HADRONS IN THE NUCLEAR MEDIUM
– INTRODUCTION AND OVERVIEW

U. MOSEL
Institut fuer Theoretische Physik, Universitaet Giessen
D-35392 Giessen, Germany

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Abstract

In this talk I first discuss predictions based on QCD sum rules and on hadronic models for the properties of vector mesons in the nuclear medium. I then describe possible experimental signatures and show detailed predictions for dilepton invariant mass spectra with a special emphasis on nuclear reactions involving elementary incoming beams and nuclear targets. I will in particular illustrate that the sensitivity of pion and photon induced reactions to in-medium effects is comparable to that of heavy-ion reactions.

1 Introduction

The investigation of in-medium properties of hadrons has found widespread interest during the last decade. This interest was triggered by two aspects.

The first aspect was a QCD sum-rule based prediction by Hatsuda and Lee in 1992 that the masses of vector mesons should drop dramatically as a function of nuclear density. It was widely felt that an experimental verification of this prediction would establish a long-sought direct link between quark degrees of freedom and nuclear hadronic interactions. In the same category fall the predictions of Brown and Rho that argued for a general scaling for hadron masses with density.

The second aspect is that even in ultrarelativistic heavy-ion reactions, searching for observables of a quark-gluon plasma phase of nuclear matter, inevitably also many relatively low-energy (√s ≈ 2 – 4 GeV) final state interactions take place. These interactions involve collisions between many mesons for which the cross-sections and meson self-energies in the nuclear medium are not known, but may influence the interpretation of the experimental results.

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†Based on results of work with E. Bratkovskaya, W. Cassing, M. Effenberger, H. Lenske, S. Leupold, W. Peters, M. Post and T. Weidmann.
‡mosel@theo.physik.uni-giessen.de
Hadron properties in medium involve masses, widths and coupling strengths of these hadrons. In lowest order in the nuclear density all of these are linked by the $t\rho$ approximation that assumes that the interaction of a hadron with many nucleons is simply given by the elementary $t$-matrix of the hadron-nucleon interaction multiplied with the nuclear density $\rho$. For vector mesons this approximation reads

$$\Pi_V = -4\pi f_{VN}(0)\rho$$

where $f_{VN}$ is the forward-scattering amplitude of the vector meson (V) nucleon (N) interaction. Approximation (1) is good for low densities ($\Pi_V$ is linear in $\rho$) and/or large relative momenta where the vector meson ‘sees’ only one nucleon at a time. Relation (1) also neglects the Fermi-motion of the nucleons although this could easily be included.

Simple collision theory\[3, 4\] then gives the shift of mass and width of a meson in nuclear matter as

$$\delta m_V = -\gamma_\nu \sigma_{VN} \eta \rho$$
$$\delta \Gamma_V = \gamma_\nu \sigma_{VN} \rho.$$\hspace{1cm}(2)\hspace{1cm}$$\\\\\\\\\\\\$$

Here, according to the optical theorem, $\eta$ is given by the ratio of real to imaginary part of the forward scattering amplitude

$$\eta = \frac{\Re f_{VN}(0)}{3 f_{VN}(0)}.$$\hspace{1cm}(3)\hspace{1cm}$$\\\\\\\\\\\\$$

The expressions (2) are interesting since an experimental observation of these mass- and width-changes could give valuable information on the free cross sections $\sigma_{VN}$ which may not be available otherwise. The more fundamental question, however, is if there is more to in-medium properties than just the simple collisional broadening predictions of (3).

2 Fundamentals of Dilepton Production

From QED it is well known that vacuum polarization, i.e. the virtual excitation of electron-positron pairs, can dress the photon. Because the quarks are charged, also quark-antiquark loops can dress the photon. These virtual quark-antiquark pairs have to carry the quantum numbers of the photon, i.e. $J^z = 1^-$. The $q\bar{q}$ pairs can thus be viewed as vector mesons which have the same quantum numbers; this is the basis of Vector Meson Dominance (VMD).

