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Two-meson exchange hyperonic three-body forces and consequences for neutron stars

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Abstract

We construct two-meson exchange three-baryon potentials between two nucleons and one hyperon (NNY) consistent with the two body nucleon–hyperon (NY) J04 potential of the Jülich group. In particular, we focus on the $NN\Lambda$ and $NN\Sigma^-$ forces since Λ and Σ^- are the first hyperons expected to appear in microscopic calculations of neutron star matter. Brueckner–Hartree–Fock calculations of the hyperonic matter are then performed including the effect of these three-body forces. Our results show that at high densities the total contribution of the NNY force is repulsive making the resulting equation of state stiffer, as required from neutron star mass observations.

Keywords: Neutron stars; Hyperons; Hyperonic three body forces

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1. Introduction

Neutron stars offer an interesting interplay between nuclear processes and astrophysical observables [1]. A good knowledge of the nuclear equation of state (EoS) at very high densities is required to understand the properties of neutron stars. Near nuclear saturation density ($\rho_0 \sim 0.16$ fm^{-3}), neutron star matter is mainly composed of neutrons, protons and leptons (electrons and muons) in β-equilibrium. When the density increases new degrees of freedom may appear in addition to nucleons. Hyperons are an example of these degrees of freedom. Since the pioneer work of Ambartsumyan and Saakyan [2] the presence of hyperons in neutron stars has been considered by many authors using either phenomenological [3] or microscopic

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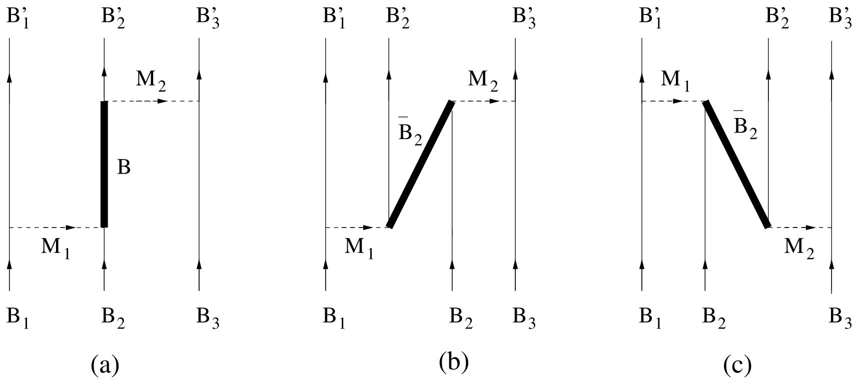

Fig. 1. Two-meson exchange processes contributing to the three-body baryon force.

[4] approaches. All these works agree that hyperons appear in the inner core of neutron stars at densities of about $2-3\rho_0$. The conversion of nucleons into hyperons, which at such densities is energetically favorable, relieves the Fermi pressure and makes the EoS softer. This softening leads to theoretical predictions of maximum masses that are (mainly in microscopic approaches) not compatible with observation. The solution of this problem is not easy, and it is presently a subject of very active research, specially in view of the recent measurements of unusually high masses of the millisecond pulsars PSR J1614-2230 ($1.97 \pm 0.04 M_\odot$) [5] and PSR J1903+0327 ($1.667 \pm 0.021 M_\odot$) [6]. It has been suggested, see *e.g.* [7], that a possible solution to this problem is the inclusion of three-body forces (TBF) involving one or more hyperons (*i.e.*, nucleon–nucleon–hyperon (NNY), nucleon–hyperon–hyperon (NYY), and hyperon–hyperon–hyperon (YYY)). These forces could eventually provide the additional repulsion needed to make the EoS stiffer and, therefore, the maximum mass compatible with the current observational limits. Whereas three-body forces among nucleons have been the subject of many studies, three-body forces involving hyperons have not received so much attention. Some earlier works on this issue [8] focused on the $NN\Lambda$ force produced by a two-pion exchange mechanism. In this work we construct a two-meson exchange model for the $NN\Lambda$ and $NN\Sigma^-$ forces consistent with the two-body nucleon–hyperon (NY) J04 potential of the Jülich group [9]. This model includes the contribution from $\pi\pi$-, KK-, $\sigma\sigma$-, $\sigma\omega$- and $\omega\omega$-exchanges. The effect of such TBF is then analyzed in Brueckner–Hartree–Fock (BHF) calculations of hyperonic matter.

2. The NNY force

We approximate the three-body NNY scattering amplitude in terms of all possible two-meson exchange processes of the type of those shown in Fig. 1 (with one of the baryons being a Λ or a Σ^- and the other two nucleons) that preserve isospin conservation at each vertex and that involve the excitation of a baryon (N, Λ, Σ, Δ or Σ^*) or an antibaryon ($\bar{N}$, $\bar{\Lambda}$ or $\bar{\Sigma}$). The contribution of each one of these processes can be written in general as the product of the baryon–baryon–meson vertices $B_1B'_1M_1$ and $B_3B'_3M_2$, and the scattering amplitude of the two-body process $M_1 + B_2 \to M_2 + B'_2$, where the intermediate baryon (diagram (a)) or antibaryon (diagrams (b) and (c)) is excited by the exchange, in our case, of $\pi\pi$, KK (diagram (a)) or $\sigma\sigma$, $\sigma\omega$ and $\omega\omega$ (diagrams (b) and (c)). The exchange of vector mesons is not included here, although work in this direction is in progress. All coupling constants and cut-offs have been fixed at the two-body