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Vector mesons in strongly interacting matter

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Abstract. Properties of hadrons in strongly interacting matter provide a link between quantum chromodynamics in the strong coupling regime and experimental observables. QCD sum rules show that changes in chiral and higher-order condensates, partially associated with a restoration of chiral symmetry in the nuclear medium, will lead to significant changes in the low-energy spectrum of hadrons. Heavy-ion collisions and reactions with elementary probes have been used to extract experimental information on in-medium properties of hadrons. Results on the light vector mesons ρ, ω, and ϕ, are summarized and compared. Almost all experiments report a softening of the spectral functions with increases in width depending on the density and temperature of the hadronic environment. No evidence for mass shifts is found in majority of the experiments. Remaining inconsistencies among experimental results demonstrate the need for further measurements with higher statistics and inrceased acceptance in particular for low-momentum vector mesons.

Keywords. Hadrons; in-medium properties.

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1. Introduction

The properties of hadrons in a strongly interacting environment are a longstanding issue in hadron and heavy-ion physics. The interest in this field is motivated by a possible restoration of chiral symmetry in a nuclear medium. Chiral symmetry is one of the fundamental symmetries of quantum chromodynamics (QCD) – the underlying theory of the strong interactions – in the limit of vanishing quark masses. This symmetry implies that left- (right-) handed quarks stay left- (right-) handed when they interact with each other via gluon exchange. In the non-perturbative domain of QCD where the coupling strength parameter α_s becomes large, other degrees of freedom, baryons and mesons, become relevant. If chiral symmetry were to hold also in the hadronic sector chiral partners, hadronic states – with the same spin but opposite parity – would be expected to be degenerate in mass. Figure 1 shows that this is not observed experimentally and that chiral symmetry is obviously broken in the hadronic sector. Mass splittings of several hundred MeV are found which are almost of the same oder of magnitude as the masses themselves.

Several theoretical papers discuss the idea that chiral symmetry may at least be partially restored in a nuclear medium [1–4]. As a consequence, one would expect

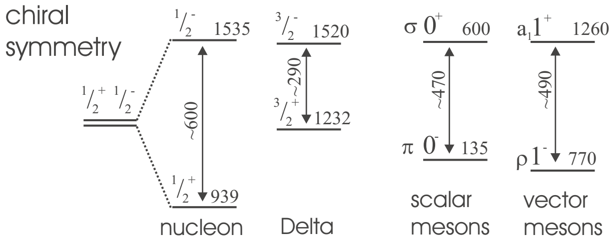

Figure 1. Mass splittings between chiral partners in the baryon and meson sector [6].

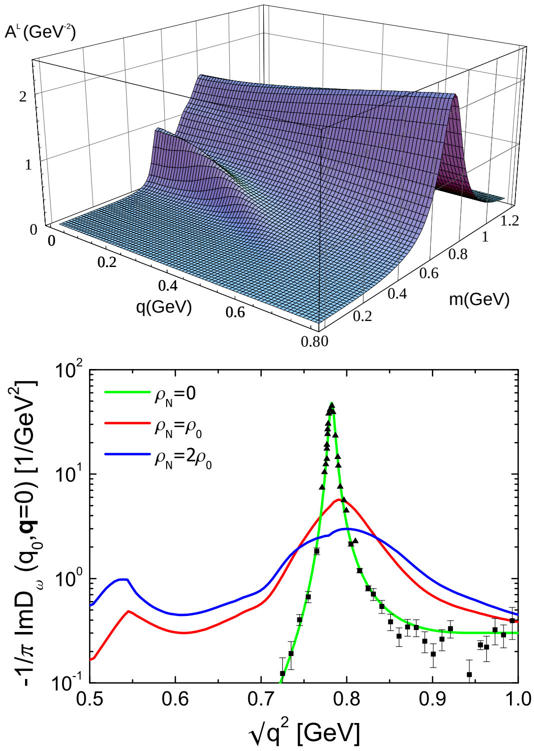

Figure 2. Top: Spectral function of the ρ-meson at normal nuclear matter density as a function of mass and momentum relative to the nuclear medium (from [10]). Bottom: The ω spectral function for an ω at rest in the nuclear medium. The data and the solid curve describe the spectral function of the free ω-meson. The other curves show the spectral function for normal density $\rho_0 = 0.16\ \mathrm{fm}^{-3}$ and $\rho = 2 \cdot \rho_0$, respectively (from [10]).

the mass splittings to decrease due to mass shifts or that the mass distributions of hadrons become softer in the nuclear medium and tend to overlap. These ideas have fostered widespread theoretical and experimental activities to identify and search for signals of in-medium modifications of hadrons. This field has recently been reviewed in [5].

