Relativistic RPA theory for finite nuclei

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Relativistic theory provides a natural basis to study the nuclear ground state properties. Using a small number of fitting parameters, having clear physical meaning, relativistic mean field approximation (RMFA) reproduces the nuclear bulk properties reasonably well. The extended version of this approximation by including the nonlinear meson self-inter action terms is now used as a standard model for description of finite nuclei [1,2]. The small component of the single-particle wave function is essentially enhanced in this approximation due to a small value of the nucleon effective mass in the nuclear medium. The success of the relativistic Hartree and Hartree-Fock [3] approximations ensures a good basis for the study of nuclear excitations in relativistic models. As usual, elementary excitations occur because of the displacement of nucleons from occupied states to unoccupied states, while the random-phase approximation (RPA) provides a method for constructing collective states, which can arise as a result of the residual particle-hole interaction.

It is well known that the RPA method corresponds to small-amp litude oscillations of the self-consistent field when the influence of these oscillations on the single-particle states can be taken into account by perturbation theory (linear response).

Explicit relativistic RPA calculations for nuclear matter have been carried out in Refs.[4,5]. The nuclear matter ground state is stable against small amplitude oscillations of the meson fields which form the ground state (excitations of normal parity). The problem may appear for excitation of the fields with symmetry different from that of the ground state (excitations of abnormal parity, for example, with symmetry of the pion field). In Ref.[6] the problem of stability of the relativistic nuclear matter against pion condensation has been treated in the framework of the relativistic RPA method. It has been shown that relativistic treatment of the problem of the pion condensation gives new essential features to the solution of the problem. In particular, in the case of pseudovector pion-nucleon coupling, it is shown that for particular choice of parameters (which determine the nuclear matter ground state) the system is stable at all densities. Such behavior is directly related to the relativistic treatment of the problem: the polarization integral appears in this case with a factor (squared ratio of the effective nucleon mass to the bare one), suppressing essentially contribution of the polarization integral. This effect brings stability to the system. In Ref.[6] stability problem has been investigated also for pseudoscalar pion- nucleon coupling, relativistic effects (of different character) are manifested in this case also. New relativistic effects appear in the problem of pion condensation because transition operator in this case mixes big and small components of the nucleon wave function,

the latter one being essentially enhanced as was mentioned above. Polarization of nuclear medium by vector mesons has been investigated explicitly in Ref.[7] by the RPA method. As for finite nuclei, in Refs.[8-11] relativistic RPA theory has been utilized to describe giant resonances in the relativistic models without self-interactions of mesonic fields and in Refs.[12-14] in models having non-linear self-interaction terms. In the present paper the authors have developed a new version of the relativistic linear response method (RPA) treating small deviations of the amplitudes of the fields from the self-consistent static (ground state) Hartree solutions. Theory suggested is based on the relativistic Green's function method and leads to a coupled system of integro-differential equations. The method may be utilized for description of different types of nuclear excitations, with arbitrary spins and parities. In particular, this theory is applied to treatment of nuclear excitations of both normal and abnormal parity (states with normal parity have even spin values and positive parity or odd spin values and negative parity and vice versa for states of abnormal parity, excitations with quantum numbers of the pion field, for example). In the first case (normal parity) the following meson fields are involved in description of excitations:
i) scalar-isoscalar field;
ii) vector ω and ρ fields (both vector and tensor couplings);
while in the second case (abnormal parity) the contribution is made by:
i) pseudoscalar field;
ii) vector ω and ρ fields (for the ρ field both vector and tensor couplings are considered).
The Lagrangian including all these fields together with their interactions is given by

$$\begin{aligned} L = \bar{\psi}(i\gamma_\mu\partial^\mu - m)\psi + \frac{1}{2}(\partial_\mu\sigma\partial^\mu\sigma - m_\sigma^2\sigma^2) \\ + \frac{1}{2}m_\omega^2\omega_\mu\omega^\mu - \frac{1}{4}\Omega_{\mu\nu}\Omega^{\mu\nu} + \frac{1}{2}m_\rho^2\vec{\rho}_\mu\cdot\vec{\rho}^\mu - \frac{1}{4}\vec{R}_{\mu\nu}\cdot\vec{R}^{\mu\nu} \\ + \frac{1}{2}(\partial_\mu\vec{\pi}\cdot\partial^\mu\vec{\pi} - m_\pi^2\vec{\pi}^2) \\ - g_\sigma\bar{\psi}\sigma\psi - g_\omega\bar{\psi}\gamma_\mu\omega^\mu\psi - g_\rho\bar{\psi}\gamma_\mu\vec{\rho}^\mu\cdot\vec{\tau}\psi + \frac{f_\rho}{2M}\bar{\psi}\sigma_{\mu\nu}\partial^\nu\vec{\rho}^\mu\cdot\vec{\tau}\psi \\ - \frac{f_\pi}{m_\pi}\bar{\psi}\gamma_5\gamma_\mu\partial^\mu\vec{\pi}\cdot\vec{\tau}\psi \end{aligned}$$

where $\Omega_{\mu\nu}$ and $\vec{R}_{\mu\nu}$ are the antisymmetric tensors. In order to get the RPA equations,we introduce the meson fields Φ to be written as $\Phi = \bar{\Phi} + \Phi'$ where Φ' is a small deviation of the amplitude of the Bose field from the self-consistent static mean field(RMF). The RMF equations are obtained by making the coefficients of Φ' be zero,while the RPA equations are obtained by taking the terms upto p'^2 (the harmonic approximation).All the details will be published elsewhere [15]. The arrows refer to isotopic spin and other notations are obvious.

The method developed allows natural and straightforward extension to include non-linear self-interactions of mesonic fields and to consider oscillations of the Hartree-Fock basis.

There is a particular motivation to start calculations for the excitations of ab-

normal parity (0^- and 2^-) with isospin $T = 0$ and $T = 1$ (for ^4He and ^{16}O). The properties of these states were suggested as signatures of precursors to pion condensation. Because of the reasons mentioned above, relativistic treatment of these excitations would bring new manifestations of relativity in nuclear structure.

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