DENSITY DEPENDENT MESON NUCLEON COUPLINGS FOR NUCLEAR MATTER AND FINITE NUCLEI

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The medium dependence of nuclear interactions is described by an effective Lagrangian characterized by density dependent meson nucleon couplings. The density dependence of the coupling parameters of the σ, ω, δ, and ρ mesons is deduced by reproducing the nucleon self-energy resulting from the relativistic Brueckner–Hartree–Fock approach at each density for symmetric and asymmetric nuclear matter. The inclusion of the density dependent isovector mesons couplings, δ and ρ, affects the density and charge distributions of finite nuclei. The results are discussed and compared with experimental data and with results from similar approaches.

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1. Introduction

The relativistic Brueckner–Hartree–Fock theory (RBHF) is generally accepted as one of the most reliable and feasible microscopic methods for the description of effective interactions in the nuclear medium [1, 2].

Attempts have been made to calculate finite nuclei using effective meson nucleon interactions, deduced from the RBHF self-energy. Density dependent σ and ω meson couplings were derived from RBHF calculations using the Bonn A, B, and C potentials [1, 2] by reproducing the nucleon self-energies resulting from the RBHF at each density [3]. The parametrizations of Ref. [3] have been used in Ref. [4] in a fully covariant approach to a density dependent hadron field theory. They have been successfully used in the description of the properties of spherical nuclei [4], deformed nuclei [5], hypernuclei [6], neutron star matter [7], and exotic nuclei [8]. But they were unable to account for binding energies and deformations of typical deformed nuclei, including rare-earth nuclei and nuclei in the actinide region of special importance for nuclear applications [5].

In order to obtain a better quantitative description of nuclear properties, phenomenological interactions with explicit density dependence of the meson nucleon couplings have been adjusted to the properties of nuclear matter and finite nuclei [9, 10]. They have been successfully applied in the calculations of spherical and deformed nuclei [11], and ground state properties of rare-earth nuclei [12]. An alternative way, which is directly related to the underlying microscopic description of nuclear interaction, would be to extend the parametrization of the density dependence of coupling parameters to include isovector δ and ρ mesons couplings. Refs. [13, 14] extend the RBHF calculations of Ref. [2] to the case of asymmetric nuclear matter, providing the nucleon self-energy at each density for different proton fractions.

This work refines and extends the parametrization given in Ref. [3] for the RBHF Bonn A potential by including also the isovector mesons δ and ρ, in order to completely reproduce the RBHF results of Refs. [13, 14] for the nucleon self-energy at each density for symmetric and asymmetric nuclear matter. Section 2 reviews the general theory of an effective one-boson-exchange (OBE) Lagrangian and the resulting nucleon self-energy. Section 3 presents a new parametrization of the density dependent coupling parameters of the isoscalar mesons σ and ω and the isovector mesons δ and ρ. And the coefficients of this parametrization are adjusted to the outcome for the nucleon self-energy of the RBHF treatment of symmetric and asymmetric nuclear matter of Refs. [13, 14]. The relativistic Thomas–Fermi approach with density dependent coupling parameters RDTF is used in Section 4 to analyze the effects of the inclusion of the density dependent isovector mesons couplings on the results for finite nuclei in a first test of the new parametrization. The main conclusions are summarized in the last section.

2. General theory

A standard one-boson-exchange (OBE) Lagrangian with four mesons: the isoscalar scalar meson σ, the isoscalar vector meson ω, the isovector scalar meson δ, and the isovector vector meson ρ, is used

