Chiral Dynamics of Nuclear and Hypernuclear Matter ◇

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We extend a recent three-loop calculation of nuclear matter in chiral perturbation theory by including systematically the effects from two-pion exchange with single and double virtual $\Delta(1232)$-isobar excitation [1]. Regularization dependent short-range contributions from pion-loops etc. are encoded in a few NN-contact coupling constants. The empirical saturation point of isospin-symmetric nuclear matter, $\bar{E}_0 = -16\,\mathrm{MeV}$, $\rho_0 = 0.16\,\mathrm{fm}^{-3}$, can be well reproduced by adjusting the strength of a two-body term linear in density. The resulting equation of state $\bar{E}(k_f)$ is shown in the left part of Fig. 1. The nuclear matter compressibility comes out as $K = 304\,\mathrm{MeV}$. The real part of the single-particle potential $U(p, k_{f0})$ (shown in the right part of Fig. 1) is substantially improved by the inclusion of the chiral $\pi N\Delta$-dynamics. In comparison to previous calculations [2] it grows now monotonically with the nucleon momentum p. The effective nucleon mass at the Fermi surface $p = k_{f0}$ takes on a realistic value of $M^*(k_{f0}) = 0.88M$. As a consequence the density of states at the Fermi surface is now well described and the critical temperature of the liquid-gas phase transition gets lowered to the value $T_c \simeq 15\,\mathrm{MeV}$ (see Fig. 2 for the calculated pressure isotherms $P(\rho, T)$).

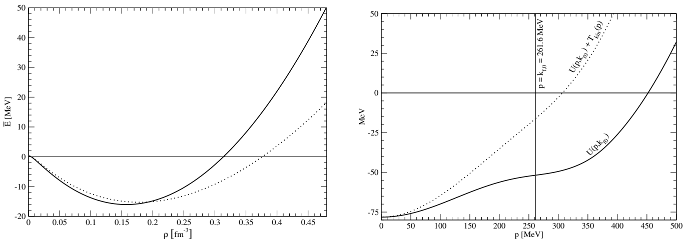

Figure 1: Left: Energy per particle $\bar{E}(k_f)$ of isospin-symmetric nuclear matter versus the nucleon density $\rho = 2k_f^3/3\pi^2$. Right: Real part $U(p, k_{f0})$ of the single-particle potential at saturation density $k_{f0} = 261.6\,\mathrm{MeV}$ versus the nucleon momentum p.

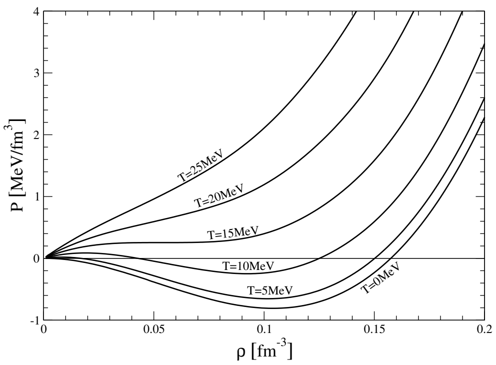

Figure 2: Pressure isotherms $P(\rho, T)$ of isospin-symmetric nuclear matter at finite temperature T. The coexistence region of the liquid and the gas phase ends at the critical point: $\rho_c \simeq 0.053\,\mathrm{fm}^{-3}$, $T_c \simeq 15\,\mathrm{MeV}$.

We continue the complex single-particle potential $U(p, k_f) + i\,W(p, k_f)$ also into the region above the Fermi surface $p > k_f$. The effects from 2π-exchange with virtual Δ-excitation on the nuclear energy density functional are also investigated. The predicted strength of the surface term $F_\nabla(k)\,(\vec{\nabla}\rho)^2$ agrees in the density regime $0.1\,\mathrm{fm}^{-3} < \rho < 0.2\,\mathrm{fm}^{-3}$ well with that of phenomenological Skyrme forces. We find that the isospin properties of nuclear matter get significantly improved by including the chiral $\pi N\Delta$-dynamics. Instead of bending downward above ρ_0 as in previous calculations, the energy per particle of pure neutron matter $\bar{E}_n(k_n)$ and the asymmetry energy $A(k_f)$ now grow monotonically with density. In the density regime $\rho = 2\rho_n < 0.2\,\mathrm{fm}^{-3}$ relevant for conventional nuclear physics our results agree well with sophisticated many-body calculations and semi-empirical values.

As a further application of our in-medium effective field theory approach we consider the mean field and spin-orbit coupling of a Λ-hyperon in a nuclear many-body system [3]. The leading long-range ΛN-interaction arises from kaon exchange and from 2π-exchange with a Σ-hyperon in the intermediate state. The empirical Λ-nucleus potential depth of about $-28\,\mathrm{MeV}$ is well reproduced with a single cutoff scale, $\bar{\Lambda} = 0.7\,\mathrm{GeV}$, effectively representing all short-distance (high-momentum) dynamics not resolved at scales characteristic of the nuclear Fermi momentum $k_f \leq 270\,\mathrm{MeV}$. The smallness of the Λ-nuclear spin-orbit interaction finds a natural (yet novel) explanation [3] in terms of an almost complete cancellation between short-range contributions (properly rescaled from the known nucleonic spin-orbit coupling strength) and long-range terms (of the "wrong" sign) generated by 2π-exchange with intermediate Σ-hyperons. The small $\Sigma\Lambda$-mass difference $M_\Sigma - M_\Lambda = 77.5\,\mathrm{MeV}$ figures prominently in this context.

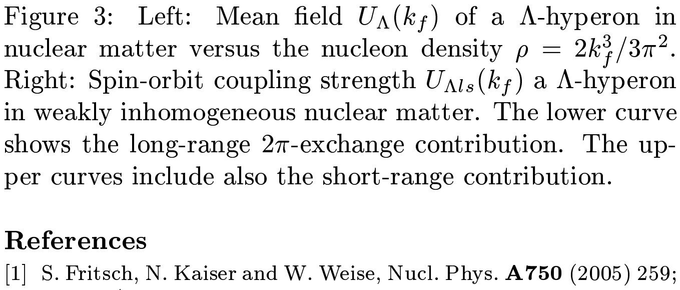

Figure 3: Left: Mean field $U_\Lambda(k_f)$ of a Λ-hyperon in nuclear matter versus the nucleon density $\rho = 2k_f^3/3\pi^2$. Right: Spin-orbit coupling strength $U_{\Lambda ls}(k_f)$ a Λ-hyperon in weakly inhomogeneous nuclear matter. The lower curve shows the long-range 2π-exchange contribution. The upper curves include also the short-range contribution.

References

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