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# ρ thermometry in hot hadronic matter

H.W. Barz [a,b], G. Bertsch [c], B.L. Friman [b,d], H. Schulz [a] and S. Boggs [d]

[a] *Zentralinstitut für Kernforschung, Rossendorf, O-8051 Dresden, FRG*
[b] *Gesellschaft für Schwerionenforschung (GSI), W-6100 Darmstadt, FRG*
[c] *NSCL, Michigan State University, East Lansing, MI 48824, USA*
[d] *Institut für Kernphysik, Technische Hochschule Darmstadt, W-6100 Darmstadt, FRG*

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The position and shape of the ρ resonance is sensitive to the degree of equilibration and the temperature of hot hadronic matter. This might be studied experimentally by the lepton pair spectra in ultrarelativistic heavy ion collisions.

The study of hadronic matter by ultrarelativistic heavy ion collisions depends crucially on the formation of locally equilibrated matter on time scales of a few fm/$c$ past the initial collision point. If rapid equilibration is achieved, new phases such as the quark–gluon plasma would be observable and information about thermodynamic properties could be extracted.

A complete equilibration including flavor degrees of freedom seems unlikely, but one can hope to create thermal matter composed of light quark and gluon fields. Unfortunately, there are very few probes to give us information about the degree of equilibration.

The aim of this note is to point out that the ρ meson spectra may be interesting from this point of view. The ρ mesons have a rather short lifetime, about 1 fm/$c$, which means that they will be continually reformed in a thermal ensemble. Thus the ρ mesons can uniquely probe time scales of the order $\hbar/\Gamma_\rho \simeq 1\,\mathrm{fm}/c$.

There are a number of ways we can imagine that ρ mesons are created. Depending on whether the process is direct or thermal, the spectrum can have a different shape and shift in the peak position.

Let us first assume that the ρ mesons originate solely from the ππ scattering and that the pion spectrum is thermal. In this case the production and the decay (detailed balance) of the ρ meson is dominated by the resonance-like structure of the cross section. Consequently, the rate for some observable process involving the ρ meson is given by the resonant cross section multiplied by the flux of scattering pions (see e.g. eq. (3.3) in ref. [1]). After integrating over the pion momenta we find the resulting mass spectrum

$$\frac{\mathrm{d}N_\rho}{\mathrm{d}M} \sim M^2 K_1\left(\frac{M}{T}\right)\frac{\Gamma_\pi \Gamma_x}{(M-M_\rho)^2+\Gamma^2/4}. \qquad (1)$$

In this equation, the thermal distribution of pions (assumed maxwellian) is responsible for the factor of $K_1(M/T)$, the Bessel function of the second kind. The cross section is taken to have a Breit–Wigner shape, but the widths are in general energy dependent. In the formula one needs both the width for two-pion decay $\Gamma_\pi$ and the width for the process measured $\Gamma_x$. Typically this might be lepton pair decay. The ρ meson width is dominated by the two-pion decay: $\Gamma \simeq \Gamma_\pi$. For our numerical calculation, we use the parametrization of the resonant π–π cross section given in ref. [2].

The intrinsic ρ meson mass may be shifted due to many-particle interactions [3–7]. However, since the predictions of the various models differ, it is not yet settled whether the in-medium mass is shifted up or down. Furthermore, no such shift is seen experimentally in photoproduction of ρ mesons on nuclei [8]. Although the experimental evidence is only suggestive, since it applies to a different temperature–density regime, we neglect any such shift. Thus, we explore the consequences of thermalization on e.g. the dilepton spectrum in the ρ mass region under the as-

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sumption, that the *intrinsic* ρ meson mass is not affected by the presence of the hot pion gas, i.e., $M_\rho = 770$ MeV.

The width is dominated by the π–π channel with

$$\Gamma(q) = 0.095q\left(\frac{q/m_\pi}{1+(q/M_\rho)^2}\right)^2 . \qquad (2)$$

In this equation $q$ is the pion momentum,

$q = \frac{1}{2}\sqrt{M^2-(2m_\pi)^2}$ .

The energy shift of the maximum of the energy spectrum of the ρ mesons is then

$$\Delta M_\rho \approx \frac{\Gamma^2}{8}\left(\frac{1}{T}-\frac{3}{2M_\rho}\right), \qquad (3)$$

which is of the order of 20 MeV for a temperature $T \approx 120$ MeV. This is illustrated in fig. 1 where the ρ meson spectrum

$$M^2 K_1\left(\frac{M}{T}\right)\frac{\Gamma}{(M-M_\rho)^2+\Gamma^2/4} \qquad (4)$$

is shown for $T = 120$ MeV and $T = 150$ MeV, respectively. We see also, that in addition to the shift of the peak, the resulting ρ meson spectrum is also somewhat narrower than that given by the Breit–Wigner expression.

