MENU 2007
11th International Conference
on Meson-Nucleon Physics and
the Structure of the Nucleon
September10-14, 2007
IKP, Forschungzentrum Jülich, Germany

HADRONS IN MEDIUM – THEORY MEETS EXPERIMENT

U. Mosel [1]
Institut für Theoretische Physik
Universität Giessen
Giessen, Germany, D-35392

Abstract

In this talk I give a short review of theoretical results on the properties of hadrons in cold, equilibrium nuclear matter. I then discuss the observable consequences of any changes of these properties inside the medium in actual experiments. I demonstrate that any experimental verification of in-medium effects requires a state-of-the-art treatment of the reaction dynamics and, in particular, also the final state interactions.

1 Introduction

The interest in in-medium properties of hadrons has been growing over the last decade because of a possible connection with broken symmetries of QCD and their partial restoration inside nuclear matter. Already two decades ago Bernard and Meissner predicted on the basis of the NJL model that the scalar strength should drop considerably inside nuclei whereas the vector mesons were only little affected in that approach [1]. Somewhat later there were theoretical predictions that masses of vector mesons should generally decrease in medium as a function of density due to a partial restoration of chiral symmetry [2,3]. In addition, there existed well-worked out predictions that the scalar 2π strength should decrease in medium and that the vector meson masses should drop [4,5]. All of these calculations were performed for idealized situations (infinite cold nuclear matter at rest) and little attention was paid to the actual observability of these predicted changes. At the same time experiments (CERES, TAPS) seemed to show the predicted behavior. The CERES results indicated a significant broadening of the ρ meson in medium [6], whereas the TAPS results on the 2π strength exhibited the predicted lowering of the σ strength inside nuclei [7]. Most recently, the

[1] mosel@physik.uni-giessen.de

CBELSA/TAPS experiment has also obtained an indication for a lowering of the ω meson mass in nuclei [8]. Other interesting data in this context have been obtained by groups at JLAB [9], KEK [10] and CERN [11].

Motivated by these developments we have concentrated our theoretical work on in-medium properties along two different lines. First, we have performed state-of-the-art calculations of vector meson spectral functions in cold nuclear matter. Second, we have followed closely the CBELSA/TAPS experiment and have performed various feasibility studies and analyses of this experiment searching for in-medium changes of the ω meson in medium. In a third step we have also analyzed the lowering of scalar strength in nuclei observed by the TAPS experiment.

2 In-Medium Properties of Vector Mesons

On the first aspect we have initially finished a major calculation on the in-medium properties of the π, ρ and η mesons [12]. In this work we have generated the in-medium selfenergies of these mesons by nucleon-hole and resonance-hole excitations which in turn are affected by the changed in-medium properties of the mesons. This self-consistency problem has been solved here for the first time. Special care was taken to respect the analyticity of the spectral functions and to take into account effects from short-range correlations both for positive and negative parity states.

Our model has been shown to produce sensible results for pion and Δ dynamics in nuclear matter, as a test. For the ρ meson we find a strong interplay with the D13(1520), which moves spectral strength of the ρ spectrum to smaller invariant masses and simultaneously leads to a broadening of the baryon resonance. The strong interplay between the ρ meson and the D13(1520)-nucleon hole excitation leads to a dominant lower hump in the ρ spectral function also in this relativistic and selfconsistent calculation; it confirms our earlier result obtained in a more simplified approach. Whereas the longitudinal component of the ρ meson only broadens somewhat, the transverse component shows a major distortion which evolves as a function of the ρ momentum (see Fig. 1). At the same time, the D13(1520) resonance broadens considerably due to the opening of phase-space for ρ-decay. For the η meson the optical potential resulting from our model is rather attractive whereas the in-medium modifications of the S11(1535) are found to be quite small.

