Proc. Budapest'02 Workshop on
Quark & Hadron Dynamics (2002) 000–000

Budapest'02 Workshop on
Quark & Hadron Dynamics
Budapest, Hungary
March 3–7, 2002

From meson- and photon-nucleon scattering to vector mesons in nuclear matter

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Abstract. We present a relativistic and unitary approach to pion- and photon-nucleon scattering taking into account the πN, ρN, ωN, ηN, $\pi\Delta$, $K\Lambda$ and $K\Sigma$ channels. Our scheme dynamically generates the s- and d-wave baryon resonances $N(1535)$, $N(1650)$, $N(1520)$ and $N(1700)$ and as well as $\Delta(1620)$ and $\Delta(1700)$ in terms of quasi-local two-body interaction terms. We obtain a fair description of the experimental data relevant for the properties of slow vector-mesons in nuclear matter. The resulting s-wave ρ- and ω-meson nucleon scattering amplitudes, which define the leading density modification of the ρ- and ω-meson spectral functions in nuclear matter, are presented.

Keywords: meson-nucleon scattering, vector mesons in matter
PACS: 25.20.-x, 25.80.Hp, 11.80.Gw, 12.40.Vv, 14.20.Gk, 14.40.Cs

1. Introduction

The in-medium properties of hadrons is a topic of high current interest. The decay of vector mesons into e^+e^- and $\mu^+\mu^-$ pairs offers a unique tool to explore the properties of dense and hot matter in nuclear collisions. The lepton pairs provide virtually undistorted information on the current-current correlation function $\langle j_\mu j_\nu \rangle$ in the medium [1]. At invariant masses in the range $500-1000$ MeV, $\langle j_\mu j_\nu \rangle$ is sensitive to in-medium modifications of the mass distribution of the light vector mesons ρ and ω. There is a longstanding and controversial discussion about the vector meson properties in dense nuclear matter [2–5]. To leading order in the baryon density, modifications of the mass distribution are determined by the vector-meson nucleon scattering amplitudes. Since these amplitudes are not directly constrained by data, the predictions for the vector-meson spectral densities in nuclear matter are strongly model dependent.

This work is an attempt to overcome this problem by using the constraints from data on pion- and photon-nucleon scattering considering in particular the ω- and ρ-meson production data in a systematic way. We construct a coupled-channel scheme for meson-baryon scattering, including the πN, ρN, ωN, $\pi\Delta$, ηN, $K\Lambda$ and $K\Sigma$ channels. In such a scheme the amplitudes for experimentally non-accessible processes like ρN and ωN scattering are constrained by the data on elastic πN scattering and inelastic reactions like the pion- and photon-induced production of vector mesons. Our goal is to determine the vector-meson nucleon scattering amplitudes close to threshold. Consequently we concentrate on the energy window $1.4\ \mathrm{GeV} < \sqrt{s} < 1.8\ \mathrm{GeV}$. It is sufficient to consider only s-wave scattering in the ρN and ωN channels. This implies that in the πN and $\pi\Delta$ channels we need only s- and d-waves. In particular, we consider the S_{11}, S_{31}, D_{13} and D_{33} partial waves of πN scattering. In order to systematically derive the momentum dependence of the vector-meson self energy, vector-meson nucleon scattering also in higher partial waves would have to be considered.

2. Relativistic coupled-channel dynamics

Here we only outline our model, the detailed discussion can be found in [6]. We construct an effective Lagrangian with quasi-local four-point meson-baryon contact interactions in order to study the meson-baryon scattering process. Within this framework, the Bethe-Salpeter equation for the coupled-channel system reduces to a matrix equation.

The general four-point interaction Lagrangian for the coupled-channel problem in momentum space can be written in the form

$$\mathcal{L}(\bar{k},k;w) = \sum_I R^{(I)\,\dagger}(\bar{q},\bar{p})\,\gamma_0\,K^{(I)}(\bar{k},k;w)\,R^{(I)}(q,p) \;+\ldots\,, \tag{1}$$

where $K^{(I)}_{ab}(\bar{k},k;w)$ is a channel dependent interaction matrix, which in general is a function of the relative momenta of the initial and final states $k=\frac{1}{2}(p-q)$ and $\bar{k}=\frac{1}{2}(\bar{p}-\bar{q})$ as well as the total momentum $w=p+q=\bar{p}+\bar{q}$. The state vectors $R^{(I)}(q,p)$ involve the positive frequency parts of the fields specifying the various channels.

