Medium Modifications of Mesons in Elementary Reactions and Heavy-Ion Collisions

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Abstract

Experimental searches for modifications of vector mesons in the nuclear medium are reviewed. Data on $\rho$, $\omega$ and $\Phi$ mesons are presented. The results have been obtained in elementary reactions with proton and photon beams as well as in heavy-ion collisions. Compared to the free particle properties, the $\omega$ and $\Phi$ meson are found to drop in mass at normal nuclear matter density by 9-14% and 3.5% whereas their widths are reported to increase by factors of about 16 and 3.6, respectively. For the $\rho$ meson, conflicting results on in-medium mass shifts and broadening have been published. The experimental data are compared to recent model calculations.

Keywords: meson production, in-medium modifications

1 Introduction

Widespread experimental searches for changes of hadron properties in a nuclear environment were motivated by theoretical studies in the 80’s and early 90’s [1, 2, 3, 4], predicting a close connection between in-medium modifications and chiral symmetry restoration in hot and/or dense matter. Subsequent investigations revealed that the link between nuclear properties and QCD symmetries was not as direct as originally envisaged. A connection between hadronic spectral functions and QCD condensates is, however, provided by QCD sum rules which relate the integral over hadronic spectral functions to $< \bar{q}q >$ and higher order condensates. Changes of condensates with temperature and density associated with a partial restoration of chiral symmetry only constrain corresponding in-medium modifications of hadronic spectral functions [5, 6, 7, 8]; hadronic models are still needed for specific predictions of hadronic properties in the medium.

2 Theoretical predictions

Many theory groups have developed different hadronic models to study the in-medium behaviour of hadrons. Some recent results of model calculations are summarized in Figs. [1, 2, 3]

In the QMC model a lowering of the $\omega$ mass by about 15% is expected at normal nuclear matter density [9]. The sensitivity of the $\omega$ mass to the density dependence of some 4-quark condensate has been studied by Zschocke et al. [10]. Not only mass centroids but mass distributions have been calculated: Klingl et al. [11] find a pronounced shift and broadening of the $\omega$ mass in the nuclear
medium. Structures in spectral functions arising from the coupling of the respective meson to baryon resonances have been predicted for $\rho$ and $\omega$ mesons by Lutz et al. [12], Peters et al. [13] and Mühlisch and Mosel [14]. It should be noted that - as shown in Fig. 2 - these structures fade out for meson momenta above several 100 MeV/c with respect to the nuclear medium. In order to be sensitive to such structures in the experiment detector systems with sufficient acceptance for low momentum mesons have to be provided.

The variety of theoretical predictions calls for an experimental clarification. Only recently, experiments have advanced to an accuracy which allows to distinguish between different model predictions. Corresponding experiments are described in the subsequent sections.

3 Experimental approaches

Experimentally, the predicted in-medium phenomena can be studied by measuring the mass distribution of hadrons which are so shortlived that they decay within the nuclear environment, i.e. in the atomic nucleus or in the collision zone of a heavy-ion reaction, after being produced in some nuclear reaction. Information on the in-medium mass $m$ of hadron $H$ can be deduced from the 4-momentum vectors $p_1, p_2$ of the decay products $X_1, X_2$ for different 3-momenta $\vec{p}$ of the hadron with respect the nuclear medium. In general, the mass depends on the baryon density $\rho$ and temperature $T$ of the medium:

$$m(\vec{p}, \rho, T) = \sqrt{(p_1 + p_2)^2}$$

(1)

Lepton pairs are the preferred decay channel because they escape even a compressed collision zone of a heavy-ion reaction without strong final state interactions which would otherwise distort the 4-momentum vectors and thus the determination of the invariant mass. The disadvantage of this decay mode is the very small branching ratio of the order of $10^{-5} - 10^{-4}$ which makes these measurements very difficult and sensitive to the background subtraction.

As pointed out by U. Mosel et al. [15], the experimentally determined invariant mass distribution (eq. 1) does, however, not directly provide the spectral function of the meson but rather represents a
Figure 2: Left: Modification of the $\rho$ spectral function with $\rho$ momentum at normal nuclear matter density [13]. Right: The $\omega$ spectral function in vacuum and at normal nuclear matter density [11].

