Eur. Phys. J. A **12**, 161–167 (2001)

THE EUROPEAN PHYSICAL JOURNAL A

Determination of nonlinear σ-ω-ρ model parameters in the relativistic mean-field theory by nuclear-matter properties

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, PRC

Received: 27 June 2001 / Revised version: 5 October 2001
Communicated by A. Molinari

Abstract. The parameters of the σ-ω-ρ model in the relativistic mean-field theory with nonlinear σ-meson self-interaction are determined by nuclear-matter properties, which are taken as those extracted by fits to data based on nonrelativistic nuclear models. The values of the relevant parameters are $C_\sigma^2 \sim 94$, $C_\omega^2 \sim 32$, $C_\rho^2 \sim 26$, $b \sim -0.09$, $c \sim 1$, and the σ-meson mass $m_\sigma \sim 370$ MeV, while the value of the calculated nuclear-surface thickness is $t \sim 1.4$ fm. The field system is shown to be stable, since the σ-meson self-interaction energy is a lower bound in this whole parameter region with positive c. On the other hand, the effective nucleon mass M^* is larger than $0.73M$, if the symmetry incompressibility K_s is assumed to be negative and the nuclear-matter incompressibility K_0 is kept less than 300 MeV.

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

1 Introduction

Finite nuclei are found in states near the nuclear-matter standard state ($\rho_N = \rho_0, \delta = 0$), where ρ_N is the nucleon density and $\delta = (\rho_n - \rho_p)/\rho_N$ the relative neutron excess or nuclear-matter asymmetry, and ρ_0 is the nucleon density at the equilibrium state of symmetric nuclear matter with minimum energy per nucleon. Our actual knowledge of nuclear matter at the present time is mainly about nuclear matter at states close to this point $(\rho_0, 0)$. In this case, the nuclear-matter equation of state can be written approximately as [1,2]

$$e(\rho_N, \delta) = -a_1 + \frac{1}{18}\left(K_0 + K_s\delta^2\right)\left(\frac{\rho_N - \rho_0}{\rho_0}\right)^2 + \left[J + \frac{L}{3}\left(\frac{\rho_N - \rho_0}{\rho_0}\right)\right]\delta^2, \tag{1}$$

which is specified by the standard density ρ_0, volume energy a_1, symmetry energy J, incompressibility K_0, symmetry incompressibility K_s and density symmetry L. The most interesting quantity for supernova explosion calculations is the nuclear incompressibility K_0 which dictates the balance between gravity and internal pressure of the stellar system [3], while the most interesting quantities for heavy-ion collision studies are the nuclear incompressibility K_0 and the symmetry incompressibility K_s which have influences on side-flow effects and isotopic distributions of the collisions, respectively [4].

There is no direct experimental measurement of these quantities. They can be determined only from fits to data based on some specific nuclear model. Therefore, our actual knowledge about these quantities is still essentially model dependent. However, if different models give values which are close to each other within some reasonable range, then these values can be considered as realistic ones. Nowadays, the quantities which are known with nice precision are ρ_0, a_1, J and K_0, the last two still being under active investigation.

As starting point for the relativistic microscopic description of the nuclear many-body system, within the framework of quantum hadrodynamics, the well-studied σ-ω-ρ model with nonlinear σ-meson self-interaction is able to describe the saturation and other properties of nuclear matter [5]. However, the symmetry incompressibility K_s of nuclear matter calculated by the parameter sets existing in the literature for this nonlinear σ-ω-ρ model is positive, which is opposite to that given by nonrelativistic models of nuclei [2].

Actually, most of the expectations based on nonrelativistic models give negative K_s [4], *e.g.*, Myers-Swiatecki [6], Skyrme [7] and Tondeur [8] models. In particular, the minimally model-dependent data fit to nuclear masses and monopole resonance energies gives $K_s = -190$ MeV [9]. Furthermore, the K_s experimentally extracted from isoscalar giant monopole resonance energies

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

is between -566 ± 1350 to 34 ± 159 MeV [10], which also strongly suggests negative values for K_s. Physically, as it can be seen from eq. (1), $K_s < 0$ means that the nuclear equation of state becomes softer when the asymmetry δ increases.

The relevant question is: is this positiveness of the symmetry incompressibility K_s given by relativistic mean-field theory a manifestation of intrinsic properties of the model itself, or does it just reflect the selection of input data for fitting the model parameters?

The number of input data for fitting the model parameters in the relativistic mean-field theory is at most only 29, such as in a recent generalization of the model with 13 free parameters based on effective-field theories [11–13]. This is much less than the number of input data taken into account in similar fits in any nonrelativistic model. For example, in the data fit based on the Thomas-Fermi approximation with a generalized Seyler-Blanchard nucleon-nucleon interaction and with only 7 free parameters, a total of 1654 measured nuclear masses have been included, beside other data such as the nuclear-surface diffuseness and the optical-model depths as well as the fission barriers, with the fit to nuclear masses displaying a root mean square deviation of only 0.655 MeV [6]. Therefore, nuclear-matter quantities are fitted to at most 29 data in the relativistic mean-field theory, whereas they are fitted to more than 1654 in nonrelativistic phenomenological theories. From the data fit point of view, it would be interesting to discuss the confidence level of these model parameters which are fitted to only a few tens of experimental data.

