Properties of nuclear matter within the JISP16 NN interaction

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Saturation properties of the JISP16 NN interaction are studied in symmetric nuclear matter calculations, with special attention paid to the convergence properties with respect to the number of partial waves. We also present results of pure neutron matter calculations with the JISP16 interaction.

Conventional nuclear matter corresponds to the infinite Coulomb-free system with the same number of protons and neutrons and uniform density. Such an idealized model, whose properties are inferred by extrapolating from known nuclei, is a useful tool for studying saturation properties of inter-nucleon forces. In this paper we calculate nuclear matter properties with the JISP16 NN interaction.

The JISP16 NN interaction proposed in Refs. [1, 2] is constructed in the J-matrix inverse scattering approach [3]. It is known to provide an excellent description of np scattering data with $\chi^2/datum \approx 1$ [4]. The interaction was fitted in Ref. [1] by means of phase-equivalent transformations to the binding energies of nuclei with $A \leq 16$, and it provides a good description of bindings and spectra of light nuclei without referring to three-nucleon forces [1, 5–19]. In particular, the binding energy and spectrum of exotic proton-excess nucleus [14]F have been predicted [9] in No-core Full Configuration Calculations [7] with the JISP16 NN interaction. These predictions were confirmed in a subsequent experiment [20] where this nucleus was first observed.

A difficulty in nuclear matter studies with conventional NN interactions is that the calculations are nonperturbative due to the strong short-range repulsion and tensor forces [21]. However, as it was shown in Refs. [22–24], in the case of soft NN interactions, a perturbative approach can be successfully used for nuclear matter calculations. In particular, the authors of Refs. [22, 23] demonstrated that the dominant particle-particle channel contributions become perturbative in nuclear matter calculations using so-called low-momentum NN interactions ($V_{\text{low}-k}$) obtained by renormalization group methods [25, 26] from Argonne AV_{18} and chiral effective field theory N^3LO NN interactions.

JISP16 is a soft NN interaction providing faster convergence of nuclear structure calculations than typical realistic NN interactions providing high quality fits to all NN data. The interaction is completely nonlocal: by construction, it is given by a matrix in the harmonic oscillator basis in each partial wave of the NN interaction. Therefore there is nothing like a core in this interaction which is a leading source of the nonperturbative behavior of the nuclear matter calculations. The structure of the interaction guarantees description of the NN scattering phase shifts up to the energy of 350 MeV in the lab frame. At the energies of about 400 MeV and higher the JISP16 scattering phase shifts exponentially drop to zero. The $V_{\text{low}-k}$ NN interactions of Ref. [22]. have a similar falloff when renormalized to a corresponding scale which lends support to our adoption of the perturbative approach of Refs. [22, 23].

Nuclear matter is known [22, 23, 27] to collapse with the $V_{\text{low}-k}$ interactions if the renormalization group evo-
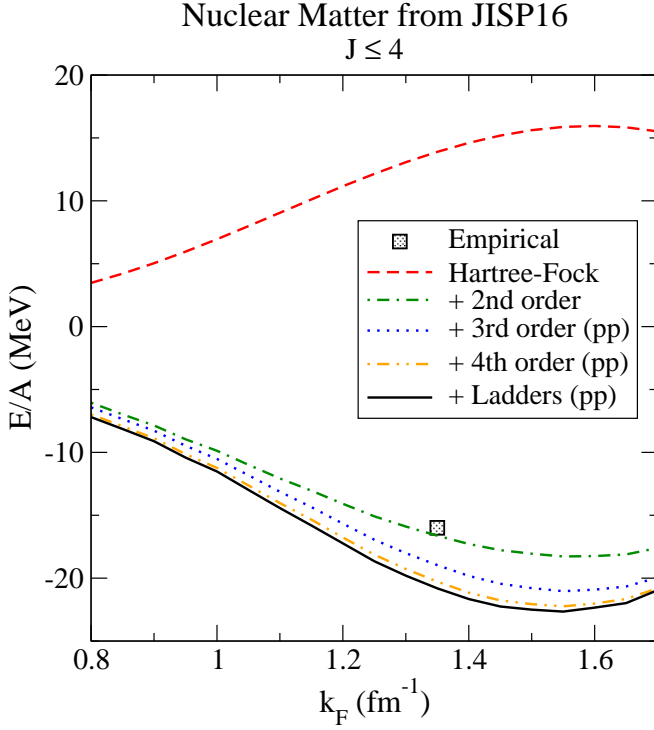
FIG. 1: (Color online) Results of perturbative nuclear matter calculations with JISP16 NN interaction.