The vacuum polarization tensor is then, in complete analogy to QED, given by

$$\Pi^{\mu\nu} = \int d^4 x e^{iqx} \langle 0 | T [j^\mu(x) j^\nu(0)] | 0 \rangle = \left( g^{\mu\nu} - \frac{q^\mu q^\nu}{q^2} \right) \Pi(q^2)$$\hspace{1cm}(4)\hspace{1cm}$$\\\\\\\\\\\\$$

where $T$ is the time ordering operator. Here the tensor structure has been exhibited explicitly. This so-called current-current correlator contains the
currents $j^\mu$ with the correct charges of the vector mesons in question. Simple VMD relates these currents to the vector meson fields

$$j^\mu(x) = \frac{m_0^2}{g_V} V^\mu(x).$$

(5)

Using this equation one immediately sees that the current-current correlator (4) is nothing else but the vector meson propagator $D_V$

$$\Pi(q^2) = \left(\frac{m_0^2}{g_V}\right)^2 D_V(q^2).$$

(6)

The scalar part of the vector meson propagator is given by

$$D_V(q^2) = \frac{1}{q^2 - m_V^2 - \Pi_V(q^2)}.$$  

(7)

Here $\Pi_V$ is the selfenergy of the vector meson.

For the free $\rho$ meson information about $\Pi(q^2)$ can be obtained from hadron production in $e^+e^-$ annihilation reactions

$$R(s) = \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)} = -\frac{12\pi}{s} \Im \Pi(s)$$

(8)

with $s = q^2$. This determines the imaginary part of $\Pi$ and, invoking vector meson dominance, also of $\Pi_V$. The data (see, e.g. Fig. 18.8 in [6], or Fig. 1 in [7]) clearly show at small $\sqrt{s}$ the vector meson peaks, followed by a flat plateau starting at $\sqrt{s} \approx 1.5$ GeV described by perturbative QCD.

In order to get the in-medium properties of the vector mesons, i.e. their selfenergy $\Pi_V$, we now have two ways to proceed: We can, first, try to determine the current-current correlator by using QCD sum rules; from this correlator we can then determine the self-energy of the vector meson following eqs. (6), (7). The second approach consists in setting up a hadronic model and calculating the selfenergy of the vector meson by simply dressing its propagators with appropriate hadronic loops. In the following sections I will discuss both of these approaches.

### 2.1 QCD sum rules and in-medium masses

The QCD sum rule for the current-current correlator is obtained by evaluating the function $R(s)$, and thus $\Im \Pi(s)$ (see [6]), in a hadronic model on one hand and in a QCD-based model on the other. The latter, QCD based, calculation uses the fact that the current-current correlator (4) can be Taylor expanded in the space-time distance $x$ for small space-like distances between $x$ and 0; this is nothing else than the Operator Product Expansion (OPE) [6]. In this way we obtain for the free meson

$$R^{\text{OPE}}(M^2) = \frac{1}{8\pi^2} \left(1 + \frac{\alpha_S}{\pi}\right) + \frac{1}{M^4} m_\text{q}(\bar{q}q) + \frac{1}{24M^4} (\frac{\alpha_S}{\pi} G^2) - \frac{56}{81M^6} \alpha_S \kappa(\bar{q}q)^2.$$ 

(9)

Here $M$ denotes the so-called Borel mass. The expectation values appearing here are the quark- and gluon-condensates. The last term here contains the mean field approximation $(\langle \bar{q}q \rangle)^2 = \kappa(\bar{q}q)^2$. 

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The other representation of $R$ in the space-like region can be obtained by analytically continuing $\Im \Pi(s)$ from the time-like to the space-like region by means of a twice subtracted dispersion relation. This finally gives

$$R_{\text{HAD}}^2(M^2) = \frac{\Pi_{\text{HAD}}(0)}{M^2} - \frac{1}{\pi M^2} \int_0^\infty ds \Im \Pi_{\text{HAD}}(s) \frac{s}{s^2 + \epsilon^2} \exp(-s/M^2).$$

(10)

Here $\Pi_{\text{HAD}}$ represents a phenomenological hadronic spectral function. Since for the vector mesons this spectral function is dominated by resonances in the low-energy part it is usually parametrized in terms of a resonance part with parameters such as strength, mass and width with a connection to the QCD perturbative result for the current-current correlator at higher energies (for details see Leupold et al.\cite{8} in these proceedings and refs.\cite{9,10,11}).

