EPJ Web of Conferences **134**, 03004 (2017) DOI: 10.1051/epjconf/201713403004
Subnuclear Structure of Matter: Achievements and Challenges

Hadrons in Nuclear Matter

Ulrich Mosel[1,⋆]

[1] *Institut für Theoretische Physik, Justus-Liebig-Universität Giessen, 35392 Giessen, Germany*

Abstract. We review the achievements of the project **B.5**, that deals with the calculation of in-medium properties of vector mesons and an analysis of their experimental signals, with a particular emphasis on the ω photoproduction data from CBELSA/TAPS. Other topics addressed include color transparency, pion electroproduction on nucleons, the Primakoff effect for nuclear targets and studies of hadronization at the EIC.

1 Introduction and motivation

The project **B.5** has been funded for the first and second funding period of the SFB/TR 16. This research project aimed at an investigation of selfenergies of vector mesons in medium and an analysis of their experimental signals. On one hand, these selfenergies were calculated using state-of-the-art many-body techniques. On the other hand, in close collaboration with the CBELSA/TAPS collaboration, the observable signals of any in-medium changes of hadronic properties were studied. Since the ELSA experiments use a semi-hadronic channel to look for the in-medium properties of the omega meson close to threshold particular focus was the study of the in-medium production cross section and the effects of final state branching ratios and interactions. Relevant data from JLAB and KEK were also studied.

Our contribution is organized as follows: Section 2 summarizes the work done in the first funding period. The results obtained in the second funding period are presented in Section 3. Due to the retirement of the PI in 2011, this very successfull project was terminated at the end of the second funding period.

2 First funding period 2004-2008

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. At the start of the present funding period there were some sophisticated 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 [1, 2]. Specifically, there existed well-worked out predictions that the scalar 2π strength should decrease in medium and that the vector meson masses should drop [3]. 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, whereas the TAPS results on the 2π strength exhibited the predicted lowering of the σ strength inside nuclei.

During the first stage of the SFB/TR 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.

2.1 Vector meson spectral functions

On the first aspect we have initially finished a major calculation on the in-medium properties of the π, ρ and η mesons [4]. 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 rho 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

⋆e-mail: ulrich.mosel@theo.physik.uni-giessen.de

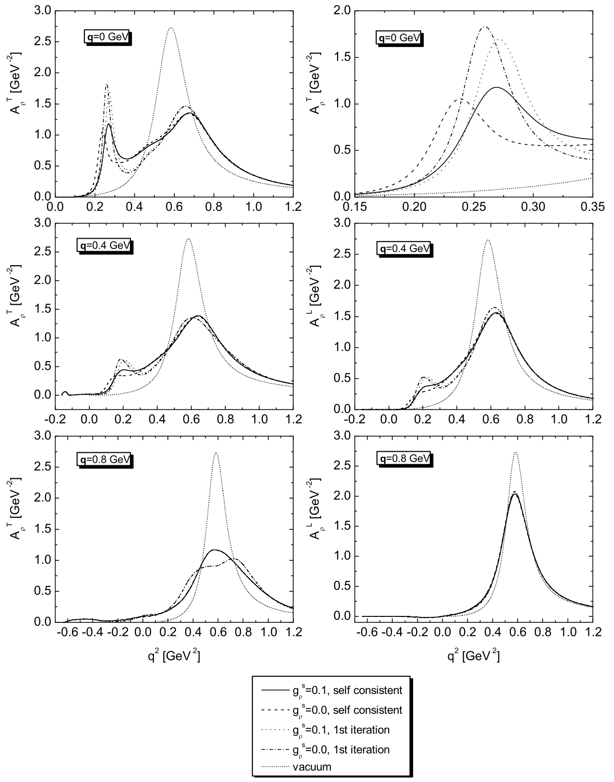

Figure 1. Spectral function of the ρ meson in nuclear matter at density ρ_0 for various momenta indicated in the figure. The left column shows the transverse spectral function, the right column that of longitudinally polarized ρ mesons. The thin dotted line in each figure is the vacuum spectral function, the other curves give the effect of selfconsistency and short-range correlations (from [4]).

