Relativistic Chiral Theory of Nuclear Matter and QCD Constraints

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Abstract

We present a relativistic chiral theory of nuclear matter which includes the effect of confinement. Nuclear binding is obtained with a chiral invariant scalar background field associated with the radial fluctuations of the chiral condensate Nuclear matter stability is ensured once the scalar response of the nucleon depending on the quark confinement mechanism is properly incorporated. All the parameters are fixed or constrained by hadron phenomenology and lattice data. A good description of nuclear saturation is reached, which includes the effect of in-medium pion loops. Asymmetry properties of nuclear matter are also well described once the full rho meson exchange and Fock terms are included.

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General context. The aim of this talk is to discuss the possible relation between fundamental properties of low energy QCD, namely chiral symmetry and confinement, with the rich structure of the nuclear many-body problem. More precisely with the introduction of the concept of nucleon substructure adjustement to the nuclear environment [1] we will bring some constraints from lattice QCD data into the modelling of many-body forces. In the relativistic mean-field approaches initiated by Walecka, the nucleons move in an attractive scalar and in a repulsive vector background fields. This provides a very economical saturation mechanism and a spectacular well known success is the correct magnitude of the spin-orbit potential since the large vector and scalar fields contribute to it in an an additive way. Now the question of the very nature of these background fields and their relationship with the QCD condensates has to be elucidated. To address this problem we formulate the effective theory in terms of the fields associated with the fluctuations of the chiral condensates in a matrix form ($W = \sigma + i\vec{\tau}\cdot\vec{\pi}$) by going from cartesian to polar coordinates *i.e.*, going from a linear to a non linear representation :

$W = \sigma + i\vec{\tau}\cdot\vec{\pi} = S\,U = (f_\pi + s)\,exp\,(i\vec{\tau}\cdot\vec{\varphi}_\pi/f_\pi)$. In ref [2] we made the physical assumption to identify the chiral invariant scalar field $s = S - f_\pi$, associated with *radial* (in order to respect chiral constraints) fluctuations of the condensate, with the background attractive scalar field.

In this approach the Hartree energy density of nuclear matter, including ω exchange, writes in terms of the order parameter $\bar{s} = \langle s\rangle$: $E_0/V = \varepsilon_0 = \int (4\,d^3p/(2\pi)^3)\,\Theta(p_F - p)\,E^*_p(\bar{s}) + V(\bar{s}) + g^2_\omega/2\,m_{\omega^2}\,\rho^2$, where $E^*_p(\bar{s}) = \sqrt{p^2 + M^{*2}_N(\bar{s})}$ is the energy of an effective nucleon with the effective Dirac mass $M^*_N(\bar{s}) = M_N + g_S\,\bar{s}$. $g_S = M_N/f_\pi$ is the scalar coupling constant of the sigma model. Here two serious problems appear. The first one is the fact that the chiral effective potential, $V(s)$, contains an attractive tadpole diagram which generates an attractive three-body force destroying matter stability. The second one is related to the nucleon substructure. The nucleon mass can be expanded according to $M_N(m^2_\pi) = a_0 + a_2\,m^2_\pi + a_4\,m^4_\pi + \Sigma_\pi(m_\pi,\Lambda) + ...$, where the pionic self-energy is explicitely separated out. The a_2 parameter is related to the non pionic piece of the πN sigma term and a_4 to the nucleon QCD scalar susceptibility. According to the lattice data analysis a_4 is found to be negative, $(a_4)_{latt} \simeq -0.5\,\mathrm{GeV}^{-3}$ [3], but much smaller than in our chiral effective model, $(a_4)_{Chiral} = -3f_\pi g_S/2\,m^4_\sigma \simeq -3.5\,GeV^{-3}$, where the nucleon is seen as a juxtaposition of three constituent quarks getting their mass from the chiral condensate. The common origin of these two failures can be attributed to the absence of confinement. In reality the composite nucleon should respond to the nuclear environment, *i.e.*, by readjusting its confined quark structure. The resulting polarization of the nucleon is accounted for by the phenomenological introduction of the scalar nucleon response, κ_{NS}, in the nucleon mass evolution : $M_N(s) = M_N + g_S\,s + \frac{1}{2}\,\kappa_{NS}\,s^2 + ...$ This constitutes the only change in the expression of the energy density but this has numerous consequences. In particular the a_4 parameter is modified : $a_4 = (a_4)_{Chiral}\left(1 - \frac{2}{3}C\right)$. The value of $C \equiv (f^2_\pi/2\,M_N)\kappa_{NS}$ which reproduces the lattice data is $C \simeq 1.25$ implying a strong cancellation effect in a_4. Moreover the scalar response of the nucleon induces an new piece in the lagrangian $\mathcal{L}_{s^2NN=} - \kappa_{NS}\,s^2\,\bar{N}N/2$ which generates a repulsive three-body force able to restore saturation.