$$\begin{aligned}\mathcal{L} \;=\; & \overline{\psi}\left[i\gamma^{\mu}\partial_{\mu} - m_N - g_{\sigma}\sigma - g_{\omega}\gamma^{\mu}\omega_{\mu} - g_{\delta}\;\vec{\tau}\cdot\vec{\delta}\right. \\ & \left. - g_{\rho}\;\vec{\tau}\cdot\gamma^{\mu}\vec{\rho}_{\mu} - \frac{e}{2}\left(1+\tau_3\right)\gamma^{\mu}A_{\mu}\right]\psi \\ & -\tfrac{1}{2}\;m_{\sigma}^2\;\sigma^2 + \tfrac{1}{2}\;\partial^{\mu}\sigma\;\partial_{\mu}\sigma \\ & +\tfrac{1}{2}\;m_{\omega}^2\;\omega^{\mu}\omega_{\mu} - \tfrac{1}{4}\;\Omega^{\mu\nu}\Omega_{\mu\nu} \\ & -\tfrac{1}{2}\;m_{\delta}^2\;\delta^2 + \tfrac{1}{2}\;\partial^{\mu}\vec{\delta}\cdot\partial_{\mu}\vec{\delta} \\ & +\tfrac{1}{2}\;m_{\rho}^2\;\vec{\rho}^{\;\mu}\cdot\vec{\rho}_{\mu} - \tfrac{1}{4}\;\vec{R}^{\;\mu\nu}\cdot\vec{R}_{\mu\nu} - \tfrac{1}{4}\;F^{\mu\nu}F_{\mu\nu}\,,\end{aligned} \tag{1}$$

with

$$\Omega^{\mu\nu} = \partial^\mu \omega^\nu - \partial^\nu \omega^\mu \,, \tag{2}$$

$$\vec{R}^{\,\mu\nu} = \partial^\mu \vec{\rho}^{\,\nu} - \partial^\nu \vec{\rho}^{\,\mu} \,, \tag{3}$$

$$F^{\mu\nu} = \partial^\mu A^\nu - \partial^\nu A^\mu \,. \tag{4}$$

The baryons, protons and neutrons, are represented by Dirac spinors $\overline{\psi} = (\overline{\psi}_p, \overline{\psi}_n)$. σ, ω_μ, $\vec{\delta}$, and $\vec{\rho}_\mu$ are the fields of the different mesons. e is the proton charge and A_μ the electromagnetic field. m_N is the nucleon mass. m_i and g_i ($i = \sigma, \omega, \delta, \rho$) are the mass and the coupling parameter of the i-meson. γ^μ are the Dirac γ matrices, $\vec{\tau}$ is the isospin vector, and τ_3 its third component, equal to $+1$ for protons and -1 for neutrons.

In addition to the σ, ω, and ρ mesons, the isovector scalar meson δ is included, which is necessary to reproduce the results of the RBHF nuclear matter calculations in the general case of different proton and neutron densities [15]. Significant scalar strength in the isovector channel has been found, which can be interpreted as an effective δ meson, which couples as strongly as the effective isovector vector ρ meson [15–17].

The nucleon self-energy in nuclear matter takes in the relativistic mean field approximation RMF [18] the form

$$\Sigma = \Sigma_s + \gamma^0 \Sigma_0 \,, \tag{5}$$

and is determined by the contributions of the four mesons included in the Lagrangian

$$\begin{aligned} \Sigma_{sp,sn} &= \Sigma_s^\sigma \pm \Sigma_s^\delta \\ &= -\frac{g_\sigma^2}{m_\sigma^2} \left(\rho_{sp} + \rho_{sn}\right) \mp \frac{g_\delta^2}{m_\delta^2} \left(\rho_{sp} - \rho_{sn}\right) \,, \end{aligned} \tag{6}$$

$$\begin{aligned} \Sigma_{0p,\,0n} &= \Sigma_0^\omega \pm \Sigma_0^\rho \\ &= -\frac{g_\omega^2}{m_\omega^2} \left(\rho_p + \rho_n\right) \pm \frac{g_\rho^2}{m_\rho^2} \left(\rho_p - \rho_n\right) \,, \end{aligned} \tag{7}$$

where p, n denote protons and neutrons, respectively, and the upper signs correspond to protons and the lower to neutrons. ρ is the density and ρ_s the scalar density.