The QCD sum rule is then obtained by setting

$$R_{\text{OPE}}^2(M^2) = R_{\text{HAD}}^2(M^2).$$

(11)

Knowing the lhs of this equation then allows one to determine the parameters in the spectral function appearing in $R_{\text{HAD}}$ on the rhs. If the vector meson moves in the nuclear medium, then $R$ depends also on its momentum. However, detailed studies\cite{10,11} find only a very weak momentum dependence.

The first applications\cite{1} of the QCDSR have used a simplified spectral function, represented by a $\delta$-function at the meson mass and a perturbative QCD continuum. Such an analysis gives a value for the free meson mass that agrees with experiment. On this basis the QCDSR has been applied to the prediction of in-medium masses of vector mesons by making the condensates density-dependent (for details see\cite{1,9,10}). This then leads to a lowering of the vector meson mass in nuclear matter.

This analysis has recently been repeated with a spectral function that uses a Breit-Wigner parametrization with finite width. In this study\cite{9} it turns out that QCD sum rules are compatible with a wide range of masses and widths (see also ref.\cite{7}). Only if the width is – artificially – kept zero, then the mass of the vector meson has to drop with nuclear density\cite{1}. However, also the opposite scenario, i.e. a significant broadening of the meson at nearly constant pole position, is compatible with the QCDSR.

### 2.2 Hadronic models

Hadronic models for the in-medium properties of hadrons start from known interactions between the hadrons and the nucleons. In principle, these then allow one to calculate the forward scattering amplitude $f_{VN}$ for vector meson interactions. Many such models have been developed over the last few years\cite{7,12,13,14,15}.

The model of Friman and Pirner\cite{14} was taken up by Peters et al.\cite{16} who also included $s$-wave nucleon resonances. It turned out that in this analysis the $D_{13} N(1520)$ resonance plays an overwhelming role. This resonance has a significant $\rho$ decay branch of about 20%. Since at the pole energy of 1520 MeV the $\rho$ decay channel is not yet energetically open this decay can only take place through the tails of the mass distributions
of resonance and meson. The relatively large relative decay branch then translates into a very strong $N^*N\rho$ coupling constant (see also [15, 17]).

The main result of this $N^*h$ model for the $\rho$ spectral function is a considerable broadening for the latter. This is primarily so for the transverse vector mesons (see Fig. 1), whereas the longitudinal degree of freedom gets only a little broader with only a slight change of strength downwards [16].

The results shown in Fig. 1 actually go beyond the simple "$t\rho$" approximation discussed earlier (see (1)) in that they contain higher order density effects: a lowering of the $\rho$ meson strength leads to a strong increase of the $N(1520)\rho$-decay width which in turn affects the spectral function. The result is the very broad, rather featureless spectral function for the transverse $\rho$ shown in Fig. 1.

3 Experimental Observables

In this section I will now discuss various possibilities to verify experimentally the predicted changes of the $\rho$ meson properties in medium.

3.1 Heavy-Ion Reactions

Early work [18, 19] on an experimental verification of the predicted broadening of the $\rho$ meson spectral function has concentrated on the dilepton spectra measured at relativistic energies (about 1 – 4 A GeV) at the BEVALAC, whereas more recently many analyses have been performed for the CERES and HELIOS data obtained at ultrarelativistic energies (150 – 200 A GeV) at the SPS. In such collisions nuclear densities of about 2 - 3 $\rho_0$ can already be reached in the relativistic domain; in the ultrarelativistic energy range baryon densities of up to 10$\rho_0$ are predicted (for a recent review see [20]). Since the selfenergies of produced vector mesons are at
least proportional to the density $\rho$ (see [1]) heavy-ion reactions seem to offer a natural enhancement factor for any in-medium changes.

