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# A novel solution to the hyperon-puzzle in neutron stars

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**Abstract.** Hyperons are baryons with strangeness content and heavier than nucleons. Due to the high densities in the neutron star interior, they are energetically allowed to appear. The strangeness baryons can thus co-exist together with nucleons and leptons in β-equilibrium. However, as a generic feature, the neutron star equation of state softens largely when hyperons are present in neutron star matter. This is the so-called hyperon-puzzle: many state-of-the-art nuclear models cannot describe the precise observations of neutron star masses, when hyperons are included in their descriptions. We propose a new solution to this persisting hyperon-puzzle issue. It is based on the explicit momentum dependence of the hyperon potentials. They modify the strangeness thresholds and forbid or strongly suppress their population in neutron stars.

## 1 Introduction

The search for the correct behaviour of hadrons in nuclear matter has been one of the most challenging tasks in nuclear physics and nuclear astrophysics over the last decades [1,2]. As the key quantities, the binding energy per particle (Equation of State (EoS)), and the Schroedinger-equivalent Optical Potential (SEP) give the most valuable information about the hadronic in-medium properties versus the baryon density $\rho_B$ and the single-particle (s.p.) momentum p.

While the EoS and the SEP are well known from empirical studies for nucleons close to the saturation density $\rho_{sat}$, the experimental uncertainties grow quite fast at densities beyond saturation and for baryons different than the nucleons. Terrestrial experiments offer an important information about the hadronic properties in free space and in compressed nuclear matter at high densities, isospin asymmetries and finite temperatures.

Neutron stars (NS) provide, on the other hand, a unique laboratory beyond terrestrial experiments with more details for the in-medium properties of highly compressed baryonic matter. Due to the very high densities in the NS interior, baryons heavier than the nucleons can be energetically populated through β-equilibrium processes. That is, baryons with strangeness content, the hyperons (Y), can co-exist together with nucleons and leptons in β-equilibrated NS matter. As a generic feature, the hyperons soften the hadronic NS EoS at very high densities. Thus, less gravitational energy is required to keep the NS stable, and the NS mass is reduced below the observations in the presence of hyperons. This is the so-called hyperon-puzzle (HP) [2].

We propose a new solution to the persisting HP based on the explicit momentum dependence (MD) of the in-medium baryon potentials with a particular attention to the hyperon SEP. The theoretical formalism is based on the non-linear derivative (NLD) approach, a covariant and thermodynamically consistent formalism, which accounts for the explicit MD of all baryon potentials. We show that the generic MD of the hyperon SEP induce generic effects to the conventional strangeness conditions and resolves the HP.

## 2 The NLD model for neutron stars

The NLD formalism is based on the conventional Quantum-Hadro-Dynamics (QHD) in the spirit of the Relativistic Mean-Field (RMF) approximation. However, as the crucial difference, the interaction Lagrangian incorporates non-linear higher-order derivative operators acting on the baryon spinor fields. For each meson (m=σ,ω,ρ) the interaction Lagrangian

$$\mathcal{L}^m_{\text{int}} = \sum_b \frac{g_{mb}}{2}[\overline{\Psi}_b \overleftarrow{\mathcal{D}}_b \Gamma_m \Psi_b \varphi_m + \varphi_m \overline{\Psi}_b \Gamma_m \overrightarrow{\mathcal{D}}_b \Psi_b], \tag{1}$$

contains all the meson-baryon interactions with b=p,n,Y and with obvious terms and parameters [3,4]. The essential quantities are the non-linear derivative operators $D_b$, referred as regulators, since they regulate the MD of all in-medium baryon potentials.

