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Nuclear matter properties in relativistic mean-field model with σ-ω coupling

K.C. Chung[1,a], C.S. Wang[1,2], A.J. Santiago[1], and J.W. Zhang[2]

[1] Instituto de Física, Universidade do Estado do Rio de Janeiro, Rio de Janeiro-RJ 20559-900, Brazil
[2] Department of Technical Physics, Peking University, Beijing 100871, China

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Abstract. The σ-ω coupling is introduced phenomenologically in the linear σ-ω model to study the nuclear matter properties. It is shown that not only the effective nucleon mass M^* but also the effective σ meson mass m_σ^* and the effective ω meson mass m_ω^* are nucleon-density–dependent. When the model parameters are fitted to the nuclear saturation point, with the nuclear radius constant $r_0 = 1.14\,\mathrm{fm}$ and volume energy $a_1 = 16.0\,\mathrm{MeV}$, as well as to the effective nucleon mass $M^* = 0.85M$, the model yields $m_\sigma^* = 1.09m_\sigma$ and $m_\omega^* = 0.90m_\omega$ at the saturation point, and the nuclear incompressibility $K_0 = 501\,\mathrm{MeV}$. The lowest value of K_0 given by this model by adjusting the model parameters is around 227 MeV.

PACS. 21.65.+f Nuclear matter – 24.10.Jv Relativistic models

1 Introduction

As the starting point for the microscopic relativistic description of nuclear many-body system, within the framework of quantum hadrodynamics, the well-studied linear σ-ω model has been proved to be able to describe the saturation and other properties of nuclear matter [1]. However, this model yields the nuclear incompressibility K_0 around 550 MeV which is unacceptably high, and also the effective nucleon mass M^* around $0.54M$ which seems uncomfortably low. In order to remedy this situation, many works have been done on the extension or generalization of this model [2]. Among others, the inclusion of nonlinear self-interaction of σ mesons, introduced originally by Boguta and Bodmer [3], is shown to be successful in reducing the nuclear incompressibility K_0 significantly. Along this line, the nonlinear self-interaction of ω mesons has been included also in the relativistic mean-field theory [4]. On the other hand, the derivative scalar coupling, which contains higher powers of σ in couplings between nucleon and σ meson as well as a coupling between σ and ω mesons, has been proposed and investigated extensively [5,6]. Following these two lines, many types of coupling between nucleon, σ, ω and ρ mesons are included in the nuclear effective field theory by Furnstahl, Serot and Tang recently, in addition to the above-mentioned nonlinear self-interaction of σ and ω mesons [7]. In this case, as the first step, it is worthwhile to investigate in more detail the effects of each type of coupling between nucleon, σ, ω and ρ mesons separately, before getting combined result by data fit to all of these couplings simultaneously.

The purpose of this paper is to investigate what is the effect on nuclear matter properties due to a σ-ω coupling, which is introduced phenomenologically and is equivalent to the η_2 term of the Furnstahl *et al.*'s effective Lagrangian density, and especially whether this coupling is able to reduce the nuclear incompressibility K_0 and in the same time to increase the effective nucleon mass M^* in relativistic mean-field theory. Section 2 gives the model and field equations. Section 3 presents the nuclear matter equation of state and related formulas for nuclear matter properties. The numerical calculation and results are given in sect. 4. Section 5 discusses the inclusion of ρ meson field, and Section 6 is the summary.

2 Model and field equations

Let us start with the following Lagrangian density:

$$\mathcal{L} = \overline{\psi}[\gamma_\mu(i\partial^\mu - g_\omega\omega^\mu) - (M - g_\sigma\phi)]\psi + \frac{1}{2}\left[(\partial_\mu - \eta g'_\omega\omega_\mu)\phi(\partial^\mu + \eta g'_\omega\omega^\mu)\phi - m_\sigma^2\phi^2\right] - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}m_\omega^2\omega_\mu\omega^\mu\,, \quad \eta = i \text{ and } 1\,, \tag{1}$$

where $F^{\mu\nu} = \partial^\mu\omega^\nu - \partial^\nu\omega^\mu$, ψ, ϕ and ω are the nucleon, σ and ω meson fields with masses M, m_σ and m_ω, respectively, while g_σ, g_ω are the respective coupling constants, and g'_ω is the σ-ω coupling constant. $\eta = i$ gives a

