The Role of Isospin Components of the Scalar σ-Meson in the Structure of Neutron Stars

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Abstract. Based on non-crossed, crossed and correlated $\pi\pi$ exchanges with irreducible N,Δ intermediate states, we predict an isovector component for the σ meson. We study dense hadronic matter in a generalized relativistic mean field approach with nonlinear self-couplings of the $I = 0,1$ components of the scalar field and compare its predictions for neutron star properties with results from different models found in the literature.

INTRODUCTION AND FORMALISM

We consider predictions based on the evaluation of non-crossed, crossed and correlated $\pi\pi$ exchange with irreducible N,Δ intermediate states assuming thereby pair suppression of antibaryons, which in addition to the conventional isoscalar $I = 0$ Lorentz scalar σ field, predict a scalar isovector $I = 1$ component. From their diagrammatic structure, the σNN vertices may be related to the corresponding σ-induced NN potential which allows to fix the parameters of the theory. The amplitudes of non-local, box and triangle diagrams are computed in the non-relativistic static limit with monopole form factors and correlation functions at each vertex. Summed are non-time-ordered diagrams, which allow an analytical result for the non-crossed diagram; the contribution from the crossed diagram is estimated from the ratio of the intermediate baryon versus "baryon + 2 mesons in the air" energy denominators.

With the model we intend to describe neutron stars in a relativistic mean field Hartree approximation with the external σ momentum as $p = 0$. For generality, we average over the spin-spin nucleon-nucleon interaction , while keeping the explicit isospin dependence of these particles $\sum_{SM} < [1/2;1/2]^{SM}|\underline{\sigma}_1 \cdot \underline{\sigma}_2|[1/2;1/2]^{SM} >= 0$. The isoscalar-isovector content is then readily obtained, for example, for the $N\Delta$ intermediate state, from the splitting

$$V_{scalar}(r) = 2\left(V_{NC}(r) + V_C(r)\right) + \frac{2}{3}\left(V_{NC}(r) - V_C(r)\right)\vec{\tau}_1 \cdot \vec{\tau}_2 \tag{1}$$

where $V_{NC}(r)$, $V_C(r)$ denote the spin-averaged strengths of the non-crossed and crossed

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$N\Delta$ diagrams, respectively. Our strategy is as follows: we calculate the scalar-isoscalar $I = 0$ contribution as the sum of the box and triangle diagrams and we fix the only parameter, the cut-off $\mathscr{M}$, by fitting in our model the result for the σ-exchange at zero momentum $V^{I=0}_{\sigma NN}(p=0) = -\frac{g^2_{\sigma NN}}{m^2_\sigma}$, to the corresponding piece in the Bonn potential. With $\mathscr{M}$ then fixed, we calculate the $I = 1$ Lorentz isovector meson contribution without any free parameter.

NUCLEAR MATTER CALCULATIONS

As the novel feature of our approach, we are guided by the previous analysis which predicts, an isovector component for the σ meson. We then study dense hadronic matter in a generalized relativistic mean field approach with nonlinear self-couplings of the $I = 0,1$ components of the scalar field σ. Our lagrangian approach describes a system of eight baryons ($B = p$, n, Λ, Σ^-, Σ^0, Σ^+, Ξ^-, Ξ^0) coupled to “four" mesons (σ, ω, ρ, ς) (the iso-vector component of the σ meson is here treated as an independent meson denoted as ς) and two leptons ($\lambda = e^-, \mu^-$)

$$\mathscr{L} = \sum_B \bar{\psi}_B \left\{ \gamma_\mu \left(i\partial^\mu - g^\star_{\omega B}\omega^\mu - \frac{1}{2} g^\star_{\rho B} \tau_B \cdot \rho^\mu \right) - \left(1 - \frac{g_\sigma \sigma}{M_N}\right)^\eta m^\star_{\alpha B} M_B \right\} \psi_B$$
$$+ \frac{1}{2}\left(\partial_\mu \sigma \partial^\mu \sigma - m_\sigma{}^2 \sigma^2\right) + \frac{1}{2}\left(\partial_\mu \vec{\varsigma} \cdot \partial^\mu \vec{\varsigma} - m_\varsigma{}^2 \vec{\varsigma}^{\,2}\right) + \left(\frac{m_\omega{}^2}{2}\omega_\mu \omega^\mu - \frac{1}{4}\omega_{\mu\nu}\omega^{\mu\nu}\right)$$
$$+ \left(\frac{1}{2} m^2_\rho \rho_\mu \cdot \rho^\mu - \frac{1}{4}\rho_{\mu\nu}\cdot\rho^{\mu\nu}\right) + \sum_\lambda \bar{\psi}_\lambda \left(i\gamma_\mu \partial^\mu - m_\lambda\right)\psi_\lambda \,. \tag{2}$$