The generalized Euler-Lagrange field-theoretical formalism [3] leads to quasi-free Dirac equations for the baryons with selfenergies

$$\Sigma^\mu_b(p) = g_{\omega b}\, \omega^\mu\, \mathcal{D}_b(p) + \tau_{3b} g_{\rho b}\, \rho^\mu\, \mathcal{D}_b(p), \tag{2}$$

and to meson-field equations

$$\begin{aligned} m^2_\sigma \sigma + \frac{\partial U}{\partial \sigma} &= \sum_b g_{\sigma b} \frac{\kappa}{(2\pi)^3} \int_{|\vec{p}| \leqslant p_{F_b}} d^3p \frac{m^*_b}{E^*_b} \mathcal{D}_b(p), \\ m^2_\omega \omega &= \sum_b g_{\omega b} \frac{\kappa}{(2\pi)^3} \int_{|\vec{p}| \leqslant p_{F_b}} d^3p\, \mathcal{D}_b(p), \end{aligned} \tag{3}$$

with meson-baryon couplings, a non-linear self-interaction term U(σ), a baryon effective (Dirac) mass $m^*_b$ and an in-medium s.p. energy

$$E_b(p) = \sqrt{m^{*2}(p) + p^2} + V_b(p), \tag{4}$$

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with the baryon effective mass $m^*_b$ and the time-like component of the vector selfenergy, $V_b$.

The important feature is the appearance of the explicitly MD regulators in both, in the baryon selfenergies, Eq. (2), and in the source terms of the meson-field equations, Eqs. (3). These non-trivial dependencies will induce generic MD effects on the thresholds of the hyperons, which they will be important in resolving the HP.

The parameters of NLD model include the conventional ones, which are fixed by the empirical values at saturation. The non-linear regulators contain cutoff parameters which are determined by the empirical nucleon optical potential at saturation density. Concerning the hyperon sector, the free couplings and the strangeness cutoffs are adjusted by microscopic calculations based on the chiral effective field (χEFT) theory [5].

Since the in-medium hyperon potentials are the relevant quantities for this work, we discuss them in Fig. 1 in terms of the SEP versus the Y-momentum at various densities.

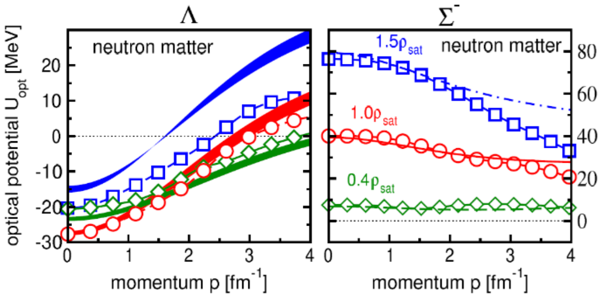

**Fig. 1.** SEP versus momentum p for Λ (left) and $\Sigma^-$ (right) hyperons. The symbols refer to the χEFT calculations (taken from [5]) and the curves are the NLD predictions [6].The green, red and blue symbols (χEFT) and curves (NLD) for Λ (left panel) and Σ (right panel) refer to three baryon densities of pure neutron matter, as indicated in the right panel. The shaded bands in the NLD curves forΛ (left panel) refer to small uncertainties when fitting the NLD to the χEFT calculations.

The NLD hyperon potentials were adjusted to the χEFT ones at saturation density only. However, one sees in Fig. 1 that the NLD model gives an adequate description of the strangeness SEPs at densities close to saturation. Note that the Λ potentials become repulsive with increasing momentum, while the $\Sigma^-$ potentials are always repulsive with a soft momentum behavior, that is, they decrease with increasing momentum as the baryon density grows.

In β-equilibrium without strangeness conservation [1], the conservation of total baryon density and charge neutrality ($q_b$ is the baryon charge)

$$\rho_B = \sum_b \rho_b, \quad \sum_b q_b \rho_b - \rho_e = 0, \tag{5}$$

determine the independent quantities. These are the neutron and electron chemical potentials, $\mu_n$ and $\mu_e$, from which the chemical potentials of all other baryons are determined via the β-equilibrium:

$$\mu_b = \mu_n - q_b\,\mu_e, \quad \mu_b = \sqrt{p^2_{F_b} + m^{*2}_b} + V_b. \tag{6}$$

The previous equation (6) (for each baryon b) is the crucial one in β-equilibrium calculations: at a fixed baryon density and during the self-consistent numerical procedure, the s.p. energy (the r.h.s. of this equation) versus the s.p. momentum p should cross the threshold $\mu_n$-$q_b\mu_e$ at a given momentum $p=p_{Fb}$ which is the Fermi-momentum of the baryon b. This is not always the case for particles heavier than the nucleon. The above equation (6) induces the threshold conditions for baryons heavier than the nucleon, that is, the strangeness thresholds: when the lowest state of the s.p. energy $E_Y(p=0)$ is lower than the threshold $\mu_n$-$q_b\mu_e$ ,

$$\mu_Y = \mu_n - q_Y\mu_e > E_Y(0), \tag{7}$$

then the hyperons Y will be produced. This is the *conventional* threshold condition for hyperons [1]. It applies always to nuclear matter models, in which no explicit momentum dependencies occur in the baryon SEPs.