The coupled-channel Bethe-Salpeter equation projected onto a given isospin then reads

$$\begin{aligned} T^{(I)}_{ab}(\bar{k},k;w) &= K^{(I)}_{ab}(\bar{k},k;w) + \sum_{c,d}\int\frac{d^4l}{(2\pi)^4}\,K^{(I)}_{ac}(\bar{k},l;w)\,G^{(I)}_{cd}(l;w)\,T^{(I)}_{db}(l,k;w)\,,\\ G^{(I)}_{cd}(l;w) &= -i\,D_{\Phi(I,c)\Phi(I,d)}(\frac{1}{2}\,w-l)\,S_{B(I,c)B(I,d)}(\frac{1}{2}\,w+l)\,, \end{aligned} \tag{2}$$

where $D_{\Phi(I,c)\Phi(I,d)}(q)$ and $S_{B(I,c)B(I,d)}(p)$ denote the meson and baryon Feynman propagators in a given channel of isospin I. A convenient labelling of the channels

is obtained by defining

$$\Phi(\tfrac{1}{2},a) = (\pi,\pi,\rho_\mu,\omega_\mu,\eta,K,K)_a\ , \qquad B(\tfrac{1}{2},a) = (N,\Delta_\mu,N,N,N,\Lambda,\Sigma)_a\ ,$$
$$\Phi(\tfrac{3}{2},a) = (\pi,\pi,\rho_\mu,K)_a\ , \qquad B(\tfrac{3}{2},a) = (N,\Delta_\mu,N,\Sigma)_a\ . \tag{3}$$

The general form of the interaction kernel may be obtained from a meson exchange model or more systematically from the chiral Lagrangian. In this paper we construct an effective field theory for meson-nucleon scattering in the resonance region. The philosophy of this approach is to approximate the interaction kernel K but to treat rescattering in the s-channel explicitly. In our scheme, we assume that the interaction kernel is slowly varying in energy in the relevant window 1.4 GeV$< \sqrt{s} <$ 1.8 GeV.

We constrain our model parameters by data from meson- and photon-nucleon reactions. For the latter we employ a gauge invariant generalization of the phenomenologically successful vector-meson dominance (VMD) model. In the original VMD formulation of Sakurai [7], the vector meson is converted into a photon via the interaction terms $A^\mu \rho_\mu^{(0)}$ and $A^\mu \omega_\mu$. Since these terms violate gauge invariance, we use a modified vector-meson dominance assumption, where the strength of the $\gamma N \to X$ vertex $K^{(I),\mu}_{\gamma N\to X}(\bar{q},q;w)$ is related to the $\rho^{(0)} N \to X$ and $\omega N \to X$ vertices through the relations:

$$\begin{aligned}
&\frac{1}{2}\left(K^{(\frac{1}{2}),\,\mu}_{\gamma\, p\to X} + K^{(\frac{1}{2}),\,\mu}_{\gamma\, n\to X}\right)(\bar{q},q;w) = e\, K^{(\frac{1}{2})}_{\nu,\,\omega N\to X}(\bar{q},q;w)\,\Gamma_S^{\nu\mu}(q;w)\,,\\
&\frac{1}{2}\left(K^{(\frac{1}{2}),\,\mu}_{\gamma\, p\to X} - K^{(\frac{1}{2}),\,\mu}_{\gamma\, n\to X}\right)(\bar{q},q;w) = \frac{e}{\sqrt{3}}\, K^{(\frac{1}{2})}_{\nu,\,\rho N\to X}(\bar{q},q;w)\,\Gamma_V^{\nu\mu}(q;w)\,,\\
&K^{(\frac{3}{2}),\,\mu}_{\gamma\, p\to X}(\bar{q},q;w) = e\sqrt{\tfrac{2}{3}}\, K^{(\frac{3}{2})}_{\nu,\,\rho N\to X}(\bar{q},q;w)\,\Gamma_V^{\nu\mu}(q;w)\,,\\
&K^{(\frac{3}{2}),\,\mu}_{\gamma\, n\to X}(\bar{q},q;w) = e\sqrt{\tfrac{2}{3}}\, K^{(\frac{3}{2})}_{\nu,\,\rho N\to X}(\bar{q},q;w)\,\Gamma_V^{\nu\mu}(q;w)\,.
\end{aligned} \tag{4}$$

Here X stands for any hadronic two-body final state with isospin I. The transverse objects $\Gamma^{\mu\nu}_{S(V)}(q;w)$ are the most general transition tensors compatible with gauge invariance. We note that our model is in spirit close to the picture that emerges in the hidden local symmetry approach [8]. Further details can be found in [6].