3. Density dependent coupling parameters

The structure of the nucleon self-energy in nuclear matter used in RBHF has the form (5). RBHF calculations provide Σ_{sp}, Σ_{sn}, Σ_{0p}, and Σ_{0n} at various proton and neutron densities, or equivalently, at various densities $\rho = \rho_p + \rho_n$ and asymmetry parameter values β. The asymmetry parameter β is defined as

$$\beta = \frac{\rho_n - \rho_p}{\rho_n + \rho_p} \, . \tag{8}$$

The easiest access to density dependent coupling parameters is obtainable by utilizing the functional form of the nucleon self-energy given in Eqs. (5)–(7). Density and asymmetry dependent coupling parameters are calculated from the RBHF results for the nuclear matter self-energy via

$$\Sigma_{sp}^{\mathrm{RBHF}}(\rho,\beta) + \Sigma_{sn}^{\mathrm{RBHF}}(\rho,\beta) \;=\; -2\;\frac{g_\sigma^2(\rho,\beta)}{m_\sigma^2}\,(\rho_{sp}+\rho_{sn}) \;, \tag{9}$$

$$\Sigma_{sp}^{\mathrm{RBHF}}(\rho,\beta) - \Sigma_{sn}^{\mathrm{RBHF}}(\rho,\beta) \;=\; -2\;\frac{g_\delta^2(\rho,\beta)}{m_\delta^2}\,(\rho_{sp}-\rho_{sn}) \;, \tag{10}$$

$$\Sigma_{0p}^{\mathrm{RBHF}}(\rho,\beta) + \Sigma_{0n}^{\mathrm{RBHF}}(\rho,\beta) \;=\; 2\;\frac{g_\omega^2(\rho,\beta)}{m_\omega^2}\,(\rho_p+\rho_n) \;, \tag{11}$$

$$\Sigma_{0p}^{\mathrm{RBHF}}(\rho,\beta) - \Sigma_{0n}^{\mathrm{RBHF}}(\rho,\beta) \;=\; 2\;\frac{g_\rho^2(\rho,\beta)}{m_\rho^2}\,(\rho_p-\rho_n) \;, \tag{12}$$

where $\Sigma_{sp}^{\mathrm{RBHF}}(\rho,\beta)$ denotes the RBHF result for Σ_{sp} at the density ρ and the asymmetry value β, *etc.* Eqs. (9)–(12) define the density and asymmetry dependent coupling parameters $g_i(\rho,\beta)$ $(i=\sigma,\omega,\delta,\rho)$.

Some references like Ref. [4] define also a so called scalar density dependence approach SDD, where the coupling parameters of the scalar mesons σ and δ depend on the scalar densities ρ_{sp} and ρ_{sn} instead of the densities ρ_p and ρ_n, while the approach of Eqs. (9)–(12) is called the vector density dependence approach (VDD). The results of these references are in favor of the VDD [4], and the VDD provides a more natural relation between the density dependent coupling parameters and the RBHF microscopic self-energies [8]. The RBHF treatment calculates the self-energy at given values of the densities ρ_p and ρ_n [2]. Therefore, this work is restricted to the definition of the density and asymmetry dependent coupling parameters given by Eqs. (9)–(12).

This work utilizes the RBHF results of Refs. [13, 14], which use the parameters of the OBE potential Bonn A of Refs. [1, 2]. The RBHF results for symmetric nuclear matter ($\rho_p = \rho_n$) given in Ref. [2] for the Bonn A potential have been already used in Ref. [3] to define density dependent coupling parameters for the isoscalar mesons σ and ω. Refs. [13, 14] extend the RBHF calculations of Ref. [2] to the case of asymmetric nuclear matter, which provides Σ_{sp}, Σ_{sn}, Σ_{0p}, and Σ_{0n} at various proton and neutron densities. Therefore, it is necessary to extend the parametrization of Ref. [3] to include also the isovector mesons δ and ρ in order to completely reproduce the RBHF results of Refs. [13,14]. Four mesons are needed to reproduce the four self-energy components, see Eqs. (9)–(12).

