Energy and density dependence of the $\bar{K}N$ and ηN amplitudes near threshold

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Chirally motivated model is used to describe meson-baryon interactions at low energies. After fixing free parameters to available experimental data on reactions in the free space the model is extrapolated to subthreshold energies and to nonzero nuclear densities. The impact of nuclear matter on the elastic $\bar{K}N$ and ηN amplitudes is discussed.

1 Introduction

The modern approach to low-energy meson baryon interactions is based on chiral dynamics that implements the QCD symmetries in a nonperturbative region infested by presence of baryon resonances. There, the standard perturbation theory fails but the higher order contributions can be (at least in their major part) accounted for by using coupled channels and resummation techniques based on Lippmann-Schwinger or Bethe-Salpeter equation.

In our contribution we demonstrate the effects of nuclear medium on the $\bar{K}N$ and ηN amplitudes. We employ effective separable potentials that match the meson-baryon amplitudes up to NLO order in the chiral perturbative expansion. These potentials are then inserted into Lippmann-Schwinger equation to get the amplitudes which are then used to calculate the measurable quantities, typically cross sections or branching ratios of specific processes. The separable potentials are particularly useful for in-medium applications where the off-shell form factors provide a natural extension to account for two-body inelasticities related to many particle dynamics. This feature represents an advantage over more popular on-shell approaches based on dispersion relation for the inverse of the scattering T-matrix or on the so called N/D method.

2 The model

In the present work we consider low energy s-wave interactions of the basic 0^- meson octet (π, K, $\bar{K}$, η) with the $1/2^+$ octet of baryons (N, Λ, Σ, Ξ). The separable potential model adopted by us was invented by Kaiser, Siegel and Weise [1] who related the kernel of the Lippmann-Schwinger equation to the scattering amplitude constructed from an effective chiral Lagrangian.

The potential matrix reads as

$$V_{ij}(k,k';\sqrt{s}) = g_i(k^2)\, v_{ij}(\sqrt{s})\, g_j(k'^2) \tag{1}$$

$$v_{ij}(\sqrt{s}) = -\frac{C_{ij}(\sqrt{s})}{4\pi f_i f_j}\sqrt{\frac{M_i M_j}{s}} \tag{2}$$

where the indexes i, j run over the space of involved meson-baryon coupled channels and the off-shell form factors are taken in the Yamaguchi form, $g_j(k) = 1/[1+(k/\alpha_j)^2]$, with the inverse ranges α_j introduced as free parameters of the model. The central inter-channel couplings C_{ij} are energy dependent and determined by the chiral SU(3) symmetry, k (k') denotes the CMS meson momenta in the initial (final) state, $\sqrt{s}$ is the total CMS energy and M_j stand for baryon masses. f_j represents a meson decay constant and we allow for its different physical values f_π, f_K and f_η depending on the meson in a specific j-th channel. The transition amplitudes obtained as simple algebraical solutions of the Lippmann-Schwinger equation are also separable,

$$F_{ij}(k,k';\sqrt{s}) = g_i(k^2)\, f_{ij}(\sqrt{s})\, g_j(k'^2) \tag{3}$$

$$f_{ij}(\sqrt{s}) = \left[(1 - v\cdot G(\sqrt{s}))^{-1}\cdot v\right]_{ij} \tag{4}$$

where the Green function $G(\sqrt{s})$ is diagonal in the channel space and becomes density dependent in nuclear medium. In general, the intermediate state Green function can be written as

$$G_n(\sqrt{s},\rho) = -4\pi \int_{\Omega_n(\rho)} \frac{d^3p}{(2\pi)^3}\frac{g_n^2(p^2)}{k_n^2 - p^2 - \Pi_n(\sqrt{s},p;\rho) + \mathrm{i}0} \tag{5}$$

Here the impact of nuclear medium is twofold. Foremostly, for channels involving nucleons the Pauli exclusion principle restricts the integration space to a domain Ω_n of allowed nucleon momenta. In addition, the in-medium hadron selfenergies shift the pole of the propagator by a sum of meson and baryon selfenergies represented by the $\Pi_n(\sqrt{s},p;\rho)$ in Eq. (5). In a free space, when the integration goes over the whole momentum space and $\Pi_n(\sqrt{s},p;\rho) = 0$, the integral has an analytical form while in nuclear matter the integration has to be performed numerically. Normally, one also constructs the meson selfenergies from the in-medium meson-baryon amplitudes, so a selfconsistent treatment is required (see Ref. [2] for details).