[a] e-mail: chung@uerj.br

σ-ω coupling similar to that introduced by usual covariant derivatives, while $\eta = 1$ gives a gauge-like virtual coupling similar to the imaginary coupling [8]. Mathematically, it is equivalent to add a term $\eta^2 g_\omega'^2 \omega_\mu \omega^\mu$ to m_σ^2, which is just the η_2 term introduced recently by Furnstahl *et al.* in their effective Lagrangian density $\mathcal{L}_M$ (see eq. (52) of ref. [7]). According to this equivalence, the present work can be considered as a study of this η_2 term in the Furnstahl *et al.*'s nuclear effective field theory. The present model reduces to the original Walecka model when the σ-ω coupling constant is zero, $g_\omega' = 0$. Physically, higher-order terms of this σ-ω coupling will give an effective nonlinear σ field self-interaction.

For static nuclear matter, the field equations derived from this Lagrangian density are reduced to the following equations in the mean-field approximation:

$$(i\gamma^\mu \partial_\mu - g_\omega \gamma^0 \omega_0 - M^*)\psi = 0, \tag{2}$$

$$m_\sigma^{*2} \phi = g_\sigma \rho_s, \tag{3}$$

$$m_\omega^{*2} \omega_0 = g_\omega \rho_N, \tag{4}$$

where the effective nucleon mass M^*, effective σ meson mass m_σ^* and effective ω meson mass m_ω^* are defined, respectively, as

$$M^* = M - g_\sigma \phi, \tag{5}$$

$$m_\sigma^{*2} = m_\sigma^2 + \eta^2 g_\omega'^2 \omega_0^2, \tag{6}$$

$$m_\omega^{*2} = m_\omega^2 - \eta^2 g_\omega'^2 \phi^2, \tag{7}$$

and $\rho_s = \langle \overline{\psi}\psi \rangle$ is the scalar density, $\rho_N = \langle \overline{\psi}\gamma^0\psi \rangle$ the baryon density. For calculating these effective masses, the above three equations can be rewritten as the following self-consistent equations:

$$\xi = \frac{M^*}{M} = 1 - \frac{\alpha}{s}\frac{\rho_s}{\rho_0}, \tag{8}$$

$$s = \xi_\sigma^2 = \frac{m_\sigma^{*2}}{m_\sigma^2} = 1 + \frac{\alpha_\sigma}{v^2}\frac{\rho_N^2}{\rho_0^2}, \tag{9}$$

$$v = \xi_\omega^2 = \frac{m_\omega^{*2}}{m_\omega^2} = 1 - \frac{\alpha_\omega}{s^2}\frac{\rho_s^2}{\rho_0^2}, \tag{10}$$

where ρ_0 is the standard nucleon number density, α, α_σ and α_ω are the dimensionless composite parameters defined, respectively, as

$$\alpha = \frac{g_\sigma^2 \rho_0}{m_\sigma^2 M}, \quad \alpha_\sigma = \frac{\eta^2 g_\omega'^2 g_\omega^2 \rho_0^2}{m_\omega^4 m_\sigma^2}, \quad \alpha_\omega = \frac{\eta^2 g_\omega'^2 g_\sigma^2 \rho_0^2}{m_\sigma^4 m_\omega^2}. \tag{11}$$

It should be noted that α_σ and α_ω are positive for $\eta = 1$ while negative for $\eta = i$. It is worthwhile to note that α_σ and α_ω are proportional to the Furnstahl *et al.*'s η_2. For example, it can be written as

$$\alpha_\sigma = -\frac{\eta_2}{2}\left(\frac{g_\sigma g_\omega \rho_0}{m_\sigma m_\omega M}\right)^2. \tag{12}$$