Refs. [13, 14] use the approximation that the self-energy components are momentum independent, though this momentum dependence is included in the calculations of the RBHF equations. This approximation is extremely good for nucleons up to slightly above the Fermi momentum [19,20]. Ref. [8] introduces momentum corrected nucleon–meson vertices, adjusted to reproduce the RBHF equation of state. The procedure to determine the momentum correction is not unique [8, 15]. And since this work utilizes the RBHF results of Refs. [13, 14], it uses the approximations done there, *i.e.*, momentum independent self-energy components in Eqs. (9)–(12).

Analyzing the RBHF results of Refs. [13, 14] and others [8], one recognizes that for asymmetry parameter β values between 0 and 0.4 and except at small densities, the dependence of the RBHF self-energy on the asymmetry in the isoscalar channel (σ, ω) is negligible. In the isovector channel (δ, ρ) the dependence on the asymmetry is mainly given by the terms $(\rho_{sp} - \rho_{sn})$ and $(\rho_p - \rho_n)$ on the right-hand side of Eqs. (10) and (12), respectively, while the dependence of g_δ and g_ρ on the asymmetry is negligible. The Brueckner scheme is an intermediate density approximation, losing its physical significance at low densities because the Brueckner independent pair assumption becomes questionable. And β varies between 0 and 0.25 in the case of finite nuclei. Therefore, the coupling parameters are chosen to depend only on the total density ρ and not on the asymmetry value β, *i.e.*, $g_i = g_i(\rho)$ $(i = \sigma, \omega, \delta, \rho)$.

Density dependent coupling parameters of the isoscalar mesons are introduced by

$$\frac{g_i(\rho)}{g_i(\rho_0)} - 1 = a_i\left(\exp\left[b_i\left(1 - \left(\frac{\rho}{\rho_0}\right)^{1/3}\right)\right] - 1\right) \quad i = \sigma, \omega\,, \tag{13}$$

where ρ_0 is the saturation density and a_i, b_i, and $g_i(\rho_0)$ are the coefficients of the density dependent function $g_i(\rho)$. Expanding the exponential function up to the quadratic term, one recovers the polynomial expansion around the saturation density ρ_0 used in Ref. [3], but the exponential function omits the instabilities resulting from the use of the polynomial expansion at high densities, where the polynomial expansion becomes infinite. At high densities $g_i(\rho)$ approaches the finite value $(1-a_i)g_i(\rho_0)$ $(i = \sigma, \omega)$. Density dependent coupling parameters of the isovector mesons are introduced by

$$g_i(\rho) = g_i(\rho_0)\exp\left[b_i\left(1 - \frac{\rho}{\rho_0}\right)\right] \quad i = \delta, \rho\,, \tag{14}$$

which is the form suggested by RBHF calculations of asymmetric nuclear matter [15, 16].

The parametrization provided by Eqs. (13)–(14) has the advantage that one obtains the density dependence of the coupling parameters over a wide range in a simple manner, and avoids the ambiguities of the RBHF treatment at lower densities.

The coefficients a_i, b_i, and $g_i(\rho_0)$ $(i = \sigma, \omega)$ are adjusted to the outcome of the RBHF calculations of symmetric nuclear matter, and the coefficients b_i and $g_i(\rho_0)$ $(i = \delta, \rho)$ to the outcome of the RBHF calculations of asymmetric nuclear matter at the value $\beta = 0.2$ for the asymmetry parameter, *i.e.*, at proton fraction 0.4. The resulting density dependent parametrization of the RBHF potential Bonn A is called D(A) in order to distinguish it from the RBHF potential itself. The coefficients of the parametrization D(A) are given in Table I.

TABLE I

The density dependent parameter set D(A). m_i is the mass of the i-meson. a_i, b_i, and $g_i(\rho_0)$ are the coefficients of the parametrization of the density dependent coupling parameters $(i = \sigma, \omega, \delta, \rho)$. $m_N = 938.926 MeV$ is the average nucleon mass used by Ref. [2] and $\rho_0 = 0.185 fm^{-3}$ is the saturation density resulting from the RBHF potential Bonn A [2].