3. Results

In accordance with the effective field theory approach only data in an appropriate kinematical window is used in the analysis. The threshold for vector-meson production off a nucleon is at $\sqrt{s} \simeq 1.7$ GeV. Close to the elastic pion-nucleon threshold we do not expect our scheme to be efficient. We therefore fit the data in the energy range 1.4 GeV $\leq \sqrt{s} \leq$ 1.8 GeV, with the energy independent coupling matrices. Our model includes four coupled-channel matrices carrying quantum numbers $I = \frac{1}{2}, \frac{3}{2}$ and $J = \frac{1}{2}, \frac{3}{2}$.

The set of parameters is adjusted to describe the partial-wave pion-nucleon phase shifts and inelasticity parameters. Furthermore the pion- and photon-induced production cross sections of pseudo-scalar meson and vector mesons are considered. All together we include $N = 1156$ data points. We obtained a fair description of the experimental data [6].

As a result of our fit the s- and d-wave baryon resonances $N(1535)$, $N(1650)$, $N(1520)$, $N(1700)$, $\Delta(1620)$ and $\Delta(1700)$ are generated dynamically in our scheme. In particular we find that the s-wave resonances $N(1535)$ and $N(1650)$ show a strong ωN component, which are required to simultaneously generate both resonances. On the other hand, only the $N(1535)$ but not the $N(1650)$ resonance appears to couple significantly to the ρN channel.

In contrast to previous coupled channel calculations, we find a fairly weak coupling of the $N(1520)$ to the ρN channel. Because of this we discuss this channel in some detail. The extraction of the coupling of the $N(1520)$ to the ρN channel from hadronic reactions alone is model dependent. Different analyses of the $\pi N \to N2\pi$ data differ by large factors [9, 10]. To remove this ambiguity was an important motivation for considering the additional constraints provided by the multipole amplitudes for the reaction $\gamma N \to \pi N$ within the generalized vector meson dominance model.

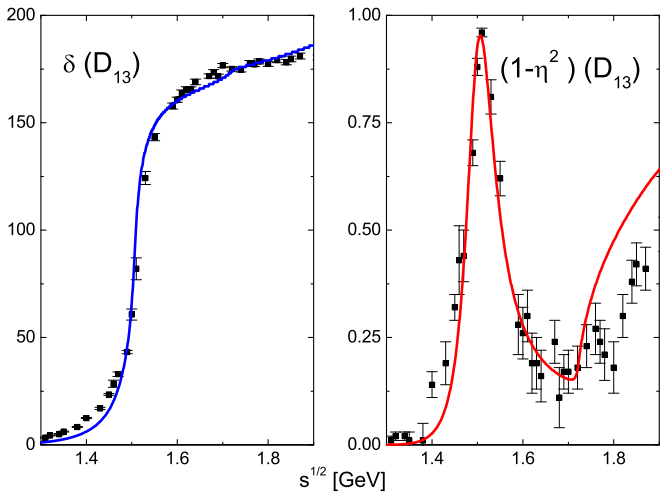

Fig. 1. Pion-nucleon scattering phase shift $\delta_{D_{13}}$ and inelasticity parameter $\eta_{D_{13}}$ of the D_{13} channel. We compare to the single-energy solution SP98 of [12, 13]

We obtain a good description of the πN scattering phase shifts in the relevant energy window (see Fig. 1). Within this framework, we find a consistent description of the ρ production cross section of [9] and of the multipole amplitudes in all four

channels (see Fig. 2). One important remark is here in order. We retain only the leading operators in th ρN and ωN channels in calculating the multipole amplitudes $E_{2-}(D_{13})$ and $M_{2-}(D_{13})$. Contributions of higher order operators are suppressed by at least two powers of the phase space factor $p_{\gamma N}$, the relative momentum in the cm system of γN. In view of this uncertainty the results shown in Fig. 2 provide a fair description of the resonance structures in the multipole amplitudes.