However, with explicit MD baryon potentials, as this is the case in the NLD approach, the conventional threshold conditions for strangeness are modified [6]. This is caused by the *non-monotonical* increasing behavior of the s.p. energy $E_Y(p)$, see Eq. (4), versus the momentum p. This new effect is demonstrated in Fig. 2.

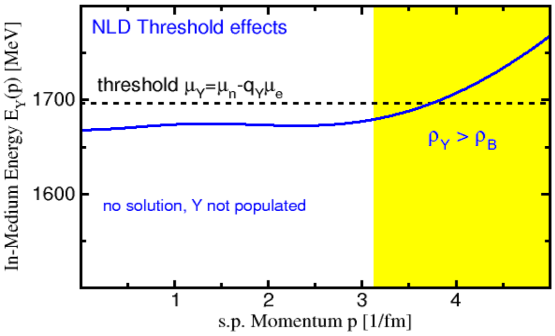

**Fig. 2.** Demonstration of the modified threshold effects for strangeness in β-equilibrated NS matter at very high densities. The solid curve shows the hyperon in-medium s.p. energy as a function of the momentum. The dotted line indicates the threshold. The yellow band marks the region of momenta greater than the Fermi-momentum of the given baryon density. Even if the hyperon threshold is fulfilled, the hyperon cannot be produced [6].

At very high densities the hyperon SEPs show a generic decreasing p-behaviour. This *soft* p-dependence of the strangeness SEPs induces a soft p-behaviour of the in-medium s.p. energy $E_Y$ too, as one can see in Fig. 2 (solid curve). The novel feature here is the existence of a solution (cross point of $E_Y$ with the threshold line), however at a Fermi-momentum much greater than the given high-density value. Due to the baryon density conservation, this solution is forbidden, and the hyperon cannot be produced.

The demonstration of the novel threshold effect in Fig. 2 is a generic feature of all hyperons. The Σ-hyperon potentials show a soft p-behavior already at densities close to saturation (see again Fig. 1, right panel). On the other hand, the Λ-potential exhibit a stiff p-dependence (increasing potential with momentum p) at densities close to saturation (Fig. 1, left panel). However, at very high densities the Λ-SEP starts to decrease with increasing momentum p. It changes its stiffness character from stiff to soft and it decreases with increasing momentum p. These new features will drastically reduce the Λ-hyperon population in NS matter and completely forbid the production of Σ-hyperons.

## 3 Results

We discuss now the results for NS matter. We have performed calculations for β-equilibrium within the NLD model and, for comparison, with a conventional RMF model in the NLρ parametrization. We have chosen the NLρ parametrization, because it gives a similar EoS as the NLD approach for NS matter without hyperons. The results are shown in Fig. 3 in terms of the particle fractions. The NS EoSs are shown too by means of the pressure versus the energy density.

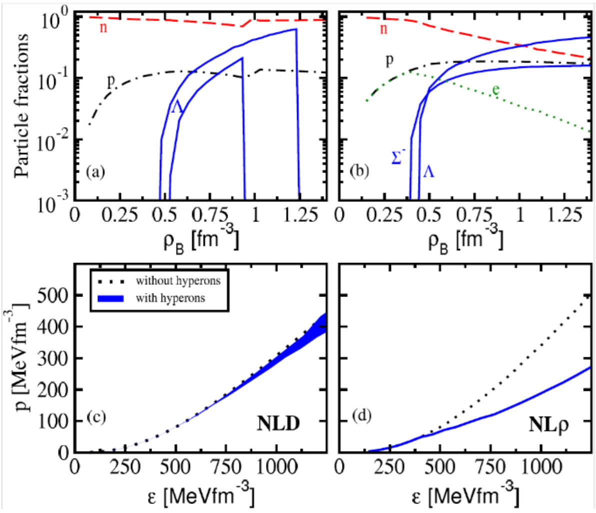

**Fig. 3.** Particle fractions as indicated (top) and the EoS (bottom) for a conventional RMF model (NLρ, right) and the NLD approach (left) for NS matter. Both Λ-fractions in the NLD model (top left) refer to NLD calculations with the upper and lower limits of the Λ-SEP (see Fig. 1). The EoSs in both models are shown without (dotted) and with (filled band and solid curve) hyperons in the NS matter [6].