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. 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 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 [5]. 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 [2]. 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

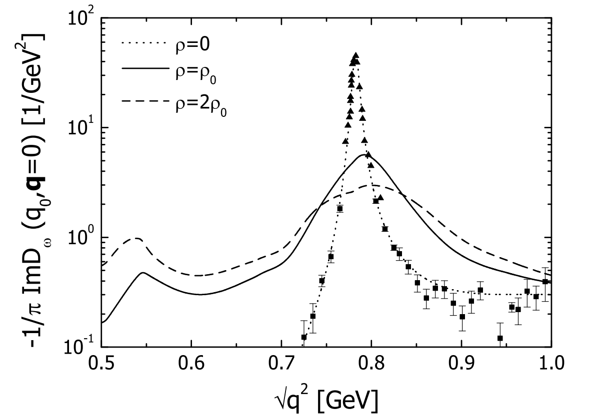

Figure 2. Spectral function of the ω meson in nuclear matter at rest, at densities 0, ρ_0 and 2 ρ_0 (from [5]).

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 is in two aspects novel and unique: it gives, for the first time, the ω selfenergy also for nonzero momenta (which corresponds to the experimental situation) and it takes the experimental constraints better into account than any other calculation of the selfenergy because it is based on a unitary K-matrix analysis of 'real' data. The result of this calculation is shown in Fig. 2.

2.2 Analysis of CBELSA/TAPS ω photoproduction data

Our second line of approach to the problem of in-medium selfenergies has concentrated on an analysis of the recent CBELSA/TAPS data and was followed in intensive collaboration – with nearly daily contacts – with the experimental colleagues of the TAPS collaboration at Giessen. 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 semi-classical transport calculations which – as we had shown earlier in extensive work – can give a consistent description of many experimental phenomena, both in heavy-ion as well as in nucleon-, pion- and photon-induced reactions. For any reaction on nuclei with hadrons in the final state a state-of-the-art transport calculation 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 [6]. It should be noted that this code is unique, we do not know about any other competitive effort for the description of inclusive or semi-inclusive incoherent reactions with elementary probes on nuclei.

With this method we have first analysed both results on the experimental determination of the nuclear transparency ratio for ϕ mesons [7], measured by a Japanese group at SPRING8 that lead to an unexpectedly large inelastic cross section for ϕN interactions. 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.

A major effort has gone into an analysis of the ω photoproduction experiment at CBELSA/TAPS [8, 9]. 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. 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 spectral function with the partial decay probability into the channel under study ($\pi^0\gamma$ here). If the latter depends 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 and also planned for the second period of the SFB/TR (see below).

The CBELSA/TAPS collaboration has also measured the nuclear transparency for ω mesons. 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. We have shown that our calculations reproduce the measured attenuation quite well if the inelastic cross section is increased by about a factor of 2 beyond theoretical expectations. A fit to the data can actually also determine the momentum-dependence of this cross section which at low momenta comes out to be larger than the usually used parametrizations [9].

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. 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. Various explanations for these findings have been advanced by the Valencia group and by a group in Lyon in terms of chiral symmetry restoration or $\pi-\pi$ correlations in nuclei, based on a chiral effective field theory model.

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 using the GiBUU method which is ideally suited for this task. These calculations, which did not use 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. [10] yielded a result for both charge channels that is in perfect agreement with our calculations (see Fig. 3; 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.

