PROPERTIES OF $\rho$-MESONS PRODUCED IN HEAVY ION COLLISIONS

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The mass shift and width broadening of $\rho$-mesons produced in heavy ion collisions is estimated. It is found that the mass increases by some tens of MeV but the width becomes large, increasing by 200 MeV at beam energies of a few GeV·A and by twice that amount at beam energies of about a hundred GeV·A.

In a recent paper\(^1\), two of us have argued that the mass shift and width broadening of a particle in medium can be related to the forward scattering amplitude $f(E)$ of this particle on the constituents of the medium.

$$\Delta m(E) = -2\pi \frac{\rho}{m} \text{Re} f(E), \quad \Delta \Gamma(E) = \frac{\rho}{m} k \sigma(E). \quad (1)$$

Here $m$ is the vacuum mass of the particle, $E$ is its energy in the rest frame of the constituent particle, $k$ is the particle momentum, and $\rho$ is the density of constituents. Eqs. (1) are applicable if:

1) The particle's wavelength $\lambda$ is much less than the mean distances between medium constituents $d$: $\lambda = k^{-1} \ll d$. 2) The particle's formation length $l_f$ is less than the nucleus radius $R$. 3) $|\text{Re} f(E)| < d$. 4) The main part of the scattering proceeds through small angles, $\theta \ll 1$. Only in this case is the optical analogy on which Eqs. (1) are based correct.

We estimate the mass shift and width broadening in the case of $\rho$-mesons produced in heavy ion collisions, which can be observed through the decay $\rho^0 \rightarrow e^+e^-$ or $\mu^+\mu^-$. We will assume that $\rho$-mesons are formed in the last stage of the evolution of hadronic matter created in the course of a heavy ion collision when the matter can be considered as an almost noninteracting gas of pions and nucleons. The main ingredients of our calculation are $\rho\pi$ and $\rho N$ forward scattering amplitudes and total cross sections as well as the values of nucleon and pion densities. We consider central heavy ion collisions and assume that nucleon and pion momentum distributions in the gas are just the momentum distributions measured experimentally in such collisions.

To determine the amplitudes and cross sections we use the following procedure. At low energies we saturate the cross sections and forward scattering amplitudes by resonance contributions. At high energies we determine $\sigma_{\rho N}$...
and \(\sigma_{\rho\pi}\) from \(\sigma_{\gamma N}\) and \(\sigma_{\gamma\pi}\) using the vector dominance model (VDM). The cross section \(\sigma_{\gamma N}\) is well known experimentally, \(\text{Re} f_{\gamma N}\) is determined from the dispersion relation, and \(\sigma_{\gamma\pi}\) and \(\text{Re} f_{\gamma\pi}\) can be found by the Regge approach. Since VDM allows one to find only the cross sections of transversally polarized \(\rho\)-mesons we restrict ourselves to this case. As was shown in \(\ref{2}\), when \(E_\rho \gtrsim 2\text{ GeV}\), \(\Delta m\) and \(\Delta \Gamma\) for longitudinal \(\rho\)-mesons are much smaller than for transversal ones in nuclear matter. At zero \(\rho\)-meson energy, \(\Delta m\) and \(\Delta \Gamma\) for transverse and longitudinal \(\rho\)-mesons are evidently equal. Therefore our results should be multiplied by a factor ranging between \(2/3\) and \(1\) for unpolarized \(\rho\)-mesons.

To estimate \(\text{Re} f_{\rho\pi}(E)\) and \(\sigma_{\rho\pi}(E)\) at low energy we take into account the following resonances: \(a_1(1260)\), \(\pi(1300)\), \(a_2(1320)\) and \(\omega(1420)\). The nearest resonance under the threshold, \(\omega(782)\), contributes a negligible amount due to its narrow width. According to Adler’s theorem the pion scattering amplitude on any hadronic target vanishes at zero pion energy in the target rest frame in the limit of massless pions. The corresponding factors were introduced in the resonance contributions. At high energies we assume that the Regge approach is valid for \(\gamma\pi\) scattering and apply the vector dominance model (VDM) to relate \(\rho\pi\) and \(\gamma\pi\) amplitudes. The Regge pole contributions to \(\sigma(s)\) and \(\text{Re} f(s)\) have the form:

\[
\sigma(s) = \sum_i r_i s^{\alpha_i - 1}, \quad \text{Re} f(s) = -\frac{k}{4\pi s} \sum_i \frac{1 + \cos \pi \alpha_i}{\sin \pi \alpha_i} r_i s^{\alpha_i}. \tag{2}
\]