Meson i	σ	ω	δ	ρ
m_i (MeV)	550	782.6	983	769
$g_i(\rho_0)$	9.297	11.269	4.701	2.370
a_i	0.2941	0.3451		
b_i	2.217	2.113	1.223	1.634

The masses m_N, m_σ, m_ω, m_δ, and m_ρ and the saturation density ρ_0 are those of the Bonn A potential. Figure 1 illustrates the dependency of the coupling parameters on density. Values resulting from Eqs. (9)–(12) for several densities are inserted by small diamonds in figure 1 in order to demonstrate the quality of the fitting procedure. In the case of symmetric nuclear matter, the nucleon self-energy is reproduced with an accuracy of more than 99% for densities up to twice the saturation density, see $g_\sigma(\rho)$ and $g_\omega(\rho)$ in figure 1. In the case of asymmetric nuclear matter the reproduction is of such a high accuracy only for densities up to slightly above the saturation density, see $g_\delta(\rho)$ and $g_\rho(\rho)$ in figure 1. The repulsive contribution of the ρ meson changes to an attractive contribution at densities higher than the saturation density, *i.e.*, the left-hand side of Eq. (12) becomes negative leading to an imaginary value of g_ρ. And the decrease of the δ meson coupling with increasing density is much slower than the exponential decrease at densities up to slightly above the saturation density, Eq. (14), leading to a negative effective mass of the neutron at higher densities. These obstacles in extracting the effective coupling parameters of isovector mesons can be dealt with within the RBHF approach, see Ref. [17], and do not occur when using the parametrization given by Eq. (14).

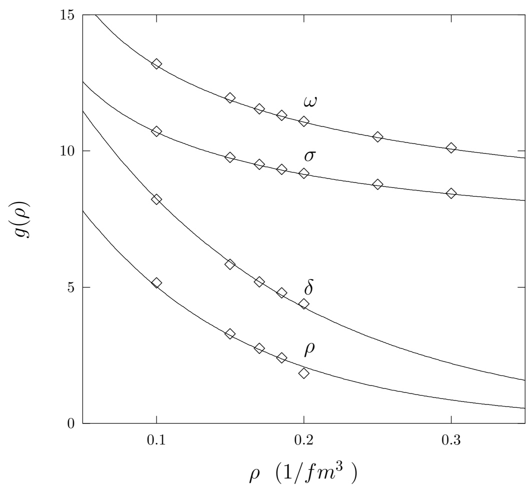

Fig. 1. Coupling parameters of the mesons $\sigma\omega\delta\rho$ of the effective interaction D(A) of Table I as functions of the density. Marked points are the values that reproduce the exact RBHF results of Refs. [13, 14].

Table II compares the saturation properties of symmetric nuclear matter resulting from the parametrization D(A) of Table I with those from the RBHF potential Bonn A [2] and from the polynomial parametrization of Ref. [3] for the Bonn A potential. The nucleon effective mass is given by

$$M_{p,n} = m_N + \Sigma_{sp,sn} \,, \tag{15}$$

and is the same for protons and neutrons in the case of symmetric matter. B/A is the saturation binding energy per nucleon. The parametrization D(A) reproduces the nuclear matter saturation properties of the RBHF treatment better than the polynomial parametrization of Ref. [3]. Figure 2 shows the nuclear matter equation of state resulting from the D(A) parametrization at three different values of the asymmetry parameter β.

TABLE II

Saturation properties of symmetric nuclear matter resulting from the parametrization D(A), from the polynomial parametrization of Ref. [3] for the Bonn A potential, and from the RBHF treatment utilizing the Bonn A potential [2].

	D(A)	Ref. [3]	RBHF [2]
ρ_0 (1/fm^3)	0.179	0.170	0.185
B/A (MeV)	15.60	15.80	15.59
M/m_N	0.602	0.618	0.601

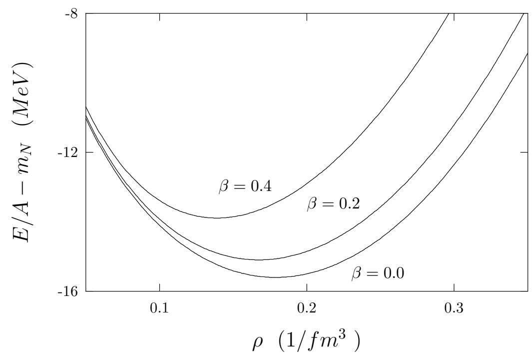

Fig. 2. Nuclear matter equation of state resulting from the D(A) parametrization at different values of the asymmetry parameter β. E is the energy.