In our previous analyses [11], where we did not include constraints from the γ induced production data we obtained a significantly larger ratio $f_{\rho N}^{(1520)}/f_{\omega N}^{(1535)} \simeq 0.9$ compared to 0.38 obtained in this work. We point out, however, that once the γ induced production data, in particular the electric and magnetic multipole amplitudes E_{2-} and M_{2-} describing the γ-induced pion production data, are considered (see Fig. 2), the coupling of the $N(1520)$ resonance to the ρN channel is reduced. Data on the dilepton production process $\pi^- p \to n\, e^+ e^-$ are expected to provide further constraints on the vector-meson coupling strengths to the subthreshold baryon resonances. In this reaction the subthreshold vector-meson nucleon production amplitudes, required for the determination of $f_{\rho N}^{(1520)}$ and $f_{\omega N}^{(1520)}$ [15] are probed.

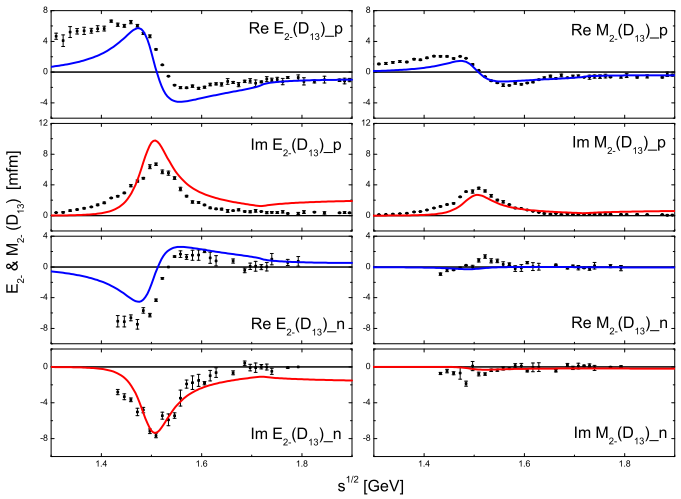

Fig. 2. Electric and magnetic multipole amplitudes $E_{2-}(D_{13})_{p,n}$ and $M_{2-}(D_{13})_{p,n}$ of photon-induced pion production. It is shown the single energy solution SM00 [14, 13]

Using our value for the resonance coupling constant we obtain a ρN-partial decay width of 2 MeV for a ρ-meson spectral function with an energy dependent, and 13 MeV with an energy-independent ρ-meson width. Thus, for a given value of the $\rho N N(1520)$ coupling constant, the ρN width of the $N(1520)$ depends crucially on the model for the ρ-meson spectral function.

We emphasize that any microscopic theory of the in-medium properties of vector mesons requires the information encoded in the ρN and ωN scattering amplitudes as input. For the spin and isospin averaged scattering lengths we find:

$$\bar{a}_{\rho N} \simeq (-0.09 + i\,0.24)\,\mathrm{fm}, \qquad \bar{a}_{\omega N} \simeq (-0.44 + i\,0.20)\,\mathrm{fm}. \tag{5}$$

We use the resulting vector-meson scattering amplitudes to compute the propagation of the ρ and ω mesons in nuclear matter. Using the low-density theorem the self energy of a vector meson in nuclear matter is expressed in terms of the s-wave scattering amplitude averaged over spin and isospin [16].

In Fig. 3 we show the vector meson spectral functions at the saturation density of nuclear matter, $\rho_0 = 0.17\ \mathrm{fm}^{-3}$ and at $\rho = 2\rho_0$. For the ρ meson we note an enhancement of the width, and a downward shift in energy, due to the mixing with the baryon resonances at $\sqrt{s} = 1.5 - 1.6$ GeV. At $\rho = \rho_0$ the center-of-gravity of the spectral function is shifted down in energy by about 3 %. The in-medium propagator of the ω meson exhibits two distinct quasiparticles, an ω like mode, which is shifted up somewhat in energy, and a resonance-hole like mode at low energies. The low-lying modes carry about 15 % on the energy-weighted sum rule. The center-of-gravity is shifted down by about 4 %. However, we stress that the structure of the in-medium ω-meson spectral function clearly cannot be characterized by this number alone.

