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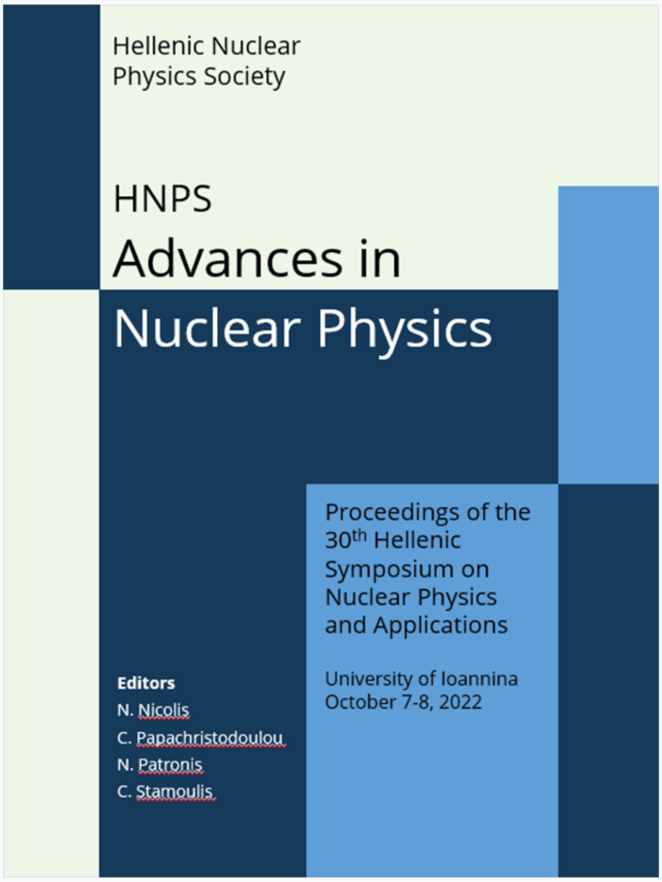

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Baryons and antibaryons in compressed nuclear matter

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Abstract In this work we discuss the in-medium properties of baryons and antibaryons in nuclear matter at densities beyond saturation. We focus attention on the in-medium optical potentials of heavy baryons with strangeness content, that is, the hyperons Λ, Σ with strangeness S=-1 and the cascade particle Ξ with S=-2. The particular treatment of the hyperons inside compressed matter is crucial in order to understand the in-medium modifications of baryons in matter conditions that may occur in the interior of neutron stars. We dicsuss further the properties of their antiparticles, since there are experimental data for the nucleonic sector (S=0), while for the strangeness sector (S=-1,-2) experimental information will be available in the near future at the new facilities, for instance, at FAIR and J-PARC.

Keywords Nuclear Equation of State, Strangeness Interactions, Hyperon potential

INTRODUCTION

In the last decades, many efforts have been made in order to understand the properties of hadrons in nuclear environments of high baryon densities. These efforts have been concentrated in the theoretical study of infinite nuclear matter, intermediate energy heavy-ion collisions and anti-hadron induced reactions, followed by experimental investigations of these nuclear reactions. The main focus of these studies has been to better understand the in-medium behaviors of hadrons at densities far above the saturation density of stable nuclei (see Refs. [1-3] for more details).

Nucleons are better accessible experimentally, thus detailed experimental data do exist from studies on heavy-ion and hadron beams on nuclear targets. The experimental measurements of yields and collective momentum distributions of nucleons together with precise data on meson (such as kaon) production allowed a precise understanding of the nuclear equation of state (EoS) at high densities. In intermediate energy nuclear reactions induced by heavy-ion beams, these densities can reach values of 2-3 times the saturation density of ordinary nuclear matter. The main conclusion was a rather soft EoS at such high densities. This was confirmed not only by phenomenological models, but successfully predicted by microscopic approaches too.

However, at supra-normal baryon densities the presence of baryons with strangeness content (hyperons) is energetically allowed. The EoS is of hadronic nature, that is, at such high densities the total energy density includes the contributions not only from nucleons, but from hyperons too. As a general consequence, the inclusion of more degrees of freedom to a system weakens the total energy density. Therefore, the hadronic EoS becomes softer at high densities, when hyperons surpass their production thresholds. A softer hadronic EoS, however, is not consistent with the precise measurements of neutron star masses. This is the so-called hyperon puzzle in neutron star physics. Hyperon physics is therefore a very important research field for nuclear physics, particle physics and nuclear astrophysics. It is the subject of current theorerical and experimental investigations.

In this work we discuss the in-medium modifications of hyperons in nuclear matter at high momenta relevant for the compressed matter which may occur in neutron star interiors. Since the experimental information is still rare for the strangeness sector, we compare our theoretical model to other microscopic approaches, which are based on effective chiral field theories and on Lattice QCD.