The CERES data [21] indeed seem to confirm this expectation. The present situation is independent of the special model used for the description of the data – that agreement with the measured dilepton mass spectrum in the mass range between about 300 and 700 MeV for the 200 A GeV $S + Au$ and $S + W$ reactions can only be obtained if $\rho$-meson strength is shifted downwards (for a more detailed discussion see [20, 22]) (for the recently measured 158 A GeV $Pb + Au$ reaction the situation is not so clear; here the calculations employing ‘free’ hadron properties lie at the lower end of the experimental error bars [20]).

However, all the predictions are based on equilibrium models in which the properties of a $\rho$ meson embedded in nuclear matter with infinite space-time extensions are calculated. An ultrarelativistic heavy-ion collision is certainly far away from this idealized scenario. In addition, heavy-ion collisions necessarily average over the polarization degrees of freedom.

The two physically quite different scenarios, broadening the spectral function or shifting simply the $\rho$ meson mass downwards while keeping its free width, thus lead to indistinguishable observable consequences in such collisions. This can be understood by observing that even in an ultrarelativistic heavy-ion collision, in which very high baryonic densities are reached, a large part of the observed dileptons is actually produced at rather low densities (see Fig. 3 in [20]).

4 $\pi + A$ Reactions

Motivated by this observation we have performed calculations of the dilepton invariant mass spectra in $\pi^-$ induced reactions on nuclei [24]; the experimental study of such reactions will be possible in the near future at GSI. The calculations are based on a semiclassical transport theory, the so-called Coupled Channel BUU method (for details see [25]) in which the nucleons, their resonances up to 2 GeV mass and the relevant mesons are propagated from the initial contact of projectile and target until the final stage of the collision. This method allows one to describe strongly-coupled, inclusive processes without any a-priori assumption on the equilibrium or preequilibrium nature of the process.

In these reactions the dominant emission channels are the same as in ultrarelativistic heavy-ion collisions; this can be seen in Fig. 2 where I show the results for the dilepton spectra produced by bombarding Pb nuclei with 1.3 GeV pions.

In the top picture in Fig. 2 I show the results of a calculation that assumes free hadronic properties for all radiation sources. The middle picture shows the results of a calculation with lowered in medium masses plus collisional broadening of the vector mesons, calculated dynamically according to [11], and the bottom figure shows the results of a calculation employing the $\rho$ spectral function calculated in the resonance-hole model discussed above [16]. In the lower 2 pictures the most relevant change takes place for the $\rho$, which is significantly widened, and the $\omega$, which develops a shoulder on its low mass tail. The latter is primarily due to the nuclear
Figure 2: Invariant mass yield of dileptons produced in pion-induced reactions at 1.3 GeV on various nuclei. The topmost part shows results of calculations employing free hadron properties, the results shown in the middle part are based on simple mass-shifts, and the curves in the lowest part show results of a calculation using the spectral function from [16] for the $\rho$ meson and a mass-shift and collisional broadening for the $\omega$ meson (from [24]).
density profile: ω’s are produced at various densities from ρ₀ down to 0.

The dilepton yield in the range of about 600 - 700 MeV is increased by the in-medium effects by up to a factor of 2.5, comparable to the ultrarelativistic heavy-ion collisions discussed above. In particular the ω shoulder should clearly be visible.

5 Photonuclear Reactions

Pion induced reactions have the disadvantage that the projectile already experiences strong initial state interactions so that many produced vector mesons are located in the surface where the densities are low. A projectile that is free of this undesirable behavior is the photon.

In addition, the calculated strong differences in the in-medium properties of longitudinal and transverse vector mesons can probably only be verified in photon (real or virtual) induced reactions, where the incoming polarization can be controlled. Another approach would be to measure the coherent photoproduction of vector mesons; here the first calculation available so far[17] shows a distinct difference in the production cross sections of transverse and longitudinal vector mesons.