FIG. 2: (Color online) Convergence of nuclear matter calculations with respect to the J-truncation of the JISP16 NN interaction. The calculations include particle-particle ladder diagrams to all orders with Hartree–Fock single-particle energies.

lution is truncated at the two-body level. Saturation is however restored if one approximates the low-momentum three-nucleon interactions that are present in the initial Hamiltonian and induced by the renormalization group evolution with the leading three-nucleon force from chiral effective field theory, refitted at each cutoff to give cutoff-independent results for the triton and alpha particle [22, 23]. See also Ref. [28]. In view of the similarities between JISP16 and the $V_{\mathrm{low}-k}$ NN interactions, one might expect that the soft JISP16 interaction would also fail to produce nuclear matter saturation at the NN-only level. It is easy to show that the JISP-like interactions represented by a matrix in the oscillator basis cause collapse in nuclear matter in a pure Hartree–Fock calculation if the trace of the two-body interaction matrix is negative. The trace of the JISP16 interaction matrix is positive, hence this NN force does not collapse nuclear matter, at least at the Hartree–Fock level.

The Hartree–Fock approximation is however very inaccurate as is seen from Fig. 1 where we present results obtained in a sequence of approximations, including contributions up to total angular momentum $J = 4$ in the NN interaction. In particular, we performed calculations in a pure Hartree–Fock approximation, then including second order corrections, then including particle-particle third and fourth order corrections, and then summing the ladder particle-particle contributions to all orders. In all cases, the single-particle energies are dressed at the Hartree–Fock level, including the full momentum dependence of the Hartree–Fock single particle potential. The
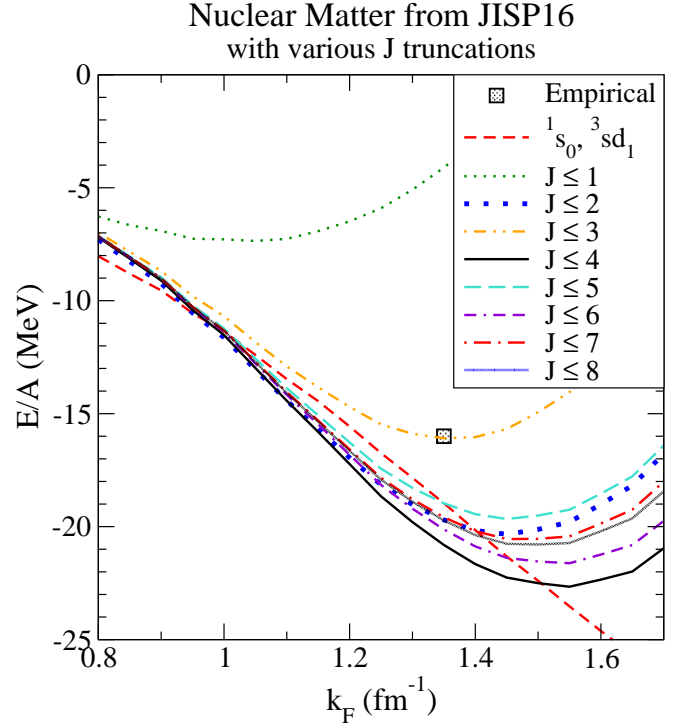
Pauli blocking operator is treated in the angle-average approximation, which has been shown to be accurate to $\sim .5$ MeV per nucleon level for soft interactions [29]. This sequence is seen to converge. The converged energy minimum corresponds to higher density (larger Fermi momentum $k_{\mathrm{F}} \approx 1.55$ fm^{-1}) and larger binding energy (≈ 22.7 MeV per nucleon) than the empirical nuclear matter saturation point.

Figure 2 demonstrates the convergence of the nuclear matter equation of state when potential energy contributions with increasing total angular momentum J are successively included in the calculations. The conventional JISP16 interaction of Refs. [1, 2] is defined in NN partial waves with $J \leq 4$ only; just these $J \leq 4$ results were presented in Fig. 1. It is clear from Fig. 2 that interaction in partial waves with $J \leq 4$ is not enough to achieve convergence at the higher densities. The sensitivity of nuclear matter saturation properties to higher partial waves was also mentioned in Refs. [30–32].

