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THE ROLE OF FOCK TERMS AND ISOVECTOR MESONS IN RELATIVISTIC HARTREE–FOCK CALCULATIONS FOR NEUTRON RICH NUCLEI*

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Density dependent relativistic Hartree–Fock theory has been extended to describe properties of exotic nuclei. The effects of Fock exchange terms and of π- and ρ-meson contributions are discussed. These effects are found to be more important for neutron rich nuclei than for nuclei near the valley of stability.

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Systematic experimental investigations of exotic nuclei have become possible because of the recent advent of radioactive beam facilities [1]. The masses and the density distributions of exotic nuclei are important to predict the abundance of elements [2]. The bulk properties of nuclei close the valley of stability are mainly determined by the exchange of the omega-meson and the so-called sigma-meson which summarizes the exchange of two correlated pions in the scalar-isoscalar sector. The large neutron excess of neutron-rich nuclei suggests that isovector mesons (*i.e.* the pion and the rho) play a more important role for the determination of binding energies and radii than they do for nuclei close to the valley of stability.

Among the various theoretical models for the bulk properties of nuclei, the relativistic mean field theory has been particularly successful [3–5]. It is based on a relativistic Lagrangian which includes the nucleon, the omega-, the sigma-, and the rho-meson (neglecting the rho-nucleon tensor coupling).

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When supplemented by non-linear sigma-sigma interactions, it reproduces both binding energies and radii of not only the spherical nuclei, but also of the known deformed nuclei throughout the periodic table. Sharma *et al.* [6], Lalazissis *et al.* [7], Maharana *et al.* [8], Hirata *et al.* [9] and Lalazissis *et al.* [10] have systematically investigated the binding energies, deformations, rms radii, one (or two) nucleon separation energies, quadrupole moments and isotopic shifts of nuclei far from the stability line.

In spite of the great success of the relativistic mean field theory, some basic questions still remain to be solved.

1. Although its Lagrangian is identical to a part of the Lagrangian of the meson-exchange model of the nucleon–nucleon interaction [11], relativistic mean field theory is not applicable to nucleon–nucleon scattering and, therefore, has to be considered a phenomenological model.

2. Despite its important role in low-energy hadron physics, the pion has to be neglected in the mean field approximation because of its negative parity.

3. The attractive nature of the non-linear sigma-sigma coupling terms may lead to instabilities at large densities.

4. The effects of Fock-terms and the influence of short-range correlations should be clarified.

In order to answer these questions, one would like to employ a theory which unifies the description of nucleon–nucleon scattering and nuclear matter. In the framework of non-relativistic many-body theories, a model of this kind that would work quantitatively does not exist. The possible relevance of a relativistic treatment of the saturation problem was pointed out by Shakin *et al.* [12]. Brockmann and Machleidt have provided a meson-exchange interaction which describes nucleon–nucleon scattering and reproduces the saturation properties of nuclear matter in a relativistic Brueckner–Hartree–Fock calculation [13]. Unfortunately, in finite nuclei, discrepancies with the experimental data remain [14]. A technically simple method to link the ground state properties of nuclei to realistic meson-exchange interactions is due to Brockmann and Toki [15]. These authors suggest a relativistic density-dependent Hartree model which includes the nucleon, the sigma- and the omega-meson. For a given density of nuclear matter, the coupling constants of both sigma and omega are adjusted to reproduce both the scalar and the vector part of the nucleon self-energy in nuclear matter. The model therefore has no free parameters. The properties of finite nuclei are now worked out using density-dependent coupling constants. Amazingly, both binding energies and radii of the finite nuclei investigated are close to the experimental values. After the inclusion of Fock terms, however, the radii are substantially reduced [16]. On the other hand, after incorporating both pion and rho-exchange (including in particular the tensor part of the rho-nucleon coupling) into the relativistic density-dependent Hartree–Fock approach, larger radii are found [17]. The findings of [17] suggest that the effects of Fock terms be investigated more thoroughly. In the case of spin-orbit splitting, the inclusion of the Fock terms appears to be essential. In ^{48}Ca, relativistic mean field theory gives a splitting of the $d_{5/2}$ and the $d_{3/2}$ levels of 9.32 MeV, whereas the relativistic density dependent Hartree–Fock theory gives 3.19 MeV which comes closer to the experimental value of 4.3 MeV [17].

In this letter, we want to investigate the relevance of both Fock-terms and isovector mesons in neutron-rich nuclei.