The model was successfully applied to describe the available low energy experimental data for K^-p reactions including the recent precise measurement of the kaonic hydrogen characteristics by the SIDDHARTA collaboration. Later on, the same methodology was used to describe the data on πN scattering and $\pi p \longrightarrow \eta n$ reaction. We refer the reader to our previous publications [3] and [4] for the details of the fitting procedure, the quality of the fits, and for all other relevant information including references to the experimental data. In general, the quality of the fits in the $\bar{K}N$ sector is quite good when only the TW term is accounted for while the inclusion of higher order NLO contributions is mandatory to achieve realistic description of the experimental data in the $\pi N - \eta N$ sector.

3 $\bar{K}N$ and ηN amplitudes

In Figure 1 we demonstrate the impact of nuclear medium on the elastic K^-p amplitude as obtained with the NLO30 model from Ref. [3]. The energy dependence of the amplitude in vacuum (shown by the dotted lines) is clearly affected by the presence of the $\Lambda(1405)$ resonance with a peak of the imaginary part $\Im F_{K^-p}$ located around 1400 MeV. We note in passing that the NLO30 model generates poles of the amplitude at energies $z_{\bar{K}N} = (1418 - \mathrm{i}44)$ MeV and $z_{\pi\Sigma} = (1355 - \mathrm{i}86)$ MeV, so the peak and poles positions are not trivially related. The Pauli blocking shifts the $\Lambda(1405)$ structure above the $\bar{K}N$ threshold and the resonance is partially dissolved in nuclear matter. However, the incorporation of hadron selfenergies has an opposing effect moving the structure back below the threshold and leading to a rapid increase of attraction in the real part of the amplitude for energies about 30 MeV below the $\bar{K}N$ threshold. Since the K^-n amplitude is much smaller in magnitude and its energy dependence is not so profound, the overall effect on K^- propagation in nuclear matter is as follows. While antikaon feels a moderate attraction at energies around and above the threshold much larger attraction is anticipated at subthreshold energies. This result is in line with phenomenological analysis of kaonic atoms, though even more attraction is required by the data, apparently due to $\bar{K}NN$ absorption [5].

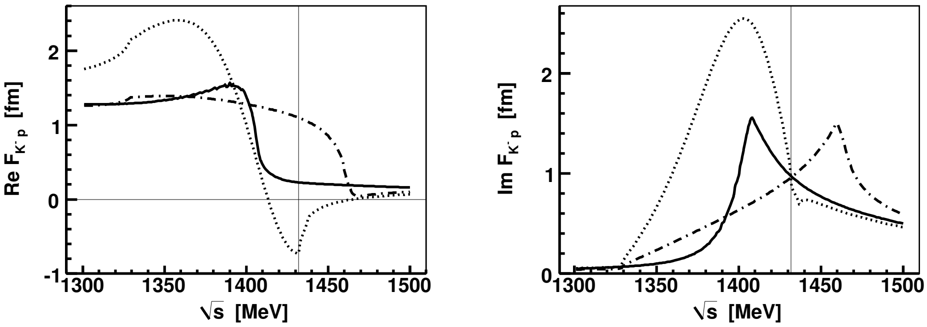

Figure 1: Energy dependence of the real (left panel) and imaginary (right panel) parts of the K^-p amplitude generated with the NLO30 model of Ref. [3]. The dotted lines show the free-space amplitude, the dot-dashed lines demostrate the effect of Pauli blocking and the dashed lines show the combined effect of Pauli blocking and hadron selfenergies. The $\bar{K}N$ threshold is marked by the thin vertical line.