These studies also allow us to assess the validity range of the often used low-density approximation. We find that this depends very much on the special couplings involved and thus varies from meson to meson. Whereas

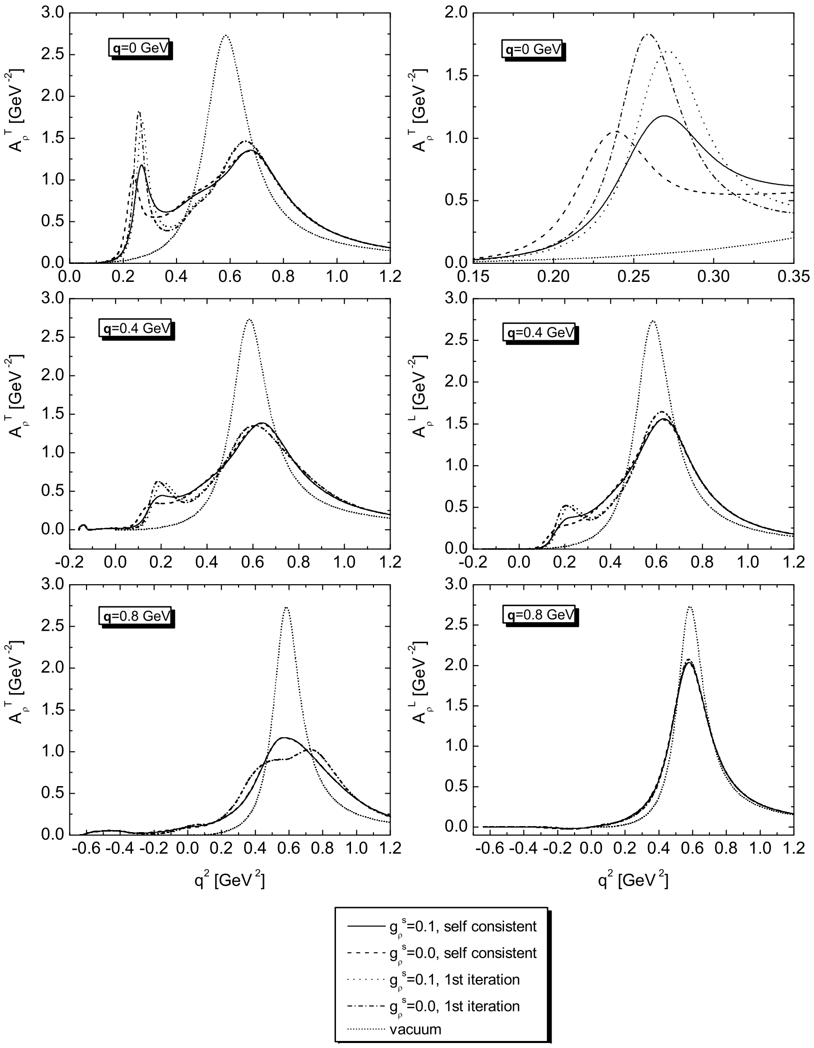

Figure 1: Spectral function of the ρ meson in nuclear matter at density ρ_0 for various momenta indicated in the figure. The left column shows the transverse spectral function, the right column that of longitudinally polarized ρ mesons. The thin dotted line in each figure is the vacuum spectral function, the other curves give the effect of selfconsistency and short-range correlations (from [12]).

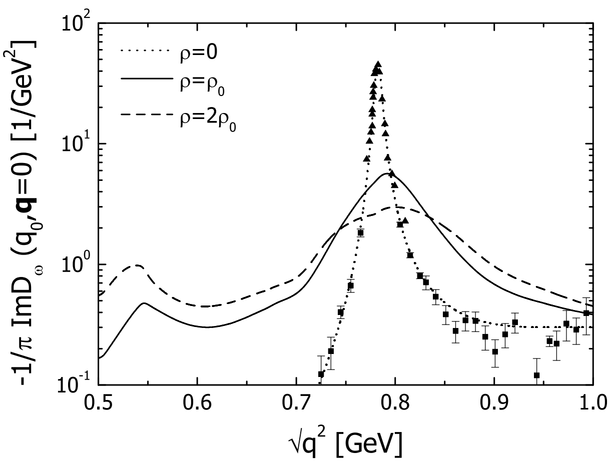

Figure 2: Spectral function of the ω meson in nuclear matter at rest, at densities 0, ρ_0 and 2 ρ_0 (from [13]).

for the η meson the validity ranges up to a density of ρ_0, for the ρ meson it already breaks down at about 0.3 ρ_0. This may serve as a warning sign for many in-medium calculations that use the low-density approximation without any further proof of its reliability.