Within the standard RMF model (NLρ) the NS EoS softens drastically when the hyperons are included in the β-equilibrated matter (bottom-right panel in Fig. 3). Indeed, the Λ and $\Sigma^-$ hyperons are produced largely, as one can see in the top-right panel in Fig. 3. Note that the $\Sigma^-$ hyperon is heavier than the Λ baryon. However, due to its isospin and charge properties is favored for population relative to the Λ hyperon. The other Σ hyperons ($\Sigma^0$, $\Sigma^+$) are less favored and they are not produced, even if they are included in the calculations.

The situation concerning the NS composition changes largely in the NLD calculations. At first, all Σ hyperons are not populated. Even the isospin and charged favored $\Sigma^-$ baryon is not produced et all (top-left panel in Fig. 3). This is due to the MD of the corresponding potential. In fact, according to Fig.1, the SEP for the $\Sigma^-$ hyperon shows a clear soft MD. This soft MD is manifested more pronounced at higher densities relevant for NS matter. This softness of the hyperon potential with increasing momentum p induces a softness of the corresponding in-medium s.p. energy versus p. Thus, even with fulfilled threshold at vanishing momentum these hyperons cannot be populated (see again discussion related to Fig. 2).

The population of the Λ hyperons is suppressed to large extend. Indeed, as shown in in left-top panel of Fig. 3, the Λ production starts at densities around $3.3\rho_{sat}$ (with $\rho_{sat}$=0.152 fm$^{-1}$), but their population is limited to a density region only. This is a generic effect, as it appears for both calculations using the lower and upper limits of the Λ potential in Fig. 1. Even if the SEP of the Λ hyperons favors their production at densities just above the energetically allowed threshold, the stiff to soft stiffness transition of the Λ potential with increasing density results to a quite soft Λ s.p. energy at high densities versus momentum. This crucial momentum dependent effect forbids the Λ production at higher densities, even if their threshold at the lowest Λ-energy is satisfied.

As an important result, the corresponding NS EoS maintains its stiffness at high densities relevant for NSs, even when the hyperons are included in the high-density hadronic matter. This is clearly seen at the bottom-left panel of Fig. 3, where the NS EoSs in the NLD approach are shown without and with the consideration of the hyperons. This is important in describing the high values of the observed NS masses. In fact, the maximum NS masses that result from the NLD model are 2.05 (in units of the solar mass) without the consideration and with hyperons included in the calculations.

It turns out that the explicit momentum dependence of the in-medium potentials of all baryons, in particular, of the hyperons, should be accounted for in β-equilibrium calculations, in order to provide an adequate description of NS properties in line with the recent astrophysical observations of high NS masses. Note that the NS radius within the NLD model calculations results in values between (13-13.5)km, which is again in agreement with recent astrophysical observations from gravitational waves analyses [7].

## 4 Conclusions and Outlook

We have proposed a new solution to the long-standing HP issue. It is based on the momentum dependencies of the in-medium hyperon potentials. For this purpose, we have extended the NLD model to hadronic matter including strangeness degrees of freedom in β-equilibrium and applied it to NS configurations.

It turns out that the explicit MD of the strangeness potentials generates novel effects on the strangeness thresholds. They are important for a significant suppression of the hyperons (Λ) and, in particular, for the strangeness disappearance (Σ). The generic MD of the baryons is thus responsible for maintaining the stiffness character of the baryonic EoS in neutron star matter environments. In conclusion, the NLD approach with its novel momentum dependent mean-fields resolves the persisting hyperon puzzle issue. It is a great step forward in understanding the complex neutron star dynamics in the future.

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