For \(\sigma_{\gamma\pi}\) only \(P\) (Pomeron) and \(P'\) Regge poles contribute. The residues of the \(P\) and \(P'\) poles in \(\gamma\pi\) scattering were found in \(\ref{3}\) using Regge pole factorization and data on \(\gamma p, \pi p\) and \(p p\) scattering.

\[
\sigma_{\pi\gamma}(s) = 7.48 \alpha \left[ (s/s_0)^{\alpha P - 1} + 0.971 (s/s_0)^{\alpha P' - 1} \right], \tag{3}
\]

where \(\alpha_P = 1.0808\), \(\alpha_{P'} = 0.5475\), \(\alpha = 1/137\), \(s_0 = 1\text{ GeV}^2\) and \(\sigma\) in Eq. (5) is given in millibarns.

For the amplitude \(\text{Re} f_{\rho N}\) at laboratory energies of the \(\rho\) above \(2\text{ GeV}\) we use the results obtained with the dispersion relation, VDM and experimental data on \(\sigma_{\gamma N}\). At lower energies we again use the resonance approximation and take \(10\) \(N\) and \(\Delta\) resonances with significant branchings into \(\rho N\) and with masses above the \(\rho N\) threshold and below \(2200\text{ MeV}\). Besides these resonances, two others with masses below the \(\rho N\) threshold were accounted for: the \(\Delta(1238)\) and the \(N(1500)\). It was assumed that VDM is valid for the contribution of these resonances to the widths \(\Gamma_{\rho N}\) and \(\Gamma_{\gamma N}\).

The results for \(\sigma_{\rho\pi}, \text{Re} f_{\rho\pi}, \sigma_{\rho N}\) and \(\text{Re} f_{\rho N}\) in the rest frame of the target, are shown in Figs.1 and 2.
As shown by the experimental data, the nucleons and pions produced in heavy ion collisions cannot be considered as a gas in global thermal equilibrium even during the last stage of evolution of hadronic matter created in the collisions. In the case of high energy collisions the longitudinal and transverse momenta of nucleons and pions are very different. In the experiment on $S + S$ collisions at 200 GeV·A it was found that $\langle p_{LM}^N \rangle = 3.3$ GeV, $\langle p_{TN} \rangle = 0.61$ GeV, and $\langle p_{LM}^\pi \rangle \approx 0.70$ GeV, $\langle p_{T\pi} \rangle \approx 0.36$ GeV.

The angular distributions of pions produced in $Ni + Ni$ collisions at $E = 1 - 2$ GeV·A shows essential anisotropy. The pion angular distribution in the centre of mass system is approximated by $1 + a \cos^2 \theta$.
follows \( a \approx 1.3 \).

When calculating the \( \rho \)-meson mass shift and width broadening an averaging must be performed over the \( \rho \)-meson direction of flight relative to nucleons and pions. Such a calculation can be done only for real experimental conditions. For this reason we restrict ourselves to rough estimates. As an example take the experiment\(^4\) for central collisions where the ratio of pion to nucleon multiplicities was found to be \( R_\pi = 5.3 \). Suppose that in this experiment the \( \rho \)-meson is produced with longitudinal and transverse momenta in the laboratory system \( k_L = 3 \text{ GeV}, \ k_T = 0.5 \text{ GeV} \). For these values of \( \rho \) momenta the formation time of the \( \rho \)-meson is close to the mean formation time of pions so a necessary condition of our approach is fulfilled. Then it is possible, using the curves of Figs. 1 and 2 to calculate the mean values:

\[
\langle \Re f_N \rangle \approx -1.1 \text{ fm}, \ \langle \Re f_\pi \rangle \approx 0.03 \text{ fm}, \ \langle \sigma_N \rangle \approx 45 \text{ mb}, \ \langle \sigma_\pi \rangle \approx 20 \text{ mb}. \]

