FROM MESON-NUCLEON SCATTERING TO
VECTOR MESONS IN NUCLEAR MATTER

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Abstract

We employ meson-nucleon scattering data to deduce the properties of
the low-mass vector mesons in nuclear matter, and present results for
the $\rho$ and $\omega$ in-medium spectral functions. The corresponding thermal
emission rate for lepton pairs is also discussed.

1 Introduction

The in-medium properties of hadrons is a topic of high current interest. This
is manifested e.g. by the flurry of activity triggered by the observed
enhancement in the production of low-mass lepton pairs \cite{1, 2, 3} in relativistic
nucleus-nucleus collisions. While “standard” models, where the properties
of the hadrons are not modified in the medium, fail to reproduce the data \cite{4},
models where medium effects of some kind are invoked, are more successful.
The low-mass enhancement in the lepton-pair spectrum has been interpreted
in terms of a modification of the mass and/or width of the $\rho$ meson in a dense
hadronic environment \cite{5, 6, 7}.

In this talk we present a novel approach, which allows us to systematically
explore the properties of $\rho$ and $\omega$ mesons in nuclear matter. We employ a
general scheme, the low-density expansion, to establish a connection between the
meson-nucleon scattering amplitudes and the properties of mesons in nuclear
matter \cite{8}. This scheme leads to a systematic expansion for the in-medium self
energy of a meson (in general any particle), in terms of the corresponding vac-
uum scattering amplitudes. The vector-meson–nucleon scattering amplitudes
are not directly related to experimental observables. However, it may be pos-
sible to determine them indirectly in a coupled-channel scheme, where the $\rho N$
and $\omega N$ channels enter in intermediate and final states of measured processes.
Here we present a calculation along these lines, where we fix the parameters of
an effective field theory by fitting the available meson-nucleon scattering data in the relevant energy range. We then employ the scattering amplitudes to construct the vector-meson self energies in nuclear matter to leading order in density. Our results are relevant for the study of vector mesons in nuclei and perhaps in nucleus-nucleus collisions at GSI energies. On the other hand, at CERN energies, where the medium presumably is drastically different from the cold nucleon liquid addressed in this calculation, our results should be applied with caution.

The aim of this work is to obtain the leading in-medium correction to the properties of the $\rho$ and $\omega$ mesons in a tenable scheme, where subleading terms can be systematically computed. A major advantage of such an approach is that it is possible to check the convergence of the expansion. On the other hand, at present it does not allow us to address the question whether modifications of the properties of vector mesons in matter are connected with the restoration of chiral symmetry in matter. We leave this intriguing question for future work.

2 Meson-nucleon scattering

In this section we describe a relativistic and unitary coupled channel approach to meson-nucleon scattering [9]. The following channels are considered: $\pi N$, $\rho N$, $\omega N$, $\pi \Delta$, $\eta N$, $K \Lambda$ and $K \Sigma$. Our goal is to determine the vector-meson–nucleon scattering amplitude and then compute the self energy of a vector meson in nuclear matter to leading order in density. In this work we focus on vector mesons with small or zero 3-momentum with respect to the nuclear medium. Therefore it is sufficient to consider only s-wave scattering in the $\rho N$ and $\omega N$ channels [4]. This implies that in the $\pi N$ channel we need to consider only the $S_{11}, S_{31}, D_{13}$ and $D_{33}$ partial waves. Furthermore, we include the pion-induced production of $\eta$, $\omega$ and $\rho$ mesons off nucleons as well as the reactions $\pi^- p \rightarrow K^0 \Lambda$ and $\pi^+ p \rightarrow K^+ \Sigma^+$. In addition to the hadronic observables employed in the fit, we use photo-induced production of pseudoscalar mesons, assuming vector-meson dominance, to eliminate an ambiguity in the $S_{11}$ channel.

We recall that at small nuclear matter densities the spectral function of a vector meson with energy $\omega$ and zero momentum probes the vector-meson nucleon scattering process at $\sqrt{s} \sim m_N + \omega$. In order to learn something about the momentum dependence of the vector-meson self energy, vector-meson–nucleon scattering also in higher partial waves would have to be considered [10].

\[1\] Also in the other ‘heavy’ channels ($\eta N$, $K \Lambda$, $K \Sigma$) only s-waves are considered so far.
In accordance with the ideas outlined above, only data in the relevant kinematical range will be used in the analysis. The threshold for vector-meson production off a nucleon is at $\sqrt{s} \simeq 1.7$ GeV. We fit the data in the energy window $1.4 \text{ GeV} \leq \sqrt{s} \leq 1.9$ GeV, using an effective Lagrangian with local 4-point meson-meson–baryon-baryon interactions. For details the reader is referred to ref. [9].