3 Nuclear matter properties

The nuclear matter equation of state derived from Lagrangian density (1) can be expressed in terms of the nuclear energy density $\mathcal{E}$ as $e = \mathcal{E}/\rho_N - M$, and

$$\mathcal{E} = \mathcal{E}_k + \mathcal{E}_\sigma + \mathcal{E}_\omega, \tag{13}$$

$$\mathcal{E}_k = \frac{M^4\xi^4}{\pi^2} \sum_{i=p,n} F_1(k_i/\xi M), \tag{14}$$

$$\mathcal{E}_\sigma = \frac{1}{2}(1-\xi) M \rho_s, \tag{15}$$

$$\mathcal{E}_\omega = \frac{1}{2}(1-\xi) y M \rho_s, \quad y = \frac{(s-1)(2v-1)}{s(1-v)}, \tag{16}$$

where k_p and k_n are the proton and neutron Fermi momenta, respectively, and the function $F_m(x)$ is defined as [9]

$$F_m(x) = \int_0^x \mathrm{d}x\, x^{2m}\sqrt{1+x^2}. \tag{17}$$

The baryon density ρ_N and scalar density ρ_s can be expressed as

$$\rho_N = \frac{1}{3\pi^2}\sum_{i=p,n} k_i^3, \tag{18}$$

$$\rho_s = \frac{M^3\xi^3}{\pi^2}\sum_{i=p,n} f_1(k_i/\xi M), \tag{19}$$

where the function $f_m(x)$ is defined as [9]

$$f_m(x) = \int_0^x \mathrm{d}x \frac{x^{2m}}{\sqrt{1+x^2}}. \tag{20}$$

Having the equation of state, the pressure p can be derived as

$$p = -\mathcal{E} + \rho_N \frac{\partial \mathcal{E}}{\partial \rho_N} = \frac{1}{3}(\mathcal{E}_k - \mathcal{E}_\sigma - M\rho_s) + \mathcal{E}_\omega - \frac{2(1-s)}{s}\mathcal{E}_\sigma. \tag{21}$$

Instead of Fermi momenta k_p and k_n, we will use the nucleon density $\rho_N = \rho_n + \rho_p$ and relative neutron excess $\delta = (\rho_n - \rho_p)/\rho_N$ as independent variables for describing the nuclear matter [10]. At the standard state $\rho_N = \rho_0$, $\delta = 0$, the pressure should be zero,

$$p\,(\rho_0, 0) = 0. \tag{22}$$

In addition, the depth of the equation of state is related to the nuclear volume energy a_1 as

$$e(\rho_0, 0) = -a_1. \tag{23}$$

The standard nucleon number density ρ_0 defined by eq. (22) is related to nuclear radius constant r_0 and Fermi momentum k_F of standard nuclear matter as $\rho_0 = 3/4\pi r_0^3 = 2k_\mathrm{F}^3/3\pi^2$.

The generalized nuclear incompressibility $K(\rho_N,\delta)$ can be defined [11] and derived as

$$K \equiv 9\frac{\partial p}{\partial \rho_N} = \frac{3(p+\mathcal{E})+12\mathcal{E}_\omega}{\rho_N} - \Big[3M\rho_s + \frac{12(3-2s)}{s}\mathcal{E}_\sigma\Big]$$

$$\times\frac{1}{\rho_s}\frac{\partial \rho_s}{\partial \rho_N} + \frac{12(3-s)}{s}\frac{\mathcal{E}_\sigma}{s}\frac{\partial s}{\partial \rho_N} - \frac{12(1-v)}{1-2v}\frac{\mathcal{E}_\omega}{v}\frac{\partial v}{\partial \rho_N}, \quad (24)$$

$$\rho_N\frac{\partial s}{\partial \rho_N} = -2(1-s)\Big[1-\frac{2(1-v)}{(1-\xi)v}\rho_N\frac{\partial \xi}{\partial \rho_N}\Big], \quad (25)$$

$$\rho_N\frac{\partial v}{\partial \rho_N} = \frac{2(1-v)}{1-\xi}\rho_N\frac{\partial \xi}{\partial \rho_N}, \quad (26)$$

$$\rho_N\frac{\partial \rho_s}{\partial \rho_N} = Q + 3(\rho_s - Q)\frac{\rho_N}{\xi}\frac{\partial \xi}{\partial \rho_N}, \quad (27)$$

$$\rho_N\frac{\partial \xi}{\partial \rho_N} = -\frac{1}{s}\Big[2(1-\xi)(1-s)+\frac{\alpha Q}{\rho_0}\Big]$$

$$\times\Big[1-\frac{4(1-s)(1-v)}{sv}+\frac{3(1-\xi)(\rho_s-Q)}{\xi\rho_s}\Big]^{-1}, \quad (28)$$

$$Q = \frac{M^3\xi^3}{3\pi^2}\sum_{i=p.n}\frac{k_i}{\xi M}f_1'(k_i/\xi M). \quad (29)$$