The shift of about 20 MeV of the ρ mesons would

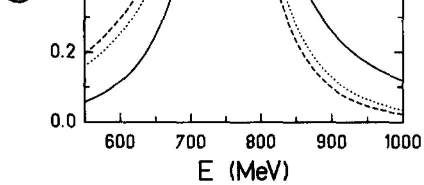


Fig. 1. The shape of the ρ meson given by the Breit–Wigner form with the parametrization in eqs. (2), (3), is shown as the solid line. The shape modified by the thermal factor at a temperature of 120 MeV and 150 MeV in eq. (4) is shown by the dashed and dotted lines, respectively.

certainly be hard to measure. It might, however, be done by measuring the decay of the ρ mesons into $\mu^+\mu^-$ pairs. In fact, the weakly interacting leptons or photons are well suited for this purpose, because, once they are formed in the medium they interact only very rarely. This way they can provide us with genuine information about the hot and dense stage of the hadronic fireball in which the ρ mesons have been formed. To detect the shift one has to compare, e.g., the $\mu^+\mu^-$ pair spectrum of p+A and A+A collisions at 200 GeV per nucleon. Finding such a shift would be very interesting from the theoretical point of view. It would, however, not unambiguously prove that the ρ mesons are in thermal equilibrium with the surrounding medium. As we noted above, the shift might also be due to many-particle interactions giving rise to modified in-medium π and ρ meson propagators. Consequently, the observation of a shift would also support such a possibility and it remains a major task of the theoretical analysis to disentangle this problem.

The ρ mesons will not only be produced via ππ collisions but also by decay of heavier objects. In one extreme, we image a phase transition with particles emitted from the surface of the denser phase. If these objects are large and have many internal degrees of freedom, they will behave as thermal sources. Then the same considerations should apply as those made above; the spectrum of mesons should be shifted. The reason for the shift in this case is the increased density of final states of the large object when emitting a low mass ρ meson.

However, it is also quite possible that the objects emitting the mesons have few internal degrees of freedom. The ρ mesons are produced by the decay of heavier hadrons, e.g., the $a_1(1275)$ meson has a dominant decay into a π and a ρ meson. In this way the ρ mesons would have nearly their natural shape because two-body phase space varies so smoothly. Many models of high energy collisions invoke some parton mechanism for ρ meson production. For example, in the Lund model [9] there is a string fragmentation, and other models such as VENUS [10] have similar dynamics. In these models the phase space is also very smoothly varying, so the resonances would keep their original shapes.

To get some feeling for the amount of thermal versus direct mesons expected, we consider a thermal and a cascade model. The thermal model is based on the scheme of refs. [11,12]. Originally, in refs. [11,12], a quark–gluon plasma was assumed, so the entire production of ρ mesons would be thermal. Here we want to see whether direct production would alter the overall character of the ρ meson spectrum. We modified the model of ref. [12] by changing the initial conditions. We assume that initially the system is composed of π, ρ, ω, and η mesons, with relative abundances given by their statistical weights. This is close to the assumption made in in string breaking models such as the Lund mode. We take the initial spatial distribution of the mesons to be uniform in a spherical volume, which is admittedly somewhat unrealistic. The subsequent meson interactions are described by rates, which are taken to be proportional to the inelastic cross sections.

The cascade model is described in ref. [13]. The model follows the interactions of individual mesons produced in some assumed initial distribution. The mesons considered are the light-quark mesons π, ρ, ω, η. Their interactions are described by a one-parameter statistical cross section model, except for the π–π scattering below 1 GeV, which is determined from phase shifts as in ref. [2].

In fig. 2 we show the production and decay rate of ρ mesons as a function of time, when the parameters are taken as follows: We started with a mixture consisting of 48 π, 140 ρ, 48 ω and 16 η mesons confined in a spherical volume of 100 $fm^3$. The initial energy density of 2.5 $GeV/fm^3$ corresponds to a temperature of $T=240$ MeV. The system expands spherically under the influence of the thermal pressure. There are several reaction channels included (see ref. [11]), whereby the $\pi+\pi\rightleftharpoons\rho$ is the most important one which proceeds within the life time of the ρ meson of 1.3 fm/$c$. We find that, depending on the model, 100–150 ρ mesons are produced during the expansion in individual hadronic collisions. This amount is comparable to the 140 originating from the initial violent impact.

