A chiral quark-soliton model with broken scale invariance for nuclear matter

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Summary. — Soliton models based on the linear $\sigma$-model fail to describe nuclear matter already at $\rho \sim \rho_0$ due to the restrictions on the scalar field dynamics imposed by the Mexican hat potential. To overcome this problem we used a chiral Lagrangian, including a logarithmic potential associated with the breaking of scale invariance, based on quarks interacting with chiral fields, $\sigma$ and $\pi$, and with vector mesons. Using the Wigner-Seitz approximation to mimic a dense system, we show that the model admits stable solitonic solutions at higher densities with respect to the linear-$\sigma$ model and that the introduction of vector mesons allows to obtain saturation. This result has never been obtained before in similar approaches.

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1. – The model

We consider the following Lagrangian [1,2]:

$$\mathcal{L}_{VM} = \bar{\psi} \left( i \gamma^\mu \partial_\mu - g(\sigma + i \pi \cdot \tau \gamma_5) + g_\rho \gamma^\mu \frac{\tau}{2} \cdot (\rho_\mu + \gamma_5 A_\mu) - \frac{g_\omega}{3} \gamma^\mu \omega_\mu \right) \psi$$

$$+ \frac{\beta}{2} \left( D_\mu \sigma D^\mu \sigma + D_\mu \pi \cdot D^\mu \pi \right) - \frac{1}{4} (\rho_{\mu\nu} \cdot \rho^{\mu\nu} + A_{\mu\nu} \cdot A^{\mu\nu} + \omega_{\mu\nu} \omega^{\mu\nu})$$

$$+ \frac{1}{2} m_\rho^2 (\rho_\mu \cdot \rho^\mu + A_\mu \cdot A^\mu) + \frac{1}{2} m_\omega^2 \omega_\mu \omega^\mu - V(\phi_0, \sigma, \pi)$$

Here $\psi$ is the quark field, $\sigma$ and $\pi$ are the chiral fields, $\omega_\mu$ is a vector-isoscalar coupled to baryon current, $\rho_\mu$ and $A_\mu$ are respectively a vector-isovector and an axial-vector-isovector fields coupled to isospin and axial-vector current. Here $\phi$ is the dilaton field.
which, in the present calculation, is kept frozen at its vacuum value $\phi_0$ [1,2]. The logarithmic potential reads

$$V(\sigma, \pi) = \lambda_1^2(\sigma^2 + \pi^2) - \lambda_2^2 \ln(\sigma^2 + \pi^2) - \sigma_0m_\sigma^2\sigma,$$

$$\lambda_1^2 = \frac{1}{4}(m_\sigma^2 + m_\pi^2), \lambda_2^2 = \frac{\sigma_0^2}{4}(m_\sigma^2 - m_\pi^2).$$

The masses of bare fields are: $m_\pi$ = 139 MeV, $m_\rho$ = $m_A$ = 776 MeV and $m_\omega$ = 782 MeV. For the sigma field, since there are no experimental constraints, we use $m_\sigma = 550$ MeV and $m_\sigma = 1200$ MeV. We fixed $g_\rho$ = 4 and we vary $g_\omega$ between 10 and 13. The pion-quark coupling constant $g$ will vary from 3.9 to 5. The calculation is performed at Mean-Field level by adopting the hedgehog ansatz for the fields.

2. – The Wigner-Seitz approximation to nuclear matter

The Wigner-Seitz approximation consists of building a spherical symmetric lattice where each soliton sits on a spherical cell of radius $R$ with specific boundary conditions imposed on fields at the surface of the sphere. In particular here we adopt the choice of ref. [3] which relates the boundary conditions at $R$ to the parity operation, $r \rightarrow -r$. The presence of a periodical lattice implies the formation of a band structure. Here we evaluate the band width in two different approaches following ref. [4].

3. – Results

3.1. The effect of the dilaton potential: going beyond $\rho_0$. – In fig. 1(a) we show how the total energy of the soliton varies as $R$ decreases:

- for each value of $m_\sigma$, the logarithmic model (solid line) admits solitonic solutions for smaller values of the cell radius $R$ (e.g. higher densities) in comparison to the linear-$\sigma$ model (dashed line);
- the introduction of vector mesons stabilises the solutions at high densities.
3.2. Getting saturation at finite density. – The saturation at finite density is obtained by including also the band effect in the evaluation of the total energy and the scenario we obtain is the following:

- the repulsive effect of vector meson prevails up to $\rho \approx \rho_0$ while at higher densities the band effect, connected to the sharing of quarks between solitons, provides the dominant contribution to repulsion (for more details see ref. [5]);

- this mechanism, as shown in fig. 1(b) is stable with respect to a wide range of parameters, $g$ and $g_\omega$, and moreover this range partially overlaps the one that provides a reasonable description of the single soliton [6].

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