The usual nuclear incompressibility K_0 can be obtained from $K(\rho_N,\delta)$ as

$$K_0 = K(\rho_0,0) = 9\Big(\rho_N^2\frac{\partial^2 e}{\partial \rho_N^2}\Big)_0, \quad (30)$$

the subscript 0 stands for the standard state $\rho_N=\rho_0$ and $\delta=0$. In addition, the following formula for symmetry energy J can be derived:

$$J \equiv \frac{1}{2}\frac{\partial^2 e}{\partial \delta^2}\Big|_0 = \frac{1}{6}\frac{k_{\mathrm{F}}^2}{\sqrt{k_{\mathrm{F}}^2+M^2\xi_0^2}}. \quad (31)$$

This formula is the same as that given by the usual Walecka model [12,13].

Around the standard state $\rho_N=\rho_0, \delta=0$, the nuclear equation of state and thus the nuclear matter properties are specified essentially by the standard density ρ_0, volume energy a_1, symmetry energy J, incompressibility K_0, density symmetry L and symmetry incompressibility K_s [10], where L and K_s are, respectively,

$$L \equiv \frac{3}{2}\Big(\rho_N\frac{\partial^3 e}{\partial \rho_N\partial \delta^2}\Big)_0 = \frac{3}{2\rho_0}\frac{\partial^2 p}{\partial \delta^2}\Big|_0, \quad (32)$$

$$K_s \equiv \frac{9}{2}\Big(\rho_N^2\frac{\partial^4 e}{\partial \rho_N^2\partial \delta^2}\Big)_0 = -6L + \frac{1}{2}\frac{\partial^2 K}{\partial \delta^2}\Big|_0. \quad (33)$$

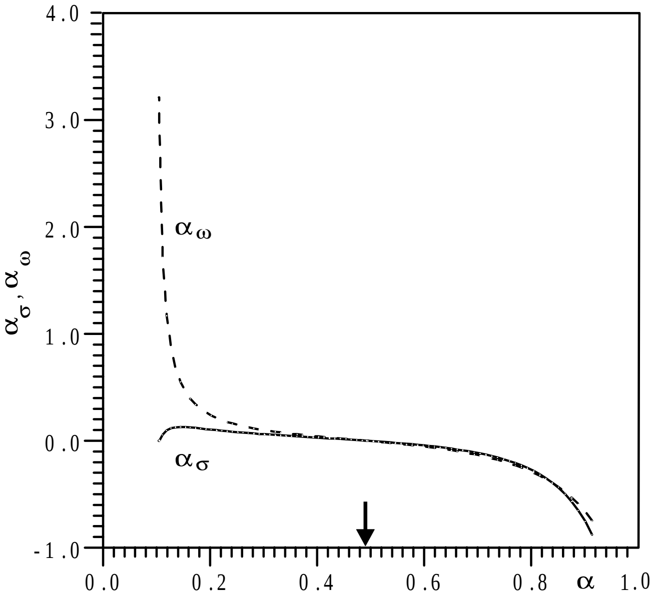

Fig. 1. α_σ and α_ω as function of α. The point $\alpha_W = 0.4908$ indicated by an arrow corresponds to the usual Walecka model where $\alpha_\sigma = \alpha_\omega = 0$.