In this case, it is likely that this positiveness of the symmetry incompressibility K_s, given by relativistic mean-field theory, is not the manifestation of intrinsic properties of the model itself, but depends on the selection of input data to be considered in the parameters fit. It is reasonable to expect that the situation will be improved very much when more experimental outcomes can be included, in the near future, in the data fit of parameters in the relativistic mean-field theory. As a consequence, the nuclear-matter properties calculated by these newly fitted parameters will be closer to those given by nonrelativistic models, and eventually can yield a negative symmetry incompressibility K_s.

Motivated by this expectation, it is worthwhile to see what will be obtained if the model parameters of the relativistic mean-field theory are determined by nuclear-matter properties such as given by data fit based on nonrelativistic nuclear models, since a better data fit with much more data in the relativistic mean-field theory is not yet available. In other words, we go back to the way of determining parameters such as in the original work of Walecka [14].

The purpose of this paper is to show that a stable result with negative symmetry incompressibility K_s and larger effective nucleon mass M^* can be obtained, if parameters are fitted to reasonable nuclear-matter properties. Firstly, the well-studied σ-ω-ρ model with nonlinear σ-meson self-interaction, having 6 free parameters, will be considered. Sections 2 and 3 address the theoretical formalism for infinite and semi-infinite nuclear matters, respectively. Section 4 gives the numerical result, and sect. 5 presents a short discussion and summary.

2 Formalism for infinite nuclear matter

The σ-ω-ρ model of the relativistic mean-field theory is specified by the following Lagrangian density [5](we use natural units with $\hbar = c = 1$):

$$\begin{aligned}\mathcal{L} = &\overline{\psi}[\gamma_\mu(i\partial^\mu - g_\omega\omega^\mu - g_\rho\boldsymbol{\tau}\cdot\mathbf{b}^\mu) - (M - g_\sigma\phi)]\psi\\ &+\frac{1}{2}(\partial_\mu\phi\partial^\mu\phi - m_\sigma^2\phi^2) - \frac{1}{3}Mb(g_\sigma\phi)^3\\ &-\frac{1}{4}c(g_\sigma\phi)^4 - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}m_\omega^2\omega_\mu\omega^\mu\\ &-\frac{1}{4}\mathbf{B}_{\mu\nu}\cdot\mathbf{B}^{\mu\nu} + \frac{1}{2}m_\rho^2\mathbf{b}_\mu\cdot\mathbf{b}^\mu,\end{aligned} \quad (2)$$

where $F^{\mu\nu} = \partial^\mu\omega^\nu - \partial^\nu\omega^\mu$, $\mathbf{B}^{\mu\nu} = \partial^\mu\mathbf{b}^\nu - \partial^\nu\mathbf{b}^\mu$; ψ, ϕ, ω and $\mathbf{b}^\mu$ are the nucleon, σ-, ω- and ρ-meson fields with masses M, m_σ, m_ω and m_ρ, respectively, while g_σ, g_ω and g_ρ are the respective meson-nucleon coupling constants; b and c are the nonlinear term coefficients, and $\boldsymbol{\tau}$ are isospin matrices. As M, m_ω and m_ρ are taken from experiment, the model parameters are g_σ, g_ω, g_ρ, b, c and m_σ.

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

$$\mathcal{E} = \mathcal{E}_k + \mathcal{E}_\sigma + \mathcal{E}_\omega + \mathcal{E}_\rho\,, \quad (3)$$

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

$$\mathcal{E}_\sigma = M^4\left[\frac{1}{2C_\sigma^2}(1-\xi)^2 + \frac{1}{3}b(1-\xi)^3 + \frac{1}{4}c(1-\xi)^4\right], \quad (5)$$

$$\mathcal{E}_\omega = \frac{C_\omega^2\rho_N^2}{2M^2}\,, \quad (6)$$

$$\mathcal{E}_\rho = \frac{C_\rho^2\rho_N^2}{2M^2}\delta^2\,, \quad (7)$$

where $k_{p(n)}$ are the proton (neutron) Fermi momenta, respectively

$$\xi = \frac{M^*}{M} = 1 - \frac{g_\sigma}{M}\phi\,, \quad (8)$$

$$C_i = g_i\frac{M}{m_i}, \qquad i = \sigma, \omega, \rho, \quad (9)$$

and the function $F_m(x)$ is defined as (see ref. [2] for details):

$$F_m(x) = \int_0^x \mathrm{d}x\, x^{2m}\sqrt{1+x^2}\,. \quad (10)$$

The reduced effective nucleon mass ξ and thus the field ϕ are determined by

$$(1-\xi) + bC_\sigma^2(1-\xi)^2 + cC_\sigma^2(1-\xi)^3 = \frac{C_\sigma^2}{M^3}\rho_s\,, \quad (11)$$

where the scalar density ρ_s can be expressed as

$$\rho_s = \frac{M^3\xi^3}{\pi^2} \sum_{i=p,n} f_1(k_i/\xi M), \quad (12)$$

and the function $f_m(x)$ is defined as (see ref. [2] for details)

$$f_m(x) = \int_0^x \mathrm{d}x \frac{x^{2m}}{\sqrt{1+x^2}} \,. \quad (13)$$

The model parameters related to the nuclear equation of state are C_σ^2, C_ω^2, C_ρ^2, b and c. As m_σ is the inverse Compton wavelength of the σ-meson, it is related only to the range of nuclear force and thus to the finite-size effects, such as surface thickness, surface energy and shell effects of the nuclei.