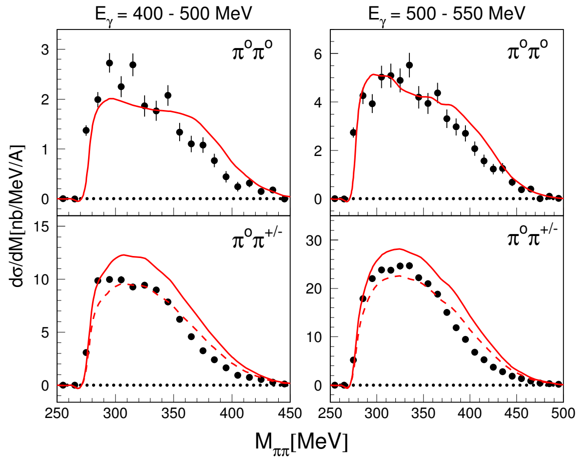

Figure 3. Data of the TAPS collaboration (Bloch et al.) for $2\pi^0$ photoproduction on a ^{40}Ca target for two different photon energies. The solid curve gives the result of a GiBUU calculation, the dashed curves in the semicharged 2π channel are normalized to the data (see text). Data from [10].

The capability we have in the field of coupled channel transport calculations for reactions with elementary probes on nuclei, absolutely essential for an understanding of actual observables, is worldwide unique. This outstanding role of the GiBUU effort is reflected in the many publications in international refereed journals and the large number of invited talks on major international conferences and workshops.

All this work has been done in very close collaboration and nearly daily discussions with the local members of the TAPS group, in particular M. Kotulla and V. Metag. It has a direct physics connection to the experimental subproject **B.4**. We also have a close working relationship with the g7 group at JLAB/North Carolina which has resulted already in one joint publication [11] and to the RIKEN/U of Tokyo group working at KEK.

3 Second funding period 2008-2012

3.1 Development of the project

The central aim of the present project was to explore if any of the theoretically predicted in-medium changes of hadronic properties could actually be observed in ongoing experiments. With this aim in mind we have kept close contacts to the relevant experiments, in particular, to CBELSA/TAPS at ELSA. With the Giessen members of the CBELSA/TAPS group we have had nearly weekly discussions meetings (project **B.4**, V. Metag, M. Nanova). Also to the experiment HADES at GSI, that aims for a determination of in-medium properties of vector mesons in hadronic reactions, we are keeping close contacts. We have also provided guidance to the analysis of the g-7 experiment at JLAB; one of our graduate students, J. Weil, spent time there to help in the evaluation of these data. In both cases the transport theory and code dubbed GiBUU, developed by us over the last twenty year, played an important role as 'work horse'.

At the start of this funding period a contradictory situation existed: on one hand, theory predicted nearly no mass shifts of the vector mesons in medium, but a sizeable collisional broadening. On the other hand, experiments (CBELSA/TAPS and KEK) seemed to show some mass-shift which was significantly bigger than theoretically expected. This discrepancy was discussed on various conferences and meetings. In both cases a possible resolution was reached when it was observed that the background subtraction process, needed to isolate, e.g., the ω signal, was unreliable. This seems to be the accepted explanation for the mass shifts observed by the KEK experiment (which did not observe any broadening, the latter is hard to accept since dispersion effects link real and imaginary parts of the self energies). Also for the CBELSA/TAPS experiment the background effects came under closer scrutiny. In Ref. [12] M. Kaskulov, the part-time postdoc in the present project, showed that the mass-shift signal depended strongly on the background subtraction method. This was also realized by the CBELSA/TAPS collaboration when a reanalysis of the data and the background determination became available [13].

From that point on we had an intensive collaboration with the Giessen experimental colleagues and have provided both theoretical and practical, computational input to their project. The specific contributions will be listed below. In addition, we broadened our approach by also analyzing other experiments at JLAB that aimed for the same physics, i.e. in-medium properties of hadrons. An important insight gained in these studies was that a reliable analysis of these experiments, that were also set up to discover color transparency, was not possible without a good understanding of the elementary production vertex. In the course of that work we could solve an old outstanding problem, i.e. that of transverse vs. longitudinal strength in hard exclusive reactions. Also these developments will be discussed in some more detail below.

Much work was also spent, as already envisaged in the application, on 'apparatus development', i.e. on further development of the GiBUU event generator. Here we improved various aspects relevant to the present work, among others the description of quasielastic lepton scattering, a better treatment of groundstate stability problems and the implementation of cross sections relevant for electroweak reactions.

