Potentiality of (anti)kaon condensation in dense matter

Vivek Baruah Thapa[1],* Monika Sinha[1], Armen Sedrakian[2], and Jia Jie Li[3]
[1] *Indian Institute of Technology Jodhpur, Jodhpur-342037, India*
[2] *Frankfurt Institute for Advanced Studies, Ruth-Moufang-Straße, 1, 60438 Frankfurt am Main, Germany*
[2] *Institute of Theoretical Physics, University of Wrocław, pl. M. Borna 9, 50-204 Wrocław, Poland and*
[3] *Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China*

Introduction

Being one of the most densest objects, neutron stars (NSs) lay out a quirky domain to study the novel states of matter [1]. Because of the immense matter densities, exotic degrees of freedom (strange, non-strange baryons, meson condensations) are expected to come into picture [2, 3]. The multi-messenger astrophysical observations (masses $\geq 2M_\odot$, radii, tidal responses, $\Lambda_{1.4} \leq 580$) of compact objects during the last decade have provided stringent constraints on the possible dense matter equation of states (EoSs). (Anti)kaon condensation in dense matter was first theorized by Kaplan and Nelson in Ref.-[4]. However with the inclusion of such boson condensation, the EoS softens drastically leading to lowering of maximum mass configurations. Such meson condensations can affect the microscopic aspects of nuclear matter such as single particle energies, effective nucleon masses and such [5]. In this paper, we investigate the possibility of (anti)kaon condensation in Δ-admixed hypernuclear matter in consistency with the recent NS astrophysical observables within the covariant density functional (CDF) model.

CDF model formalism

In order to construct the dense matter EoS, we implement the DD-MEX [6] coupling parametrization. The strong interactions among the various particles (baryon octet (b), Δ-resonances, (anti)kaons ($\bar{K}$)) are considered to be mediated via σ, ω, ρ and ϕ-mesons. The total Lagrangian describing the dense matter is given by [2, 3]

$$\begin{aligned}\mathcal{L} &= \sum_b \bar{\psi}_b(i\gamma_\mu D^\mu_{(b)} - m^*_b)\psi_b + \sum_\Delta(\psi_b \to \psi^\nu_\Delta) \\ &+ D^{(\bar{K})*}_\mu \bar{K} D^\mu_{(\bar{K})} K - m^{*2}_K \bar{K}K + \frac{1}{2}(\partial_\mu\sigma\partial^\mu\sigma \\ &- m^2_\sigma\sigma^2) - \frac{1}{4}\omega_{\mu\nu}\omega^{\mu\nu} + \frac{1}{2}m^2_\omega\omega_\mu\omega^\mu \\ &- \frac{1}{4}\boldsymbol{\rho}_{\mu\nu}\cdot\boldsymbol{\rho}^{\mu\nu} + \frac{1}{2}m^2_\rho\boldsymbol{\rho}_\mu\cdot\boldsymbol{\rho}^\mu - \frac{1}{4}\phi_{\mu\nu}\phi^{\mu\nu} \\ &+ \frac{1}{2}m^2_\phi\phi_\mu\phi^\mu + \sum_l \bar{\psi}_l(i\gamma_\mu\partial^\mu - m_l)\psi_l,\end{aligned}$$

with $D^\mu_{(i)}$ denoting the covariant derivative. The fields of baryon octet, leptons (e^-, μ^-) and Δ-baryons are represented by ψ_b, ψ_l (Dirac) and ψ^ν_Δ (Rarita-Schwinger) respectively. The chemical equilibrium conditions between species in the particle spectrum are $\mu_i = \mu_n - q_i\mu_e$, $\mu_{K^-} = \mu_e$, and $\mu_{\bar{K}^0} = 0$ where q_j is the charge of ith baryon, μ_e, μ_n, μ_{K^-}, $\mu_{\bar{K}^0}$ denote the chemical potentials of e^-, neutron and (anti)kaons respectively. The dense matter EoS is calculated self-consistently taking into account two additional constraints, viz. charge neutrality and baryon number conservation.