2. Theoretical predictions

Studies of QCD sum rules [4,7,8] have shown that changes in chiral and higher-order condensates, partially associated with a restoration of chiral symmetry, will lead to significant changes in the low-energy spectrum of hadrons when embedded in a medium. It turns out, however, that QCD sum rules only provide valuable constraints on hadronic spectral functions but cannot predict their detailed shape. Hadronic models are needed, based on our current understanding of meson–baryon interactions, to calculate the in-medium self-energies of hadrons and their spectral functions. Corresponding calculations have been performed by many theory groups. As an example, results for the ρ- and ω-mesons are shown in figure 2. It is seen that spectral functions can have quite a complicated structure which cannot be parametrized by a Breit–Wigner function. The spectral function for a ρ-meson at rest in nuclear matter exhibits a distinct lower peak at about 500 MeV whereas the main strength is concentrated at around 800 MeV. This complicated structure results from the coupling of the ρ-meson to resonance-hole excitations of the nucleon. With increasing 3-momentum of the ρ-meson, the low mass structure fades out while the main peak remains at the free ρ-mass but is considerably broadened compared to the spectral function of the free ρ-meson. A similar but less pronounced side structure is also seen in the spectral function for the ω-meson at rest. Figure 2 illustrates that experiments searching for medium modifications will have to provide detector acceptances down to very small 3-momenta of the vector mesons.

3. Observability of in-medium effects

The theoretically predicted medium modifications can be studied experimentally by measuring the mass distributions of short-lived hadrons. The light vector mesons ρ, ω and ϕ are particularly suited for these investigations since their lifetimes of 1.3 fm/c, 23 fm/c and 46 fm/c, respectively, are so short that – after they are produced in some nuclear reaction – they will decay within the nuclear medium with some probability. The in-medium mass μ of the meson can then be deduced from the 4-momentum vectors p_1, p_2 of the decay products according to

$$\mu(\vec{p}, \rho, T) = \sqrt{(p_1 + p_2)^2}\,. \tag{1}$$

In general, the mass distribution $\mu(\vec{p}, \rho, T)$ depends on the 3-momentum $\vec{p}$ of the vector meson and on the density ρ and temperature T of the nuclear medium. This nuclear medium can either be an atomic nucleus irradiated with elementary probes like photons, pions or protons or the heated and compressed hadronic matter generated in a heavy-ion collision.

Leaving any nuclear medium without strong final-state interactions, dileptons are the optimum decay channel as they avoid any final-state distortion of the 4-momenta of the decay products entering eq. (1). Unfortunately, the branching ratios into the dilepton channels are only of the order of 10^{-5}–10^{-4}, making these measurements very difficult and sensitive to background subtraction.

It should be noted that according to eq. (2)

$$\frac{\mathrm{d}\sigma_{\gamma N \to N(p_1,p_2)}}{\mathrm{d}\mu} = \frac{\mathrm{d}\sigma_{\gamma N \to VN}}{\mathrm{d}\mu} \times \frac{\Gamma_{V \to p_1 + p_2}}{\Gamma_{\mathrm{tot}}}(\mu) \tag{2}$$

any measurement of a mass distribution does not give the hadronic spectral function directly but folded with the branching ratio $\Gamma_{V\to p_1+p_2}/\Gamma_{\mathrm{tot}}$ into the specific final channel one is investigating. Since the branching ratio may depend on μ, the unfolding is not trivial.

A further complication in extracting in-medium properties of a hadron arises from the observation that contributions to the meson signal are more suppressed if the nuclear density is higher. Parametrizing the spectral function $A(\mu)$ by a Breit–Wigner function, eq. (2) can be rewritten as

$$A(\mu)\,\frac{\Gamma_{V\to \mathrm{final\ state}}}{\Gamma_{\mathrm{tot}}} = \frac{\mu\,\Gamma_{\mathrm{tot}}}{(\mu^2 - m_V^2)^2 + \mu^2\Gamma_{\mathrm{tot}}^2}\,\frac{\Gamma_{V\to \mathrm{final\ state}}}{\Gamma_{\mathrm{tot}}}\ . \tag{3}$$

Here Γ_{tot} is the total width of the meson V, obtained as a sum of the vacuum decay width, Γ_{vac}, and an in-medium contribution Γ_{med}:

$$\Gamma_{\mathrm{tot}} = \Gamma_{\mathrm{vac}} + \Gamma_{\mathrm{med}} \tag{4}$$

with

$$\Gamma_{\mathrm{med}}(\rho(r)) = \Gamma_{\mathrm{med}}(\rho_0)\,\frac{\rho(r)}{\rho_0} \tag{5}$$

in the low-density approximation.

