Chiral Dynamics of Nuclear Matter

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We calculate the equation of state of isospin-symmetric nuclear matter in the 3-loop approximation of chiral perturbation theory [1]. The contributions to the energy per particle $\bar{E}(k_f)$ from 1π- and 2π-exchange graphs are ordered in powers of the Fermi momentum k_f (modulo functions of k_f/m_π). It is demonstrated that, already at order $\mathcal{O}(k_f^4)$, 2π-exchange produces realistic nuclear binding. The underlying saturation mechanism is surprisingly simple (in the chiral limit), namely the combination of an attractive k_f^3-term and a repulsive k_f^4-term. The empirical saturation point $\bar{E}(k_{f0}) \simeq -15.3\,\mathrm{MeV}$, $\rho_0 \simeq 0.17\,\mathrm{fm}^{-3}$ and the nuclear compressibility $K \simeq 255\,\mathrm{MeV}$ are well reproduced at order $\mathcal{O}(k_f^5)$ with one single momentum cut-off of $\Lambda \simeq 7f_\pi \simeq 0.65\,\mathrm{GeV}$ which parametrizes all necessary short-range dynamics. In the same framework, we calculate the density-dependent asymmetry energy and find $A(k_{f0}) \simeq 34\,\mathrm{MeV}$, in very good agreement with the empirical value. The pure neutron matter equation of state is also in fair agreement with sophisticated many-body calculations and a resummation result of effective field theory, for low neutron densities $\rho_n < 0.25\,\mathrm{fm}^{-3}$. In the next step, we evaluate the momentum and density dependent complex-valued single-particle potential $U(p,k_f) + i\,W(p,k_f)$ [2] (i.e. the average nuclear mean field). Chiral 1π- and 2π-exchange give rise to a potential depth (for a nucleon at the bottom of the Fermi sea) of $U(0,k_{f0}) = -53.2\,\mathrm{MeV}$, in very good agreement with the depth of the optical model and the nuclear shell model potential. The momentum dependence of the real single-particle potential $U(p,k_{f0})$ is non-monotonic in the region $0 < p < k_{f0}$. Its maximal increase of $\Delta U = 8.8\,\mathrm{MeV}$ can be translated into a mean effective nucleon mass of $\bar{M}^* \simeq 0.82M$. The imaginary single-particle potential $W(p,k_f)$ is generated entirely by iterated 1π-exchange. The half width of a nucleon-hole state at the bottom of the Fermi sea comes out as $W(0,k_{f0}) = 29.7\,\mathrm{MeV}$. The basic theorems of Hugenholtz-Van-Hove and Luttinger are satisfied in our perturbative calculation. Finally, we extend the three-loop chiral perturbation theory calculation of nuclear matter to finite temperatures [3]. The free energy per particle $\bar{F}(\rho,T)$ is derived from the energy density functional by inserting a Fermi-Dirac distribution for the density of states in momentum space. The calculated pressure isotherms display the familiar first-order liquid-gas phase transition of isospin symmetric nuclear matter. The predicted critical point, $T_c \simeq 19\,\mathrm{MeV}$, $\rho_c \simeq 0.075\,\mathrm{fm}^{-3}$ and $P(\rho_c,T_c) \simeq 0.46\,\mathrm{MeVfm}^{-3}$ agrees well with that of sophisticated many-body calculations. The so-called anomalous 2π-exchange diagram (with no counterpart in the $T=0$ ground state energy density) is very important in order to get this low value of $T_c \simeq 19\,\mathrm{MeV}$. Keeping the binding energy per particle $-\bar{E}(k_{f0})$ fixed the critical temperature T_c does not change if the pion mass is sent to zero. Our results for pure neutron matter at finite T agree fairly well with elaborate calculations.

References

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