4. Finite nuclei

In this section, the relativistic Thomas–Fermi approach with density dependent coupling parameters RDTF is used to analyze the effects of the inclusion of the density dependent isovector mesons couplings, δ and ρ, on the results for finite nuclei in a first test of the D(A) parametrization. A detailed derivation of the RDTF system of coupled equations can be found, for instance, in Ref. [21]. The charge density is calculated by folding the proton density with a Gaussian representing the charge distribution of the proton [22]. The rms charge radius of the proton being 0.8 fm. A center of mass correction $-T/A$ is subtracted from the total binding energy, where T is the kinetic energy and A is the mass number.

Table III compares the results for doubly magic nuclei utilizing the D(A) parametrization of Table I with the results of the similar approaches of Refs. [8, 16] using the RBHF Bonn A [2] and Groningen [23] potentials and with experimental data. Refs. [8, 16] use relativistic mean field theory with density dependent coupling parameters. Ref. [8] uses the parametrization of Ref. [3] for the Bonn A potential, which includes isoscalar mesons only.

Ref. [16] introduces density dependent couplings into the calculations of finite nuclei by a local density and asymmetry estimation based directly on RBHF nuclear matter results, *i.e.*, no parametrization is used. The experimental data are those used in Ref. [9].

TABLE III

Binding energies per particle and rms charge radii of doubly magic nuclei for the D(A) parametrization of Table I in comparison with the results of the similar approaches of Refs. [8, 16] utilizing the RBHF Bonn A and Groningen potentials and with experimental data.

		^{16}O	^{40}Ca	^{48}Ca	^{208}Pb
D(A)	B/A (MeV)	8.29	8.70	9.23	8.41
	$r_{\rm ch}$ (fm)	2.77	3.48	3.47	5.49
Bonn A		8.58	9.02	8.96	8.17
[8]		2.75	3.46	3.49	5.53
Bonn A		7.01	7.54	7.18	6.20
[16]		2.61	3.31	3.35	5.33
Groningen		5.65	5.96	6.09	5.28
[8]		2.76	3.47	3.48	5.49
Exp.		7.98	8.55	8.67	7.87
		2.73	3.49	3.48	5.51

In order to analyze the effects of the inclusion of the density dependent isovector mesons couplings on the results for finite nuclei, Table IV compares the results utilizing the D(A) parametrization with all mesons included ($\sigma\omega\delta\rho$) with the results with only isoscalar mesons ($\sigma\omega$). For the symmetric nuclei ^{16}O and ^{40}Ca inclusion of the isovector mesons increases the proton rms radii and decreases the neutron rms radii, while for the asymmetric nuclei ^{48}Ca and ^{208}Pb the effect is reversed, proton rms radii decrease and neutron rms radii increase by inclusion of the isovector mesons. It should be noted that only with the isovector mesons included one obtains $r_{\rm ch}(^{48}{\rm Ca}) < r_{\rm ch}(^{40}{\rm Ca})$. The inclusion of the isovector mesons δ and ρ has almost no effect on binding energies in the case of symmetric nuclei, while increases binding energies of asymmetric nuclei.

TABLE IV

Binding energies per particle, rms charge, proton, and neutron radii, and neutron skin thicknesses of doubly magic nuclei. Table compares results utilizing the D(A) parametrization with all mesons included ($\sigma\omega\delta\rho$), with the results with only isoscalar mesons ($\sigma\omega$), and with available experimental data.

