Constraints on nuclear matter parameters of an effective chiral model

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Within an effective nonlinear chiral model, we evaluate nuclear matter parameters exploiting the uncertainties in the nuclear saturation properties. The model is sterner constrained with minimal free parameters, which display the interlink among nuclear incompressibility \(K\), the nucleon effective mass \(m^*\), the pion decay constant \(f_\pi\), and the \(\sigma\)-meson mass \(m_\sigma\). The best fit among the various parameter set is then extracted and employed to study the resulting equation of state (EOS). Further, we also discuss the consequences of imposing constraints on the nuclear EOS from heavy-ion collision and other phenomenological model predictions.

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I. INTRODUCTION

The framework of quantum hadrodynamics \([1,2]\) as an elegant and consistent theoretical treatment of finite nuclei as well as infinite nuclear matter laid down the pillars of relativistic theories that seem to provide solution to the so-called “the Coester band” problem \([3,4]\). However, our present knowledge of nuclear matter is confined around nuclear saturation density \(\rho_0 \approx 3 \times 10^{14} \text{ g cm}^{-3}\) and therefore, to have some meaningful correlations while extrapolating to higher densities, the nuclear equation of state (EOS) must satisfy certain minimum criteria quantified as the “nuclear saturation properties,” which are the physical constants of nature. Basically it is understood that the inherited uncertainty at \(\rho_0\) gets more pronounced at higher densities \((3–10 \rho_0)\), relevant to astrophysical context such as the modeling of neutron stars. In this context, the two most important quantities that play vital role and are known to have substantial impact on the EOS are the nucleon effective mass and the nuclear incompressibility \([5,6]\). Ironically, these two properties are not very well determined and they possess large uncertainty. The nuclear incompressibility derived from nuclear measurements and astrophysical observations exhibit a broad range of values \(K = (180–800) \text{ MeV}\) \([7]\). Further the nonrelativistic and the relativistic models fail to agree to a common consensus. The nonrelativistic calculations predict the compression moduli in the range \(K = (210–240) \text{ MeV}\) \([8–10]\), whereas relativistic calculations predicts it in the range \((200–300) \text{ MeV}\) \([11,12]\). Apart from that we are inevitably marred by the uncertainty in the determination of mass of the scalar meson \(\sigma\) meson). The attractive force resulting from the scalar sector is responsible for the intermediate range attraction that, along with the repulsive vector forces provides the saturation mechanism for nuclear matter \([2]\). The estimate from the Particle Data Group quotes the mass of this scalar meson “\(f_0(600)\)” or \(\sigma\) meson in the range \((400–1200) \text{ MeV}\) \([13]\). A recent estimate, however, for \(\sigma\) meson mass is found to be \(513 \pm 32 \text{ MeV}\) \([14]\).

Phenomenologically, parallel to the well-known \(\sigma-\omega\) model, preferably known as the Walecka model \([1,2,15]\), chiral models \([16–22]\) have been developed and were applied to nuclear matter studies. Chiral symmetry is a symmetry of strong interactions in the limit of vanishing quark masses and is desirable in any relativistic theory. However, because the current quark masses are small but finite this symmetry can be considered as an approximate symmetry. This symmetry is spontaneously broken in the ground state. In the context of \(\sigma\) models, the \(\sigma\) field (which carries the quantum numbers of the vacuum) attains a finite vacuum expectation value \(\langle \sigma \rangle = \sigma_0 = f_\pi\). Equivalently, the potential for the \(\sigma\) field attains a minimum at \(f_\pi\) \([23,24]\). The value of \(f_\pi\) reflects the strength of the symmetry breaking and experimentally it is found to be \(f_\pi \approx 131 \text{ MeV}\) \([13]\).

Time and again, the aforesaid facts and figures emphasize the need to address the importance of imposing constraints to the EOS to narrow down the uncertainties both experimentally and theoretically. Arguably, to address these issues, one needs a model that has the desired attributes of the relativistic framework and that can be successfully applied to various nuclear force problem both in the vicinity of \(\rho_0\) as well as at higher densities with the same set of parameters. With this motivation, we choose a model \([25]\) that embodies chiral symmetry and has minimum number of free parameters (total five) to reproduce the saturation properties. The spontaneous breaking of chiral symmetry relates the mass of the hadrons to the vacuum expectation value of the scalar field and thus naturally restricts the parameters of the model. Therefore, the present study, apart from testing the reliability of the model, puts valuable constraint on the EOS based on the pion decay constant and brings out correlations between between the pion decay constant \(f_\pi\), the \(\sigma\) meson mass \(m_\sigma\), the nuclear incompressibility \(K\), and the nucleon effective mass \(m^*\).

In Sec. II, we briefly describe basic ingredients of the hadronic model and the energy and pressure of many baryonic system is computed following the mean-field ansatz. Section III describes the methodology to evaluate the model parameters. In Sec. IV, we extract the best fit among the various parameter of the model and apply it to study the resulting EOS of symmetric nuclear matter. In the result and