Once the equation of state is known, the following formula for pressure p can be obtained:

$$p = -\mathcal{E} + \rho_N \frac{\partial \mathcal{E}}{\partial \rho_N} = \frac{1}{3}\mathcal{E}_k - \frac{1}{3}M\xi\rho_s - \mathcal{E}_\sigma + \mathcal{E}_\omega + \mathcal{E}_\rho. \quad (14)$$

The standard state ($\rho_N = \rho_0, \delta = 0$) is defined by the equilibrium condition, $p(\rho_0, 0) = 0$. The standard density ρ_0 can be written in terms of the nuclear radius constant r_0 or the nucleon Fermi momentum k_F as

$$\rho_0 = \frac{1}{4\pi r_0^3/3} = \frac{2k_\mathrm{F}^3}{3\pi^2}. \quad (15)$$

The 6 quantities which specify the nuclear-matter properties near the nuclear-matter standard state, *i.e.*, ρ_0, a_1, J, K_0, K_s and L, can be expressed in terms of 5 parameters C_σ^2, C_ω^2, C_ρ^2, b and c [2]. Conversely, the 5 parameters can be fixed if 5 of these 6 quantities are known. In this case, we will choose r_0, a_1, K_0, J and K_s as input data, where r_0 is equivalent to ρ_0. Specifically, the procedure is as follows.

At the standard state $(\rho_0, 0)$, $e(\rho_0, 0) = -a_1$, and $\mathcal{E}_\rho = 0$, we have

$$\mathcal{E}_k + \mathcal{E}_\sigma + \mathcal{E}_\omega = \rho_0(M - a_1). \quad (16)$$

In addition, the equilibrium condition, $p(\rho_0, 0) = 0$, can be written as

$$\frac{1}{3}(\mathcal{E}_k - M\xi\rho_s) - \mathcal{E}_\sigma + \mathcal{E}_\omega = 0. \quad (17)$$

The following formulas can be derived from the above two equations:

$$C_\omega^2 = \frac{2M^2}{\rho_0^2}\mathcal{E}_\omega = \frac{M^2}{\rho_0^2}\left[\rho_0(M - a_1) - \frac{1}{3}(4\mathcal{E}_k - M\xi\rho_s)\right], \quad (18)$$

$$\mathcal{E}_\sigma = \frac{1}{2}\left[\rho_0(M - a_1) - \frac{1}{3}(2\mathcal{E}_k + M\xi\rho_s)\right]. \quad (19)$$

Furthermore, eqs. (5) and (11) can be combined to give the parameters b and c as

$$b = \frac{12\mathcal{E}_\sigma}{M^4(1-\xi)^3} - \frac{3\rho_s}{M^3(1-\xi)^2} - \frac{3}{C_\sigma^2(1-\xi)} \,, \quad (20)$$

$$c = -\frac{12\mathcal{E}_\sigma}{M^4(1-\xi)^4} + \frac{4\rho_s}{M^3(1-\xi)^3} + \frac{2}{C_\sigma^2(1-\xi)^2} \,. \quad (21)$$

Finally, the equation for symmetry energy J [2] yields

$$C_\rho^2 = \frac{2M^2}{\rho_0}\left(J - \frac{1}{6}\frac{k_\mathrm{F}^2}{\sqrt{k_\mathrm{F}^2 + M^2\xi^2}}\right). \quad (22)$$

3 Determination of σ-meson mass

Having already 5 parameters C_σ^2, C_ω^2, C_ρ^2, b and c fixed by nuclear-matter properties, the sixth parameter m_σ can be determined by quantities related to the nuclear-force range, such as the surface thickness or the surface diffuseness of ground-state finite nuclei [15], the diffraction-minimum-sharp radius of finite nuclei [11], or the surface energy of semi-infinite nuclear-matter system. In order to be consistent with the determination of the above-mentioned 5 parameters by infinite nuclear-matter properties, we choose the surface energy a_2 of the semi-infinite nuclear-matter system to calculate the σ-meson mass m_σ.

As m_σ involves the nuclear-force range, its value should be obtained by solving the field equations. In order to do that, we choose the standard Thomas-Fermi approximation, and adjust the value of m_σ to reproduce the known nuclear-surface energy a_2 such as determined by nonrelativistic nuclear models. We have to keep in mind that this is only a very roughly evaluation to get some preliminary insight on this problem.

The equations to be solved, for the semi-infinite nuclear-matter system along the z-axis, are

$$\left(\frac{\mathrm{d}^2}{\mathrm{d}z^2} - m_\sigma^2\right)\phi = -g_\sigma\rho_s + g_2\phi^2 + g_3\phi^3 \,, \quad (23)$$

$$\left(\frac{\mathrm{d}^2}{\mathrm{d}z^2} - m_\omega^2\right)\omega_0 = -g_\omega\rho_N \,, \quad (24)$$

$$\mu = g_\omega\omega_0 + \left[k_\mathrm{F}^2 + (\xi M)^2\right]^{1/2} \,, \quad (25)$$

where $g_2 = Mbg_\sigma^3$, $g_3 = cg_\sigma^4$ and μ is the nucleon chemical potential of symmetric nuclear matter. The procedure to solve these equations can be found in refs. [16–18] and references therein.