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THE NON-LINEAR DERIVATIVE (NLD) MODEL FOR THE BARYON-OCTET

The theoretical description of hadronic matter is based on the relativistic field-theory with fermions and bosons as the degrees of freedom. The fermions are a baryon-octet, that is, protons, neutrons and the hyperons Λ, Σ and Ξ. The bosons are responsible for the interactions between the baryons in the spirit of the one-boson-exchange model. These are the isoscalar σ meson, the isoscalar-vector ω meson, and the isovector-vector ρ meson.

The Non-Linear-Derivative (NLD) model [4] was designed to describe not only the density, but also the single-particle momentum interaction of the baryons. The NLD Lagrangian density consists of the contributions for the Dirac-particles B (B=proton, neutron and hyperons) as shown in the expression:

$$\begin{aligned}\mathcal{L} =& \frac{1}{2}\sum_B \left[\overline{\Psi}_B\gamma_\mu i\overrightarrow{\partial}^\mu\Psi_B - \overline{\Psi}_B i\overleftarrow{\partial}^\mu\gamma_\mu\Psi_B\right] - \sum_B m_B\overline{\Psi}_B\Psi_B \\ &+\mathcal{L}^{free}_{\sigma,\omega,\rho} + \mathcal{L}_{int} \ ,\end{aligned}$$

where the second line includes the free Lagrangians of the meson fields [5]. The important contribution is the interaction term, which is shown below for the case of the coupling between the isoscalar-scalar σ meson with the baryons (the interactions with the other mesons have a similar structure):

$$\mathcal{L}_{int} = \sum_B \frac{g_{\sigma B}}{2}\left[\overline{\Psi}_B\,\overleftarrow{\mathcal{D}}_B\Psi_B\sigma + \sigma\overline{\Psi}_B\,\overrightarrow{\mathcal{D}}_B\Psi_B\right] .$$

It contains the standard minimal-like coupling structure, but it also includes additional non-linear derivative operators (the blue operators), which act on the Dirac-fields. This is the most effective way so far to obtain density and simultaneously momentum dependent potential, as we will see.

The application of the NLD model to infinite nuclear matter leads to NLD functions D(p), which depend explicitly on particle momentum. This is shown below in the vector and scalar self-energies for a baryon species B (B=proton, neutron, and the hyperons)

$$\begin{aligned}\Sigma^\mu_{vB} =& g_{\omega B}\omega^\mu\mathcal{D}_B + g_{\rho B}\tau_B\rho^\mu\mathcal{D}_B \\ \Sigma_{sB} =& g_{\sigma B}\sigma\mathcal{D}_B \quad .\end{aligned}$$

The self-energies include indeed the density dependence through the meson fields, but they also include the additional momentum dependence through the NLD functions D(p). Note that density and momentum are coupled together due to the source structure of the meson field equations:

$$\begin{aligned}m_\sigma^2\sigma + \frac{\partial U}{\partial\sigma} =& \sum_B g_{\sigma B}\left\langle\overline{\Psi}_B\mathcal{D}_B\Psi_B\right\rangle \\ m_\omega^2\omega =& \sum_B g_{\omega B}\left\langle\overline{\Psi}_B\gamma^0\mathcal{D}_B\Psi_B\right\rangle \\ m_\rho^2\rho =& \sum_B g_{\rho B}\,\tau_B\left\langle\overline{\Psi}_B\gamma^0\mathcal{D}_B\Psi_B\right\rangle \quad .\end{aligned}$$

This can be seen in the meson field equations above. They are determined from their sources (right hand side), which contain the mean values of all baryons. However, the NLD function D(p) is included too. All together the NLD model leads to a highly non-linear density and momentum dependence for each baryon type.

The functional form of the NLD term D(p) is not fixed from first principles. An appropriate form is to choose D(p) as a monopole-like function, that is, $D(p) = \Lambda^2/(\Lambda^2+p^2)$, with cut-off regulators Λ for each meson-baryon vertex. We call the Λ-parameter as a cut-off, because it regulates the high momentum part of the baryon potential in line with experimental data or microscopic models.

The main advantage of the NLD model is its simplicity, however, taking into account both the density and momentum dependence. Note that the NLD approach describes very well the in-medium properties of the corresponding antibaryons without the need of additional parameters. In the following we focus the discussion of the results on the potentials of the hyperons and compare the NLD results with other microscopic approaches.

RESULTS AND DISCUSSION

We start the discussion with the optical potential of (anti)protons in nuclear matter at saturation density as shown in Fig. 1. This is a good example to show the effectiveness of the NLD model.