4 Numerical calculation and results

For the description of nuclear matter, there are three independent parameters α, α_σ and α_ω in the present model. The saturation point of nuclear matter (ρ_0,a_1) defined by eqs. (22) and (23) can be used as input to determine α_σ and α_ω as function of α. The way is as follows. At the standard state ($\rho_N=\rho_0, \delta=0$), these two equations can be solved for s and y,

$$s = \frac{3(1-\xi)M\rho_s}{3\rho_0(M-a_1)-2\mathcal{E}_k-\xi M\rho_s}, \quad (34)$$

$$y = \frac{2\rho_0(M-a_1)-2\mathcal{E}_k-(1-\xi)M\rho_s}{(1-\xi)M\rho_s}, \quad (35)$$

and thus from eq. (16)

$$v = \frac{sy+s-1}{sy+2s-2}. \quad (36)$$

For given ρ_0 and a_1, s and v can be calculated by eqs. (34)-(36) for a chosen ξ. Then α, α_σ and α_ω can be calculated by eqs. (8)-(10) for a chosen ξ. In our calculation, the nuclear radius constant $r_0 = 1.14\,\mathrm{fm}$ which corresponds to the standard nucleon number density $\rho_0 = 0.161\,\mathrm{fm}^{-3}$, the nuclear volume energy $a_1 = 16.0\,\mathrm{MeV}$, nucleon mass $M = 938.9\,\mathrm{MeV}$ and constant $\hbar c = 197.327053\,\mathrm{MeV\cdot fm}$ are used. It is worthwhile to note that the value $r_0 = 1.14\,\mathrm{fm}$ is obtained from the data fit to nuclear charge radii [14] extracted from the elastic electron scattering data [15].

Figure 1 plots α_σ and α_ω as function of α. At the point $\alpha=\alpha_W=0.4908$ (indicated by an arrow), we have $\alpha_\sigma=\alpha_\omega=0$, and the present model reduces to Walecka

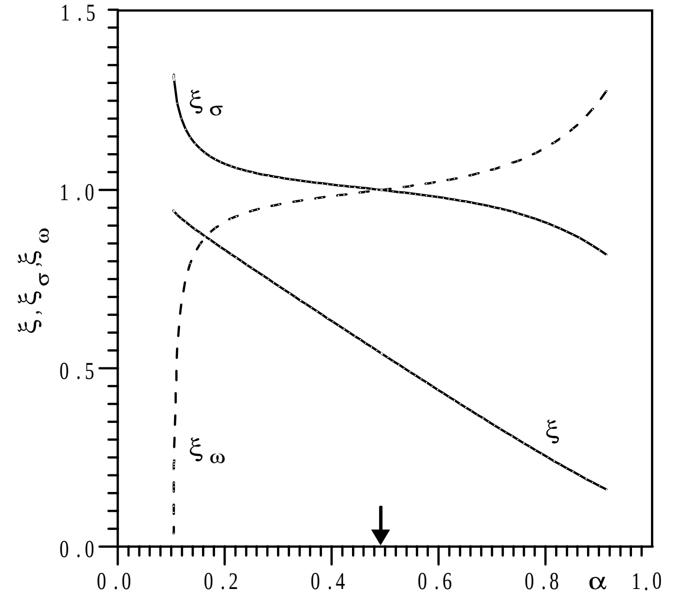

Fig. 2. The dimensionless effective nucleon mass ξ, σ meson mass ξ_σ and ω meson mass ξ_ω as function of α. At the point $\alpha_W = 0.4908$ indicated by an arrow, $\xi = 0.5437$ and $\xi_\sigma = \xi_\omega = 1$.