The formula to calculate the surface energy a_2 is [19]

$$a_2 = 4\pi r_0^2 \int_{-\infty}^{+\infty} \mathrm{d}z[\mathcal{E}(z) - \mathcal{E}(-\infty)\rho_N(z)/\rho_0] \,. \quad (26)$$

For the nuclear-energy density $\mathcal{E}(z)$, eqs. (3) and (4) are still valid, but

$$\mathcal{E}_\sigma(z) = \frac{1}{2}\left[\left(\frac{\mathrm{d}\phi}{\mathrm{d}z}\right)^2 + m_\sigma^2\phi^2\right] + \frac{1}{3}g_2\phi^3 + \frac{1}{4}g_3\phi^4 \quad (27)$$

and

$$\mathcal{E}_\omega(z) = \frac{1}{2}\left[\left(\frac{\mathrm{d}\omega_0}{\mathrm{d}z}\right)^2 + m_\omega^2\omega_0^2\right]. \quad (28)$$

For a symmetric system, $\delta = 0$, ρ-meson field quantities do not appear in the energy density calculation.

4 Numerical result

For given r_0, a_1, ξ, C_σ^2 and J, the procedure and formulas given in sect. 2 can be used to obtain C_ω^2, C_ρ^2, b and c, and thus K_0, K_s and L [2]. With the calculated K_0 and K_s, then we can fix ξ and C_σ^2. In this calculation, $M = 938.9$ MeV and $\hbar c = 197.327053$ MeV fm have been used, and the following quantities, with its experimentally acceptable values [20], have been chosen as input data:

$$r_0 \approx 1.14 \text{ fm}, \qquad a_1 \approx 16 \text{ MeV}. \tag{29}$$

Figure 1 plots the calculated K_s *vs.* K_0 for given ξ. The solid curves from top to bottom correspond to $\xi = 0.5$, 0.6, 0.7, 0.8 and 0.85, respectively. It can be seen that K_s is negative only for ξ larger than about 0.7–0.8, if $K_0 \leq 300$ MeV is assumed. This is shown more clearly in fig. 2, where the calculated K_s *vs.* ξ is displayed for given K_0. The solid curves from top to bottom correspond to $K_0 = 200$, 300, 400 and 500 MeV, respectively. It is shown that K_s is negative when ξ is larger than about 0.73, for $K_0 \leq 300$ MeV.

Figure 3 shows the calculated C_σ^2 *vs.* K_0 for given ξ. The solid curves from top to bottom correspond to $\xi = 0.5$, 0.6, 0.7, 0.8 and 0.85, respectively. Figure 4 gives the calculated C_ω^2 *vs.* ξ. It can be seen from eq. (18) that C_ω^2 depends only on ξ, for given r_0 and a_1. The calculation of C_ρ^2 depends, beside ξ, also on the input value of J and fig. 5 displays the calculated C_ρ^2 *vs.* ξ for given r_0, a_1 and $J = 30$ MeV. In turn, L depends, beside ξ and J, also on the input value of K_0, and fig. 6 shows the calculated L *vs.* ξ for given r_0, a_1, $J = 30$ MeV and K_0. The solid curves from top to bottom correspond to $K_0 = 200$, 300, 400 and 500 MeV, respectively.

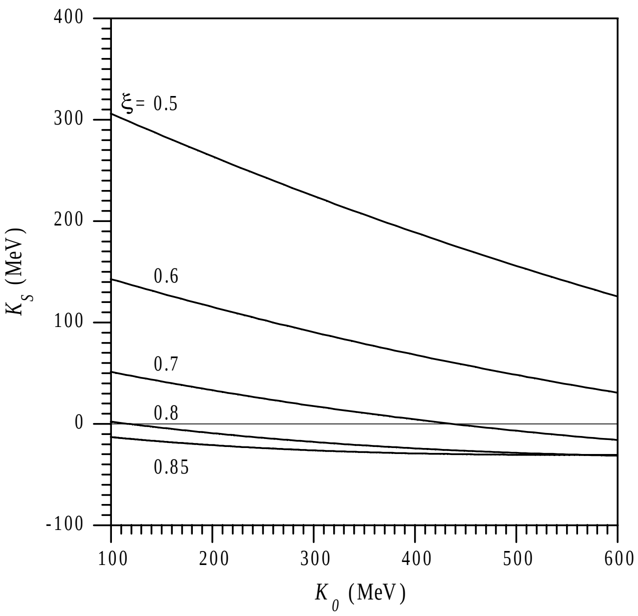

Fig. 1. Calculated K_s *vs.* K_0 for given $r_0 = 1.14$ fm, $a_1 = 16$ MeV and ξ. The solid curves from top to bottom correspond to $\xi = 0.5$, 0.6, 0.7, 0.8 and 0.85, respectively.