5.1 Dilepton Production

We have therefore – also in view of a corresponding proposal for such an experiment at CEBAF[26] – performed calculations for the dilepton yield expected from γ + A collisions. In these calculations we have used the same transport-theoretical method as above for the pion-induced dilepton emission, but now employ a better description of the population of broad resonances[27].

Results of these calculations are shown in Fig. 3. In the top figure the various sources of dilepton radiation are shown. The dominant sources are again the same as those in pion- and heavy-ion induced reactions, but the (uncertain) πN bremsstrahlung does not contribute in this reaction. The middle part of this figure shows both the Bethe-Heitler (BH) contribution and the contribution from all the hadronic sources. In the lowest (dot-dashed) curve we have chosen a cut on the product of the four-momenta of incoming photon (k) and lepton (p) in order to suppress the BH contribution. It is seen that even without BH subtraction the vector meson signal surpasses that of the BH process.

The lowest figure, finally, shows the expected in-medium effects[2]: the sensitivity in the region between about 300 and 700 MeV amounts to a factor of about 3 and is thus in the same order of magnitude as in the ultrarelativistic heavy-ion collisions.

5.2 Photoabsorption

Earlier in this paper I have discussed that a strong change of the ρ meson properties comes about because of its coupling to N∗h excitations and that this coupling – through a higher-order effect – in particular leads to a very strong increase of the ρ decay width of the N(1520) D_{13} resonance.
Figure 3: Invariant mass spectra of dileptons produced in $\gamma + ^{208}Pb$ reactions at 2.2 GeV. The top figure shows the various radiation sources, the middle figure the total yield from the top together with the Bethe-Heitler contributions, and the bottom part shows the expected in-medium effects (from [27]).
Figure 4: Photoabsorption cross section in the second resonance region. Shown are the data from ref. [28], the free absorption cross section on the proton, a Breit-Wigner fit with a total width of 300 MeV (dashed curve) and the result of a transport-theoretical calculation [29] with a medium broadened $\rho$ decay width of the $N(1520)$ (solid curve).

This increase may provide a reason for the observed disappearance of the higher nucleon resonances in the photoabsorption cross sections on nuclei [28]. The disappearance in the third region is a consequence of the Fermi-motion. The disappearance of the second resonance region, i.e. in particular of the $N(1520)$ resonance, however, presents an interesting problem; it is obviously a typical in-medium effect.

First explanations [4] assumed a very strong collisional broadening, but in ref. [29] it has been shown that this broadening is not strong enough to explain the observed disappearance of the $D_{13}$ resonance. Since at the energy around 1500 MeV also the $2\pi$ channel opens it is natural to look for a possible connection with the $\rho$ properties in medium. Fig. 4 shows the results of such an analysis (see also [17]). It is clear that the opening of the phase space for $\rho$ decay of this resonance provides enough broadening to explain its disappearance. The talk by N. Bianchi at this conference [30] covers this topic in much more detail.

6 Rho-meson properties at higher energies

The calculations of spectral functions of $\rho$-meson properties in medium so far have focussed on properties of rather slow mesons. However, the relations [3] can be used to obtain some information on the in-medium changes to be expected, because the cross sections entering here contain all the possible couplings.
A first attempt in this direction was made by Eletsky and Ioffe [3] who obtained a positive mass shift for $\rho$ mesons with momenta in the GeV region. This analysis has been linked to the low-energy behavior by including all the relevant nucleon resonances with $\rho$ meson decay branches by Kondratyuk et al. [31]. These authors find indeed that at momenta of about 100 MeV/c the mass shift according to (2) turns from negative to positive; the width stays remarkably constant as a function of $\rho$ momentum at a value of about 250 MeV, corresponding to a collisional broadening width $\delta \Gamma \approx 100$ MeV (see Fig. 5).