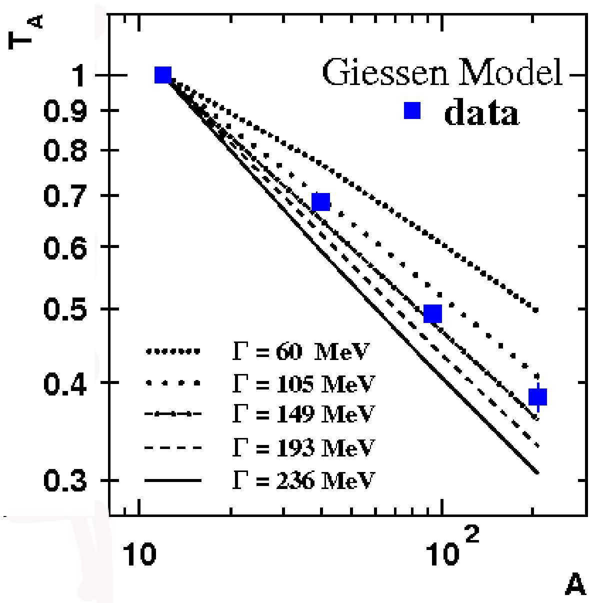

Figure 4. The nuclear transparency T_A, normalized to ^{12}C, as a function of mass number A for various assumed widths Γ. Also shown are the datapoints from the CBELSA/TAPS experiment (project **B.4).**

3.2 Analysis of transparency ratio

In a new series of experiments the CBELSA/TAPS group had explored the transparency of nuclei for ω mesons. We have analyzed these data within the framework of GiBUU, a semiclassical coupled channel transport calculation (for details see later subsection). In a joint publication with the experimental group [14] we have shown that the measured transparency ratios require an ω- width in medium of about 150 MeV at a momentum of about 1 GeV (see Fig. 4). Thus, considerable collisional broadening takes place, since the free width of the ω meson is only 9 MeV. The numbers extracted agreed with the ones obtained in a simplified analysis by the Valencia group.

Interesting about this analysis is that it allows the extraction of an $\omega - N$ inelastic cross section, under the assumption of low density, i.e. prevalence of two-body collisions. These inelastic cross sections are generally unknown, but play a role in any in-medium scenario. The values extracted all lie relatively high ($\approx 60 - 70$ mb) for momenta of about 1 GeV, see detailed discussion in project **B4**.

3.3 Lineshape analysis

We had shown already in [15] that nucleon spectral functions are quite insensitive to collisional broadening. The reason is that observed line-shapes always represent an average over many nuclear densities and that the contribution of resonances at the largest density, where they experience most of the collisional broadening, tends to become indistinguishable from background contributions. The same physics holds also for the observability of collisional broadening of meson spectral functions. An ex-

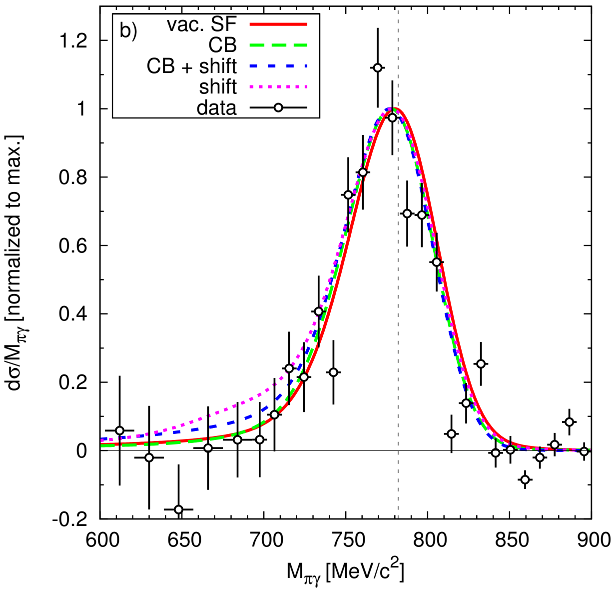

Figure 5. ω signal for the *Nb* target from the CBELSA/TAPS collaboration in comparison to recent GiBUU simulations for the following scenarios: no medium modification (solid), in-medium broadening of Γ_{coll} = 140 MeV at nuclear saturation density (long dashed), an additional mass shift by -16% (short dashed), mass shift without broadening (dotted).

ample of a calculation is given in Fig. 5, together with the data from CBELSA/TAPS (project **B.4**).