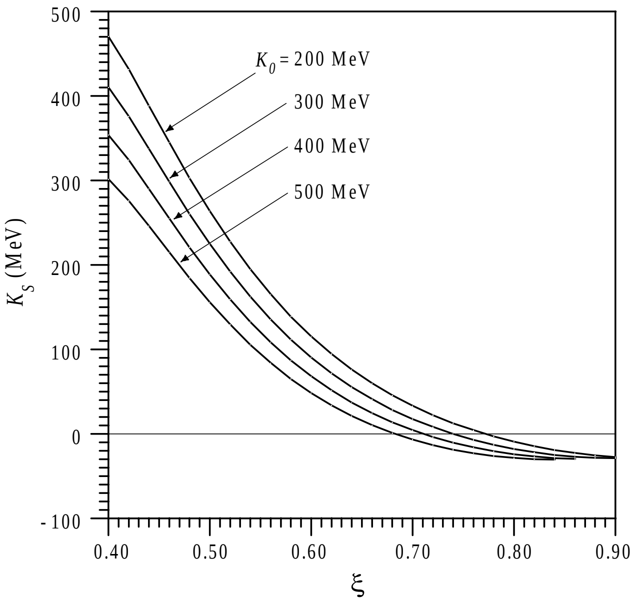

Fig. 2. Calculated K_s *vs.* ξ for given $r_0 = 1.14$ fm, $a_1 = 16$ MeV and K_0. The solid curves from top to bottom correspond to $K_0 = 200$, 300, 400 and 500 MeV, respectively.

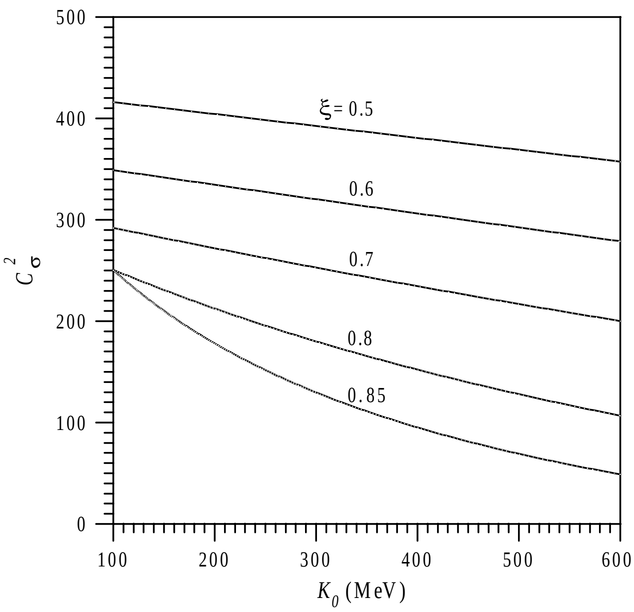

Fig. 3. Calculated C_σ^2 *vs.* K_0 for given $r_0 = 1.14$ fm, $a_1 = 16$ MeV and ξ. The solid curves from top to bottom correspond to $\xi = 0.5$, 0.6, 0.7, 0.8 and 0.85, respectively.

Figure 7 presents the nonlinear coefficient b *vs.* K_0 for given ξ. On the right-hand side of the plot, the first three curves correspond to $\xi = 0.5$, 0.6 and 0.7 from top to bottom, respectively. In the middle of the plot, the lower two curves correspond to $\xi = 0.8$ and 0.85 from top to bottom, respectively, being the first curve scaled by 1/2 and the second one by 1/10.

Figure 8 displays the nonlinear coefficient c *vs.* K_0 for given ξ. On the right-hand side of the plot, the solid curves correspond to $\xi = 0.5$, 0.6, 0.7, 0.8 and 0.85 from bottom

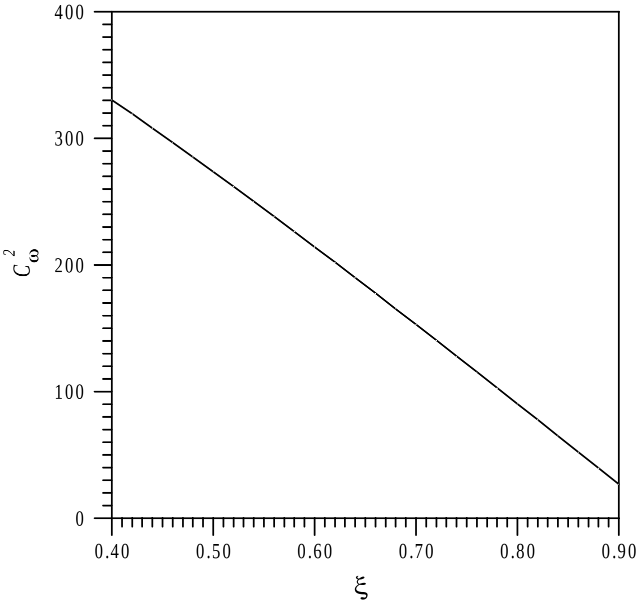

Fig. 4. Calculated C_ω^2 *vs.* ξ for given $r_0 = 1.14$ fm and $a_1 = 16$ MeV.

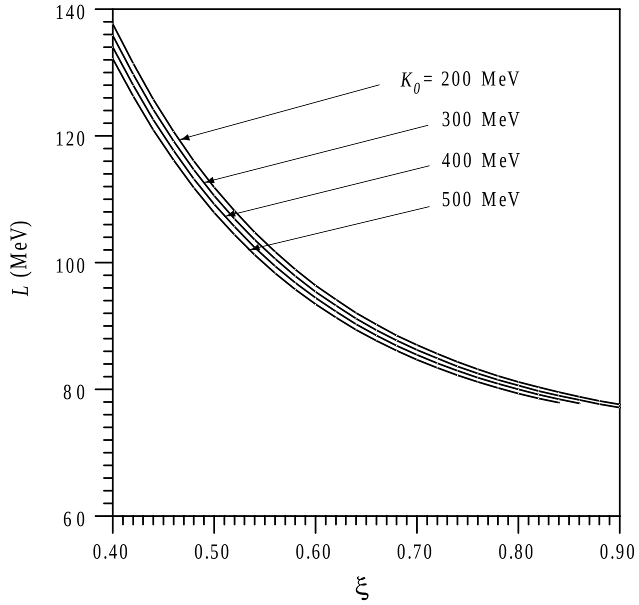

Fig. 6. Calculated L *vs.* ξ for given $r_0 = 1.14$ fm, $a_1 = 16$ MeV, $J = 30$ MeV and K_0. The solid curves from top to bottom correspond to $K_0 = 200$, 300, 400 and 500 MeV, respectively.