If the meson is strongly broadened in the nuclear medium due to inelastic reactions $\Gamma_{\mathrm{med}} \gg \Gamma_{\mathrm{vac}}$ as in the case of ω- and ϕ-mesons – see below – then $\Gamma_{\mathrm{tot}} \sim \rho$. This implies that both factors in (3) are proportional to $1/\rho$ leading to a suppression of contributions from high densities. The sensitivity of a meson production experiment is thereby shifted to the nuclear surface. In the case of a strong in-medium broadening of a meson, it is thus in principle difficult to detect in-medium modifications by an analysis of the signal shape since contributions from high densities are suppressed.

The suppression of higher-density contributions is less pronounced in heavy-ion collisions. In the fireball of the collision zone mesons are regenerated as the system approaches a thermal equilibrium. Then the number of dilepton decays of a vector meson is not determined by the lifetime of the meson – which is shortened by the in-medium broadening – but by the lifetime of the fireball, i.e. the factor $\Gamma_{V\to \mathrm{final\ state}}/\Gamma_{\mathrm{tot}}$ in (3) is to be replaced by $\Gamma_{V\to \mathrm{final\ state}} \times \tau_{\mathrm{fireball}}$, which is independent of the baryon density.

4. Experimental results

4.1 *In-medium properties of the ρ-meson*

Pioneering experiments on dilepton emission in heavy-ion reactions started in the late-1980s. First results indicating medium modifications of the ρ-meson were reported by the CERES Collaboration [11] who studied S + Au and Au + Au collisions at 158 A GeV at the CERN SPS. An enhanced e^+e^- yield in the mass range below the ϕ mass was observed which was attributed to the annihilation process $\pi^+\pi^- \rightarrow \rho \rightarrow e^+e^-$ and also to the formation and decays of baryon resonances like $\pi N \rightarrow N^*, \Delta, \Delta^* \rightarrow N\rho \rightarrow Ne^+e^-$. Since all these processes involve the ρ-meson, its in-medium properties at high densities and temperatures become accessible experimentally.

A breakthrough in statistics and resolution in dilepton spectroscopy of nucleus–nucleus collisions has been achieved by the NA60 Collaboration [12] who studied the $\mu^+\mu^-$ decay channel in the In + In reaction at 158 A GeV. As shown in figure 3, peaks from the ω and ϕ decays are cleanly resolved in the $\mu^+\mu^-$ invariant-mass spectrum after subtracting the combinatorial background. The mass distribution remaining after subtracting in addition to the contributions from the longer-lived η-, ω- and ϕ-mesons is attributed to the in-medium ρ. A monotonic broadening of this distribution is observed for increasing centrality of the collision. The $\mu^+\mu^-$ mass distribution for the most central collisions is compared in figure 3 with the spectral function of a free ρ-meson. A strong in-medium broadening of the ρ-meson is found while the centroid of the distribution remains at the nominal ρ mass of 770 MeV/c^2. This observation has been interpreted by the authors of [12] as a melting of the ρ-meson which is indicative of a restoration of chiral symmetry in the fireball of the collision zone which may be associated with the phase transition into the quark-gluon plasma.

The properties of ρ-mesons in the nuclei have also been investigated in reactions using photon and proton beams. Corresponding experiments have been performed at JLab and KEK, respectively. The CLAS Collaboration studied dilepton decays of vector mesons produced on a series of targets with tagged photon beams in the range of 0.6–3.8 GeV [13]. The resulting e^+e^- invariant mass spectra are shown in figure 4. After subtracting the combinatorial background and the contributions from the longer lived η-, ω- and ϕ-mesons – as in the NA60 analysis – the resulting

