IL NUOVO CIMENTO Vol. 36 C, N. 1 Gennaio-Febbraio 2013
DOI 10.1393/ncc/i2013-11472-y

Colloquia: IFAE 2012

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

V. Mantovani Sarti and A. Drago

Dipartimento di Fisica, Università di Ferrara and INFN, Sezione di Ferrara via Saragat 1, 44121 Ferrara, Italy

ricevuto il 31 Agosto 2012

Summary. — Soliton models based on the linear σ-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, σ and π, 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-σ model and that the introduction of vector mesons allows to obtain saturation. This result has never been obtained before in similar approaches.

PACS 12.39.Fe – Chiral Lagrangians.
PACS 21.65.Mn – Nuclear matter-equations of state.
PACS 21.30.Fe – Hadrons-nuclear forces.

1. – The model

We consider the following Lagrangian [1, 2]:

$$\begin{aligned}\mathcal{L}_{VM} = \bar{\psi}\bigg(i\gamma^\mu\partial_\mu - g(\sigma + i\boldsymbol{\pi}\cdot\boldsymbol{\tau}\gamma_5) + g_\rho\gamma^\mu\frac{\boldsymbol{\tau}}{2}\cdot(\boldsymbol{\rho}_\mu + \gamma_5\boldsymbol{A}_\mu) - \frac{g_\omega}{3}\gamma^\mu\omega_\mu\bigg)\psi \\ +\frac{\beta}{2}(D_\mu\sigma D^\mu\sigma + D_\mu\boldsymbol{\pi}\cdot D^\mu\boldsymbol{\pi}) - \frac{1}{4}(\boldsymbol{\rho}_{\mu\nu}\cdot\boldsymbol{\rho}^{\mu\nu} + \boldsymbol{A}_{\mu\nu}\cdot\boldsymbol{A}^{\mu\nu} + \omega_{\mu\nu}\omega^{\mu\nu}) \\ +\frac{1}{2}m_\rho^2(\boldsymbol{\rho}_\mu\cdot\boldsymbol{\rho}^\mu + \boldsymbol{A}_\mu\cdot\boldsymbol{A}^\mu) + \frac{1}{2}m_\omega^2\omega_\mu\omega^\mu - V(\phi_0,\sigma,\pi)\end{aligned}$$

Here ψ is the quark field, σ and π are the chiral fields, ω_μ is a vector-isoscalar coupled to baryon current, $\boldsymbol{\rho}_\mu$ and $\boldsymbol{A}_\mu$ are respectively a vector-isovector and an axial-vector-isovector fields coupled to isospin and axial-vector current. Here ϕ is the dilaton field

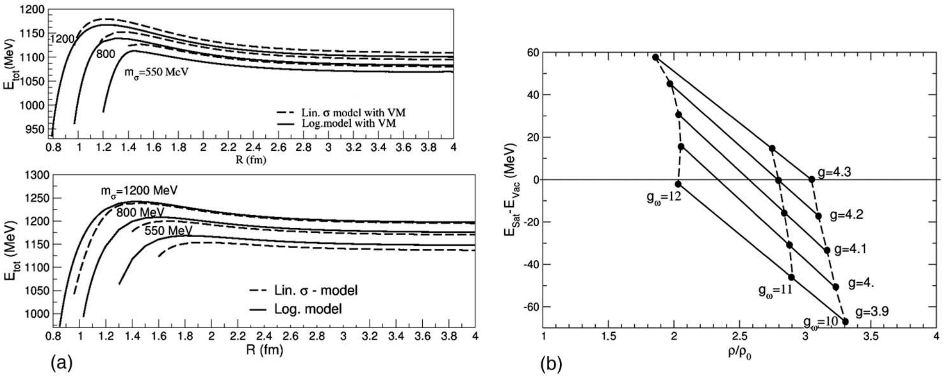

Fig. 1. – (a) Total energy of the soliton as a function of the cell radius R in the model without (upper panel) and with vector mesons (lower panel). (b) Minimum of the total energy as a function of the density.

which, in the present calculation, is kept frozen at its vacuum value ϕ_0 [1, 2]. The logarithmic potential reads

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

The masses of bare fields are: $m_\pi = 139\,\text{MeV}$, $m_\rho = m_A = 776\,\text{MeV}$ and $m_\omega = 782\,\text{MeV}$. For the sigma field, since there are no experimental constraints, we use $m_\sigma = 550\,\text{MeV}$ and $m_\sigma = 1200\,\text{MeV}$. We fixed $g_\rho = 4$ and we vary g_ω 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, $\boldsymbol{r} \to -\boldsymbol{r}$. 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* ρ_0. – In fig. 1(a) we show how the total energy of the soliton varies as R decreases:

– for each value of m_σ, 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-σ 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_ω, and moreover this range partially overlaps the one that provides a reasonable description of the single soliton [6].

REFERENCES

[1] Heide E. K., Rudaz S. and Ellis P. J., *Nucl. Phys. A*, **571** (1994) 713; Carter G. W., Ellis P. J. and Rudaz S., *Nucl. Phys. A*, **603** (1996) 367; Carter G. W., Ellis P. J. and Rudaz S., *Nucl. Phys. A*, **618** (1997) 317; Carter G. W. and Ellis P. J., *Nucl. Phys. A*, **628** (1998) 325.
[2] Bonanno L. and Drago A., *Phys. Rev. C*, **79** (2009) 045801.
[3] Weber U. and McGovern J. A., *Phys. Rev. C*, **57** (1998) 3376.
[4] Hahn D. and Glendenning N. K., *Phys. Rev. C*, **36** (1987) 1181; Birse M. C., Rehr J. J. and Wilets L., *Phys. Rev. C*, **38** (1988) 359.
[5] Drago A. and Sarti V. M., arXiv:1109.5399 [nucl-th].
[6] Broniowski W. and Banerjee M. K., *Phys. Rev. D*, **34** (1986) 849.