		^{16}O	^{40}Ca	^{48}Ca	^{208}Pb
$\sigma\omega\delta\rho$	B/A (MeV)	8.292	8.699	9.227	8.414
	$r_{\rm ch}$ (fm)	2.765	3.477	3.468	5.489
	r_p (fm)	2.647	3.383	3.374	5.430
	r_n (fm)	2.567	3.247	3.569	5.559
	t (fm)	−0.080	−0.136	0.195	0.129
$\sigma\omega$	B/A	8.286	8.684	9.053	8.103
	$r_{\rm ch}$	2.747	3.445	3.491	5.496
	r_p	2.628	3.351	3.399	5.437
	r_n	2.581	3.268	3.549	5.549
	t	−0.047	−0.084	0.150	0.111
Exp.	B/A	7.976	8.551	8.667	7.868
	$r_{\rm ch}$	2.730	3.485	3.484	5.505

The effect of the inclusion of the density dependent isovector mesons couplings on the charge density distributions is small, and is even smaller on neutron density and total density distributions, as can be seen in Figs. 3–5 for the ^{208}Pb nucleus.

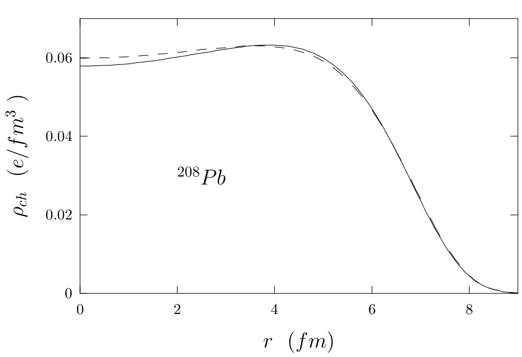

Fig. 3. Effect of the inclusion of the density dependent isovector mesons couplings on the charge density distribution of ^{208}Pb. The solid curve represents the result with all mesons included and the dashed curve with only isoscalar mesons.

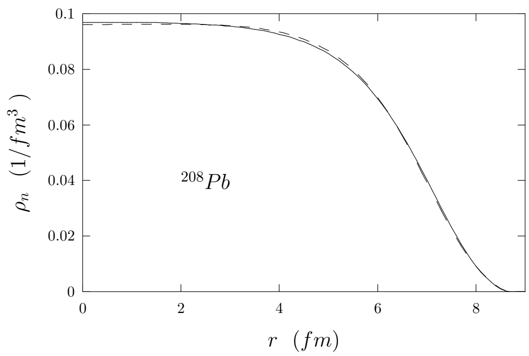

Fig. 4. Neutron density distribution of ^{208}Pb. Labeling as in Fig. 3.

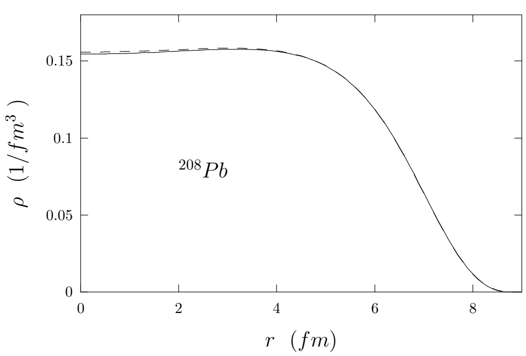

Fig. 5. Total density distribution of ^{208}Pb. Labeling as in Fig. 3.

5. Summary

Density dependent coupling parameters of the σ, ω, δ, and ρ mesons are deduced from the RBHF nucleon self-energy.

A parametrization of the density dependence is derived, which reproduces the self-energy of symmetric nuclear matter with high accuracy for densities up to twice the saturation density, and the self-energy of asymmetric nuclear matter up to slightly above the saturation density.

As one would expect, the inclusion of the isovector mesons δ and ρ affects symmetric and asymmetric nuclei differently. For the symmetric nuclei ^{16}O and ^{40}Ca it increases the proton rms radii and decreases the neutron rms radii, while for the asymmetric nuclei ^{48}Ca and ^{208}Pb the effect is reversed. One result is that the rms charge radius of ^{48}Ca becomes smaller than the rms charge radius of ^{40}Ca.

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