In fig. 1 our result for the $\pi N$ scattering is illustrated by the $S_{11}$ channel. In the remaining channels the fit is of similar quality. Furthermore, in fig. 2 the cross sections for the reactions $\pi^- p \rightarrow \rho^0 n$, $\pi^- p \rightarrow \omega n$, $\pi^- p \rightarrow K^0 \Lambda$ and $\pi^+ p \rightarrow K^+ \Sigma^+$ are shown. The agreement with the data is good close to threshold, where $s$-waves in the final state are expected to dominate. At higher energies there is room for higher partial waves. For the $K^+ \Sigma^+$ channel we use the partial-wave analysis of ref. [13] to extract the $s$-wave contribution to the cross section, shown by the triangles in fig. 2 d. Not shown are the cross sections for the reactions $\pi^- p \rightarrow \eta n$ and $\pi^+ p \rightarrow \rho^+ p$. We obtain a good description of the former up to $s^{1/2} \simeq 1.7$ GeV, where the $p$-wave contribution is expected to set in. In view of the scarce data at low energies in the latter channel, we find a reasonable fit [9].

The bumps in the $\rho$-production cross section at $\sqrt{s}$ below 1.6 GeV are due

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1. In the $s$-wave $\pi N$ scattering channels we extend the energy window down to 1.2 GeV.
Figure 2: The cross sections for the reactions a) $\pi^- p \rightarrow \rho^0 n$, b) $\pi^- p \rightarrow \omega n$, c) $\pi^- p \rightarrow K^0 \Lambda$ and d) $\pi^+ p \rightarrow K^+ \Sigma^+$. The data are from ref. [12] and the partial-wave analysis used in d) from ref. [13].

to the coupling to resonances below the threshold, like the $N^*(1520)$. This indicates that these resonances play an important role in the $\rho$-nucleon dynamics, in agreement with the results of Manley and Saleski [14]. We have extracted coupling constants for the vector mesons to some of the resonances. For instance, for the $N^*(1520)$ we use the non-relativistic interaction Lagrangian [15]

$$\mathcal{L}_{\text{int}} = \frac{f_{N^*V}}{m_V} \Psi_{N^*} \cdot (\vec{S} \cdot \vec{V} q_0 - V_0 \vec{S} \cdot \vec{q}) \Psi_N + \text{h.c.},$$

where $\vec{S}$ is the transition spin operator and $V^\mu = \rho^\mu \cdot \tau, \omega^\mu$. The $\rho N \rightarrow \rho N$ and $\omega N \rightarrow \omega N$ scattering amplitudes obtained in our model are then fitted with Breit-Wigner amplitudes, where the decay of the resonance into the vector-meson–nucleon channel is described by the interaction (1). We find a $\rho$ meson
coupling to the $N^*(1520)$ of $f_{N^*N\rho} = 3.2$. Note that our value is a factor two smaller than that extracted by Peters et al. [15]. This is at least in part due to the fact that we use the cross section for pion-induced $\rho$ production of Brody et. al [16] (Fig. 2 a)), while Peters et al. [15] use a partial width for the decay $N^*(1520) \to \rho N$, extracted from the analysis of Manley and Saleski [14]. Close to the threshold [17], the cross section implicit in the analysis of Manley and Saleski is much larger than that of Brody et. al. This difference may reflect the difficulties involved in extracting the $\rho$ production cross section close to threshold. Data on pion-induced production of $e^+e^-$ pairs in this energy regime would provide additional constraints on the amplitudes, which may allow one to greatly reduce this uncertainty [18].

We also find a strong $\omega$ coupling to the $N^*(1520)$, $f_{N^*N\omega} = 6.5$. Furthermore, we find that the $N^*(1535)$ resonance couples strongly to the $\rho$ channel, while the $N^*(1650)$ interacts strongly with both vector-meson channels. These findings are qualitatively consistent with the photon decay helicity amplitudes, assuming vector-meson dominance [17, 19]. We note the the hadronic observables used in the fit do not determine the relative phases of off-diagonal amplitudes, like e.g. those of the $\pi N \to \rho N$ and $\pi N \to \omega N$ reactions. These phases are of course crucial for the interference in the pion-induced production of $e^+e^-$ pairs [18]. We determine the phases by comparing with the photon-decay helicity amplitudes of the resonances in each channel [19].