Bearing this in mind we have recently also performed a calculation of the selfenergy of the ω meson in medium. This calculation is based on a unitary coupled channel analysis of all existing πN and γN data up to an invariant mass of 2 GeV [13]. The coupled channel character of this calculation is of utmost importance here because it is the only way to include experimental constraints on the 2π decay channel that was found to be dominant in [4]. This analysis and thus also the selfenergy of the ω meson extracted from the ωN scattering amplitude gives a broadening of about 60 MeV at ρ_0 and a small upward shift of the peak mass. In addition, due to a nonzero coupling of the ω to the S11(1535) resonance the ω spectral function exhibits a small peak at a mass of around 550 MeV. This calculation gives, for the first time, the ω selfenergy also for nonzero momenta (which corresponds to the experimental situation) and it takes the experimental constraints on the important 2π channel into account because it is based on a unitary K-matrix analysis of 'real' data. The result of this calculation is shown in Fig. 2. For vanishing ω momentum this result qualitatively agrees with that of [14] in that it yields a lower mass structure in the spectral function at an invariant mass of 500 - 600 MeV and only a very small shift of the main peak; the latter is in contrast to the results of [4] (for a recent discussion of the results obtained in [4] see [15]) and of [16]. The latter was based on a relativistic mean-field model and does not contain any dispersive effects.

Our second line of approach to the problem of in-medium selfenergies has concentrated on an analysis of the recent CBELSA/TAPS data [8] Since the experiment looks for the channel $\gamma + A \rightarrow A^* + \omega \rightarrow A^* + \gamma + \pi^0$ it is mandatory to control the effects of final state interactions on the π^0 in a quantitative way. The only method available for this is that of coupled channel semiclassical transport calculations which – as we had shown earlier in extensive work – can give a consistent description of many experimental phenomena, both in heavy-ion [18] as well as in nucleon-, pion- [19], photon- [20] and neutrino-induced reactions [21]. For any reaction on nuclei with hadrons in the final state a state-of-the-art transport calculation of the final state interactions is an indispensible part of the theory. We have, therefore, spent significant effort on developing a new code, dubbed 'GiBUU', for the transport calculations. This code is written in object-oriented FORTRAN 95/2003 and incorporates all the experience we have gained with earlier numerical implementations at Giessen over the last 20 years [17].

With this method we have first analysed both results on the experimental determination of the nuclear transparency ratio for ϕ mesons [22], measured by a group at SPRING8. This transparency gives directly the imaginary part of the meson's selfenergy in medium; using a low-density approximation one can then extract the inelastic ωN cross section. In this way an an unexpectedly large inelastic cross section for ϕN interactions was extracted. We have found that indeed cross sections about a factor 3 larger than those theoretically expected are needed to explain the mentioned data, in line with a simple Glauber analysis by the SPRING8 group.

For ω mesons the CBELSA/TAPS collaboration has measured the nuclear transparency [23]. We have shown that our calculations reproduce the measured attenuation quite well if – similar to the ϕN case – the inelastic cross section is increased by about a factor of 3 beyond earlier theoretical expectations. A fit to the data can actually also determine the momentum-dependence of this cross section [24].