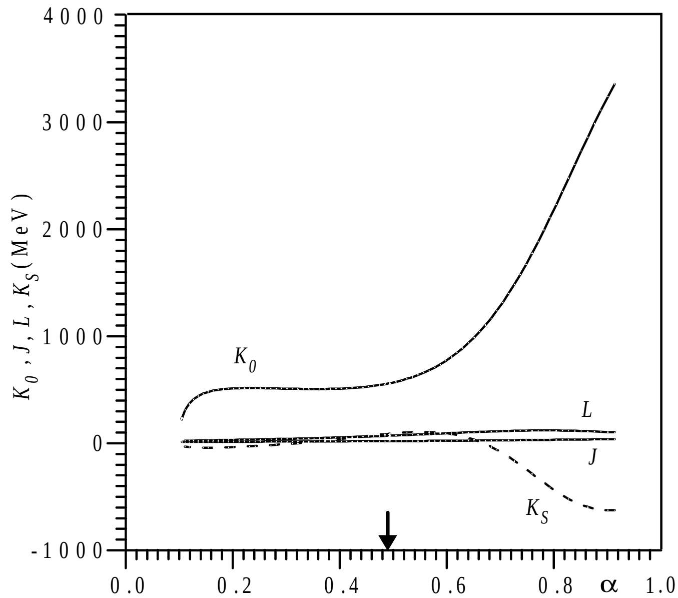

Fig. 3. K_0, J, L, and K_s as function of α. At the point $\alpha_W = 0.4908$ indicated by an arrow, $K_0 = 553\,\text{MeV}$, $J = 20.2\,\text{MeV}$, $L = 70.6\,\text{MeV}$, and $K_s = 88\,\text{MeV}$. At the lower limit $\alpha_{\min} = 0.1037$, $K_0 = 227\,\text{MeV}$.

model. For $\alpha > \alpha_W$, α_σ and α_ω are negative, which corresponds to $\eta = i$. For $\alpha < \alpha_W$, α_σ and α_ω are positive, which corresponds to $\eta = 1$. There is a lower limit $\alpha_{\min} = 0.1037$, below this point there is no physical solution, as the effective ω meson mass becomes imaginary, $\xi_\omega^2 < 0$. Figure 2 shows the dimensionless effective nucleon mass ξ, the dimensionless effective σ meson mass ξ_σ and the dimensionless effective ω meson mass ξ_ω as function of α. At the point α_W, $\xi = 0.5437$ and $\xi_\sigma = \xi_\omega = 1$. From α_W to the right, ξ decreases as α increases, and we have $\xi_\sigma < 1$ and $\xi_\omega > 1$. From α_W to the left, ξ increases as α decreases, and we have $\xi_\sigma > 1$ and $\xi_\omega < 1$. Figure 3 gives K_0, J, L, and K_s as function of α. At α_W, $K_0 = 553\,\text{MeV}$, $J = 20.2\,\text{MeV}$, $L = 70.6\,\text{MeV}$, and $K_s = 88\,\text{MeV}$. As α decreases, K_0 decreases at first and then increases slowly, passing through a very flat plateau, and finally decreases rapidly to a lower limit 227 MeV. J and L as well as K_s decrease slowly as α decreases. It is worthwhile to note that K_s is negative in the low α side, in opposition to what is obtained in the usual σ-ω model. Experimentally, K_s obtained from the isoscalar giant monopole resonance energy is between -566 ± 1350 and $34 \pm 159\,\text{MeV}$ [16]. On the other hand, K_0 increases to very high values rapidly as α increases. In this aspect, the case of $\eta = i$ is not acceptable.

The dimensionless effective nucleon mass ξ at the saturation point can be used as the third input to fix the parameter α. For example, if $\xi = 0.85$ at the saturation point, we have $\alpha = 0.1822$. Correspondingly we have $\alpha_\sigma = 0.1134$, $\alpha_\omega = 0.2938$, $\xi_\sigma = 1.085$, $\xi_\omega = 0.895$, $K_0 = 501\,\text{MeV}$, $J = 13.8\,\text{MeV}$, $L = 30.1\,\text{MeV}$, and $K_s = -38\,\text{MeV}$, where the values of ξ_σ and ξ_ω are those at the saturation point. Instead of ξ, the nuclear incompressibility K_0 could be also used to fix α. If $K_0 = 250\,\text{MeV}$ is chosen, it yields $\alpha = 0.1050$, $\alpha_\sigma = 0.00783$, $\alpha_\omega = 2.642$, $\xi = 0.939$, $\xi_\sigma = 1.295$, $\xi_\omega = 0.328$, and $K_s = -31.2\,\text{MeV}$, where the values of ξ, ξ_σ and ξ_ω are those at the saturation point.

