Chiral Dynamics of Nuclear Matter ◇

S. Fritsch, N. Kaiser, and W. Weise [a]

[a] ECT* Trento, 38050 Villazzano (Trento), Italy, and Technische Universität München

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 $\bar{E}(k_f)$ arising from 1π- and 2π-exchange diagrams are ordered in powers of the Fermi momentum k_f. It is demonstrated that the empirical saturation point $\bar{E}(k_{f0}) \simeq -15.3\,\mathrm{MeV}$, $\rho_0 \simeq 0.17\,\mathrm{fm}^{-3}$ and the nuclear matter compressibility $K \simeq 255\,\mathrm{MeV}$ are well reproduced at order $\mathcal{O}(k_f^5)$ with just one single momentum cut-off of $\Lambda = 7f_\pi \simeq 0.65\,\mathrm{GeV}$ which parametrizes the necessary short-range NN-dynamics. The underlying saturation mechanism is surprisingly simple (in the chiral limit $m_\pi = 0$), namely the combination of an attractive k_f^3-term and a repulsive k_f^4-term. In the same framework, we calculate the density-dependent asymmetry energy $A(k_f)$ and find $A(k_{f0}) \simeq 34\,\mathrm{MeV}$, in good agreement with the empirical value. The pure neutron matter equation of state is also in fair agreement with sophisticated many-body calculations for low neutron densities $\rho_n < 0.25\,\mathrm{fm}^{-3}$.

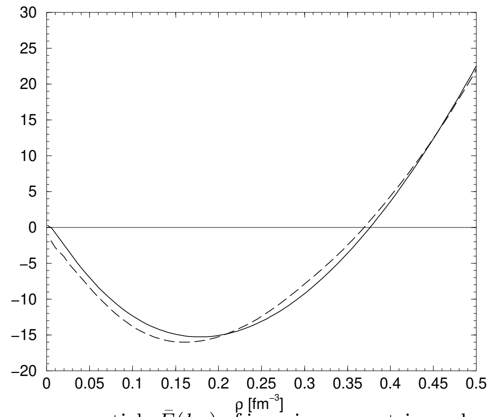

Fig. 1: Energy per particle $\bar{E}(k_f)$ of isospin symmetric nuclear matter versus the nucleon density ρ.

Furthermore. we evaluate the momentum and density dependent complex 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 good agreement with the depth of the optical model potential and the nuclear shell model potential. 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.

Next, we extend this calculation of nuclear matter to finite temperatures [3]. The free energy per particle $\bar{F}(\rho, T)$ is constructed from the interaction kernels by convoluting them with Fermi-Dirac distributions. The calculated pressure isotherms $P = \rho^2\,\partial\bar{F}/\partial\rho$ display the familiar first-order liquid-gas phase transition of isospin-symmetric nuclear matter. The predicted critical point, $T_c \simeq 25.5\,\mathrm{MeV}$ and $\rho_c \simeq 0.09\,\mathrm{fm}^{-3}$, lies however too high in temperature. This feature originates from the too strong momentum dependence of the single-particle potential $U(p, k_f)$ near the Fermi-surface $p = k_f$.

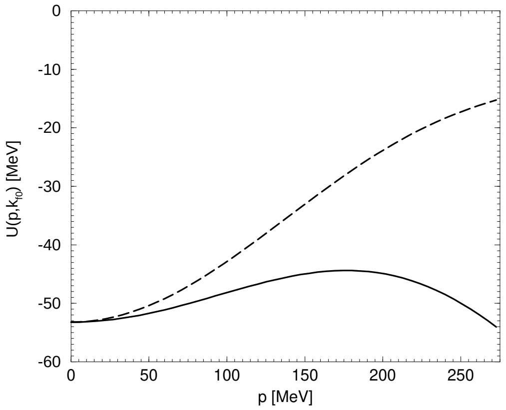

Fig. 2: The real part of the single particle potential $U(p, k_{f0})$ versus the nucleon momentum p at saturation density $k_{f0} = 272.7\,\mathrm{MeV}$. The dashed line includes in addition the kinetic energy $T_k(p) = p^2/2M - p^4/8M^3$.

Finally, chiral 1π- and 2π-exchange determine a nuclear energy density functional of the form: $\mathcal{E}[\rho, \tau, \vec{J}] = \rho\bar{E}(k_f) + [\tau - 3\rho k_f^2/5]/2\widetilde{M}^*(\rho) + (\vec{\nabla}\rho)^2 F_\nabla(k_f) + \vec{\nabla}\rho \cdot \vec{J}\,F_{so}(k_f) + \vec{J}^{\,2}\,F_J(k_f)$. This functional opens a novel approach to nuclear structure calculations which truly start from the long-range pion-induced NN-interaction.

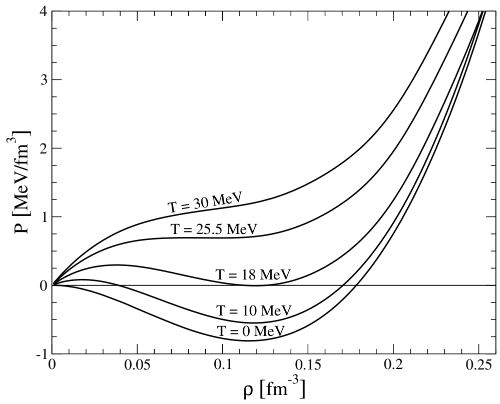

Fig. 3: Pressure isotherms $P(\rho, T)$ of isospin symmetric nuclear matter versus the nucleon density ρ.

References

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◇ supported in part by BMBF project 06 TM 980 and DFG project We 655/14-3