The formalism can be found in Refs [16–20] in more detail, here we want to describe the RDHF theory only briefly. As in the one-boson-exchange (OBE) description of the nucleon–nucleon interaction, our starting point is an effective Lagrangian density which couples a nucleon (ψ) to two isoscalar mesons (σ, ω) and two isovector ones (π, ρ). The electromagnectic field (A_μ) is also included. The effective Lagrangian density can be written as the sum of free and interaction parts:

$$\mathcal{L} = \mathcal{L}_{\mathcal{O}} + \mathcal{L}_{\mathcal{I}} \,. \tag{1}$$

The free Lagrangian density is given by

$$\begin{aligned}\mathcal{L}_{\mathcal{O}} \;=\;& \bar{\psi}(i\gamma^\mu\partial_\mu - M)\psi + \tfrac{1}{2}(\partial^\mu\sigma\partial_\mu\sigma - m_\sigma^2\sigma^2) \\ & + \tfrac{1}{2}m_\omega^2\omega^\mu\omega_\mu - \tfrac{1}{4}W^{\mu\nu}W_{\mu\nu} + \tfrac{1}{2}m_\rho^2\rho^\mu\cdot\rho_\mu - \tfrac{1}{4}\boldsymbol{R}^{\mu\nu}\cdot\boldsymbol{R}_{\mu\nu} \\ & - \tfrac{1}{4}F^{\mu\nu}F_{\mu\nu} + \tfrac{1}{2}(\partial^\mu\pi\cdot\partial_\mu\pi - m_\pi^2\pi^2)\end{aligned} \tag{2}$$

with

$$\begin{aligned} W^{\mu\nu} &= \partial^\mu\omega^\nu - \partial^\nu\omega^\mu \,, \\ \boldsymbol{R}^{\mu\nu} &= \partial^\mu\rho^\nu - \partial^\nu\rho^\mu \,, \\ F^{\mu\nu} &= \partial^\mu A^\nu - \partial^\nu A^\mu \,. \end{aligned} \tag{3}$$

Here the meson fields are denoted by σ, ω^μ, ρ^μ and π, and their masses are m_σ, m_ω, m_ρ and m_π, respectively. The nucleon field is denoted by ψ and its rest mass is M. A_μ is the electromagnetic field. The interaction Lagrangian density is given by

$$\begin{aligned}\mathcal{L}_{\mathcal{I}} \;=\;& \bar{\psi}(g_\sigma\sigma - g_\omega\gamma^\mu\omega_\mu - g_\rho\gamma^\mu\rho_\mu\cdot\tau)\psi \\ & + \frac{f_\rho}{2m}\bar{\psi}\sigma^{\mu\nu}\partial_\mu\rho_\nu\cdot\tau\psi \\ & - \bar{\psi}e\gamma^\mu A_\mu\tfrac{1}{2}(1+\tau^3)\psi - \frac{f_\pi}{m_\pi}\bar{\psi}\gamma_5\gamma^\mu\partial_\mu\pi\cdot\tau\psi \,,\end{aligned} \tag{4}$$

where τ_i indicate the isospin Pauli matrices. The effective strengths of couplings between the nucleon and mesons are denoted by the coupling constants g_i or f_i $(i = \sigma, \omega, \rho, \pi)$, respectively.

We will study the properties of exotic nuclei using three different approaches:

1. Relativistic density dependent Hartree theory (RDH) with σ and ω mesons only.

2. Relativistic density dependent Hartree-Fock theory (RDHF) with σ and ω mesons only.

3. Relativistic density dependent Hartree-Fock theory with σ, ω, π and ρ mesons (RDHF+π+ρ).

As an example for our study we choose the Ca isotope chain. In both the relativistic density dependent Hartree- and Hartree–Fock-approximation, the omega-nucleon and the sigma-nucleon coupling constants are adjusted to reproduce the nucleon self energy in nuclear matter. Therefore it is not too surprising that both methods reproduce the binding energies of $N = Z$ nuclei with comparable accuracy. Indeed, Fritz *et al.* find in ^{40}Ca a binding energy per particle of $E/A = -8.21$ MeV in the RDH approach, while the RDHF calculation yields $E/A = -7.76$ MeV which is in fair agreement with the experimental value of -8.50 MeV. The inclusion of the pion did not change the radius of ^{40}Ca, but slightly increased the binding energy [16].

In Fig. 1, we show the binding energies of the Ca isotopes obtained in our model. The effect of the Fock terms on the binding energies in the vicinity of the $N = Z$ nucleus ^{40}Ca is small, as expected. With increasing neutron excess, however, the inclusion of the Fock terms leads to a reduction of the binding energy. The inclusion of both pion and rho further decreases the binding energies of the exotic nuclei. Experimentally, the binding energies of the Ca isotopes are known only till $A = 56$ (open circles).