The small value of \( \langle \Re f_\pi \rangle \) arises from a compensation of positive and negative contributions from low and high energy collisions. For the nucleon and pion densities we take

\[
\rho_N = \frac{\rho^0_N}{1 + R_\pi \beta}, \ \rho_\pi = \rho^0_\pi R_\pi / (1 + R_\pi \beta), \quad (4)
\]

where \( \rho^0_N = 1/v_N \) and \( \beta = v_\pi/v_N \) and it is assumed that at this stage of evolution any participant – nucleon or pion – occupies the fixed volume \( v_N \) or \( v_\pi \), respectively. For numerical estimates we take \( \rho^0_N = 0.3 \text{ fm}^{-3} \), about two times standard nucleon density. Using (1) and (4) together with the experimental values \( R_\pi = 5.3 \) and \( \beta = 1 \), we get

\[
\Delta m_\rho = 18 - 2 = 16 \text{ MeV}, \ \Delta \Gamma_\rho \approx 150 + 400 = 550 \text{ MeV} \quad (5)
\]

The first numbers above refer to the contributions from \( \rho - N \) and second from \( \rho - \pi \) scattering. Because the \( \rho \)-meson width broadening appears to be very large, a basic condition of our approach, \( \Delta \Gamma \ll m_\rho \), is badly fulfilled. The applicability condition of the method, \( | \Re f | < d \), is not well satisfied either since in this case \( d = 0.9 \text{ fm} \). For these reasons the values of \( \Delta m_\rho \) and \( \Delta \Gamma_\rho \) may be considered only as estimates.

The main uncertainty in our approach comes from the assumed value of the nucleon density at the final stage of evolution: \( \rho^0_N = 0.3 \text{ fm}^{-3} \). If this density would be a factor of two smaller then \( \Delta \Gamma_\rho \sim 250 \text{ MeV} \) and the \( \rho \)-meson could be observed as a broad peak in the \( e^+e^- \) or \( \mu^+\mu^- \) mass spectrum.

Our qualitative conclusion is that in central collisions of heavy nuclei at high energies, \( E \sim 100 \text{ GeV} \cdot \text{A} \), where a large number of pions per participating nucleon is produced, the \( \rho \)-peak will be observed in \( e^+e^- \) or \( \mu^+\mu^- \) mass distributions only as a very broad enhancement, or even no enhancement at all. Inspite of the assumptions we made, including noninteracting nucleon and
pion matter at the final stage of evolution and the specific numerical value of the nucleon density, we believe that this qualitative conclusion is still valid. This conclusion is in qualitative agreement with the measurement of $e^+e^-$ pair production in heavy ion collisions where no $\rho$-peak was found and only a smooth $e^+e^-$ mass spectrum from 0 to 1 GeV was observed. If, however, such a peak would be observed in future experiments it would indicate that the hadronic (nucleon and pion) density at the final stage of evolution, where the $\rho$-meson is formed, is very low, even lower than normal nuclear density.

Let us turn now to the case of lower energy heavy ion collisions, $E \sim a$ few GeV·A. Consider, as an example, heavy ion collisions at $E_{\text{kin}} = 3$ GeV·A and production of $\rho$-mesons of energy $E_\rho = 1.2$ GeV in the forward direction.

The number of pions produced can be estimated by extrapolation of the data on $Ni + Ni$ collisions. We find that $R_\pi = 0.48$. At such low energies it is reasonable to suppose that for pions $\langle p_L \rangle = \langle p_\perp \rangle \approx 0.2$ GeV and for nucleons $\langle p_{T,N} \rangle = 0.61$ GeV. Then we obtain the mean values: $\langle Re\rho N \rangle = -0.54$ fm, $\langle Re\rho \pi \rangle = 0.30$ fm, $\langle \sigma_{\rho N} \rangle = 45$ mb, $\langle \sigma_{\rho \pi} \rangle = 13$ mb. For the $\rho$-meson mass shift and width broadening we have:

$$\Delta m_\rho = 37 - 10 = 27 \text{ MeV}, \quad \Delta \Gamma_\rho = 245 + 35 = 280 \text{ MeV}. \quad (6)$$

The first numbers above refer to $\rho N$ scattering, the second ones to $\rho \pi$. The conclusion is that in low energy heavy ion collisions a $\rho$-peak may be observed in $e^+e^-$ or $\mu^+\mu^-$ mass distributions as a broad enhancement approximately at the position of $\rho$-mass.

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