The figure shows clearly that the observable effects of assumed in-medium modifications are relatively minor and that any experiment that aims to distinguish between the different scenarios shown in the figure (collisional broadening alone, mass shift alone, both collisional broadening and mass shift) would require systematic and statistical uncertainties well below those of presently feasible experiments. The present data are clearly compatible with some collisional broadening, but any mass-shift can not be inferred.

These results are all compatible with the observations of in-medium hadronic properties in the g-7 experiment at JLAB. Here we have – in close collaboration with that group – analyzed data on photon-induced dilepton production on nuclei which lead to a joint publication [16]. This is in principle an ideal experiment since it involves neither initial state nor final state interactions. The experiment was sensitive to the ρ meson's spectral shape. Because of the ρ's considerable broadening in medium (see our report for the last funding period) this was indeed observable and confirmed previous theoretical predictions.

3.4 Color transparency

In the projects discussed before the analysis relied on the transport generator GiBUU. A very interesting application of it, that found widespread interest, is the analysis of pion and ρ-meson electroproduction on nuclei with the aim to look for possible effects of color transparency (CT). In [17] we have investigated the onset of color transparency

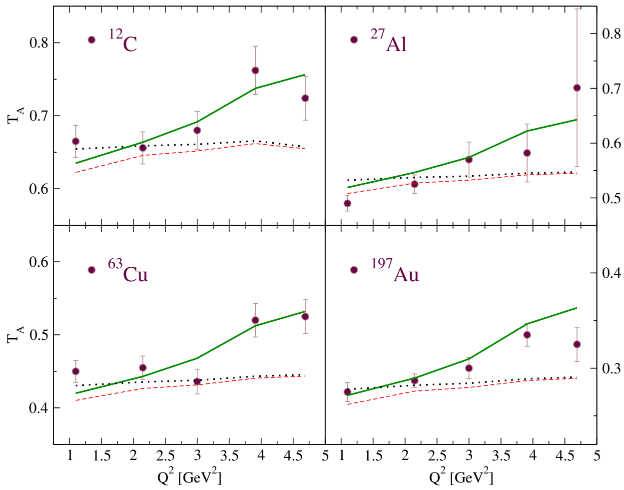

Figure 6. Transparency, T_A, vs. Q^2 for ^{12}C (left, top panel), ^{29}Al (right, top), ^{63}Cu (left, bottom) and ^{197}Au (right, bottom). Data from JLAB experiment πCT.

in semi-exclusive pion electroproduction on nuclei. We have found that the data of the experiment πCT at JLAB could be well reproduced only if hard partonic processes dominate the transverse channel. The needed formation times were found to be compatible to our earlier analyses of HERMES and EMC data [18]. Fig. 6 illustrates the CT effect. The result of a calculation in which the formed hadrons interact without any delay with the full cross section is shown by the dotted curves. These curves are nearly flat and thus do not exhibit the observed rise with Q^2. The same is true for the short–dashed curves which include in addition shadowing; the influence of the latter is very small due to the very small coherence lengths in this kinematical regime. Finally, to show the effect of diminished prehadronic cross sections independent of Q^2 during their formation time we plot the solid curves which provide a very satisfactory agreement with data.

For the ρ meson production experiment [19], also at JLAB, GiBUU allowed a full event simulation. This was essential since the experiment 'suffered' from various kinematical cuts that had to be reproduced by the calculations for any meaningful comparison. We have compared various different hadronization and CT scenarios and have found that a detailed analysis of elementary cross section, nuclear effects and experimental cuts is needed to reveal the early onset of ρ-CT at the presently available JLAB energies [20]. Here the major strength of an analysis based on a full event-generator becomes obvious again: the entanglement of kinematic cuts and Fermi-motion effects in this experiment could not be treated in any other calculation.