5 Inclusion of the ρ meson field

The symmetry energy J can be increased by including the ρ meson field in the present model. In this case, the additional term in the Lagrangian density is

$$\mathcal{L}_\rho = -\frac{1}{4}\mathbf{B}_{\mu\nu}\cdot\mathbf{B}^{\mu\nu} + \frac{1}{2}m_\rho^2\mathbf{b}_\mu\cdot\mathbf{b}^\mu - g_\rho\overline{\psi}\gamma_\mu\boldsymbol{\tau}\cdot\mathbf{b}^\mu\psi, \quad (37)$$

where $\mathbf{B}^{\mu\nu} = \partial^\mu\mathbf{b}^\nu - \partial^\nu\mathbf{b}^\mu$, $\mathbf{b}^\mu$ is the ρ meson field with mass m_ρ and coupling constant g_ρ, and $\boldsymbol{\tau}$ are the isospin matrices. The resulting nucleon field equation, in the mean-field approximation for static nuclear matter, has an additional term $-g_\rho\tau_3\gamma^0 b_0$:

$$(i\gamma^\mu\partial_\mu - g_\omega\gamma^0\omega_0 - g_\rho\tau_3\gamma^0 b_0 - M^*)\psi = 0. \quad (38)$$

The equation for the ρ meson field is

$$b_0 = -\frac{g_\rho\rho_N\delta}{m_\rho^2}, \quad (39)$$

while eqs. (3) and (4) are the same. The additional terms to the nuclear energy density, pressure, generalized incompressibility, symmetry and density symmetry energies are, respectively,

$$\mathcal{E}_\rho = \frac{1}{2}\alpha_\rho M\rho_N^2\delta^2/\rho_0\,, \qquad p_\rho = \mathcal{E}_\rho\,, \qquad K_\rho = \frac{18\mathcal{E}_\rho}{\rho_N}\,,$$
$$J_\rho = \frac{1}{2}\alpha_\rho M\,, \qquad L_\rho = 3J_\rho\,, \quad (40)$$

where

$$\alpha_\rho = \frac{g_\rho^2 \rho_0}{m_\rho^2 M} \tag{41}$$

is the ρ meson dimensionless composite parameter. It is easy to prove that there is no contribution to K_s from the ρ meson field. It is worthwhile to note that the additional term J_ρ for the symmetry energy is the same as that given by the usual linear σ-ω-ρ model [12,13].

It can be seen that, as $\mathcal{E}_\rho = 0$ at the standard state where $\delta = 0$, the inclusion of ρ meson produces no change in nuclear energy density $\mathcal{E}$, pressure p and generalized incompressibility K at the standard state. Therefore, the parameters α, α_σ and α_ω have no change, and thus the dimensionless effective masses ξ, ξ_σ and ξ_ω are the same even if the ρ meson field is included. The parameter α_ρ can be fixed by using the symmetry energy J as the fourth input, if parameters α, α_σ and α_ω have been fixed.

6 Summary

In conclusion, the σ-ω coupling is introduced phenomenologically in the linear σ-ω model to study the nuclear matter properties. It is shown that, in comparison with the usual Walecka model, not only the effective nucleon mass M^* but also the effective σ meson mass m_σ^* and the effective ω meson mass m_ω^* are nucleon-density–dependent. When the model parameters are fitted to the nuclear radius constant $r_0 = 1.14\,\text{fm}$ and volume energy $a_1 = 16.0\,\text{MeV}$ as well as to the effective nucleon mass $M^* = 0.85M$, the model yields $m_\sigma^* = 1.09 m_\sigma$ and $m_\omega^* = 0.90 m_\omega$ at the same nuclear saturation point, and the nuclear incompressibility $K_0 = 501\,\text{MeV}$. This incompressibility seems too high. On the other hand, if the model parameters are fitted to $K_0 = 250\,\text{MeV}$, in addition to $r_0 = 1.14\,\text{fm}$ and $a_1 = 16.0\,\text{MeV}$, it yields $M^* = 0.938M$, $m_\sigma^* = 1.295 m_\sigma$ and $m_\omega^* = 0.328 m_\omega$ at the nuclear saturation point. This effective ω meson mass seems too low. In addition, the lower limit of incompressibility $K_0 = 227\,\text{MeV}$ is not low enough. Therefore, our conclusion is: Even if this σ-ω coupling is able to reduce the nuclear incompressibility and also to increase the effective nucleon mass simultaneously, there is not yet enough degree of freedom to adjust the parameters in order to give a more reasonable result.

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