Figure 3: Spectral functions at zero, normal, and twice normal nuclear matter density for the $\rho$ and $\omega$ meson [12] (left) and for the $\omega$ meson [14] (right). The structures at lower masses arise from the coupling of the $\rho$ and $\omega$ meson to nucleon resonances.

The convolution of this spectral function $A(m)$ with the partial decay width $\Gamma_{H\to X_1,X_2}(m)$ into the channel being studied:

$$\frac{d\sigma_{H\to X_1,X_2}}{dm} \sim A(m) \cdot \frac{\Gamma_{H\to X_1,X_2}(m)}{\Gamma_{tot}(m)}$$

Since $\Gamma_{H\to X_1,X_2}(m)$ depends itself on the invariant mass $m$ this may lead to deviations of the experimentally determined mass distribution from the true spectral function, in particular for broad resonance states.

Medium modifications have been investigated experimentally both in elementary reactions and heavy-ion collisions. Both approaches have advantages and disadvantages. Any signal from heavy-ion reactions represents an integration over the full space-time evolution of the collision, involving strong variations in densities and temperatures. On the other hand, a regeneration of mesons in the collision zone helps to enhance the in-medium effects. In elementary reactions on nuclei there is no time dependence of the density and temperature which makes the theoretical analysis of the results much easier. Because of the lower densities probed in these reactions medium effects may, however, be less pronounced.
3.1 Medium modifications studied in elementary reactions

Proton as well as photon induced reactions have been studied to search for medium modifications of mesons in elementary processes. In-medium properties of the $\rho$ meson have been deduced from two experiments at Jlab [16] and KEK [17], irradiating various targets with photon beams of $E_\gamma = 0.6 - 3.8$ GeV and 12 GeV proton beams, respectively. The $e^+e^-$ invariant mass spectra resulting after subtraction of the combinatorial background are shown in Fig. 4. Despite of the similarity of both spectra both groups come to conflicting conclusions: while the Jlab experiment [16] reports no mass shift and a small in-medium broadening Naruki et al. [17] claim a drop of the $\rho$ meson mass by 9% and no in-medium broadening. This discrepancy is most likely due to differences in treating the combinatorial background and to details of the fitting procedures. In particular, it appears important to normalize the combinatorial background from mixed events at low invariant $e^+e^-$ masses to that determined on an absolute scale from like sign pairs. It should be noted that both experiments have acceptance only for mesons with 3-momenta above 0.5-0.8 GeV/c and are thus not sensitive to possible in-medium modifications as predicted in Fig. 3 which are expected at momenta less than 500 MeV/c.

The KEK experiment has also investigated possible in-medium modifications of the $\Phi$ meson (see Fig. 5) [18]. A significant excess on the low-mass side of the $\Phi$ meson peak is observed for slow $\Phi$ mesons ($\beta \cdot \gamma < 1.25$) which have a higher probability to decay in the Cu nucleus than fast $\Phi$ mesons. From an analysis of the structure in the spectrum Muto et al. [18] extract a drop of the $\Phi$ mass by 3.4% and an increase of the $\Phi$ width by a factor 3.6 at normal nuclear matter density $\rho_0$.

The $\omega$ meson in the medium has been studied at much lower momenta ($< 500$ MeV/c) in a photoproduction experiment [19] at ELSA. Here, the decay mode $\omega \to \pi^0\gamma$ has been investigated which has a much higher branching ratio of 9%. Another advantage of this decay mode is the insensitivity to possible in-medium modifications of the $\rho$ meson ($\rho \to \pi^0\gamma : 7 \cdot 10^{-4}$). A serious disadvantage, however, are possible strong final state interactions of the $\pi^0$ meson within the nucleus which may distort the extracted invariant mass distribution. Detailed Monte Carlo simulations [20] show that this effect is small in the mass range of interest ($600 \text{ MeV}/c^2 < m_{\pi^0\gamma} < 800 \text{MeV}/c^2$) and can even be further reduced by appropriate cuts.