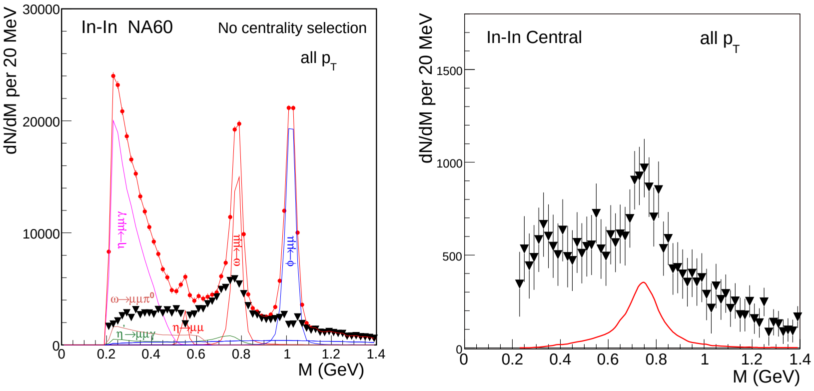

Figure 3. Left: Background-subtracted $\mu^+\mu^-$ invariant-mass spectrum before (dots) and after subtraction (triangles) of the known hadronic decay sources for In + In collisions at 158 A GeV. Right: $\mu^+\mu^-$ invariant-mass spectrum for central collisions in comparison to the spectral function of a free ρ-meson [12].

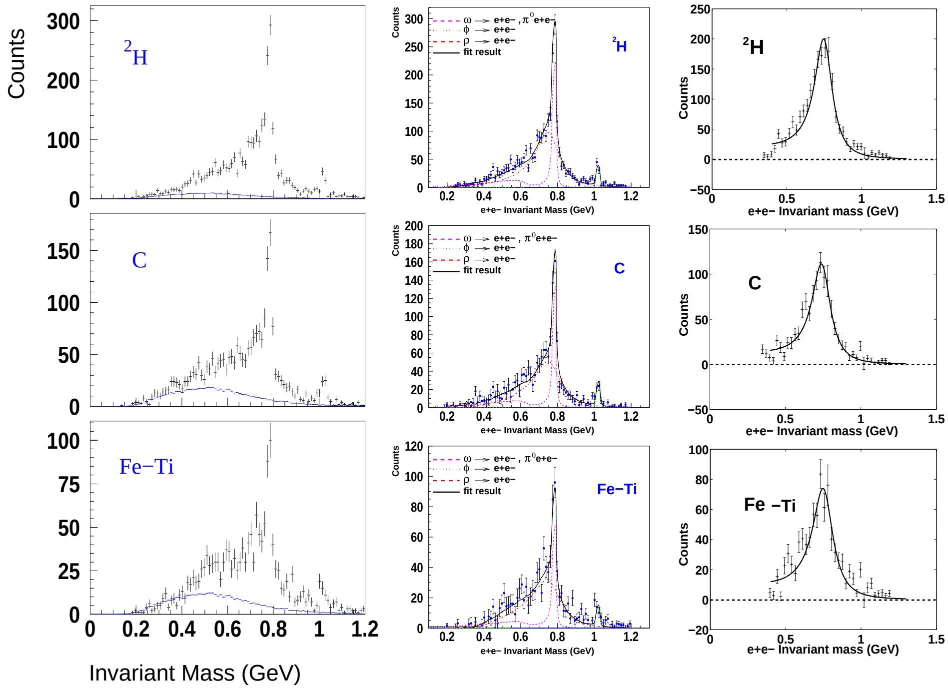

Figure 4. Left panels: e^+e^- spectra with combinatorial background normalized to like-sign pairs for different target nuclei. Middle panels: Same spectra after subtracting the combinatorial background, decomposed into contributions from different vector meson decays [13,14]. The curves are transport model calculations with the GiBUU code [15]. Right panels: Same spectra with contributions from ρ-mesons only.

ρ-mass distributions exhibit a broadening by about 70 MeV for medium size nuclei like Fe and Ni compared to the width of the free ρ-meson. The centroid of the distribution remains unchanged, i.e., a broadening without mass shift is observed. It should be noted, however, that this experiment is not sensitive to the medium modifications displayed in figure 2 because of the detector acceptance which is limited to ω momenta above about 800 MeV/c.

Opposite conclusions have been drawn from the KEK-E325 experiment [16]. Here, protons of 12 GeV were used for the production of vector mesons on different targets. The observed dilepton spectra for C and Cu are shown in figure 5 after fitting and subtracting the combinatorial background. Fits of the invariant mass distributions indicate a downward mass shift of the ρ- and ω-mesons by $\approx 9\%$ without any broadening. This result is surprising as hadrons in the medium have additional ‘decay’ options through inelastic channels and as a consequence their width is expected to increase in the nuclear environment. Future experiments will have to clarify this discrepancy.