3.5 Pion electroproduction on nucleons

In the CT analyses of pion production on nuclei we have shown that a proper distinction between the soft hadronic and the hard partonic components of the electroproduction amplitude is of utmost importance. Here the partonic components show up primarily in the transverse part of the reaction amplitude while the hadronic components dominate the longitudinal components. It turned out that the available, widely used model for the calculation of elementary electroproduction of pions on nucleons was seriously deficient: while the longitudinal part of the cross section was described very well, the transverse part was significantly underestimated (by about 1 order of magnitude!). We have, therefore, developed a new model that describes both reaction components over a very wide kinematical range extremely well [17, 21, 22]. In particular, the new model is able to describe the observed onset of transverse strength with increasing momentum transfer Q^2, which is in contradition to simple pQCD based expectations for exclusive reaction channels. Essential for this agreement is the consideration of s-channel processes in the exclusive electroproduction that involve high-lying nucleon resonances. The publication was listed by the APS on a webpage for 'exceptional research' (http://physics.aps.org/synopsis-for/10.1103/PhysRevC.81.045202).

3.6 Hadronization in the EIC

The projects just listed gave us all the necessary experience and tools to also contribute to studies of hadronization, measured in the EMC experiment and with HERMES. Our calculations of hadronic attenuation as a function of energy transfer, rapidity and momentum transfer for these two experiments are still the only ones available that can describe the measurements for all hadron species [18]. Based on this success we had already earlier made predictions for the 12 GeV beam at JLAB. This led to an invitation to contribute to the plans for an electron-ion collider (EIC). On two workshops we presented our results and contributed to the first major write-up of a scientific program for such a machine [23].

3.7 Primakoff effect

As a direct application both of the development for in-medium production of pions in the two preceding subsections we have performed a new calculation of the Primakoff effect which relies on a very reliable calculation of the amplitude for photoproduction of π^0 on nuclear targets [24]. Required is not only a calculation of the Primakoff amplitude itself, but in addition also of the nuclear amplitude which interferes with the former. Essential for a good agreement with recent JLAB data is that our calculations allow for photon shadowing and final state interactions of the outgoing pions. In this paper we also make predictions for planned experiments on η and η' Primakoff production.

3.8 Review articles

During the present funding period 2 major review articles have been written.

Hadrons in strongly interacting matter:

In this review in International Journal of Modern Physics, published together with S. Leupold and V. Metag in [25], we have summarized the current status of theories and and experiments aiming at an understanding and a determination of the properties of light vector and scalar mesons inside strongly interacting hadronic matter . Starting from a discussion of the relevant symmetries of QCD and their connection with the hadronic description through QCD sum rules we have then discussed hadronic models used to calculate the in-medium self-energies of hadrons and their spectral functions. Finally, we have reviewed in detail all the running experiments searching for in-medium changes of vector and scalar mesons, both with relativistic heavy-ion reactions as well as with elementary reactions on (cold) nuclei. Inconsistencies among experimental results were discussed.

Transport-theoretical description of nuclear reactions:

In this review in Physics Reports, published with a number of Giessen coauthors [26], we have first outlined the basics of transport theory and its recent generalization to off- shell transport. We have then presented in some detail the main ingredients of the Giessen Boltzmann-Uehling-Uhlenbeck (GiBUU) implementation of this theory. The central part of this review covered applications of GiBUU to a wide class of reactions, starting from pion-induced reactions over proton and antiproton reactions on nuclei to heavy-ion collisions (up to about 30 AGeV). A major part concerns also the description of photon-, electron- and neutrino-induced reactions (in the energy range from a few 100MeV to a few 100 GeV). For this wide class of reactions GiBUU gives an excellent description with the same physics input and the same code being used. We have argued in this review that GiBUU is an indispensable tool for any investigation of nuclear reactions in which final-state interactions play a role. Studies of pion-nucleus interactions, nuclear fragmentation, heavy-ion reactions, hypernucleus formation, hadronization, color transparency, electron-nucleus collisions and neutrino-nucleus interactions are all possible applications of GiBUU and are described well.