We extended the JISP16 interaction to higher partial waves using the J-matrix inverse scattering approach described in detail in Ref. [3] and used Nijmegen partial waves analysis [33] as an input. The JISP16 interaction is defined with the truncation in oscillator quanta $N = 2n + L \leq 9$. Hence this interaction can be defined only in NN partial waves with $J \leq 8$: the potentials in partial waves with orbital momenta $L = 8$ and 9 are
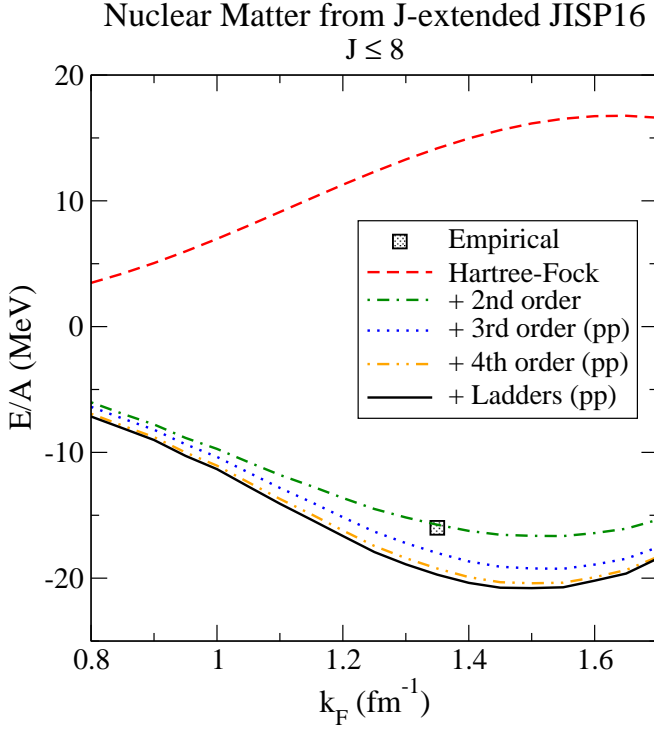
Nuclear Matter from J-extended JISP16
$J \leq 8$

FIG. 3: (Color online) Results of perturbative nuclear matter calculations with JISP16 NN interaction extended up to $J = 8$.

Neutron Matter from JISP16
$J \leq 4$

FIG. 4: (Color online) Results of perturbative pure neutron matter calculations with JISP16 NN interaction.

Neutron Matter from JISP16
with various J truncations

FIG. 5: (Color online) Convergence of pure neutron matter calculations allowing for corrections up to the fourth order and summing of ladder diagrams with respect to the J-truncation of the JISP16 NN interaction.

presented by 1×1 matrices in the oscillator basis. Nevertheless, the Nijmegen phase shifts are reasonably well reproduced even in the partial waves with the highest possible angular momenta.

The results obtained with this J-extended JISP16 NN interaction are also presented in Fig. 2. It is seen that the convergence of the nuclear matter equation of state with respect to J is achieved when the interaction in all partial waves with $J \leq 7$ is included in our calculations.

The convergence of our sequence of nuclear matter calculations with the JISP16 NN interaction extended up to $J = 8$ partial waves is illustrated by Fig. 3. The saturation point in this case is slightly shifted to smaller densities and smaller binding energies as compared to the results obtained with the conventional JISP16 interaction (see Fig. 1). Nevertheless this J-extended JISP16 interaction still overbinds and overcompresses nuclear matter.