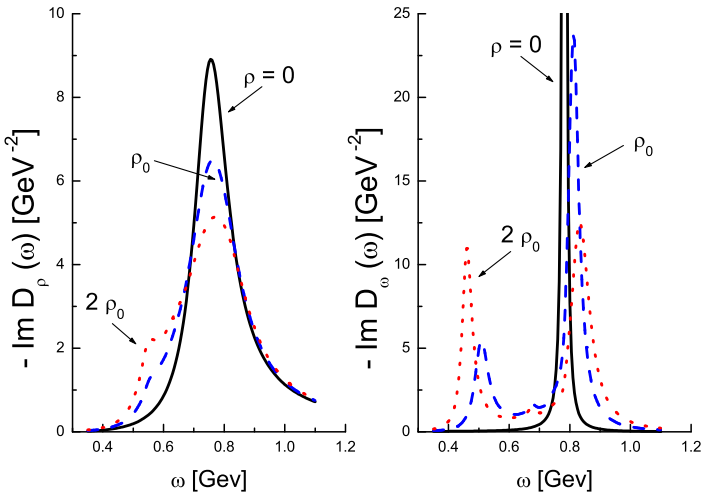

Fig. 3. Imaginary parts of the ρ and ω propagators in nuclear matter at $\rho = \rho_0$ and $2\rho_0$, compared to those of the free-space propagators.

A simple estimate on the accuracy of the leading order result follows by investigating the size of the leading correction term determined by the Pauli blocking

effect. Take for example the upper peak in the ω meson spectral function for which its leading and subleading mass shift terms require only the s-wave scattering length $a^{\frac{1}{2}}_{\omega N} = (-0.45 + i0.31)$ fm and $a^{\frac{3}{2}}_{\omega N} = (-0.43 + i0.15)$ fm [6]. At nuclear saturation density the correction term of order k_F^4 implies a further repulsive mass shift of 1 MeV and increase of the decay width of 2 MeV for the ω meson. Thus, we expect that the results obtained with only the leading term in the low-density expansion are qualitatively correct at normal nuclear matter density. However, on a quantitative level, the spectral functions may change when higher order terms in the density expansion are included. For instance, we expect that the in-medium properties of the baryon resonances depend sensitively on the meson spectral functions. If this is the case, a self consistent calculation, which corresponds to a partial summation of terms in the density expansion, would have to be performed [17].

4. Summary and conclusion

In this work we extracted the amplitudes that describe the s-wave scattering of the light vector mesons off nucleons. To leading order in a density expansion these amplitudes determine the spectral functions of the ρ- and ω-meson in nuclear matter. Since data on vector-meson nucleon scattering is not available we constrained our analysis by all relevant elastic and inelastic γN and πN data. The coupled channel unitarity condition together with the causality property of local quantum field theory then leads to quite robust predictions for the vector-meson nucleon scattering amplitudes. Our amplitudes show rapid energy variations due to the presence of nucleon and isobar resonances. In our novel and covariant coupled channel approach, where the γN, πN, $\pi\Delta$, ρN, ωN, ηN, $K\Lambda$ and $K\Sigma$ states are included, the s- and d-wave nucleon and isobar resonances are generated dynamically by coupled channel effects. In nuclear matter our scattering amplitudes lead to a ω-meson spectral functions with considerable support at energies smaller than the free-space mass representing resonance nucleon-hole type excitations. On the other hand, as an immediate consequence of the moderate strength of the coupling to the ρN channel in the $N(1520)$ d-wave resonance, the in-medium effects for the ρ meson are found to be significantly smaller as compared to previous works.

The results of our work are relevant for the experimental program at GSI. The HADES detector will help to further explore the properties of the light vector mesons in nuclear matter by measuring their dilepton final state with high accuracy. Complementary experimental programs are pursued at Jefferson Lab, MAMI and KEK with photon and nucleon induced reactions off nuclei. To further substantiate the structure of the vector-meson nucleon scattering amplitudes it would be desirable to establish a more microscopic understanding of the effective interaction vertices employed in our work.

Acknowledgement(s)

This work were partly supported by Hungarian Research Foundation (OTKA) grants: T 32038 and T 30855.

Notes

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