

Chiral dynamics of nuclear matter¹

S. Fritsch^a, N. Kaiser^a and W. Weise^{a,b}

^a Physik Department, Technische Universität München,
D-85747 Garching, Germany

^b ECT*, I-38050 Villazzano (Trento), Italy

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 $\bar{E}(k_{f0}) \simeq -15.3$ MeV, $\rho_0 \simeq 0.17$ fm⁻³ and the nuclear compressibility $K \simeq 255$ MeV are well reproduced at order $\mathcal{O}(k_f^5)$ with one single momentum cut-off of $\Lambda = 7f_\pi \simeq 0.65$ GeV which parametrizes all necessary short-range dynamics. In the same framework, we calculate the density-dependent asymmetry energy and find $A(k_{f0}) \simeq 34$ 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 $\rho_n < 0.25$ fm⁻³.

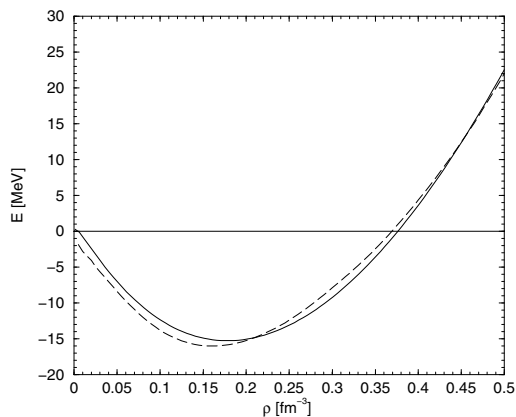


Figure 1: Energy per particle $\bar{E}(k_f)$ of isospin symmetric nuclear matter versus the nucleon density ρ .

In the next step, we evaluate the momentum and density dependent complex single particle potential $U(p, k_f) + iW(p, k_f)$ [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 $U(0, k_{f0}) = -53.2$ 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 $0 < p < k_{f0}$ and 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 $W(0, k_{f0}) = 29.7$ MeV. The

basic theorems of Hugenholtz-Van-Hove and Luttinger are satisfied in our perturbative calculation.

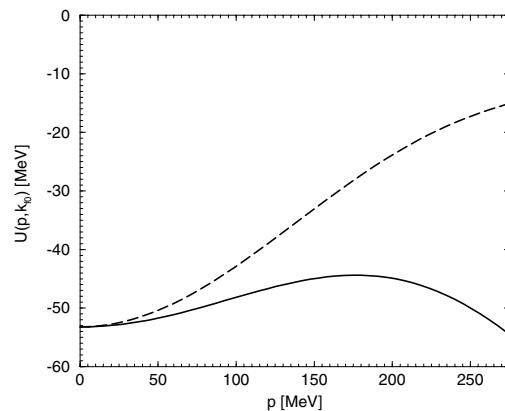


Figure 2: The real part of the single particle potential $U(p, k_{f0})$ versus the nucleon momentum p at saturation density $k_{f0} = 272.7$ MeV. The dashed line includes in addition the kinetic energy $T_k(p) = p^2/2M - p^4/8M^3$.

Finally, we extend the three-loop chiral perturbation theory calculation of nuclear matter to finite temperatures T [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, $T_c \simeq 24$ MeV and $\rho_c \simeq 0.08$ fm⁻³, lies slightly higher in temperature than the values of $T_c \simeq 16 - 19$ MeV commonly discussed. This may point to the necessity of some fine-tuning in the treatment of the short-range NN-interaction, but the overall picture achieved with this (systematic) one-parameter calculation to yield a large number of nuclear matter properties is quite remarkable.

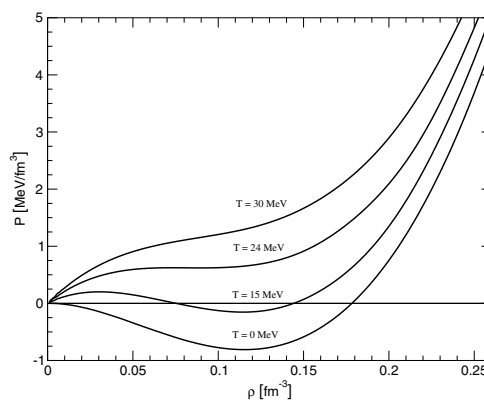


Figure 3: Pressure isotherms $P(\rho, T)$ of isospin symmetric nuclear matter versus the nucleon density ρ .

References

- [1] N. Kaiser, S. Fritsch and W. Weise, Nucl. Phys. **A697** (2002) 255; and refs. therein.
- [2] N. Kaiser, S. Fritsch and W. Weise, Nucl. Phys. **A700** (2002) 343; and refs. therein.
- [3] S. Fritsch, N. Kaiser and W. Weise, submitted to Phys. Lett. **B.** (2002)

¹Supported in part by BMBF, GSI and DFG.