The empirical analyses predict a saturation of both the proton and antiproton optical potentials with increasing kinetic energy or single-particle momentum. This is shown in Fig. 1 by the open symbols (left) and shaded areas (right). The conventional models of Relativistic Hadro-Dynamics (RHD), which do not include any explicit momentum dependence, do fail in reproducing the correct behavior of the nuclear potential at high momenta, and they behave always linearly versus kinetic energy or momentum. Only more microscopic models such as the Dirac-Brueckner-Hartree-Fock (DBHF) are consistent with the empirical data. The phenomenological D3C model does include a momentum dependence, however, only at a limited order.

The NLD approach includes all higher-order derivatives. With the two cut-offs for scalar and vector couplings to the nucleon it can describe very well the entire energy region by choosing the monopole-like form for the NLD function D(p).

The remarkable result is, however, the antiproton optical potential which is shown on the right part in Fig. 1. By applying G-parity we calculated the antiproton optical potential for nuclear matter at saturation without any re-adjustment of parameters. That is, the NLD approach provides the antiproton optical potential in a parameter free way, and describes the real part of it fairly well in comparison with available empirical analyses. On the contrary, the conventional RHD does diverge to infinity and cannot explain the empirical data, neither at high momenta nor at zero kinetic energy, where data from stopped antiprotons exist. Note that the NLD model describes the imaginary part of the antiproton optical as well (not shown here). It is the first time that a phenomenological mean-field based relativistic model does predict correctly the in-medium antiproton behaviors in a parameter free way.

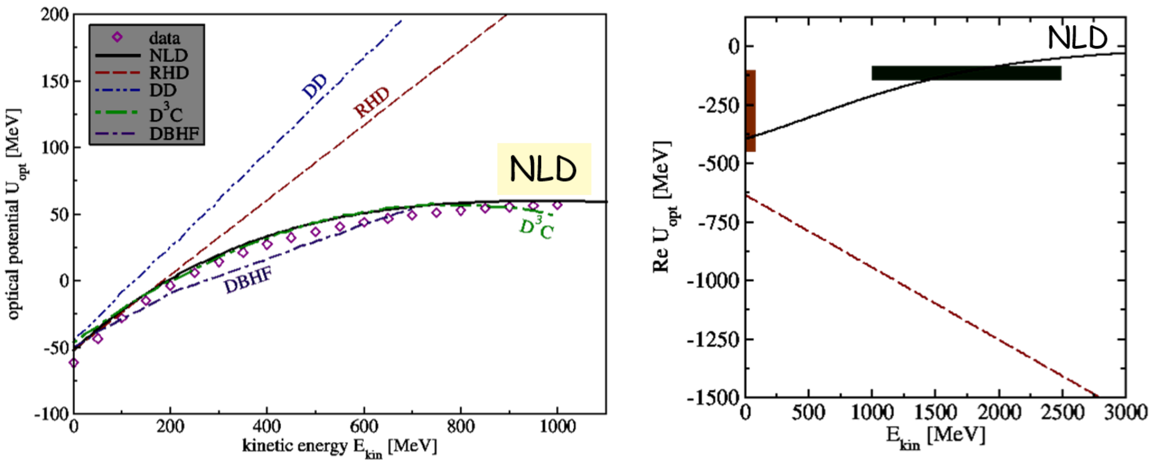

Figure 1. *(Left) Proton optical potential as function of the kinetic energy of nuclear matter at saturation density. The different curves show theoretical calculations with the NLD results denoted by the thick-blue curve. The open symbols are experimental data. (Right) The same as the figure on the left, but for antiprotons. The theoretical calculations for NLD (thick) and conventional RHD (dotted) are compared with empirical analyses (shaded bands). See Refs. [4,6] for details.*

As a next step we consider the hyperons with a particular momentum inside a nuclear matter at fixed baryon density at saturation. As described in the theoretical section, the hyperons obey Dirac equations with similar interaction Lagrangians as the nucleons. The only difference comes from the different meson-hyperon couplings, which are fixed from the meson-nucleon ones by SU(6) symmetry. As for the cut-off of the hyperons, these are fixed to reproduce the correct hyperon potential at zero momentum and the correct momentum dependence of the chiral effective field theoretical calculations.

This is shown in Figs. 2 and 3 for the in-medium optical potentials of the Λ- and Σ-hyperons for symmetric nuclear matter at saturation density. The behavior of the micrsoscopic calculations (gray band, NLO) shows a quite non-trivial momentum dependence, starting from an attractive potential at low momenta which becomes repulsive at high momenta. Any conventional RHD model without any explicit momentum dependence would not be able to reproduce these microscopic results without modifying the SU(6) symmetry and without introducing more terms into the interaction Lagrangian at the cost of many more parameters than already exist. Furthermore, note that the optical potential for the Σ-hyperon is not attractive, but repulsive according to the microscopic calculations. Such a repulsive dependence cannot be explained within the conventional RHD models.

