Cherenkov and Fano effects at the origin of asymmetric vector mesons in nuclear media

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Abstract

It is argued that the experimentally observed phenomenon of asymmetric vector mesons produced in nuclear media during high energy nucleus-nucleus collisions can be explained as Cherenkov and Fano effects. The mass distributions of lepton pairs created at meson decays decline from the traditional Breit-Wigner shape in the low-mass wing of the resonance. That is explained by the positive real part of the amplitude in this wing for classic Cherenkov treatment and further detalized in quantum mechanics as the interference of direct and continuum states in Fano effect. The corresponding parameters are found from the comparison with ρ-meson data and admit reasonable explanation.

Resonance peaks are observed in many natural phenomena. The traditional way of their description is to compare their shapes with the symmetric Breit-Wigner formula [1]

$$f = \frac{k}{(m_r^2 - M^2)^2 + m_r^2\Gamma^2}, \tag{1}$$

where f denotes a signal strength, k is the normalization constant, M is the scanning energy, m_r is the maximum position (the resonance mass), Γ is the resonance width. One measures the signal intensity at different energies. For example, the atoms behaving as oscillators emit as Breit-Wigner resonances. The resonance shape is a purely statistical phenomenon. It depends on many details of interactions and need not to be necessarily symmetric.

The asymmetric resonance peaks were experimentally observed in various fields of physics even before the formula (1) was proposed. E.g., the resonance of He atoms observed in the inelastic scattering of electrons is strongly asymmetric (see [2, 3]).

In particle physics, such peaks are identified with unstable particles. The symmetric shape is observed for resonances directly produced in particle collisions. Their characteristics are compiled by the PDG (Particle Data Group). The situation has changed after the high energy nucleus-nucleus collisions became available. The created particles have to leak somehow from the nuclear medium. Medium interactions may lead to some modification of their characteristics. Really, there are numerous experimental data [4, 5, 6, 7, 8, 9, 10, 11, 12, 13] about the in-medium modification of widths and positions of prominent vector meson resonances. Some of them even contradict each other. They are mostly obtained from the shapes of dilepton (decay products) mass and transverse momentum spectra in nucleus-nucleus collisions. The dilepton mass spectra decrease approximately exponentially with increase of masses but show peaks over this trend at some masses which can be identified with prominent resonances. The ρ-meson peak is usually the strongest one [4, 5, 6, 7] in the ratio $\rho : \omega : \phi = 10 : 1 : 2$. Below, we concentrate on properties of in-medium ρ-mesons.

The dilepton mass spectrum in semi-central In-In collisions at 158 AGeV measured by NA60-Collaboration [6] is shown in Fig. 1 by dots with error bars in the region of ρ and ω-mesons. Its asymmetry is easily seen with some excess in the low-mass wing. The shape is quite distinct from the familiar ρ-peak.

Several approaches have been advocated for explanation of the excess [15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25]. See the review [26]. However, either positions, widths or heights presented some problems. An alternative hypothesis about the role of Cherenkov gluon effect was promoted in Ref. [14]. The necessary condition for Cherenkov effects to be observable within some energy interval is an excess of the refractivity index of the medium n over 1. According to general formulas this excess is proportional to the real part of the forward (depicted by 0 in formulas below) scattering amplitude.

$$\Delta n = \mathrm{Re}n - 1 \propto \mathrm{Re}F(M, 0) > 0. \tag{2}$$

For the nuclear quark-gluon medium this requirement should be fulfilled for the chromopermitivity of gluons [27]. The derivation of Eq. (1) shows that the real part is positive within the low-energy (left) wing of any resonance described by the Breit-Wigner formula. Therefore one could expect that the collective excitations of the quark-gluon medium may contribute in these energy intervals in addition to the traditional effects. Herefrom one gets the general prediction that the shape of *any* resonance formed in nuclei collisions must become asymmetric with some excess within its left wing compared to the usual Breit-Wigner shape. Since the probability of Cherenkov radiation is proportional to Δn the asymmetry must be proportional to it. Then the dilepton mass distribution must get the shape (the formula in [14] is slightly corrected):

$$\frac{dN_{ll}}{dM} = \frac{A}{(m_r^2 - M^2)^2 + m_r^2\Gamma^2}\left(1 + w_r\frac{m_r^2 - M^2}{m_r\Gamma}\Theta(m_r - M)\right) \tag{3}$$

The first term corresponds to the ordinary Breit-Wigner cross section depicted by the solid line in Fig. 1 with a new width of 354 MeV obtained from the fitting procedure. According to the optical theorem it is proportional to the imaginary part of the forward scattering amplitude. The second term is due to the coherent Cherenkov response of the medium proportional to the real part of the amplitude. It is in charge of the observed asymmetry. It vanishes for $M > m_r$ because only positive Δn lead to Cherenkov effects. Here, we take into account that the ratio of real to imaginary parts of Breit-Wigner amplitudes is

$$\frac{\mathrm{Re}F(M,0)}{\mathrm{Im}F(M,0)} = \frac{m_r^2 - M^2}{m_r\Gamma}. \tag{4}$$

The weight of the second term to ordinary processes is described by the only adjustable parameter w_r for a given resonance r. It must be found from comparison with experimental data. The sum is shown by the dashed line in Fig. 1. The fitted parameters are A=104 GeV^3, Γ=354 MeV, w_ρ=0.19. The shift of the ρ-meson mass is negligibly small. The width of the in-medium peak is about twice larger than that of the in-vacuum ρ-meson equal 150 MeV. The asymmetry parameter w_ρ implies a reasonably small admixture of Cherenkov effects. It will be compared with the corresponding parameter q in Fano treatment below.