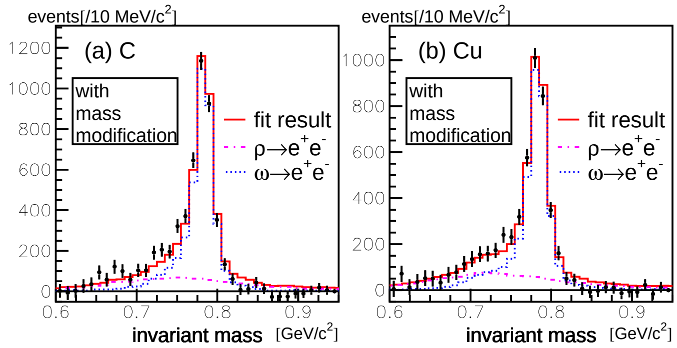

Figure 5. Invariant-mass spectra of e^+e^- pairs for the ρ, ω mass range after the subtraction of combinatorial background. The shapes of the $\rho \to e^+e^-$ (dash–dotted) and $\omega \to e^+e^-$ (dotted curve) contributions are fitted by the formula $m_V(\rho)/m_V(0) = 1 - k \cdot (\rho/\rho_0)$ with $k = 0.092$ [16].

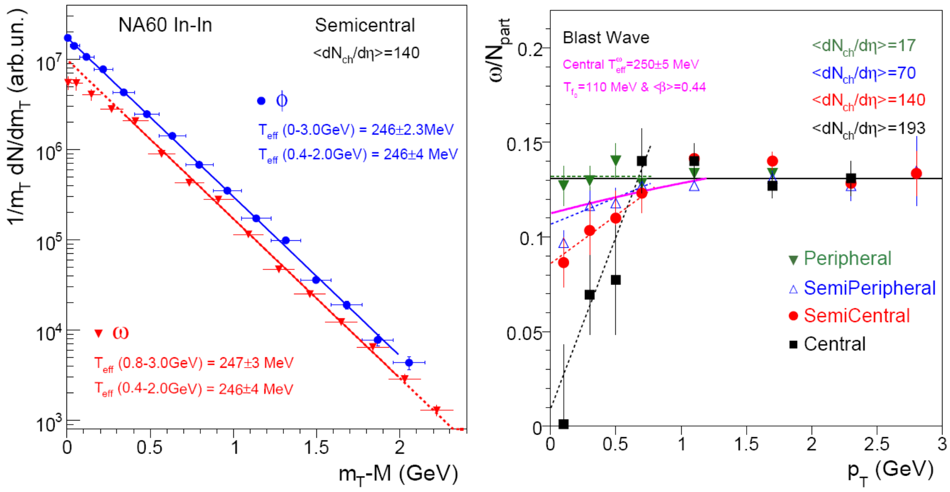

Figure 6. Left: Acceptance-corrected transverse kinetic energy spectra of the ω- and ϕ-mesons for semicentral In + In collisions at 158 A GeV. A depletion of the ω yield relative to the exponential fit is observed at low transverse masses. Right: p_T dependence of the ω yield relative to the fit line for different centralities, absolutely normalized for the full phase space. The solid curve for $p_T \leq 1$ GeV/c shows the result of a blast wave fit [17] to the ω for central collisions (from [18]).

4.2 *In-medium properties of the ω-meson*

In-medium properties of the ω-meson have also been studied both in heavy-ion collisions and reactions with elementary probes. A clean ω signal has been observed in the NA60 experiment (In + In at 158 A GeV) as shown in figure 3. Most of the

ω-mesons live longer than the fireball and upon decay they will then exhibit the spectral function of a free ω-meson. In-medium effects can only be expected for very low-energy ω-mesons. The transverse kinetic energy distributions $m_t - m = \sqrt{p_t^2 + m^2} - m$ for both ω- and ϕ-mesons are shown in figure 6, fitted with an exponential $1/m_t \cdot \mathrm{d}N/\mathrm{d}m_t = N_0 \cdot \exp(-m_t/T_{\mathrm{eff}})$. In contrast to the ϕ-meson a deviation from a straight exponential fall off is observed for the ω-meson at transverse energies below 0.5 GeV. This suppression indicates that slow ω-mesons may either be broadened or shifted in mass within the fireball. As illustrated in the right-hand side of figure 6, this effect increases with the centrality of the collision. For the most central collisions, the highest baryon densities and temperatures and therefore also the largest medium modifications are expected. The experiment can, however, not distinguish between a mass shift and a broadening scenario.

