Inference of Dense Matter Equation of State with Antikaon Condensation

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Introduction

Advances in multimessenger astronomy and nuclear theory have expanded our understanding of neutron star (NS) physics. The complex structure of NSs, with vast density variations across their crust and core, presents significant modeling challenges. By combining observational data with theoretical models, we can refine our understanding of NS properties and their equation of state (EOS), though developing a fully comprehensive EOS remains an ongoing challenge.

At higher densities inside NSs, exotic particles like hyperons and meson condensates may emerge. Antikaon condensation, in particular, has drawn attention due to its potential to form Bose-Einstein condensates in dense matter [1]. The aim of this study is to explore the role of antikaon condensation in NS matter, using a phenomenological approach with density-dependent couplings to describe nuclear matter properties. We will investigate how the inclusion of kaon condensation affects NS properties like mass-radius configurations, tidal deformability, and the speed of sound, using Bayesian statistical analysis and comparing results with observations from NICER and LIGO/Virgo [2].

Theoretical Formalism

We present a density-dependent relativistic hadronic model (DDRH) [3, 4] to analyze the phase transition from hadronic matter to antikaon-condensed matter, which may occur in either first-order or second-order configurations. Our study includes nucleons ($N \equiv n, p$), electrons, and muons within the hadronic phase. The strong interactions between baryons and antikaons are mediated by scalar σ, isoscalar-vector ω^{μ}, and isovector-vector $\rho^{\mu\nu}$ meson fields.

We employ a mean-field model with density-dependent coupling constants. To estimate the model parameters, we use Bayesian inference. The posterior probability distribution of the parameter set $\mathbf{X}$, given the data (D), follows Bayes' theorem:

$$P(\mathbf{X}|D) = \frac{P(D|\mathbf{X})P(\mathbf{X})}{P(D)}, \tag{1}$$

where $P(\mathbf{X})$ represents the prior probability of the parameter set $\mathbf{X}$. This prior is updated by the experimental or observational data through the likelihood function $P(D|\mathbf{X})$. The denominator, $P(D)$, ensures the posterior distribution $P(\mathbf{X}|D)$ is properly normalized. In this study, the parameter set $\mathbf{X}$ includes the DDRH Lagrangian parameters

To perform Bayesian analysis, we use the nested sampling Monte Carlo algorithm MLFriends [5] with the UltraNest package [6]. UltraNest is well-suited for exploring parameter spaces with multiple modes, non-linear correlations, and heavy or light-tailed posteriors. The constraints used include those derived from χEFT calculations, nuclear saturation properties, and astrophysical observations from pulsars PSR J0030+0451, PSR J0740+66, and the GW170817 event [2].

Results and Discussion

Figure 1 displays the 90% CI of the EOS derived from our Bayesian analysis, which integrates constraints from χEFT calculations, nuclear saturation properties, and astrophysical observations of pulsars PSR J0030+0451,

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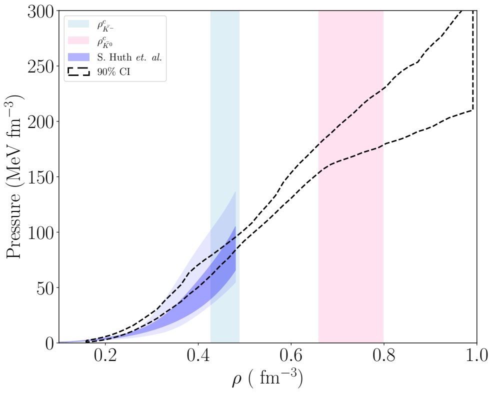

FIG. 1: The 90% confidence interval for the equation of state (EOS) of neutron star matter with antikaon condensation is presented. This EOS is compared with recent estimates derived from both microscopic models and multi-messenger astrophysics [7]. The onset densities of K^- and K^0 are indicated by the vertical shaded areas.

PSR J0740+66, and the GW170817 event. Our analysis yields onset densities of $2.80^{+0.35}_{-0.05}$ fm^{-3} for K^- and $4.45^{+0.70}_{-0.20}$ fm^{-3} for $\bar{K}^0$, along with an antikaon potential of $-129.36^{+12.536}_{-3.837}$ MeV. Two distinct kinks in the EOS indicate the onset of K^- and $\bar{K}^0$ condensation. The 68% CI ranges for the onset densities $\rho^c_{K^-}$ and $\rho^c_{\bar{K}^0}$ are represented by vertical bands. After calculating the mass-radius profile we find that the antikaon condensation is not supported in canonical neutron stars, as the onset densities exceed their central densities. Furthermore, while K^- condensation is not feasible in canonical neutron stars, it becomes possible in more massive neutron stars. For neutron stars with masses $M \leq 1.4 M_\odot$, antikaon condensation is unlikely, highlighting the need for the EOS to adhere to astrophysical constraints. The antikaon potential depends on the scalar coupling parameter in the kaonic sector calculated at ρ_0. Thus, determining the optimal antikaon potential requires integrating both nuclear matter parameters at saturation density and astrophysical observations.

Our EOS shows reasonable agreement with the results of S. Huth *et al.* [7], who obtained their final EOS constraints by combining heavy-ion collision data with multi-messenger astrophysical observations. Furthermore, we found that the maximum neutron star mass is constrained to approximately $2M_\odot$ due to the significant softening of the EOS caused by antikaon condensation, which results in a notable reduction in the speed of sound.

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