooth distribution. Nevertheless, some indications on the substructure with maxima at definite angles have been found at the same energies by CERES collaboration [27]. It is not clear yet if it can be ascribed to Cherenkov gluons. To recover a definite maximum, it would be better to detect a single parton jet, i.e. to have a trigger.

The prediction of asymmetrical in-medium widening of any resonance at its low-mass side due to Cherenkov gluons is universal. This universality is definitely supported by experiment. Very clear signals of the excess on the low-mass sides of $\rho$, $\omega$ and $\phi$ mesons have been seen in [5, 6]. This effect for $\omega$-meson is also studied in [8]. Slight asymmetry of $\phi$-meson near 0.9 - 1 GeV is noticeable in the Fig. 1 shown above but the error bars are large there. We did not try to fit it just to deal with as small number of parameters as possible. There are some indications at RHIC (see Fig. 6 in [7]) on this effect for $J/\psi$-meson.

At much higher energies one can expect better alignment of the momenta of initial partons. This would favour the direct observation of emitted by them rings in non-trigger experiments. The first cosmic ray event [26] with ring structure gives some hope that at LHC energies the initial partons are really more aligned and this effect can be found. The possible additional signature at high energies could be the enlarged transverse momenta of particles within the ring.
To conclude, the new mechanism is proposed for explanation of the low-mass excess of dilepton pairs observed in experiment. It is the Cherenkov gluon radiation which adds to the ordinary processes at the left wing of any resonance.

Acknowledgments

We thank S. Damjanovic for providing us with experimental data. I.D. is grateful to S. Damjanovic and H. Specht for very illuminating and fruitful discussions, in particular, on the role of the experimental acceptance.

This work has been supported in part by the RFBR grants 06-02-16864, 06-02-17051.

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