The KEK-E325 experiment has extracted information not only on in-medium properties of the ρ- but also of the ω-meson. Fitting the invariant mass spectrum of figure 5, Naruki *et al* [16] concluded that the ω-meson also droped in mass by 9% at normal nuclear matter density. A drop by 14% was initially claimed [19] by the CBELSA/TAPS Collaboration who searched for in-medium effects in the photoproduction of ω-mesons on various nuclei. Here, the $\omega \rightarrow \pi^0\gamma$ decay branch leading to a 3-photon final state was employed. This decay mode has a branching ratio of 9% which is about three orders of magnitude larger than the dilepton decay. A serious disadvantage of this exit channel, though, is a possible strong final-state interaction of the π^0-meson after the ω decay within the nuclear medium which may distort the extracted invariant mass distribution. This effect, however, is small in the mass range of interest (600 MeV/c$^2 \leq m_{\pi^0\gamma} \leq$ 800 MeV/c^2) [20] and can be further suppressed by removing low-energy pions with kinetic energies less than 150 MeV, typical of rescattered pions [21,22].

The background subtraction used in the analysis by Trnka *et al* [19] was criticized in [22]. A re-analysis of the data [23], applying a model-independent background determination in shape and absolute magnitude directly from the data, does not confirm the earlier claim of a mass shift [19]. It has been questioned [24,25] whether an experiment with incident photon energies up to 2.2 GeV is sensitive to medium modifications of the ω-meson because of the high fraction of ω decays outside the nuclear medium, despite a cut on low momentum ω-mesons: $p_\omega \leq 500$ MeV/c. A higher sensitivity to medium modifications is expected near the production threshold of $E_\gamma \approx 1100$ MeV [24,25]. A new measurement in this lower-energy regime has been performed with better statistics which will hopefully clarify the situation. At present, the experimental results are consistent with current theoretical predictions of no mass shift but some broadening.

An independent access to the in-medium width of the ω-meson is provided by attenuation measurements on nuclei with different mass number. In a nuclear medium, mesons can be removed by inelastic reactions with neighbouring hadrons, thereby the lifetimes of these mesons are shortened and their widths are increased. The in-medium width of mesons can be extracted from the transparency ratio [22,26]

$$T = \frac{\sigma_{\gamma A \rightarrow \omega X}}{A \cdot \sigma_{\gamma N \rightarrow \omega X}}. \tag{6}$$

This ratio compares the cross-section per nucleon for ω production on nuclei with the ω production cross-section on a free nucleon. The nucleus serves as a target and at the same time also as an absorber. If there were no ω absorption in the nuclei this ratio would be one. Since the ω photoproduction cross-section on the neutron is not yet known, here the transparency ratio is normalized to carbon. Within the low-density approximation, the ω absorption cross-section is related to the inelastic ω width by $\Gamma_\omega = \hbar c \beta \rho \sigma$. A comparison of CBELSA/TAPS data [27] with calculations of the Valencia [22] and Giessen [26] theory groups (figure 7) yields an in-medium ω width in the nuclear reference frame of about 130–150 MeV at normal nuclear matter density and at an average ω momentum of 1100 MeV/c. This implies an in-medium broadening of the ω-meson by a factor ≈16, i.e., the ω-meson in the nuclear medium is about as broad as the ρ-meson in free space.

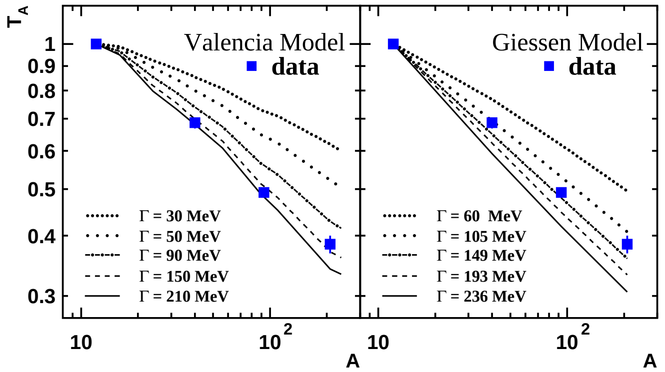

Figure 7. Experimentally determined transparency ratio for ω-mesons normalized to the carbon data in comparison with a Monte–Carlo calculation [22] (left) and a BUU transport calculation [26] (right). The widths are given in the nuclear rest frame [27].