The best way to identify possible in-medium modifications is to compare $\omega$ photoproduction on nuclei with a corresponding measurement on the proton which serves as reference. From the subgroup

![Figure 4: $e^+e^-$ invariant mass spectra after background subtraction obtained (left) in photonuclear reactions ($E_\gamma = 0.6 - 3.8$ GeV) [16] and (right) in 12 GeV proton induced reactions [17].](image-url)
of 3 γ events Trnka et al. \cite{18} deduced π⁰γ invariant mass spectra. After fitting and subtracting the background the comparison of the corresponding invariant mass spectra for Nb and LH₂ targets exhibited a shoulder on the low mass side of the ω signal on the nuclear target. This was taken as evidence for an ω in-medium mass shift by 60±10−35 MeV at an average nuclear density of 0.6 ρ₀. An extrapolation to normal nuclear density leads to a drop in the ω mass by about 14%.

The shape of the ω signal is sensitive to the way the background is treated. In \cite{19} the background was fitted with an arbitrary function. In a more rigorous treatment one could try to reproduce the background by summing up all possible sources which can contribute to the π⁰γ channel due to limited acceptances and/or particle misidentification. Another possibility is to determine the background with the mixed-event technique as used in the lepton pair experiments. This approach has been chosen for the analysis of new data taken on a carbon target. Fig. 5 shows the π⁰γ invariant mass spectrum together with the uncorrelated π⁰γ background obtained by event-mixing \cite{21}. Here, the invariant mass is calculated by combining a π⁰ from one event with a photon from another event. The mixed-event background describes the experimental data over an invariant mass range of about 400 MeV/c² with an accuracy of better than 5%. This is demonstrated in Fig. 6 (right) which shows the ratio of the data
to the mixed event background on a linear scale.

Figure 7: $\pi^0\gamma$ invariant mass distribution near the $\omega$ mass after subtracting the mixed event background of Fig. 6. For comparison the line shape from the corresponding measurement on the LH$_2$ target (histogram) and from a simulation (curve) are shown.

Subtracting this combinatorial background leads to the $\omega$ signal shown in Fig. 7 which again exhibits a shoulder on the low mass side in comparison to the $\omega$ signal measured on the liquid hydrogen target and to a simulation of the free $\omega$ signal, including the experimental resolution. Thereby, the observation of an in-medium lowering of the $\omega$ meson [19] is confirmed. To quantify the effect, the $\omega$ signal has to be decomposed into an in-medium decay and an in-vacuum decay contribution. The lineshape of the in-vacuum decay component is known from the measurement on the LH$_2$ target, the in-medium decay distribution is taken from BUU simulations [22]. A best fit to the signal is obtained by assuming a drop of the $\omega$ mass by 14% at normal nuclear matter density in accordance with [19].

Because of the sensitivity of the $\omega$ signal to the background treatment an approach [23, 24] to assume the background on the nuclear target to be the same as for the LH$_2$ target can only lead to wrong conclusions. The experimental data clearly show that the background distributions for the LH$_2$ and nuclear targets are different. This becomes evident when one compares the background distributions over a wider mass range than the limited one considered in [23, 24].

Due to the detector resolution and uncertainties in the decomposition of the $\omega$ signal in an in-medium and in-vacuum decay contribution it is difficult to extract an in-medium $\omega$ width from the above experiment. An access to the in-medium width of the $\omega$ is provided by measuring the transparency ratio $T$ [24, 25]

$$T = \frac{\sigma \gamma A - \omega X}{A \cdot \sigma \gamma N - \omega X},$$

i.e. the ratio of the $\omega$ production cross section on a nucleus divided by the number of nucleons A times the $\omega$ production cross section on a free nucleon. As the $\omega$ photoproduction cross section on the neutron is not yet known the transparency ratio is here normalized to carbon. If nuclei were completely transparent to $\omega$ mesons, the transparency ratio would be $T=1$. Consequently, $T$ is a measure for the loss of $\omega$ flux via inelastic processes in nuclei and can be determined in attenuation experiments on nuclei of different mass A. Within the low density approximation the $\omega A$ absorption cross section $\sigma$ is related to the inelastic $\omega$ width by $\Gamma_\omega = h \rho v \sigma$. A comparison of preliminary data from the CBELSA/TAPS collaboration [26] with calculations of the Valencia [24] and Giessen [25] theory groups (s. Fig 8) yields an in-medium $\omega$ width in the nuclear reference frame of about 130-150 MeV at normal nuclear matter density and at an average $\omega$ momentum of 1100 MeV/c. This implies an in-medium broadening of the
\( \omega \) meson by a factor \( \approx 16 \). Assuming the momentum dependence of the \( \omega \) width given in [25] this value corresponds to a total width of the \( \omega \) meson at rest in the medium of about 70 MeV.