Applications. The restoration of saturation properties has been confirmed at the Hartree level [4] with a value of the dimensionless scalar response parameter, C, close to the value estimated from the lattice data. The next step has been to include pion loops on top of the Hartree mean-field calculation [5]. We use a standard many-body (RPA) approach which includes the effect of short-range correlation (g' parameters). Non relativistically, the main ingredient is the full polarization propagator Π_L (which also includes the $\Delta - h$ excitations) in the longitudinal spin-isospin channel. To be complete we also add the transverse spin-isospin channel (Π_T) and the associated rho meson exchange. The calculation of $E_{loop} = E - E_0$ is done using the well-known charging formula with residual interaction $V_L = \pi + g'$, $V_T = \rho + g'$:

$$\frac{E_{loop}}{V} = 3\,V\int_{-\infty}^{+\infty}\frac{i\,d\omega}{2\pi)}\int\frac{d\mathbf{q}}{(2\pi)^3}\int_0^1\frac{d\lambda}{\lambda}\left(V_L(\omega,\mathbf{q})\Pi_L(\omega,\mathbf{q};\lambda) + 2\,V_T(\omega,\mathbf{q})\Pi_T(\omega,\mathbf{q};\lambda)\right)\ .$$

The parameters associated with spin-isospin physics are fixed by nuclear phenomenology and the calculation has no real free parameters apart for a fine tuning for C (around the lattice estimate) and for g_ω (around the VDM value). The result of the calculation is

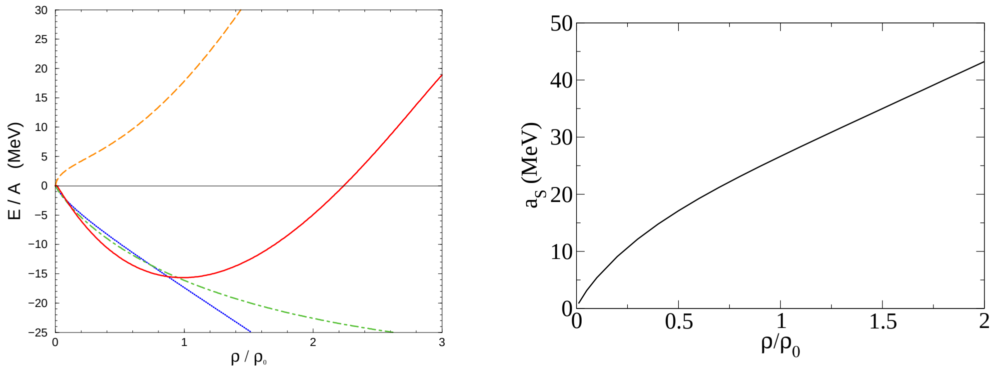

Fig. 1. Left panel: Binding energy of nuclear matter with $g_\omega = 8$, $m_\sigma = 850$ MeV and $C = 0.985$ with the Fock and correlation energies on top of σ and ω exchange. Full line: full result. Dotted line: without Fock and correlation energies. Dot-dashed line: Fock terms. Decreasing dotted line (always negative): correlation energy [5]. Right panel: Asymmetry energy versus density in the RHF approach [6].

shown on fig. 1. We stress the relatively modest value of the correlation energy ($-8\,MeV$ and $-7\,MeV$ for the L and T channels), much smaller that what is obtained from iterated pion exchange (planar diagramm) in in-medium chiral perturbation theory. This effect is mainly due to the strong sceening of pion exchange from short-range correlations.

We have also performed a full relativistic Hartree-Fock (RHF) calculation with the notable inclusion of the rho meson exchange which is important to also reproduce the asymmetry properties of nuclear matter [6]. Again in an almost parameter free calculation, saturation properties of nuclear matter can be reproduced with $g_S = 10$, $m_\sigma = 800\,MeV$ (lattice), $g_\rho = 2.6$ (VDM), $g_\omega = 6.4$ (close to the VDM value $3\,g_\rho$) and $C = 1.33$ (close to the lattice value). For the tensor coupling we a first take the VDM value $\kappa_\rho = 3.7$. The corresponding asymmetry energy, a_S, is shown on the right panel of fig 1. It is important to stress that the rho Hartree contribution ($7\,MeV$) is not sufficient when keeping the VDM value for the vector coupling constant g_ρ. The Fock term through its tensor contribution is necessary to reach the range of accepted value of a_S around $30\,MeV$. Increasing κ_ρ (strong rho scenario) to $\kappa_\rho = 5$ allows a particularly good reproduction of both symmetric and asymmetric nuclear matter. The model also predicts a neutron mass larger than the proton mass with increasing neutron richness in agreement with ab-initio BHF calculations [7]. This approach gives very encouraging results and raises question of how confinement can generate such a large and positive scalar response of the nucleon, κ_{NS}. This is presumably linked to a delicate balance of (partial) chiral symmetry restoration and confinement mechanism inside the nucleon.

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