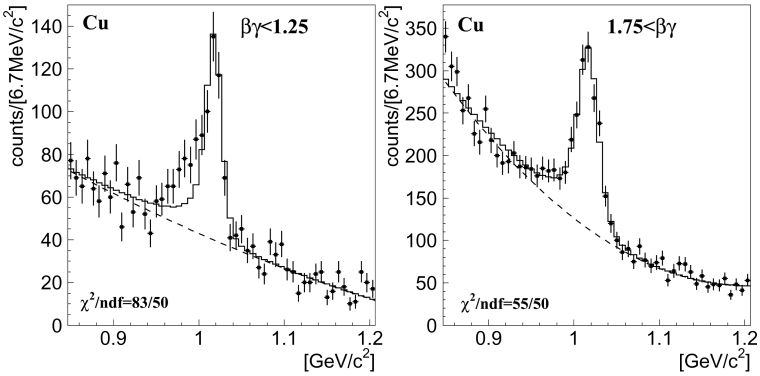

Figure 8. e^+e^- invariant mass distributions near the ϕ mass obtained in $p+\mathrm{Cu}$ for slow ($\beta\gamma \leq 1.25$) and fast ($\beta\gamma \geq 1.25$) recoiling ϕ-mesons. No difference in line shape is observed for the corresponding measurement on a C target [28].

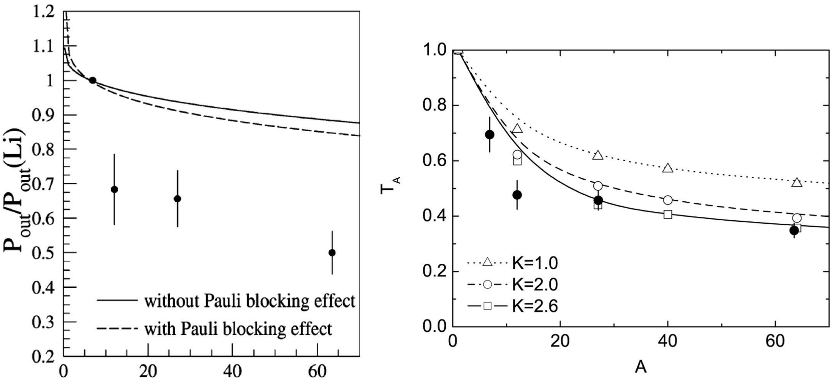

Figure 9. Left: Transparency ratio for ϕ-mesons as a function of mass, normalized to the Li data in comparison to a calculation [31] with (dashed curve) and without (solid curve) Pauli blocking [29]. Right: The same data (normalized to hydrogen) in comparison to a BUU calculations [32]. The K-factor indicates the increase in the ϕN cross-section needed to reproduce the experimentally determined transparency ratio.

4.3 *In-medium properties of the ϕ-meson*

In-medium modifications of the ϕ-meson have so far only been studied in reactions with elementary probes. In the KEK-E325 experiment, the production of ϕ-mesons in proton-induced reactions at 12 GeV on a heavy nucleus (Cu) and a light nucleus (C) have been compared [28]. As seen in figure 8, no difference in line shape is observed for ϕ-mesons recoiling with different velocities from the light C target. For the heavier Cu nucleus, a significant excess on the low-mass side of the ϕ-meson peak is observed for slow ϕ-mesons ($\beta \cdot \gamma < 1.25$) which have a higher probability to decay within the nucleus. Analysing the structure in the Cu spectrum, Muto *et al* [28] extracted a drop of the ϕ mass by 3.4% and an increase of the ϕ width by a factor 3.6 at normal nuclear matter density ρ_0.

The in-medium width of the ϕ-meson has also been deduced from a transparency ratio measurement [29]. At SPring8 the photoproduction of the ϕ-meson has been measured on a series of nuclei. The resulting transparency ratio – here normalized to Li – is shown in figure 9. A ϕN cross-section of ≈30 mb is needed to explain the observed attenuation [26,29,30]. A cross-section of 30 mb corresponds to an in-medium ϕ width of ≈70 MeV at normal nuclear matter density.

5. Summary

Table 1 summarizes the experimental results on medium modifications of vector mesons. Almost all experiments find a softening of the vector meson spectral functions. In experiments with photon beams, probing density $\rho \approx \rho_0/2 - \rho_0$, an increase in width of the order of 60–130 MeV is observed. Earlier claims of mass shifts have not been confirmed. At densities and temperatures reached in

Table 1. Experimental results on in-medium modifications of ρ-, ω- and ϕ-mesons.