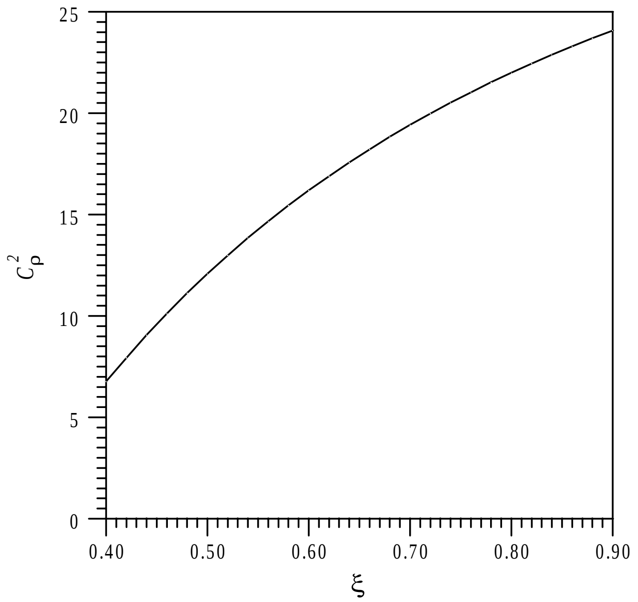

Fig. 5. Calculated C_ρ^2 *vs.* ξ for given $r_0 = 1.14$ fm, $a_1 = 16$ MeV and $J = 30$ MeV.

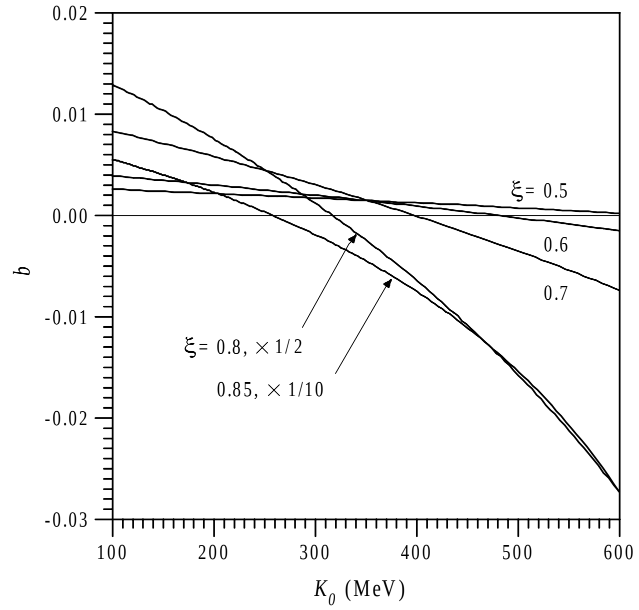

Fig. 7. Nonlinear coefficient b *vs.* K_0 for given $r_0 = 1.14$ fm, $a_1 = 16$ MeV and ξ. The solid curves correspond to $\xi = 0.5$, 0.6, 0.7, 0.8 and 0.85, respectively.

to top, respectively. The value of c should be scaled by 1/10 for the curve of $\xi = 0.8$, while by 1/50 for the curve of $\xi = 0.85$. It can be seen from fig. 8 that c is positive, if ξ is larger than about 0.7–0.8, for $K_0 \leq 300$ MeV.

In addition to these general results, it is worthwhile to see what could be obtained specifically, if realistic nuclear-matter properties, extracted from measured data of finite nuclei by nonrelativistic models, are used as input data. In this case, the results given by Myers-Swiatecki phenomenological nucleon-nucleon interaction [6,21], Skyrme interaction [7] as well as Tondeur interaction [8] have been employed.

The results of the calculation are presented in table 1. The input data set (r_0, a_1, K_0, J, K_s) is taken from the compilation of ref. [22]. MS stands for the Myers-Swiatecki interaction, SIII, Ska, SkM, SkM* and RATP for the Skyrme interactions, and Tondeur for the Tondeur interaction. It is worthwhile to note that the input value of K_s is negative for all of these interactions.

The results have shown that the model parameters $C_\sigma^2 \sim 94$, $C_\omega^2 \sim 32$, $C_\rho^2 \sim 26$, $b \sim -0.09$, and $c \sim 1$.