The resulting $\rho$- and $\omega$-nucleon scattering amplitudes are shown in Fig. 3. The $\rho - N$ and $\omega - N$ scattering lengths, defined by $a_{VN} = f_{VN}(\sqrt{s} = m_N + m_V)$,
$m_V$), are $a_{\rho N} = (-0.1+0.6 \, i)$ fm and $a_{\omega N} = (-0.5+0.2 \, i)$ fm. To lowest order in density, this corresponds to the following in-medium modifications of masses and widths at nuclear matter density: $\Delta m_{\rho} \simeq 10 \text{ MeV}$, $\Delta m_{\omega} \simeq 50 \text{ MeV}$, $\Delta \Gamma_{\rho} \simeq 120 \text{ MeV}$ and $\Delta \Gamma_{\omega} \simeq 40 \text{ MeV}$. However, as we show in the next section, the coupling of the vector mesons to baryon resonances below threshold, which is reflected in the strong energy dependence of the amplitudes, cannot be neglected.

3 Vector mesons in nuclear matter

In this section we present results for the propagators of the $\rho$- and $\omega$-mesons at rest in nuclear matter, obtained with the scattering amplitudes presented in section 2, to leading order in density. The low-density theorem states that the self energy, $\Delta m_V^2(\omega)$, of a vector meson $V$ in nuclear matter is given by

$$\Delta m_V^2(\omega) = -4 \pi (1 + \frac{\omega}{m_N}) f_{VN} (\sqrt{s} = m_N + \omega) \rho_N + \ldots ,$$

where $\omega$ is the energy of the vector meson, $m_N$ the nucleon mass, $\rho_N$ the nucleon density and $f_{VN}$ denotes the $VN$ s-wave scattering amplitude averaged over spin and isospin. In fig. 4 we show the resulting propagators at the saturation density of nuclear matter, $\rho_0 = 0.17 \text{ fm}^{-3}$ and at $\rho = 1.5\rho_0$. For the $\rho$ meson we note a strong enhancement of the width, and a downward shift in energy, due to the mixing with the baryon resonances at $\sqrt{s} = 1.5 - 1.6 \text{ GeV}$. 

Figure 4: Imaginary parts of the $\rho$ and $\omega$ propagators in nuclear matter at $\rho = \rho_0$ and $1.5\rho_0$, compared those in vacuum.
At $\rho = \rho_0$ the lower peak carries about 20% of the energy-weighted sum rule, while the center-of-gravity of the spectral function is shifted down in energy by $\simeq 10\%$. As the density is increased, more strength is shifted down to the resonance-hole like peak at low energies and the width of the $\rho$-like peak is enhanced.

The in-medium propagator of the $\omega$ meson exhibits three distinct quasiparticles, an $\omega$ like mode, which is shifted up somewhat in energy, and resonance-hole like modes at low energies. The low-lying modes carry about 20% on the energy-weighted sum rule. Again, the center-of-gravity is shifted down by $\simeq 10\%$. However, we stress that the structure of the in-medium $\omega$ spectral function clearly cannot be characterized by this number alone.

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, it may be 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 [20, 15].

Finally, in Fig. 5 we show thermal rates for lepton-pair production due to the decay of in-medium $\rho$ and $\omega$ mesons in uniform nuclear matter at temperatures $T = 80$ and 140 MeV and densities $\rho/\rho_0 = 0, 0.5, 1.0, 1.5$. We consider
only back-to-back pairs, since the model includes only s-wave vector-meson-nucleon interactions so far. At $T = 140$ MeV, which corresponds roughly to the conditions expected in heavy-ion collisions at CERN energies, the resonance-hole like mode in the $\rho$ channel gives rise to a strong enhancement in the invariant-mass region 400-600 MeV, where the CERES and HELIOS-3 experiments find an excess of lepton pairs [1, 3]. The low-energy tail of the $\rho$-meson spectral function yields a fairly constant contribution down to the pion threshold. At the lower temperature ($T = 80$ MeV), which approximately corresponds to GSI/SIS energies, the relative enhancement is even stronger.

4 Conclusions

A relativistic and unitary, coupled channel approach to meson-nucleon scattering was presented. The parameters of the effective interaction are determined by fitting elastic pion-nucleon scattering and pion-induced meson production data in the relevant energy regime. We obtain a good overall description of the data and a model for the $\rho$- and $\omega$-N scattering amplitudes, which in turn allows us to compute the vector-meson self energies in nuclear matter. In this approach we minimize the model dependence and avoid the potentially dangerous extrapolation from low-energy data [10, 21]. Further constraints on the vector-meson scattering amplitudes, in particular in the subthreshold regime, can be obtained from the reaction $\pi N \rightarrow e^+e^-N$, which is discussed in the talk of M. Soyeur [18].

An prominent feature of the scattering amplitudes is the strong coupling to baryon resonances below threshold. This leads to two characteristic features of the vector-meson spectral functions, namely repulsive scattering lengths and a spreading of the vector-meson strength to states at low energy. The latter is qualitatively what seems to be required by the heavy-ion data. Clearly, complementary experiments with e.g. photon and pion induced vector meson production off nuclei would be extremely useful for exploring the in-medium properties of these mesons in more detail.

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