A major effort has gone into an analysis of the ω photo-production experiment at CBELSA/TAPS. Fig. 3 shows the result of such an analysis together with the data of the CBELSA/TAPS collaboration. Our simulations give a full event analysis and thus allow to calculate also background contributions on the same footing as the actual signal. They also allow insight into the effects of rescattering of the pions produced in the decay of the ω meson and have suggested a method to suppress the rescattered pion background that has actually been adopted by the experimental group. The result of this analysis is that the data can be explained if a lowering of the ω meson mass in medium by about 16 % is assumed together with the appropriate

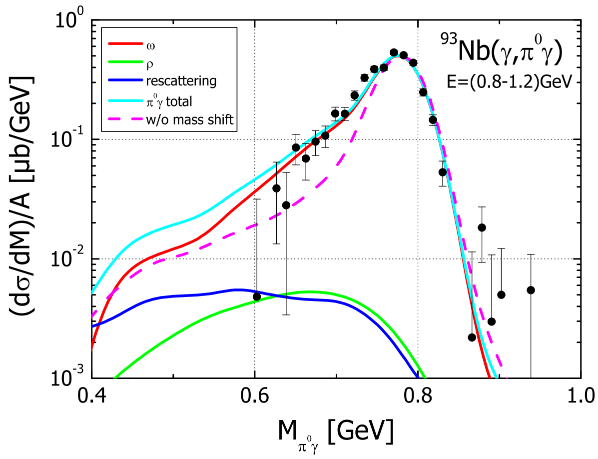

Figure 3: Comparison of CBELSA/TAPS data on ω production on different targets in the energy range $E_\gamma = 0.8 - 1.2$ GeV [8]. The dashed line shows a comparison of the GiBUU transport calculation with free ω meson spectral functions (using the experimental mass resolution) and the solid line at the top gives the results of a calculation with mass-shift and collisional broadening. The solid line at the bottom gives the contribution of rescattered pions to the reconstructed spectral function and the grey line at the bottom gives the contribution of the decay channel $\rho \rightarrow \pi^0\gamma$. The top curve shows the sum of all contributions (from [24]).

collisional broadening.

A problem in this context is that the experiment does not determine the spectral function of the ω meson itself. Instead, we have noted that the result of the experimental analysis is the product of the primary production cross section with the spectral function and the partial decay probability into the channel under study ($\pi^0\gamma$ here). If the first and the latter depend strongly on the invariant mass itself, as it does for the CBELSA/TAPS experiment, then significant distortions of the spectral function may arise. This is a topic under intensive study by us presently [25]

3 In-Medium Properties of Scalar Mesons

Finally, we have analyzed the TAPS data on $2\pi^0$ photoproduction on nuclei. The motivation for this experiment was a prediction that – due to chiral symmetry restoration in nuclei – the scalar strength of the σ meson should be lowered in nuclei [5]. The TAPS collaboration had indeed initially seen an effect as predicted in the $2\pi^0$ data, whereas a comparison measurement in the

$\pi^0\pi^\pm$ channel did not seem to show such an effect [7]. Various explanations for these findings have been advanced by the Valencia group [26] and by a group in Lyon [27] in terms of chiral symmetry restoration or $\pi - \pi$ correlations in nuclei, based on a chiral effective field theory model.