Table 1. The nuclear-matter properties r_0 (fm), a_1 (MeV), J (MeV), K_0 (MeV), L (MeV), a_2 (MeV), the parameters C_σ^2, C_ω^2, C_ρ^2, b, c, m_σ (MeV), the effective nucleon mass M^*/M and the nuclear-surface thickness t (fm), for nonlinear σ-ω-ρ model in the relativistic mean-field theory. See text for details.

	r_0	a_1	K_0	J	K_s	L	a_2	M^*/M	C_σ^2	C_ω^2	C_ρ^2	b	c	m_σ	t
MS	1.140	16.24	234.4	32.65	−147.1	85.55	18.63	0.8934	92.728	30.908	27.729	−0.09203	1.1137	363.94	1.45
SIII	1.180	15.86	355.5	28.16	−393.9	72.87	18.13	0.8774	77.041	47.982	24.665	−0.15264	1.0935	551.27	0.89
Ska	1.154	15.99	263.1	32.91	−78.45	86.77	18.79	0.8851	96.522	38.415	29.434	−0.08115	0.8458	390.88	1.39
SkM	1.142	15.77	216.6	30.75	−148.8	79.90	16.85	0.8973	95.423	28.962	25.294	−0.08287	1.1499	366.12	1.42
SkM*	1.142	15.77	216.6	30.03	−155.9	77.73	17.51	0.8975	94.984	28.842	24.267	−0.08441	1.1655	354.85	1.48
RATP	1.143	16.05	239.6	29.26	−191.3	75.43	18.80	0.8936	89.460	31.269	23.183	−0.10318	1.1808	371.44	1.43
Tondeur	1.145	15.98	235.8	19.89	−39.78	47.60	18.41	0.8862	107.753	36.378	9.705	−0.04911	0.6885	352.64	1.57

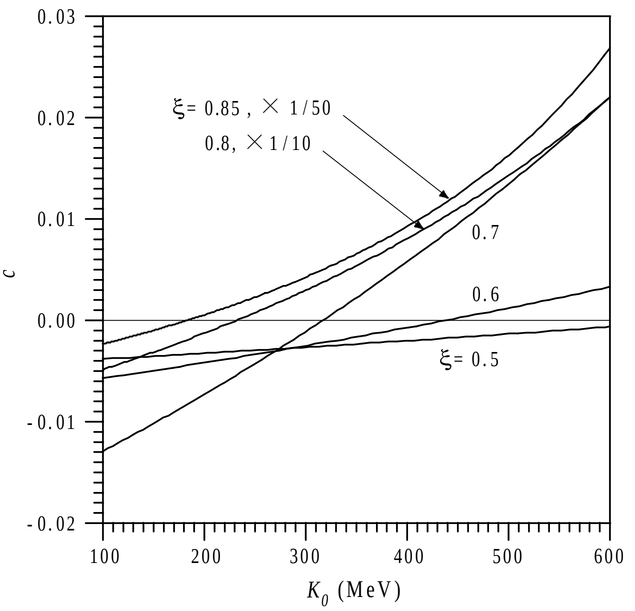

Fig. 8. Nonlinear coefficient c *vs.* K_0 for given $r_0 = 1.14$ fm, $a_1 = 16$ MeV and ξ. The solid curves correspond to $\xi = 0.5$, 0.6, 0.7, 0.8 and 0.85, respectively.

It is also interesting to note that the effective nucleon mass M^*/M is around 0.89, which is much larger than that given by the data fits existing in the literature [15]. Furthermore, the nonlinear coefficient c is positive, which means the field system is stable for all of these parameter sets.

In the determination of m_σ, the following values are used:

$$m_\omega = 783 \text{ MeV}, \qquad m_\rho = 763 \text{ MeV}. \tag{30}$$

Then the nuclear-surface thickness t, defined as the 90%-10% fall-off distance of the nucleon density in the surface region, can be calculated. The surface energy a_2 used in this calculation is listed in table 1. The value of a_2, for the Myers-Swiatecki interaction is taken from ref. [6], for the Skyrme interaction and Tondeur interaction are taken from refs. [7] and [8], respectively. The σ-meson mass m_σ determined by the Thomas-Fermi approximation and the simultaneously calculated nuclear-surface thickness t are listed, respectively, in the last two columns of this table.

The determined σ-meson mass m_σ is around 370 MeV, except SIII which gives $m_\sigma = 551.27$ MeV. However, both the nuclear radius constant $r_0 = 1.180$ fm and the nuclear incompressibility $K_0 = 355.5$ MeV given by SIII are much larger than others. The calculated nuclear-surface thickness t is around 1.4 fm, except that given by SIII, which is $t = 0.89$ fm.

5 Discussion and summary

The present work is based on the expectation that the nuclear-matter properties, *i.e.*, the standard density ρ_0, volume energy a_1, symmetry energy J, incompressibility K_0, symmetry incompressibility K_s and density symmetry L of infinite nuclear matter, as well as the surface energy a_2 of the semi-infinite nuclear-matter system, should have values which are independent of nuclear models, either relativistic mean-field models or nonrelativistic nuclear models.

Motivated by this expectation, the σ-ω-ρ model parameters of the relativistic mean-field theory with nonlinear σ-meson self-interaction are determined by nuclear-matter properties, which are taken as those given by data fit based on nonrelativistic nuclear models. The results show that $C_\sigma^2 \sim 94$, $C_\omega^2 \sim 32$, $C_\rho^2 \sim 26$, $b \sim -0.09$, $c \sim 1$, and the σ-meson mass $m_\sigma \sim 370$ MeV, while the calculated nuclear-surface thickness $t \sim 1.4$ fm.

The field system is stable in this whole parameter region with positive c, since there is a lower limit for the σ-meson self-interaction energy. It is also shown that the effective nucleon mass M^* is larger than $0.73M$, if the symmetry incompressibility K_s is assumed to be negative and the nuclear-matter incompressibility K_0 is kept less than 300 MeV.