We would like to thank all our collaborators that have contributed to the success of this project, in particular also to the experimental colleagues from project **B.4**. The work reported here would not have been possible without the support from the Deutsche Forschungsgemeinschaft within the SFB/TR16.

References

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

[2] 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].

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

[4] M. Post, S. Leupold and U. Mosel, Nucl. Phys. A **741**, 81 (2004) [arXiv:nucl-th/0309085].

[5] P. Muehlich, V. Shklyar, S. Leupold, U. Mosel and M. Post, Nucl. Phys. A **780**, 187 (2006) [arXiv:nucl-th/0607061].

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

[7] P. Muhlich and U. Mosel, Nucl. Phys. A **765**, 188 (2006) [arXiv:nucl-th/0510078].

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

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

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

[11] R. Nasseripour, M. H. Wood, C. Djalali, D. P. Weygand, C. Tur, U. Mosel, P. Muehlich, CLAS Collaboration, Phys. Rev. Lett. **99** (2007) 262302 [arXiv:0707.2324 [nucl-ex]].

[12] M. Kaskulov, E. Hernandez and E. Oset, Eur. Phys. J. A **46** (2010) 223 [arXiv:1003.2363 [nucl-th]].

[13] M. Nanova *et al.* [CBELSA/TAPS Collaboration], Phys. Rev. C **82** (2010) 035209 [arXiv:1005.5694 [nucl-ex]].

[14] M. Kotulla *et al.* [CBELSA/TAPS Collaboration], Phys. Rev. Lett. **100** (2008) 192302 [arXiv:0802.0989 [nucl-ex]].

[15] J. Lehr and U. Mosel, Phys. Rev. C **64** (2001) 042202 [nucl-th/0105054].

[16] M. H. Wood *et al.* [CLAS Collaboration], Phys. Rev. C **78** (2008) 015201 [arXiv:0803.0492 [nucl-ex]].

[17] M. M. Kaskulov, K. Gallmeister and U. Mosel, Phys. Rev. C **79** (2009) 015207 [arXiv:0808.2564 [nucl-th]].

[18] K. Gallmeister and U. Mosel, Nucl. Phys. A **801** (2008) 68 [nucl-th/0701064].

[19] L. El Fassi *et al.* [CLAS Collaboration], Phys. Lett. B **712** (2012) 326 [arXiv:1201.2735 [nucl-ex]].

[20] K. Gallmeister, M. Kaskulov and U. Mosel, Phys. Rev. C **83** (2011) 015201 [arXiv:1007.1141 [hep-ph]].

[21] M. M. Kaskulov and U. Mosel, Phys. Rev. C **80** (2009) 028202 [arXiv:0904.4442 [hep-ph]].

[22] M. M. Kaskulov and U. Mosel, Phys. Rev. C **81** (2010) 045202 [arXiv:1001.1952 [hep-ph]].

[23] D. Boer, M. Diehl, R. Milner, R. Venugopalan, W. Vogelsang, D. Kaplan, H. Montgomery and S. Vigdor *et al. (K. Gallmeister, U. Mosel),*, arXiv:1108.1713 [nucl-th].

[24] M. M. Kaskulov and U. Mosel, Phys. Rev. C **84** (2011) 065206 [arXiv:1103.2097 [nucl-th]].

[25] S. Leupold, V. Metag and U. Mosel, Int. J. Mod. Phys. E **19** (2010) 147 [arXiv:0907.2388 [nucl-th]].

[26] O. Buss, T. Gaitanos, K. Gallmeister, H. van Hees, M. Kaskulov, O. Lalakulich, A. B. Larionov and T. Leitner *et al.*, Phys. Rept. **512** (2012) 1 [arXiv:1106.1344 [hep-ph]].