It is interesting also to obtain predictions for the pure neutron matter equation of state with JISP16. Our perturbative approach is seen from Fig. 4 to converge. The convergence of the neutron matter energy with respect to J (see Fig. 5) is achieved much faster than in the case of the symmetric nuclear matter. Figure 6 presents a comparison of the JISP16 induced neutron matter equation of state with the results obtained with Argonne AV14 NN interaction solely and in combination with Urbana UVII NNN force [34] and with Argonne AV18 NN interaction solely and in combination with Urbana UIX NNN force [35]. It appears that JISP16 generates pure neutron
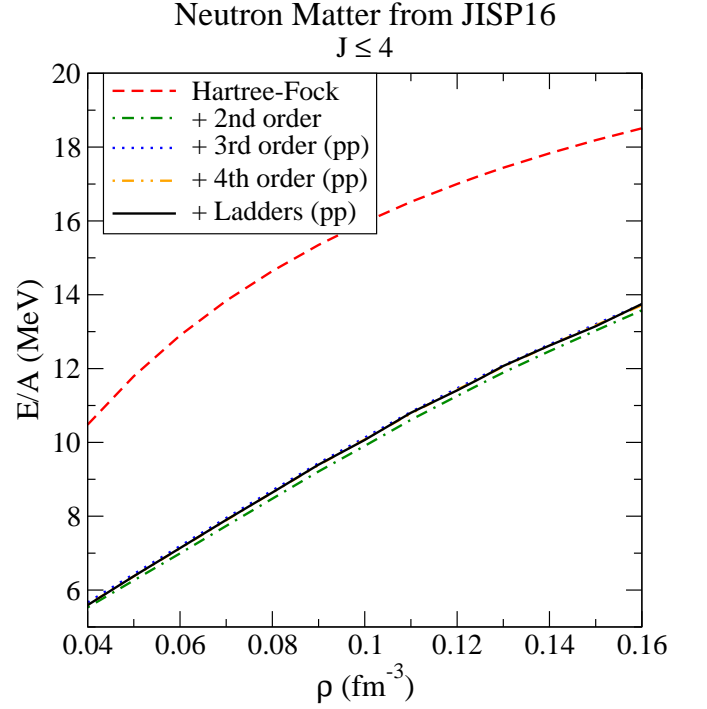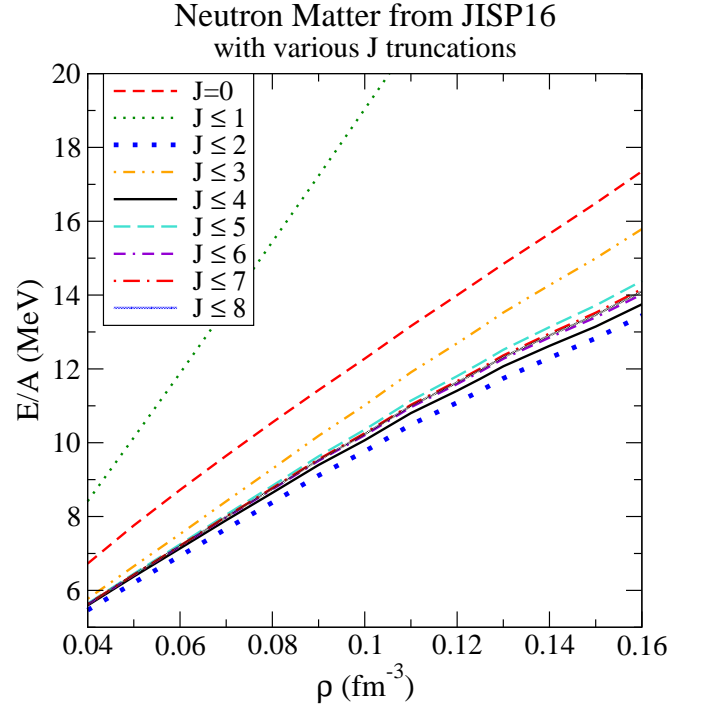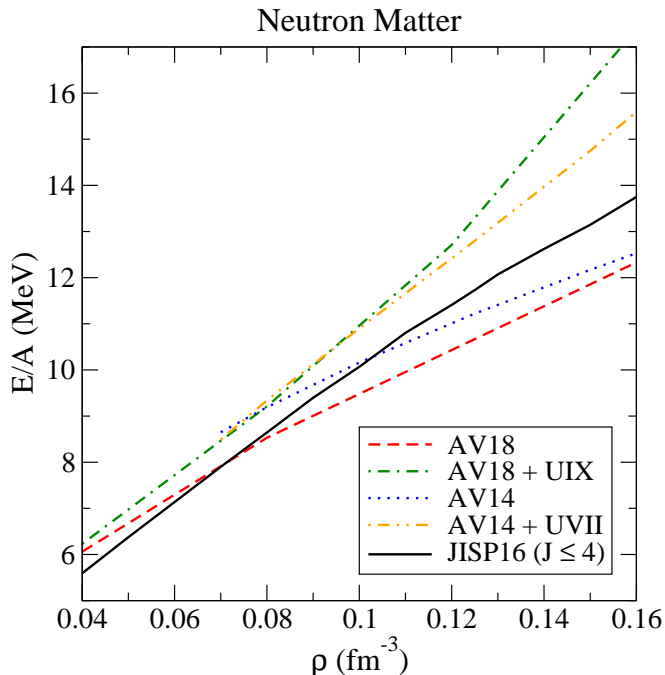
FIG. 6: (Color online) Comparison of pure neutron matter equations of state obtained with JISP16 and other interaction models.