We use the finite range liquid drop model by Möller, Nix and Kratz [22] to extrapolate the binding energies of the exotic nuclei till $A = 70$. The comparison with the experimental data shows that the RDH approach is not able to reproduce the slope of the curve of the experimental binding energies. The slope is properly described as soon as the Fock term is included. The isovector mesons contribute significantly for nuclei with large neutron excess. The contributions of the pion and of the rho are roughly of the same size and are not shown separately in Fig. 1. One has to realize that the contribution of the Fock terms is more important than the shift due to the additional inclusion of the pion and the rho. One should keep in mind here, that the parameters of the models have not been fitted to the experimental data, so that no quantitative agreement should be expected.

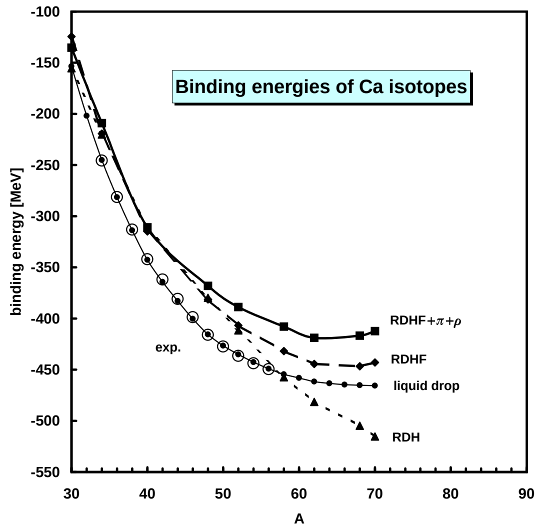

Fig. 1. The binding energies of the Ca isotopes are shown. The open circles represent the experimental data [21] and the full line with the filled circles shows a fit using a liquid drop model [22]. Theoretical results are shown for the RDH approach and the RDHF approach with and without isovector mesons.

The proton radii are displayed in Fig. 2. The Fock term reduces the proton radii for all nuclei of the isotope chain. But the inclusion of the pion

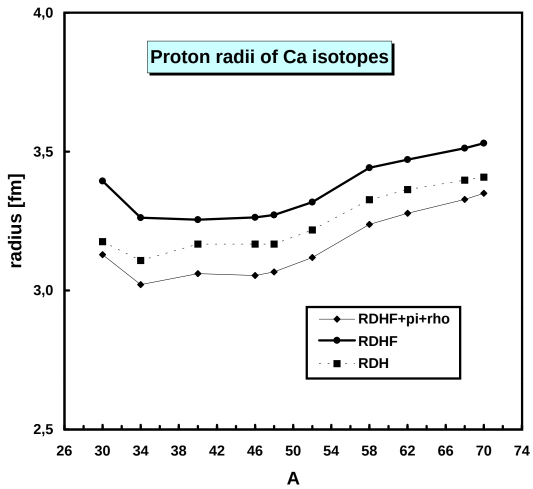

Fig. 2. The proton radii of the Ca isotopes are shown. Theoretical results obtained with the RDH approach and the RDHF approach with and without isovector mesons are compared.

and in particular the rho-meson increases the proton radii. For the neutron radii (Fig. 3), a reduction due to the Fock term is found for mass numbers less than $A = 62$, while for the extremely neutron rich nuclei, one even finds an increase of the neutron radii. The inclusion of the pion and the rho leads to an overall increase of the neutron radii.

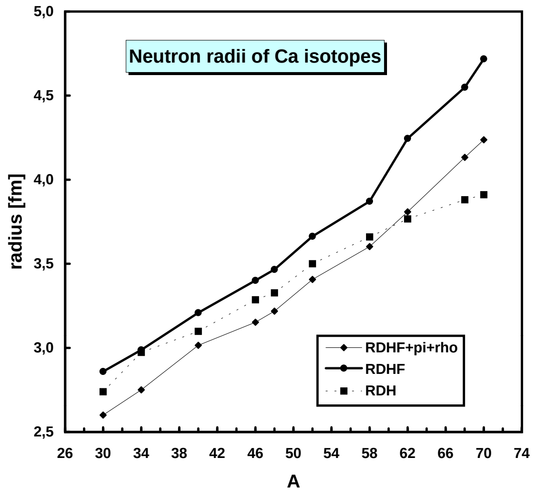

Fig. 3. The neutron radii of the Ca isotopes are shown. Theoretical results obtained with the RDH approach and the RDHF approach with and without isovector mesons are compared.

To conclude, the density dependent relativistic Hartree–Fock theory has been employed to investigate properties of neutron rich nuclei. For the first time the effect of Fock exchange terms and isovector mesons on these properties has been studied. It is found that these terms give large contributions to properties of exotic nuclei as compared to the Hartree approach. It is still a challenge to develop proper effective interactions in relativistic Hartree–Fock theory and to describe properties of exotic nuclei systematically.

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