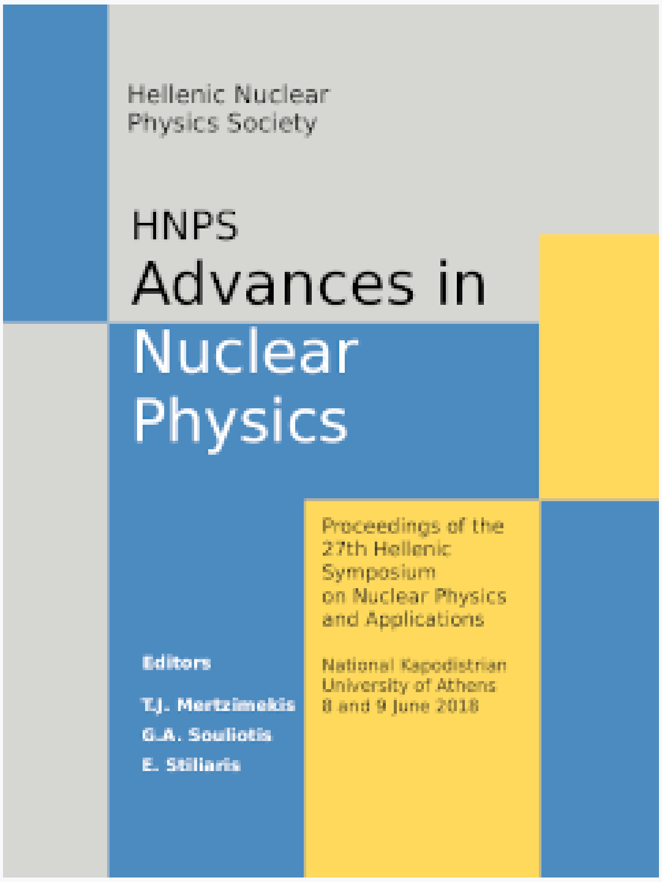
HNPS Advances in Nuclear Physics

Vol 26 (2018)

HNPS2018



In-Medium Strangeness Production and Hyperon-Potentials

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doi: 10.12681/hnps.1802

In-Medium Strangeness Production and Hyperon-Potentials

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Abstract A hot topic of current research concerns the Equation of State (EoS) of nucleons and, in particular, of hyperons in dense nucleonic media. The study of the EoS at nucleon densities far beyond saturation has been initiated several decades ago, however, the behavior of the EoS for strangeness particles is still an open issue. The strangeness part of the EoS is very important not only for the physics of exotic (hyper)nuclei, but also crucial for nuclear astrophysics, e.g., neutron star physics.

Here we present our recent investigations related to the theoretical treatment of in-medium hyperon-interactions as well as first preliminary experimental results from pion-induced reactions. The theoretical study is based on the well-established Non-Linear Derivative (NLD) model, which is extended to the strangeness sector via SU(6) symmetry arguments. It turns out that the NLD-predictions are consistent with microscopic models based on the chiral-EFT theory. On the other hand, recent experimental HADES-data on hyperon and kaon production from pion-induced reactions indicate sensitivities on the underlying in-medium hyperon potentials. We thus conclude that, the recent experimental data from pion-induced reactions will definitely set stringent constraints on the still less understood hyperon-potentials in nucleonic matter.

Keywords Pion-induced reactions, hyperon-nucleon interactions, equation of state (EoS)

INTRODUCTION

The interaction of baryons with strangeness degree of freedom (the so-called $\Lambda,\Sigma,\Xi,\Omega$ hyperons) inside nuclear matter is a hot topic under current investigations theoretically and experimentally. In fact, the presence of hyperons in nuclear matter affects strongly the density dependence of the EoS at high baryon densities, in which hyperons can be exist [1]. Due to the additional strangeness degrees of freedom the high-density EoS becomes naturaly more softer. This property has important consequences for neutron star physics. Indeed, many nuclear matter models, which have been applied successfully to nuclear structure and reactions, are not able to describe precise mass-measurements of neutron stars, if hyperons are taken into account. This issue has been regognized as the hyperon-puzzle [2]. A main reason for the hyperon-puzzle is that the in-medium hyperon interactions are only little explored experimentally relative to the very well known in-medium nucleon-interactions. Thus, due to the experimental uncertainty many nuclear matter models predict rather different results for the hyperon-interactions at densities around saturation and beyond.

Therefore, new experimental and also theoretical studies are still required in order to better access the nuclear EoS as function not only of density, temperature and isospin-asymmetry, but also as function of strangeness too. This task is addressed here by discussing new

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theoretical results on in-medium hyperon potentials and presenting first preliminary experimental data on hyperon momentum spectra. This ongoing investigation will be important for the experiments at FAIR, in particular HADES and PANDA, but it will be crucial for nuclear astrophysics too.