Thus, Cherenkov effect asks for interaction of ρ-meson quarks with some third component of a medium (gluon, collective modes...?). Such an interaction can result either in continuum or quasistable states. In quantum mechanics, the interference of the continuum states and discrete levels of the reaction leads to the well known Fano effect [3, 28]. They interfere with opposite phase on the two sides of the resonance as shown in [28]. The resonance asymmetry is described by the following formula [28]:

$$\sigma = \frac{(q+\epsilon)^2}{1+\epsilon^2} = 1 + \frac{q^2 - 1 + 2q\epsilon}{\epsilon^2 + 1}, \tag{5}$$

where at the relativistic notation

$$\epsilon = \frac{M^2 - m_r^2}{m_r \Gamma}. \tag{6}$$

The parameter q describes the relative strength of discrete states and unperturbed continuum. The asymmetric components are proportional to $M^2 - m_r^2$ in both formulas (3) and (5). Equating them, one gets the relation between the parameters q and w_r:

$$q = -w_\rho/2 \approx -0.1 \tag{7}$$

which shows that the interference is not very strong but nevertheless quite noticeable in the left wing (the negative sign!).

The admixture of the contribution of direct states to this effect compared to the influence of the continuum was estimated in [28] equal $\pi q^2/2$ which amounts to about 0.014 in our case. Thus we conclude that continuum scattering plays an overwhelming role while quasibound states are formed rather rarely.

The interference of continuum and quasibound states is at the origin of asymmetric resonances and of the phenomenologic prescription of $\Delta n > 0$. The similar effect for the compound nuclei is known in nuclear physics as Feshbach resonances [29]. In our case, the nature of the third component interacting with ρ-meson quarks and producing quasibound states is however left unknown. With the above estimate of low admixture of the direct states one is even tempted to speculate that electromagnetic forces could be in charge of this effect. It is quite possible that such a component initiates the binding of two otherwise independent quarks in the medium. The formation of the weakly bound triple-states in the collisions of three particles when two-particle forces are too weak to produce bound two-quark dimers is known as Efimov effect [30, 31]. From the theoretical side, models of (collective?) excitations in the nuclear medium which help to get an insight to this problem are welcome. From the experimental side, very little is still known about other resonances but the low-mass asymmetry seems universal and gives some hope for further progress.

At the end, let us stress once again that the electromagnetic interaction of electrons with atoms in ordinary media with $\Delta n > 0$ is described in quantum mechanics as interference of continuum and quasibound states. Thus, beside asymmetric resonances, it is in charge of famous Cherenkov rings of photons as well. The analogous explanation of *hadronic* ring-like events observed [32] in high energy nuclear collisions in terms of Cherenkov gluons was proposed in [33, 34].

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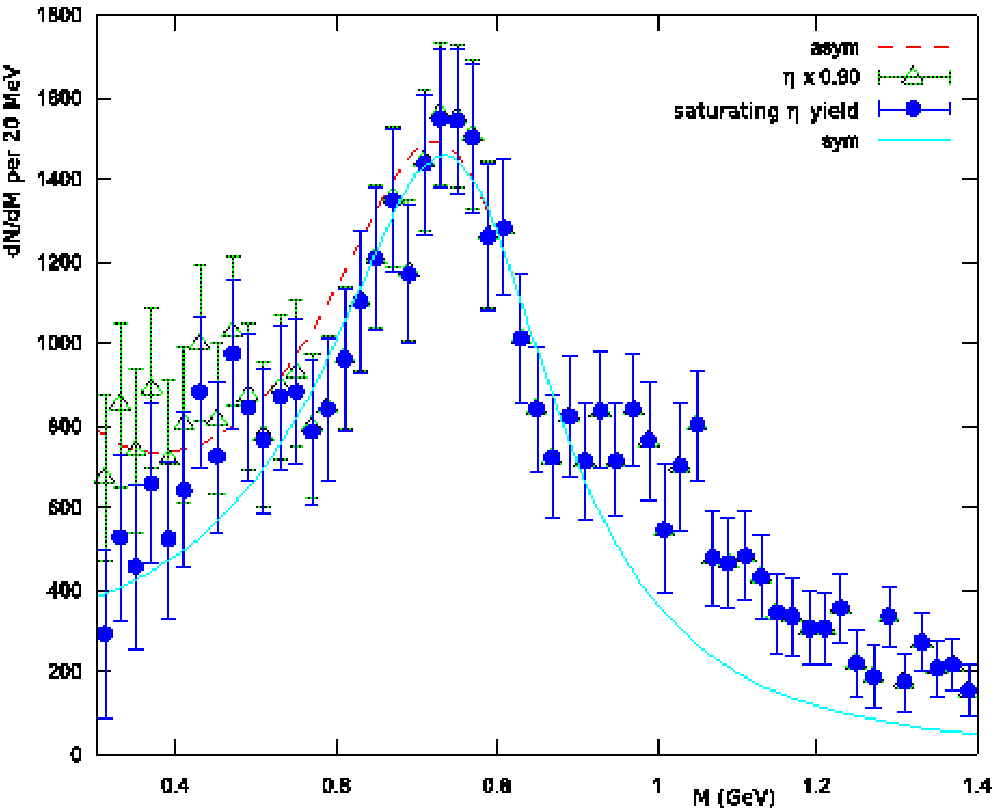

Figure 1: The spectrum of dileptons in semi-central collisions In(158 A GeV)-In measured by NA60-Collaboration [7] (points with error bars) compared to the ρ-meson peak in the medium with additional Cherenkov contribution (the dashed line). The solid line shows the Breit-Wigner shape with the modified width. Borrowed from [14].