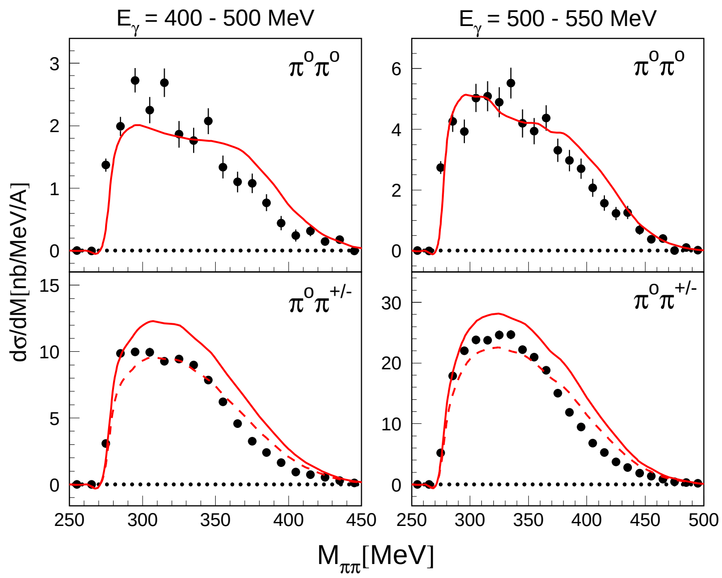

Figure 4: Data of the TAPS collaboration (Bloch et al.) for $2\pi^0$ photoproduction on a ^{40}Ca target for two different photon energies. The solid curve gives the result of a GiBUU calculation [28], the dashed curves in the semicharged 2π channel are normalized to the data (see text). Data from [29].

None of these calculations, however, did look into the simplest possible explanation of the observed effects in terms of mundane pion rescattering. We have, therefore, performed such calculations [19] using the GiBUU method which is ideally suited for this task. These calculations, which did not contain any effects connected with $\pi\pi$ correlations, could reproduce the observed effect for the $\pi^0\pi^0$ channel, but they also predicted a similar effect in the semi-charged channel where it had not been seen experimentally. However, a more recent analysis with higher statistics by Bloch et al. [29] yielded a result for both charge channels that is in perfect agreement with our calculations (see Fig. 4; the dashed lines in this figure are normalized in height to the data, this normalization reflects uncertainties in the elementary cross sections). In particular the yield in the semi-charged channel is strongly influenced by a coupled-channel effect, the charge transfer in πN interactions; Glauber based absorption models miss this contribution. This illustrates that a very sophisticated treatment of final state interactions is absolutely mandatory when looking for more 'exotic' effects in nuclei. We conclude that any analysis of the $2\pi^0$ data with respect to a lowering of the scalar strength in nuclei has to take the pion rescattering effects into account. Present day's data are all consistent with simple rescattering.

4 Summary

The main message we have learned from the studies reported here is that it is important to calculate not only in-medium properties under idealized conditions (static, uniform matter in equilibrium), but to also explore the influence of these properties on actual observables. The spectral function itself, which contains the information on in-medium selfenergies, in particular in-medium masses and widths, is not directly observable. Instead, both the creation of the studied hadron as well as its decay influence the observables as much as the spectral function itself and thus have to be under good control. The same holds for the final state interactions on hadronic decay products. Here a state-of-the-art treatment of final state interactions is mandatory. There is now general agreement on the amount of collisional broadening of vector mesons in medium, but the verification of an actual mass-shift still requires more work, both theoretical and experimental.

References

[1] V. Bernard, U. G. Meissner and I. Zahed, Phys. Rev. Lett. **59** (1987) 966; V. Bernard and U. G. Meissner, Nucl. Phys. A **489** (1988) 647.

[2] T. Hatsuda, S. H. Lee and H. Shiomi, Phys. Rev. C **52**, 3364 (1995) [arXiv:nucl-th/9505005].

[3] G. E. Brown and M. Rho, Phys. Rev. Lett. **66** (1991) 2720.

[4] F. Klingl and W. Weise, Nucl. Phys. A **606** (1996) 329; F. Klingl, N. Kaiser and W. Weise, Nucl. Phys. A **624** (1997) 527 [arXiv:hep-ph/9704398].

[5] K. Yokokawa, T. Hatsuda, A. Hayashigaki and T. Kunihiro, Phys. Rev. C **66** (2002) 022201 [arXiv:hep-ph/0204163].

[6] G. Agakishiev *et al.* [CERES Collaboration], Phys. Rev. Lett. **75** (1995) 1272.

[7] J. G. Messchendorp *et al.*, Phys. Rev. Lett. **89**, 222302 (2002) [arXiv:nucl-ex/0205009].

[8] D. Trnka *et al.* [CBELSA/TAPS Collaboration], Phys. Rev. Lett. **94**, 192303 (2005) [arXiv:nucl-ex/0504010].