THEORETICAL ASPECTS

The theoretical description of nuclear (or in general hadronic) matter is based on relativistic field theory. The relevant degrees of freedom are the baryons (nucleons and/or hyperons) and the σ-, ω- and ρ-mesons. The baryons are described by the Dirac equation, while the mesons are given by equations of Klein-Gordon type. The mesons here are virtual and mediate the interaction between the baryons in the spirit of the One-Boson-Exchange (OBE) model [3]. This theoretical framework is known in the literature as the Quantum-Hadrodynamics (QHD) [4].

The QHD is applied in various nuclear systems (e.g., infinite nuclear matter, finite nuclei, nuclear reactions at relativistic energies) within the mean-field approximation. That is, the baryons maintain their quantal structure characterized by Spinor field-operators, while the virtual exchange mesons are described by classical relativistic fields by distinct Lorentz-properties. These are the scalar-isoscalar σ-, the vector-isoscalar ω- and the vector-isovector ρ-mesons. Having the relevant degrees of freedom of the system one constructs a Lagrangian density. It contains the free Lagrangians for the baryons and virtual mesons by including an interaction Lagrangian in a minimal-coupling scheme in analogy to Electrodynamics. From the given Lagrangian one derives then all the information about the system under consideration. The Euler-Lagrange equations of motion and from the Noether-Theorem the energy-momentum tensor.

In our theoretical considerations we maintain the QHD-Lagrangian, however, by extending it to infinite series of partial derivatives in the interaction terms. This leads to a generalized field-theoretical formulation of the system, as in detail described in [5]. The main reason for this new model (we call it the Non-Linear Derivative (NLD) model) is that the NLD approach leads to a natural and explicit momentum dependence of the in-medium interaction between baryons inside matter. Within the NLD-model the in-medium interactions are density and simultaneously momentum dependent. This additional momentum dependence is important to describe nuclear dynamics, that is, nuclear reactions. The NLD formalism has been applied with success to the description of nuclear matter, in-medium scattering of protons and also anti-protons and to neutron stars too [5].

Here we extend the NLD formalism by including the strangeness as an additional degree of freedom within SU(6) symmetry [6].

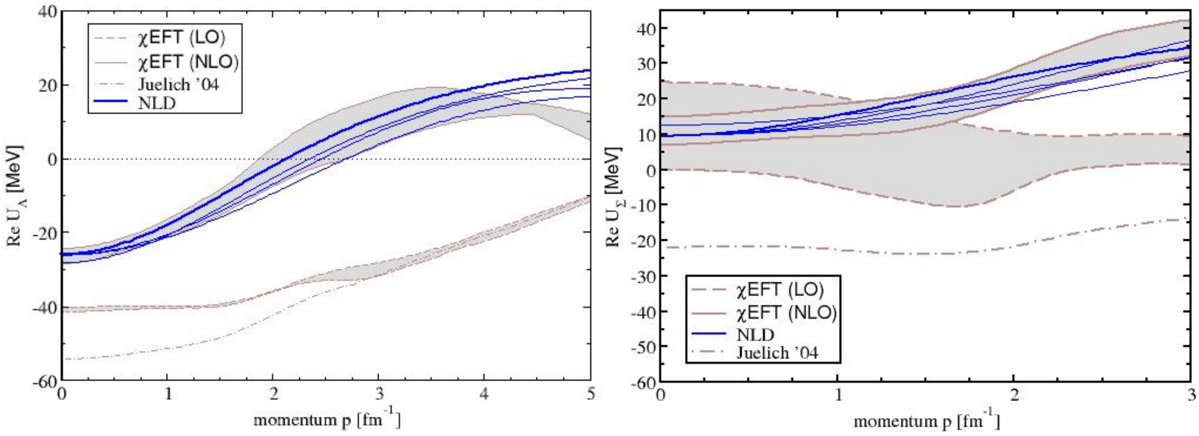

Fig. 1. Optical potentials of Λ (left) and Σ (right) hyperons as function of their momentum inside nuclear matter at saturation density. The gray bands and the gray dotted curve are microscopic calculations [7] while the blue solid curves result from our NLD-calculations, as indicated.

