# Scales in Nuclear Matter: Chiral Dynamics with $\pi N$ Form Factors $^\diamond$

M. Mühlbauer, N. Kaiser, and W. Weise

A systematic calculation of nuclear matter is performed which includes explicitly the long-range correlations between nucleons arising from one- and two-pion exchange [1]. Effects from two-pion exchange with excitations of virtual $\Delta(1232)$-isobars are also taken into account in our diagrammatic calculation of the energy per particle $\bar{E}(k_f)$. In order to monitor the sensitivity on the "spatial resolution" of the pion-baryon interactions we introduce at each pion-baryon vertex a form factor of monopole type

$$F_\Lambda(q^2) = \frac{\Lambda^2 - m_\pi^2}{\Lambda^2 - q^2}\,, \qquad (1)$$

with $\Lambda$ the monopole mass. Saturation of nuclear matter arises in our approach primarily from Pauli blocking on second order (iterated) one-pion exchange. Without any additional short-range terms the empirical saturation point of nuclear matter ($\rho_0 \simeq 0.16\,\mathrm{fm}^{-3}$, $\bar{E}_0 \simeq -16.7\,\mathrm{MeV}$) can be reproduced by adjusting the monopole mass to the value $\Lambda_0 = 1.15\,\mathrm{GeV} \simeq 4\pi f_\pi$. The full line in Fig. 1 shows the corresponding saturation curve as a function of the nucleon density $\rho = 2k_f^3/3\pi^2$. The nuclear matter compressibility comes out as $K = k_{f0}^2 \bar{E}''(k_{f0}) \simeq 290\,\mathrm{MeV}$. The dashed curves in Fig. 1, obtained by leaving out all three-body terms, clearly demonstrated the importance of the long-range pion-induced three-nucleon interaction for the saturation of isospin-symmetric nuclear matter.

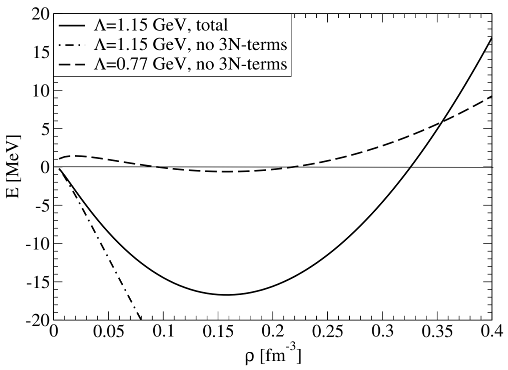


Figure 1: Energy per particle $\bar{E}(k_f)$ of isospin-symmetric nuclear matter versus the nucleon density $\rho = 2k_f^3/3\pi^2$. In the dashed lines all three-body terms have been omitted.

Our approach to nuclear matter has similarities to the recent perturbative nuclear matter calculation of Schwenk et al. [2] based on the universal low-momentum NN-potential $V_{\mathrm{low-k}}$. There, three-nucleon interactions are also essential in order to achieve saturation, while the $V_{\mathrm{low-k}}$-potential in Hartree-Fock approximation alone would fail.

The dependence of the pion-exchange contributions to the energy per particle $\bar{E}(k_f)$ on the regulator mass $\Lambda$ can be balanced in our calculation by that of two "running" short-distance contact-terms

$$\bar{E}(k_f)^{\mathrm{ct}} = B_3(\Lambda)\frac{k_f^3}{M_N^2} + B_5(\Lambda)\frac{k_f^5}{M_N^4}\,. \qquad (2)$$

A rather narrow band of saturation curves result from varying the monopole mass $0.5\,\mathrm{GeV} \le \Lambda \le 1.5\,\mathrm{GeV}$ when the "running" short-distance parameters $B_3(\Lambda)$ and $B_5(\Lambda)$ are readjusted at each $\Lambda$ to the empirical saturation point.

The momentum and density dependent single-particle potential $U(p, k_f)$ resulting from our calculation is shown in Fig. 2. It is important to stress that the Hugenholtz-van-Hove theorem holds strictly. The total single-particle energy $T_{\mathrm{kin}}(p) + U(p, k_{f0})$ reaches at the Fermi surface $p = k_{f0}$ the binding energy per particle $\bar{E}(k_{f0}) = -16.7\,\mathrm{MeV}$.

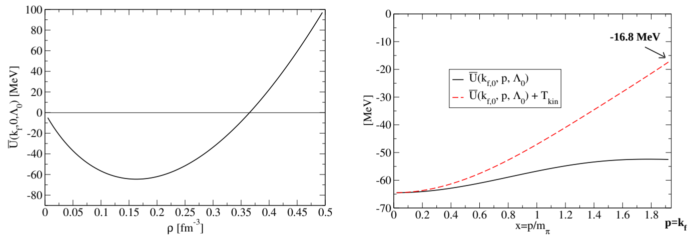


Figure 2: Left: Nuclear mean field $U(0, k_f)$ of a zero-momentum nucleon versus the nucleon density $\rho = 2k_f^3/3\pi^2$. Right: Momentum dependence of the nuclear mean field $U(p, k_{f0})$ at saturation density $k_{f0} = 262\,\mathrm{MeV}$.

As a further application of our nuclear matter calculation with explicit pion-exchange dynamics we can study the in-medium chiral condensate $\langle \bar{q}q\rangle(\rho)$ beyond the linear density approximation. These corrections are obtained by differentiating the energy density of nuclear matter $\rho\bar{E}(k_f)$ with respect to the pion mass (or equivalently the light quark mass). As Fig. 3 shows, these corrections are small below saturation density $\rho \le 0.16\,\mathrm{fm}^{-3}$. At higher densities a tendency which counteracts chiral restoration sets in. Moreover, there is little dependence of the derivative $d\bar{E}(k_f)/dm_\pi$ on the monopole mass $\Lambda$ which serves as a regulator for possible high momentum contributions.

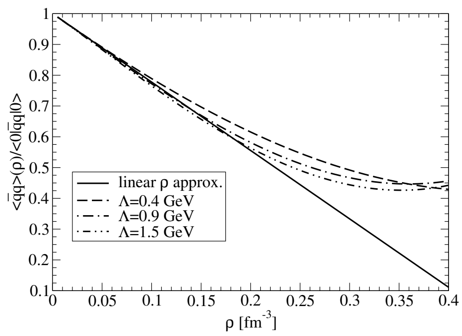


Figure 3: Density dependence of the chiral condensate.

## References


[1] N. Kaiser, M. Mühlbauer and W. Weise, Eur. Phys. J. **A31** (2007) 53 and references therein.

[2] S.K. Bogner, A. Schwenk, R.J. Furnstahl and A. Nogga, Nucl. Phys. **A763** (2005) 59; and references therein.


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