Experiment	Momentum acceptance	ρ	ω	ϕ
KEK-E325 pA 12 GeV	$p > 0.6$ GeV/c	$\frac{\Delta m}{m} = -9\%$ $\Delta\Gamma \approx 0$	$\frac{\Delta m}{m} = -9\%$ $\Delta\Gamma \approx 0$	$\frac{\Delta m}{m} = -3.4\%$ $\frac{\Gamma_{\phi}(\rho_0)}{\Gamma_{\phi}} = 3.6$
CLAS γA 0.6–3.8 GeV	$p > 0.8$ GeV/c	$\Delta m \approx 0$ $\Delta\Gamma \approx 70$ MeV $(\rho \approx \rho_0/2)$		
CBELSA/ TAPS γA 0.9–2.2 GeV	$p > 0$ MeV/c		$\Delta m \approx ?$ $p_{\omega} < 0.5$ GeV/c $\Delta\Gamma(\rho_0) \approx 130$ MeV $\langle p_{\omega} \rangle = 1.1$ GeV/c	
SPring8 γA 1.5–2.4 GeV	$p > 1.0$ GeV/c			$\Delta\Gamma(\rho_0) \approx 70$ MeV $\langle p_{\phi} \rangle = 1.8$ GeV/c
CERES Pb + Au 158 A GeV	$p_{\mathrm{T}} > 0$ GeV/c	Broadening favoured over mass shift		
NA60 In + In 158 A GeV	$p_{\mathrm{T}} > 0$ GeV/c	$\Delta m \approx 0$ strong broadening		

heavy-ion collisions an even stronger broadening without mass shift is reported. Although a general picture is emerging that hadrons do change their properties in the nuclear medium, further high resolution experiments at e.g. CLAS, HADES, JPARC, CBELSA/TAPS and CB@MAMI will still be needed to obtain an overall consistent description of in-medium properties of the light vector mesons.

References

[1] R D Pisarski, *Phys. Lett.* **B110**, 155 (1982)
[2] V Bernard and U G Meissner, *Nucl. Phys.* **A489**, 647 (1988)
[3] G E Brown and M Rho, *Phys. Rev. Lett.* **66**, 2720 (1991)
[4] T Hatsuda and S H Lee, *Phys. Rev.* **C46**, 34 (1992)
[5] S Leupold, V Metag and U Mosel, arXiv:0907.2388
[6] V Metag, *Prog. Theo. Phys. Suppl.* **168**, 503 (2007)
[7] S Leupold, W Peters and U Mosel, *Nucl. Phys.* **A628**, 311 (1998)
[8] S Leupold, *Nucl. Phys.* **A743**, 283 (2004)
[9] W Peters *et al*, *Nucl. Phys.* **A632**, 109 (1998)
[10] P Mühlich *et al*, *Nucl. Phys.* **A780**, 187 (2006)
[11] G Agakichiev *et al*, *Phys. Rev. Lett.* **75**, 1272 (1995)

[12] R Arnaldi *et al*, *Phys. Rev. Lett.* **96**, 162302 (2006)
[13] R Nasseripour *et al*, *Phys. Rev. Lett.* **99**, 262302 (2007)
[14] M H Wood *et al*, *Phys. Rev.* **C78**, 015201 (2008)
[15] http://gibuu.physik.uni-giessen.de/GiBUU
[16] M Naruki *et al*, *Phys. Rev. Lett.* **96**, 092301 (2006)
[17] S Damjanovic *et al*, *J. Phys.* **G35**, 104036 (2008)
[18] S Damjanovic *et al*, *Eur. Phys. J.* **C49**, 235 (2007)
[19] D Trnka *et al*, *Phys. Rev. Lett.* **94**, 192303 (2005)
[20] J G Messchendorp *et al*, *Eur. Phys. J.* **A11**, 95 (2001)
[21] P Mühlich, T Falter and U Mosel, *Eur. Phys. J.* **A20**, 499 (2004)
[22] M Kaskulov, E Hernandez and E Oset, *Eur. Phys. J.* **A31**, 245 (2007)
[23] M Nanova, *Proc. Eur. Phys. Soc. Nucl. Phys. Conf.*, Bochum, 2009
[24] P Mühlich, Dissertation (Giessen University, 2007)
[25] K Gallmeister *et al*, *Prog. Part. Nucl. Phys.* **61**, 283 (2008)
[26] P Mühlich and U Mosel, *Nucl. Phys.* **A773**, 156 (2006)
[27] M Kotulla *et al*, *Phys. Rev. Lett.* **100**, 192302 (2008)
[28] R Muto *et al*, *Phys. Rev. Lett.* **98**, 042501 (2007)
[29] T Ishikawa *et al*, *Phys. Lett.* **B608**, 215 (2005)
[30] V K Magas, L Roca and E Oset, *Nucl. Phys.* **A755**, 495 (2005)
[31] D Cabrera *et al*, *Nucl. Phys.* **A733**, 130 (2004)
[32] P Mühlich and U Mosel, *Nucl. Phys.* **A765**, 188 (2006)