[9] R. Nasseripour, M. H. Wood, C. Djalali, D. P. Weygand, C. Tur, U. Mosel, P. Muehlich, CLAS Collaboration, Phys. Rev. Lett. (2007) in press [arxiv.org/abs/0707.2324v3].

[10] S. Yokkaichi *et al.* [KEK-PS325 Collaboration], Int. J. Mod. Phys. A **22**, 397 (2007).

[11] S. Damjanovic *et al.* [NA60 Collaboration], Nucl. Phys. A **783** (2007) 327 [arXiv:nucl-ex/0701015].

[12] M. Post, S. Leupold and U. Mosel, "Hadronic spectral functions in nuclear matter," Nucl. Phys. A **741**, 81 (2004) [arXiv:nucl-th/0309085].

[13] P. Muehlich, V. Shklyar, S. Leupold, U. Mosel and M. Post, "The spectral function of the omega meson in nuclear matter from a coupled-channel resonance model," Nucl. Phys. A **780**, 187 (2006) [arXiv:nucl-th/0607061].

[14] M. F. M. Lutz, G. Wolf and B. Friman, Nucl. Phys. A **706** (2002) 431 [Erratum-ibid. A **765** (2006) 431] [arXiv:nucl-th/0112052].

[15] F. Eichstaedt, S. Leupold, U. Mosel and P. Muehlich, Prog. Theor. Phys. Suppl. **168**, 495 (2007) [arXiv:0704.0154 [nucl-th]].

[16] K. Saito, K. Tsushima, D. H. Lu and A. W. Thomas, Phys. Rev. C **59**, 1203 (1999) [arXiv:nucl-th/9807028].

[17] for details see: http://gibuu.physik.uni-giessen.de/GiBUU/

[18] A. B. Larionov, O. Buss, K. Gallmeister and U. Mosel, Phys. Rev. C **76** (2007) 044909 [arXiv:0704.1785 [nucl-th]].

[19] O. Buss, L. Alvarez-Ruso, A. B. Larionov and U. Mosel, Phys. Rev. C **74**, 044610 (2006) [arXiv:nucl-th/0607016].

[20] O. Buss, T. Leitner, U. Mosel and L. Alvarez-Ruso, Phys. Rev. C **76**, 035502 (2007) [arXiv:0707.0232 [nucl-th]].

[21] T. Leitner, L. Alvarez-Ruso and U. Mosel, Phys. Rev. C **73**, 065502 (2006) [arXiv:nucl-th/0601103].

T. Leitner, L. Alvarez-Ruso and U. Mosel, Phys. Rev. C **74**, 065502 (2006) [arXiv:nucl-th/0606058].

[22] P. Muhlich and U. Mosel, "Attenuation of Phi mesons in gamma A reactions," Nucl. Phys. A **765**, 188 (2006) [arXiv:nucl-th/0510078].

[23] V. Metag, arXiv:0711.4709 [nucl-ex].

[24] P. Muehlich, "Mesons in Nuclei and Nuclear Reactions", PhD Dissertation, University of Giessen, 2007, http://theorie.physik.uni-giessen.de/documents/dissertation/muehlich.pdf

[25] K. Gallmeister, M. Kaskulov and U. Mosel, arXiv:0712.2200 [nucl-th].

[26] L. Roca, E. Oset and M. J. Vicente Vacas, Phys. Lett. B **541**, 77 (2002) [arXiv:nucl-th/0201054].

[27] G. Chanfray, Z. Aouissat, P. Schuck and W. Noerenberg, Phys. Lett. B **256**, 325 (1991).

[28] O. Buss, L. Alvarez-Ruso, P. Muhlich and U. Mosel, Eur. Phys. J. A **29** (2006) 189 [arXiv:nucl-th/0603003].

[29] F. Bloch *et al.*, Eur. Phys. J. A **32** (2007) 219 [arXiv:nucl-ex/0703037].