While the subthreshold energy dependence of the $\bar{K}N$ amplitude is strongly affected by nuclear medium, the effect on the ηN amplitude is much less profound at least at subthreshold energies. This can be seen in Fig. 2 where the impacts of Pauli blocking and hadron selfenergies are visualized. The peak structure observed in the figure can be assigned to the $N^*(1535)$ resonance generated dynamically by the model. It is shifted to higher energies due to Pauli blocking and made more pronounced. The implementation of hadron selfenergies spreads the resonance structure over a large interval of energies and it practically dissolves in the nuclear matter. The main difference with respect to the $\bar{K}N$ case may be related to a different origin of the dynamically generated resonances. While the $\Lambda(1405)$ results from a quasi-bound $\bar{K}N$ molecular state the $N^*(1535)$ originates from a virtual $K\Xi$ state that is shifted to much lower energies by inter-channel dynamics. In effect, the in-medium dynamics of the $N^*(1535)$ resonance is not so strongly correlated with the ηN system as it is in the $\bar{K}N$ sector. Still, the ηN scattering length is reduced from $a_{\eta N} = (0.65 + \mathrm{i}0.15)$ fm in a free space to about $a_{\eta N} = (0.35 + \mathrm{i}0.13)$ fm in nuclear matter. This results into a sizeable reduction of η-nuclear attraction at the ηN threshold. However, the effect is much smaller at energies about 20-30

MeV below the threshold that are relevant for a possible existence of η-nuclear bound states.

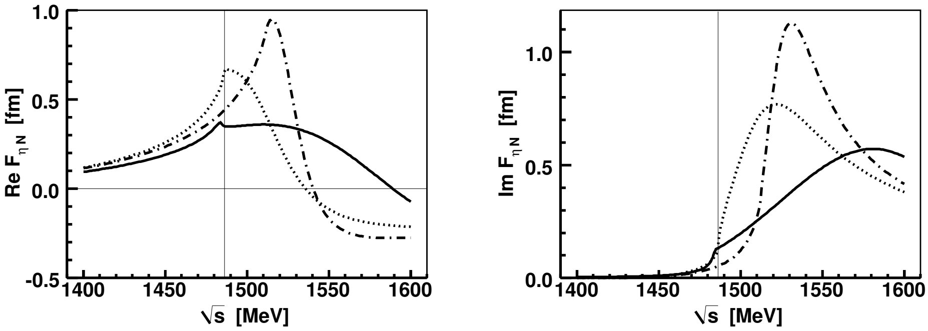

Figure 2: Energy dependence of the real (left panel) and imaginary (right panel) parts of the ηN amplitude obtained with the NLO30$_\eta$ model from Ref. [4]. The dotted lines show the free-space amplitude, the dot-dashed lines demostrate the effect of Pauli blocking and the dashed lines show the combined effect of Pauli blocking and hadron selfenergies. The ηN threshold is marked by the thin vertical line.

4 Summary

We have looked at an impact of nuclear medium on the energy dependence of the $\bar{K}N$ and ηN amplitudes. The most striking feature of the in-medium $\bar{K}N$ amplitude is represented by a sharp increase of the $\bar{K}N$ attraction at energies about $30 - 40$ MeV below the threshold. As it was shown in Refs. [2], [5] an anticipated energy shift from threshold to subthreshold $\bar{K}N$ energies provides a link between the shallow $\bar{K}$-nuclear optical potentials obtained microscopically from threshold $\bar{K}N$ interactions and the phenomenological deep ones deduced from kaonic atoms data. On the contrary, the ηN attraction is reduced in nuclear matter, both by the Pauli blocking and by the hadron selfenergies. Nevertheless, the subthreshold energy region is affected only moderately and it was shown in [6] that the in-medium ηN attraction appears sufficient to bind the η mesons in nuclei.

Acknowledgments

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