matter properties at high densities intermediate between predictions of conventional realistic NN and $NN+NNN$ interaction models.

Summarizing, we have shown that the soft and nonlocal JISP16 interaction gives a saturating nuclear matter equation of state that converges rapidly in many-body perturbation theory, at least in the particle-particle channel. Due to the soft nature of the JISP16 interaction, and the fact that the dominant contributions to bulk properties of nuclei and nuclear matter are known to be given by the Brueckner Hartree–Fock type correlations treated in our calculations, we expect a more sophisticated many-body treatment will not substantially alter our conclusions, especially for pure neutron matter where it has been shown that low-order perturbative calculations reproduce sophisticated coupled-cluster [36] and Auxiliary-Field Diffusion Monte Carlo (AFDMC) calculations [37, 38] for sufficiently soft input interactions. Our symmetric nuclear matter calculations, on the other hand, come with somewhat larger uncertainties due to the omission of particle-hole and three-body correlations in the medium, both of which contribute at the 1 MeV/nucleon level near saturation for coupled-cluster calculations using soft chiral effective field theory NN and NNN interactions [36].

The saturation property of the JISP16 potential differs from $V_{\mathrm{low}-k}$ NN interactions at low cutoffs ($\Lambda \lesssim 3.0$ fm^{-1}) that give comparably soft and nonlocal potentials, which indicates that the adjustment of the JISP16 off-shell properties by fitting light nuclei may simulate some contributions attributable to three-body

forces in the $V_{\mathrm{low}-k}$ approach. However, the JISP16 saturation point is still overbound at too high a density as compared to conventional extrapolations to the infinite mass limit of heavy nuclei properties. The main idea of the JISP-type interaction is to utilize an *ab exitu* approach [1, 39, 40] in the NN force design, i. e., first the J-matrix inverse scattering approach [3] is used to construct an NN interaction perfectly describing the two-nucleon data (deuteron properties and NN scattering), next the interaction is modified by phase-equivalent transformations in order to achieve a reasonable description of many-body nuclear systems. Following this route, the JISP6 interaction fitted to nuclei with $A \leq 6$ was proposed in Refs. [39, 40]. A subsequent phase-equivalent modification of this NN interaction resulted in construction of the JISP16 version [1] fitted to nuclei with $A \leq 16$. The nuclear matter overbinding presented here poses a challenge to develop a subsequent phase-equivalent modification of JISP16 that achieves an improved description of the nuclear matter saturation without sacrificing the good description of light nuclei. Such an improved interaction may also improve the description of $N \approx Z$ nuclei with $A \geq 12$ — the overbinding of nuclei at the end of the p shell that was revealed with the help of very accurate *ab initio* NCFC approach (see review [19]) introduced in Ref. [7].

It is interesting to note that the JISP16 interaction with the $J \leq 3$ truncation provides a nuclear matter equation of state with the minimum at the phenomenological saturation point (see Fig. 2). Higher-J interaction terms shift the equation of state minimum. The high-J sensitivity of the saturation point can be used to fit the interaction to the nuclear matter properties. In fact, the J-dependence depicted in Fig. 2 suggests how to design a set of phase-equivalent transformations of the JISP16 interaction in the $J \geq 4$ partial waves that will result in cancellation of these high-J interaction terms in the nuclear matter calculations. On the other hand, nuclei with $A \leq 16$ are insensitive to these high-J NN interactions. Therefore the suggested fitting procedure should not affect the description of light nuclei involved in the initial fit of the JISP16 NN interaction.

The fact that a soft NN interaction, such as JISP16 truncated at $J \leq 3$, provides a reasonable saturation curve for nuclear matter is itself an interesting result. It demonstrates that the long-held belief that soft NN interactions cannot properly saturate nuclear matter [41] is not strictly true.

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