In fig. 3 we show the production and decay rates obtained in the cascade model for more realistic initial conditions. The distribution of particles was initialized to simulate the collision of oxygen on a heavy target. The particles are placed in a spatial volume whose transverse size is determined by the transverse density distribution of the projectile. The particles have a collective longitudinal momentum distributed as a gaussian with a standard deviation of 1.3 units of rapidity. This is approximately the measured distribution of negatively charged particles in ref. [14]. The particles materialize at a proper time $\tau=1$ fm/$c$ after the collision point, with a longitudinal position given by the distance that the particle would move from the collision point, travelling at the collective velocity. The total number of particles in the initial distribution, 250, corresponds to 500 final state pions and a final state rapidity density of the pions of

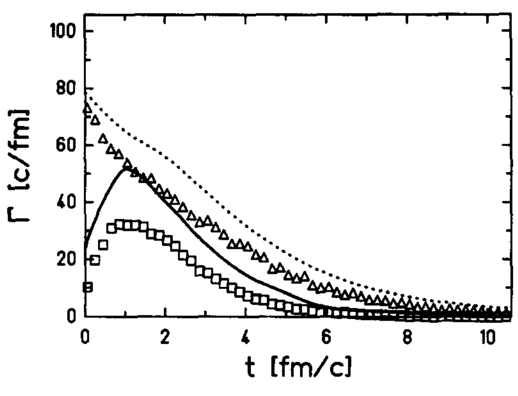


Fig. 2. The production and decay rate of the ρ meson as a function of time for the thermal model of refs. [11,12] (solid and dashed lines) and the cascade type model of ref. [2] (squares and triangles). Initially the system consists of 48 π, 140 ρ, 48 ω and 16 η mesons, confined in a spherical volume of 100 $fm^3$. The initial energy density of 2.5 $GeV/fm^3$ corresponds to a temperature of $T=240$ MeV. For the cascade model a similar initial condition is used.

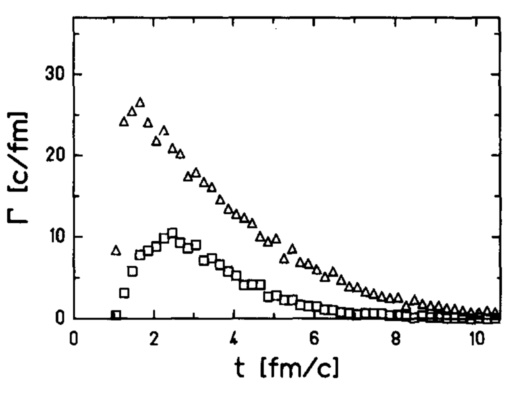


Fig. 3. The production and decay rate of the ρ meson as a function of time in the cascade model with longitudinal expansion. The initial conditions are described in the text.

$dN/dy=150$. This approximates the value seen in experiments [14,15].

The rates shown in fig. 3 correspond to the rapidity interval $|y|<1$. Within this rapidity interval the number of thermally produced ρ mesons is 30, compared to the 60 primary ones. Comparison of these results and those obtained for the spherical initial conditions, illustrates the dependence on the lifetime of the interaction zone. For the spherical initial conditions, the system expands more slowly, leaving more time for thermal ρ mesons to be produced.

Thus our calculations based on rather different model assumptions demonstrate that the thermal ρ mesons are important. According to our reasoning, the resulting ρ meson spectrum would exhibit a shift, whose magnitude reflects the degree of thermalization in hadronic system. Only a fully thermalized system, without primary ρ mesons, would exhibit the full shift of ≈ 20 MeV. The presence of primary ρ mesons would lead to a smaller shift.

In summary, if the shift of the ρ meson peak were observed, this indicates that local thermal equilibrium existed at least in the hadronic phase of the expansion. On the other hand, if no shift is observed, this implies that the entire collision must be treated as a dynamic process without the simplifications of local equilibrium. This would make the outlook more pessimistic for a quantitative study of the equation of state and properties of the perturbative quark–gluon plasma. As we noted already, the resonance parameters may change due to medium effects, possibly leading to an additional shift of the ρ meson peak. However, at present neither the magnitude nor the sign of such a shift is settled. Hence, further theoretical studies of these problems are needed before any firm conclusions can be drawn.

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