### 3.2 Medium modifications studied in heavy-ion collisions

The dropping \( \rho \) mass scenario initially proposed in [1, 3, 4] was a prime motivation for the CERES collaboration to study e\(^+\)e\(^-\) pair emission in ultra-relativistic nucleus-nucleus collisions. An excess in
Table 1: Compilation of experimental results on the in-medium mass and width of the $\rho$, $\omega$, and $\Phi$ meson, measured in different experiments. The production reaction and the momentum acceptance of the respective detector system are given.

| reaction | KEK | Jlab | CBELSA/TAPS | CERES | NA60 |
|----------|-----|------|-------------|-------|------|
| momentum | $p > 0.5$ GeV/c | $p > 0.8$ GeV/c | $p > 0.0$ GeV/c | $p_t > 0.0$ GeV/c | $p_t > 0.0$ GeV/c |
| acceptance | $p > 0.5$ GeV/c | $p > 0.8$ GeV/c | $p > 0.0$ GeV/c | $p_t > 0.0$ GeV/c | $p_t > 0.0$ GeV/c |
| $\rho$ | $\Delta m/m = -9\%$ | $\Delta m \approx 0$ | broadening | $\Gamma_{\omega(\rho)} \approx 16$ | 
| | no | some broadening | | | |
| $\omega$ | broadening | $\Delta m \approx -14\%$ | broadening | $\Gamma_{\omega(\rho)} \approx 16$ | 
| $\Phi$ | $\Delta m/m = -3.4\%$ | $\Gamma_{\Phi(\rho)} \approx 3.6$ | broadening | $\Gamma_{\omega(\rho)} \approx 16$ | 

the dilepton yield above expectations from post-freeze-out leptonic decays of hadrons was observed \[27\] and attributed to $\pi^+\pi^- \rightarrow \rho \rightarrow e^+e^-$ annihilation via an intermediate $\rho$. The dilepton excess is, however, smeared out over a much wider mass range than expected for the dropping $\rho$ mass scenario \[3\]. Adamova et al. \[28\] come to the conclusion that a broadening of the $\rho$ spectral function has to be favoured over a density dependent downward shift in mass.

A breakthrough with regard to statistics and resolution in dilepton spectroscopy of nucleus-nucleus collisions has been achieved by the NA60 collaboration \[29, 30\] who studied the $\mu^+\mu^-$ decay channel in the In+In reaction at 158 AGeV. Fig. 9 shows the $\mu^+\mu^-$ invariant mass spectrum after subtracting the combinatorial background. Peaks from the $\omega$ and $\Phi$ decays are easily identified. The quality of the data allowed to subtract the measured post-freeze-out dilepton cocktail separately for different centrality bins. The remaining di-muon invariant mass spectrum is attributed mainly to the $\rho \rightarrow \mu^+\mu^-$ decay. Fig. 9 (right) indicates a strong in-medium broadening but no mass shift of the $\rho$ meson. S. Damjanovic et al. \[30\] conclude that the dropping mass scenario \[3\] is incompatible with the experimental data.

4 Conclusion

The results on medium modifications of mesons reported in the previous sections are summarized in table 1. Dropping masses associated with a sizable broadening are found for the $\omega$ and $\Phi$ meson. For the $\rho$ meson, conflicting results are reported which need to be further clarified. Medium effects in nucleus-nucleus collisions at SPS energies rule out \[30\] or at least disfavour \[28\] a universal downscaling of hadron masses in the nuclear medium. When comparing the experimental results it should be noted that some detector systems have no or little acceptance for low meson momenta for which strong medium modifications are expected. The observed differences in the in-medium behaviour of $\rho$, $\omega$, and $\Phi$ mesons may be attributed to their different coupling to the nuclear medium because of their isovector and isoscalar nature, respectively.

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