This number allows an easy estimate for the onset of shadowing in high-energy photon-induced particle production experiments. For example, in high-energy vector meson production [32] a crucial scale is given by the so-called coherence length

$$l_c = \frac{2\nu}{M_v^2 + Q^2}$$

(12)

where $Q$ is the four-momentum transfer, $\nu$ the energy transfer and $M_v$ the vector meson mass. This length gives a measure for the distance over which the photon appears as a rho meson. An obvious condition for the onset of shadowing is then $l_c \geq \lambda_{\rho}$, where $\lambda_{\rho}$ is the mean free path of the $\rho$ meson in nuclear matter. The value of $\delta \Gamma_{\rho}$ of about 100 MeV calculated in ref. [31] translates into a value of $\lambda_{\rho}$ of about 2 fm at high momenta. Using this value in yields for the ‘shadowing threshold’

$$\frac{2\nu}{M_v^2 + Q^2} \geq 2 \text{fm}.$$  

(13)

For example, at an energy transfer of 10 GeV, corresponding to the Hermes regime, we obtain as condition for the shadowing regime

$$Q^2 \leq 1.5 \text{GeV}^2.$$  

(14)
Increasing $Q^2$ (at fixed $\nu$) beyond this value yields a larger transparency of the photon. This effect, which also shows up in the calculations of Kopeliovich and Huefner\cite{33}, must clearly be taken into account in experiments of this sort searching for color transparency; for further discussions of this exciting topic I refer to the talk of T. O'Neill at this conference\cite{32}.

7 Summary

In this talk I have concentrated on a discussion of the in-medium properties of the vector mesons. I have shown that the scattering amplitudes of these mesons on nucleons determine their in-medium spectral functions, at least in lowest order in the nuclear density. The dilepton channel can give information on the properties of the $\rho$ and $\omega$ deep inside nuclear matter whereas the $\pi$ decay channels – because of their strong final state interactions – can give only information about the vector mesons in the low-density region.

The original QCD sum rule predictions of a lowered vector meson mass have turned out to be too naive, because they were based on the assumption of a sharp resonance state. In contrast, all specific hadronic models yield very broad spectral functions for the $\rho$ meson with a distinctly different behavior of longitudinal and transverse $\rho$'s. Recent QCD sum rule analyses indeed do not predict a lowering of the mass, but only yield – rather wide – constraints on the mass and width of the vector mesons.

I have also discussed that hadronic models that include the coupling of the $\rho$ meson to nucleon resonances and a corresponding shift of vector meson strength to lower masses give a natural backreaction on the width of these resonances. In particular, the $N(1520)D_{13}$ resonance is significantly broadened because of its very large coupling constant to the $\rho N$ channel. Since the $\rho$ decay of this resonance is deduced only from a partial wave analysis of $2\pi$ production\cite{34}, it would be very essential to have new, better data (and a new analysis of these) for this channel.

A large part of the unexpected surplus of dileptons produced in ultrarelativistic heavy-ion collisions can presently be reproduced only by including a shift of $\rho$ strength to lower masses. However, heavy-ion reactions are quite insensitive to details of in-medium changes.

Motivated by this observation I have then discussed predictions for experiments using pion and photon beams as incoming particles. In both cases the in-medium sensitivity of the dilepton mass spectra is comparable to that in heavy-ion experiments. In addition, such experiments take place much closer to equilibrium, an assumption on which all predictions of in-medium properties are based. Furthermore, only in such experiments it will be possible to look for polarization effects. I have also discussed the intriguing suggestion that the observed disappearance of the second resonance region in the photoabsorption cross section is due to the broadening of the $N(1520)$ resonance caused by the shift of $\rho$ strength to lower masses.

At high energies, finally, the in-medium broadening of the $\rho$ leads to a mean free path of about 2 fm in nuclear matter. Shadowing will thus only be essential if the coherence length is larger than this mean free path.
Increasing the four-momentum transfer $Q^2$ at fixed energy transfer $\nu$ leads to smaller coherence length and thus leads to a larger transparency. This effect is essential to verify experimentally; it is superimposed on the color-transparency effect that is still being looked for.

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