Results & Discussions

In this work, the isospin component of the paramterization is recalibrated to $E_{\text{sym}} = 38.1$ MeV and $L_{\text{sym}} = 70$ MeV at nuclear saturation density (n_0) following recent implications from PREX-2 data [7]. We have considered the optical potentials of hyperons viz. Λ, Ξ, Σ to be $-28, -14, +30$ MeV respectively

*Electronic address: thapa.1@iitj.ac.in

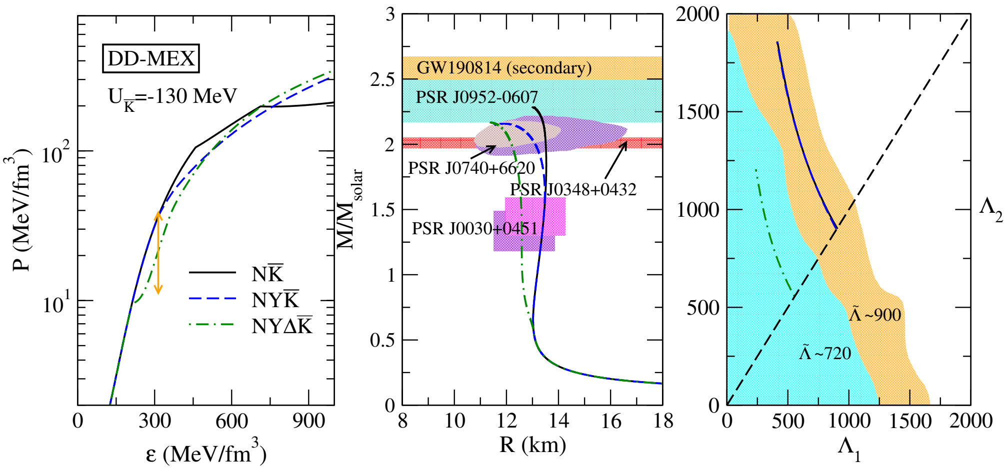

FIG. 1: Left panel: EoSs of various matter compositions, middle panel: Mass-radius (M-R) relations for the mentioned EoSs and right panel: Tidal deformability parameters corresponding to the binary components with the considered EoSs. The different shaded regions in the M-R plot denote the astrophysical observations. (Please refer to text for description)

TABLE I: Dense matter and maximum mass NS properties. The threshold densities of (anti)kaons are denoted by n_u^i, while n_c represent the central number density of respective maximum mass NSs.

Config.	$n_u^{K^-}/n_0$	$n_u^{\bar{K}^0}/n_0$	$M_{\rm max}/M_\odot$	n_c/n_0
$N\bar{K}$	2.88	4.07	2.28	4.89
$NY\bar{K}$	5.49	7.02	2.17	5.91
$NY\Delta\bar{K}$	5.97	6.31	2.18	6.70

[3]. As for the (anti)kaon optical potential in symmetric nuclear matter, it is set to -130 MeV. Since not much information is known in Δ-resonances sector, we consider the couplings to be $R_{\sigma\Delta}, R_{\omega\Delta}, R_{\rho\Delta}$ to be $1.23, 1.10$ and 1.00 with $R_{i\Delta} = g_{i\Delta}/g_{iN}$. The EoSs with various matter configurations ($N\bar{K}-$ nucleons with (anti)kaons, $NY\bar{K}-$ Baryon octet with (anti)kaons, $NY\Delta\bar{K}-$ Δ-admixed hypernuclear matter with (anti)kaons) are shown in left panel of fig.-1. The EoSs satisfy the matter pressure constraint (represented by vertical line) at $2n_0$ deduced from GW170817 data. From the mass-radius (middle panel of fig.-1) plot obtained by solving the Tolman-Oppenheimer-Volkoff equations, it is seen that confronting with the recent observation of heaviest NS (PSR J0952 − 0607), the (anti)kaon potential shows to be a possible nucleation interior to NS. The EoSs constructed in this study do satisfy the tidal deformability constraints of $\tilde{\Lambda} \leq 900$ as well as $\tilde{\Lambda} \leq 720$ obtained from recent reanalysis of GW170817 data. The curves for $N\bar{K}$ and $NY\bar{K}$ overlap due to the reason that no exotic degrees of freedom nucleate in $\leq 1.5M_\odot$ NSs. This can be understood from the M-R relation curves and table-I. While Δ-admixed matter fulfill the strict $\tilde{\Lambda}$ constraint denoting its worth in comprehending dense matter.

References

[1] N. K. Glendenning, *Compact Stars* (1996).
[2] V. B. Thapa & M. Sinha, *Phys. Rev. D*, **102(12)**, 123007 (2020).
[3] V. B. Thapa, A. Kumar & M. Sinha, *MNRAS*, **507(2)**, 2991 (2021).
[4] D. B. Kaplan & A. E. Nelson, *Nucl. Phys. A*, **479**, 273 (1988).
[5] W. B. Ding *et al.*, *A&A*, **506**, L13 (2009).
[6] A. Taninah *et al.*, *Phys. Lett. B*, **800**, 135065 (2020).
[7] B. T. Reed *et al.*, *Phys. Rev. Lett.*, **126**, 172503 (2021).