It should be noted that the parameters C_σ^2, C_ω^2, C_ρ^2, b and c depend only on the choice of the properties of infinite nuclear matter; they do not depend on the choice of the properties of semi-infinite nuclear-matter system, and thus do not depend on the specific approximation used to solve the field equations. Therefore, as m_σ depends on the value of a_2 through the chosen approximation, it will give a different value if another approximation is chosen, for example the Hartree approximation instead of the Thomas-Fermi approximation we have adopted here.

The σ-meson mass m_σ is expected to be increased to around 400 MeV, if the Hartree approximation, instead of the Thomas-Fermi approximation, is used [16–18]. However, even so, this value is still lower than that given by the existing data fits [2]. Therefore, determined in this way, the parameters C_σ^2, C_ω^2, C_ρ^2 and m_σ are much smaller while the absolute values of b and c are much larger than those existing in the literature. In addition, the nuclear-surface thickness t calculated from these parameters is smaller than what is acceptable. This is due to the small m_σ, because the smaller m_σ, the larger the range of the nuclear force is, thus the surface thickness should be reduced in order to keep the same surface energy. On the other hand, if the nuclear-surface thickness t, instead of the nuclear-surface energy a_2, is chosen to fix the σ-meson mass m_σ, the result will be even worse. In this case, m_σ will be reduced further as t increases to an acceptable value, and thus the surface energy a_2 will be larger than what is given by nonrelativistic models [16–18].

The arisen question is: is this parameter set acceptable? The answer to this question depends on the criterion applied to the final result. If the agreement between calculated and measured nuclear masses is required, it is very likely to be able to accept this parameter set, because the main quantities which have some influence on this agreement are just the standard density ρ_0, volume energy a_1, symmetry energy J, incompressibility K_0, symmetry incompressibility K_s and density symmetry L of infinite nuclear matter, and the surface energy a_2 of semi-infinite nuclear-matter system. However, the σ-meson mass m_σ and thus the nuclear-surface thickness t are smaller than the usually accepted values, they will have some influence on the nucleon distribution in the nuclear-surface region, on the spin-orbit interaction and thus on the nuclear-shell effects. Therefore, the calculation of finite-nuclei properties by using this parameter set is needed, before we can say any definite words about this question.

Our conclusion is: the positiveness of the symmetry incompressibility K_s given by relativistic mean-field theory is not a manifestation of intrinsic properties of the model itself; it is possible to have negative K_s, if appropriate input data are chosen for fitting the model parameters. However, it seems that, in order to have negative K_s, the price to pay is to have a small m_σ and thus a small surface thickness t, in this σ-ω-ρ model of the relativistic mean-field theory with a nonlinear σ-meson self-interaction.

K.C.C. acknowledges partial support from the Fundação de Amparo à Pesquisa do Estado do Rio de Janeiro (FAPERJ), Brazil.

References

1. W.D. Myers, W.J. Swiatecki, Ann. Phys. (N.Y.) **55**, 395 (1969).
2. K.C. Chung, C.S. Wang, J.A. Santiago, J.W. Zhang, Eur. Phys. J. A **9**, 453 (2000).
3. A. Akmal, V.R. Pandharipande, D.G. Ravenhall, Phys. Rev. C **58**, 1804 (1998).
4. B.A. Li, C.M. Ko, W. Bauer, Int. J. Mod. Phys. E **7**, 147 (1998).
5. B.D. Serot, J.D. Walecka, Int. J. Mod. Phys. E **6**, 515 (1997).
6. W.D. Myers, W.J. Swiatecki, Nucl. Phys. A **601**, 141 (1996).
7. M. Brack, C. Guet, H.-B. Håkansson, Phys. Rep. **123**, 275 (1985).
8. F. Tondeur, Nucl. Phys. A **315**, 353 (1978).
9. K.C. Chung, C.S. Wang, J.A. Santiago, Phys. Rev. C **59**, 714 (1999).
10. S. Shlomo, D.H. Youngblood, Phys. Rev. C **47**, 529 (1993).
11. R.J. Furnstahl, B.D. Serot, H.B. Tang, Nucl. Phys. A **598**, 539 (1996).
12. H. Müller, B.D. Serot, Nucl. Phys. A **606**, 508 (1996).
13. R.J. Furnstahl, B.D. Serot, H.B. Tang, Nucl. Phys. A **615**, 441 (1997).
14. J.D. Walecka, Ann. Phys.(N.Y.) **83**, 491 (1974).
15. P.-G. Reinhard, Rep. Prog. Phys. **52**, 439 (1989).
16. J. Boguta, A.R. Bodmer, Nucl. Phys. A **292**, 413 (1977).
17. W. Stocker, M.M. Sharma, Z. Phys. A **339**, 147 (1991).
18. M. Centelles, X. Viñas, Nucl. Phys. A **563**, 173 (1993).
19. W.D. Myers, W.J. Swiatecki, C.S. Wang, Nucl. Phys. A **436**, 185 (1985).
20. K.C. Chung, C.S. Wang, A.J. Santiago, J.W. Zhang, Phys. Rev. C **61**, 047303 (2000).
21. W.D. Myers, W.J. Swiatecki, Phys. Rev. C **57**, 3020 (1998).
22. K.C. Chung, C.S. Wang, A.J. Santiago, J.W. Zhang, Eur. Phys. J. A **10**, 27 (2001).