The effective coupling constants in the model are defined as $g^\star_{\alpha\sigma B} \equiv m^\star_{\alpha B} g_\sigma$, $g^\star_{\beta\omega B} \equiv m^\star_{\beta B} g_\omega$, $g^\star_{\gamma\rho B} \equiv m^\star_{\gamma B} g_\rho$, $g^\star_{\alpha\varsigma B} = m^\star_{\alpha B} g_\varsigma$, with the nonlinear self-couplings parameterized as $m^\star_{\kappa B} \equiv \left(1 + \frac{g_\sigma \bar{\sigma} + g_\varsigma \tau_{3B} \varsigma_3}{\kappa M}\right)^{-\kappa}$, $\kappa = \alpha, \beta, \gamma$, where τ_{3B} is the third component of the isospin vector $\vec{\tau}$ associated to the baryon B fields while $\bar{\sigma}$ and ς_3 represent the mean field components of the σ and ς mesons.

RESULTS AND COMMENTS

In this contribution we predict an isospin $I = 1$ component for the scalar σ meson. From the evaluation of the underlying Feynman diagrams we fit the mass of the iso-vector component of the σ meson as well as the ςNN coupling constant as a function of the cut off mass $\mathscr{M}$. Our main findings, shown in Fig.1 for the mass and the mass-radius relation of neutron stars, indicate that static global properties of these objects are not substantially affected by the presence of the iso-vector component of the σ meson. A possible explanation for this result must be connected with the complex role of the iso-vector component of the σ meson, which originates attractive and repulsive components in the scalar sector of the strong interaction involving the fundamental baryon octet, giving rise this way to mutual cancelations of these contributions in the evaluation of global static properties of neutron stars. We presume, signatures of the role of the iso-vector component of the σ meson in neutron star matter may be more sensitive to properties linked to $\tau_{3B} = 0$ baryon dominance, as for instance in the inner regions of neutron stars for which the role of the σ meson is enhanced. For detailed results we refer to a forthcoming publication [1].

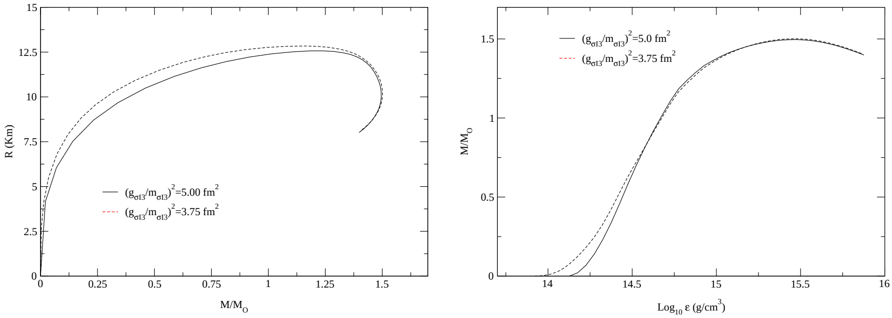

FIGURE 1. Left panel: mass-radius relation for neutron stars with $(g_{\sigma I_3}/m_{\sigma I_3})^2 = 5.00\,fm^2$ (full line) and $(g_{\sigma I_3}/m_{\sigma I_3})^2 = 3.74\,fm^2$ (dotted line). Right panel: maximum mass of neutron stars (lines have the same meaning as on the left panel).

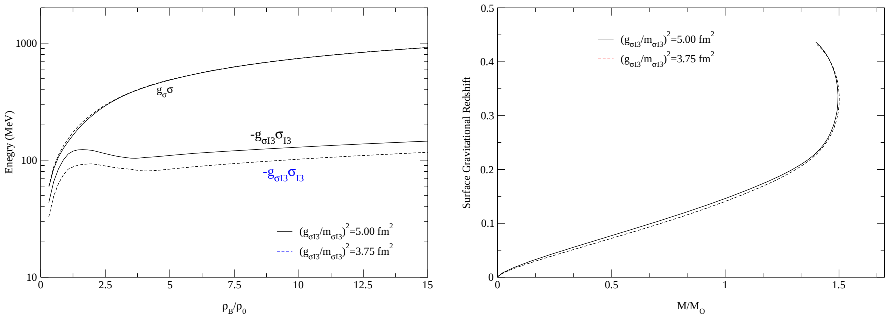

FIGURE 2. Left panel: energy in MeV of the scalar condensate. Right panel: redshift for neutron stars (the various lines are defined as in Fig. 1).

REFERENCES

1. M. Dillig, E.F. Lütz, M. Razeira, C.A.Z. Vasconcellos and B. E. J. Bodmann, *in progress (2004)*.