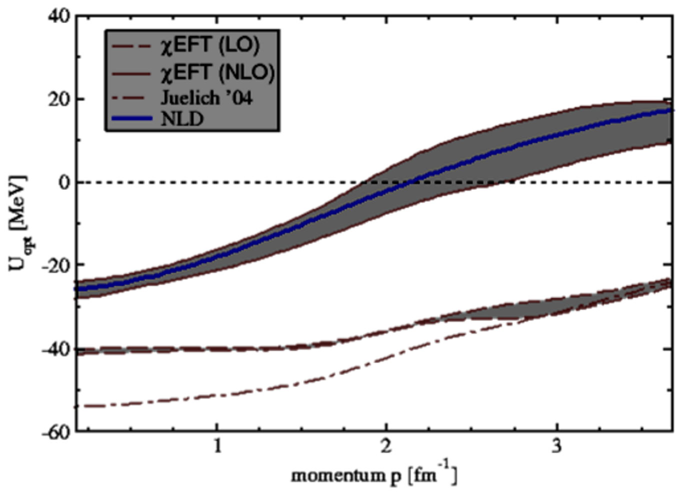

Figure 2. *Λ-optical potential as function of momentum for nuclear matter at saturation density. The NLD calculation (thick red curve) is compared with results of the chiral effective field theory (gray bands). See Ref. [5] for details.*

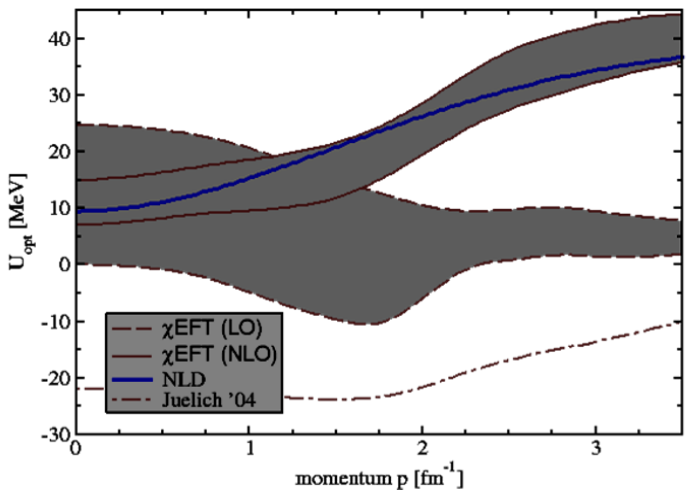

Figure 3. *Same as Fig. 2, but for the Σ-hyperon. See Ref. [5] for details.*

Within the NLD model, however, the hyperon cut-offs can regulate the momentum dependence in order to reproduce an attractive/repulsive Λ-optical potential and – at the same time – a repulsive Σ-optical potential. Note that the meson-hyperon couplings in the NLD model are fixed by SU(6) arguments. The NLD model predicts the correct hyperon potentials at zero momentum, and in particular predicts the non-trivial momentum dependence of the S=-1 hyperons.

Similar NLD results exist for the cascade Ξ-hyperon, not shown here. Within the NLD model, the Ξ-hyperon is slightly attractive for symmetric nuclear matter, but it is split to a repulsive (Ξ^-) and an attractive (Ξ^0) optical potential for pure neutron matter, in accordance with Lattice QCD predictions.

It is therefore of great importance to extend this study for hadronic matter in β-equilibrium using the NLD predictions for the baryons of interest. This work is in progress.

Note that calculations using the conventional RHD soften the EoS to a large extent when hyperons are included in the chemical equilibrium. Concerning the NLD study, first preliminary results show that within the NLD model the hyperon thresholds are shifted to very high densities.

CONCLUSIONS

In summary, we discussed the NLD model which is based on the simplicity of the Relativistic Mean-Field Theory, but it includes in a covariant way interaction terms with non-linear derivative operators. These NLD terms are responsible for a non-trivial density and momentum dependence in consistency with available data/microscopic predictions for protons, antiprotons and hyperons. We conclude the importance of the NLD predictions for nuclear astrophysics applications, such as neutron star dynamics.

References

[1] P. Demorest, T. Pennucci, S. Ransom, M. Roberts, J. Hessels, Nature 467, 1081 (2010)
[2] T. Klähn *et al*., Phys. Rev. C 74, 035802 (2006)
[3] C. Fuchs, Prog. Part. Nucl. Phys. 56, 1 (2006)
[4] T. Gaitanos, M. Kaskulov, Nucl. Phys. A899 133 (2013)
[5] T. Gaitanos, A. Chorozidou, Nucl. Phys. A1008, 122153 (2021)
[6] T. Gaitanos, M. Kaskulov, Nucl. Phys. A940, 181 (2015)