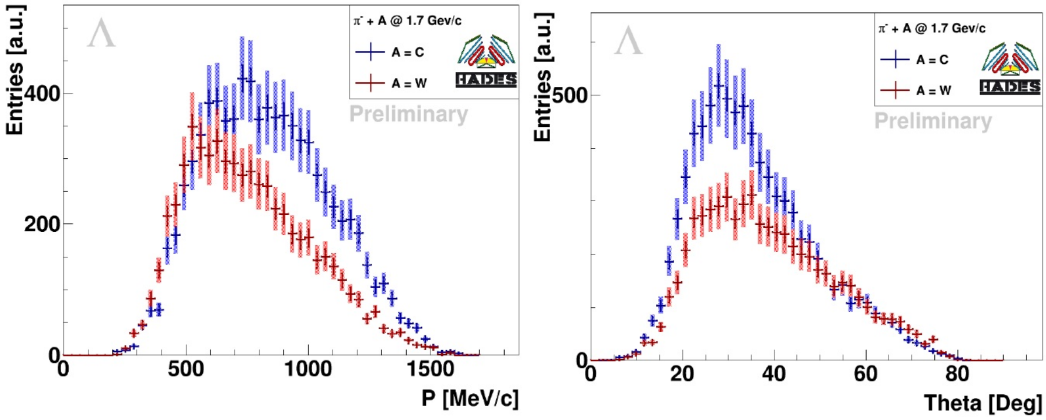

Fig. 2. Preliminary HADES data [8] for the Λ-distributions versus momentum (left) and polar angle (right) for pion-induced reactions using two different target-systems, as indicated.

RESULTS AND DISCUSSION

We have applied the NLD-model to describe the momentum dependence of the optical potential of hyperons inside nuclear matter. The results are shown in Fig. 1 in terms of the (real part) of the optical potential for the Λ- and Σ-hyperons as function of their momentum for symmetric nuclear at saturation density and zero temperature. It is seen, that the in-medium potential of Λ-hyperons is attractive at low momenta, but it becomes repulsive with increasing Λ-momentum. This general trend is also confirmed by microscopic calculations, which they are based on various orders in a chiral-perturbative expansion (NLO) [7]. It is important to note that the NLD predicts the well-known value of around -32 MeV for the Λ-optical potential at zero momentum and, in particular, it predicts the highly non-trivial momentum dependence of the microscopic (and so far most realistic) NLO-calculations. The situation is similar for the in-medium Σ-optical potential, as shown in the same Fig. 1, but on the right panel. Here the NLD-model predicts a rather repulsive interaction for the Σ-hyperons inside matter, which is confirmed by the microscopic NLO-calculations too.

It is important to stress that the explicit momentum dependence of the in-medium potentials, which is the novel feature of the NLD approach, is necessary to predict the complex momentum dependencies of the Λ- and Σ-hyperonic in-medium optical potentials. In particular, the NLD model can predict the repulsive character of the Σ-optical potential. Such a description would not be possible by using conventional nuclear models, in which an explicit momentum dependence is missing.

It is thus naturally to compare theoretical calculation with experimental data. Concerning hyperon-interactions this has been not possible so far. Indeed, only little is experimentally known about the behavior of hyperons inside matter. Experimental information on hyperonic interactions at high momenta has been completely missed so far. The HADES collaboration has proposed an experiment by using pion beams at nuclear targets at low relativistic energies [8]. Such a dynamical system gives final hyperonic states with a rather clear background, in which one has a good experimental access. In fact, it is possible to measure various distributions of neutral particles (such as the Λ-hyperons). This is demonstrated in Fig. 2 in terms of momentum and polar angle distributions of produced Λ-particles from pion-induced reactions at two different target systems. The comparison with the theoretical NLD model is under current investigations. First dynamical calculations (not shown here) indicate indeed that the HADES data can constrain the models for the in-medium hyperonic interactions. A definite conclusion here would defninitely help to better understand the physical behavior of hyperons inside matter, not only at densities close to saturation, but also beyond at momenta higher than the Fermi-momentum of saturated nuclear matter. This will be a crucial step to understand also better the hyperon-puzzle in neutron star physics.

CONCLUSIONS

To conclude, the interaction of hyperons inside baryonic media is still an object of current research, theoretically and experimentally. The knowledge of in-medium hyperonic interactions at various densities beyond that of ordinary matter is important for nuclear physics, hadronic physics and, in particular, for nuclear astrophysics. So far the lack on experimental data concerning hyperons has not allowed to draw clear conclusions on the equation of state as function of strangeness. The new experimental data from the HADES collaboration [8] will definitely provide access into the strangeness sector of the nuclear equation of state.

The NLD formalism was initialy developed for pure nuclear matter. It was applied to various nuclear systems such as infinite nuclear matter, finite nuclei, proton and anti-proton reactions and neutron stars. It turned out that with a minimal set of parameters the NLD approach predicted all available empirical balk properties of nuclear matter and – at the same time – all available experimental information of reactions with protons and antiprotons. Such an overall description of empirical data was not possible in the past by using conventional nuclear matter models in the spirit of QHD. This has been considered as a novel feature of the NLD formalism and it is fairly well confirmed here by the additional comparisons between the NLD results with microscopic model calculations.

We thus conclude that a detailed comparison between our calculations and the experimental HADES data on hyperon dynamics [9] will provide us with more clear constraints on the strangeness part of the nuclear equation of state at high baryon momenta (respectively high densities), which will be definitely relevant for nuclear astrophysics.

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