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Relativistic mean-field description of collective motion in nuclei: the pion field

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Abstract. The influence of the pion field on isovector dipole and spin-dipole collective oscillations is investigated in a time-dependent model based on relativistic mean field theory. We find that the inclusion of the long range pion-nucleon interaction provides an additional strong damping mechanism for the isovector dipole vibrations. The inclusion of the pion field has also a strong effect on the dynamics of spin-dipole vibrations, and in particular on the splitting of excitation energies of the J^π $(0^-,1^-,2^-)$ components of the isovector spin-dipole resonance.

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Relativistic quantum field models [1, 2] have been applied with success to nuclear matter and finite nucleus calculations. In comparison with conventional nonrelativistic descriptions, relativistic models include explicitly mesonic degrees of freedom, and treat the nucleons as Dirac particles. In Refs. [3, 4] we have used a time dependent version of the relativistic mean field model to investigate the dynamics of collective oscillations that correspond to giant resonances in nuclei. Starting from the Hartree solution for the ground-state of the nucleus, and with an appropriate choice of initial conditions, the model describes the time evolution of the nuclear system. Initial conditions were chosen in such a way that there was no contribution of the pion field. It is known that the inclusion of the pion field has a relatively small effect on results in relativistic Hartree-Fock models [5, 6, 7]. In the present work we study initial conditions that generate the pion field dynamically, and investigate its influence on collective isovector dipole and spin-dipole motion.

In relativistic quantum hadrodynamics the nucleons, described as Dirac particles, are coupled to exchange mesons and photon through an effective Lagrangian. The model is based on the one boson exchange description of the nucleon-nucleon interaction. The model Lagrangian density is

$$
\begin{aligned}
\mathscr{L} = &\bar{\psi}(i\gamma\cdot\partial - m)\psi \\
&+\frac{1}{2}(\partial\sigma)^2 - U(\sigma) - \frac{1}{4}\Omega_{\mu\nu}\Omega^{\mu\nu} + \frac{1}{2}m_\omega^2\omega^2 - \frac{1}{4}\mathbf{R}_{\mu\nu}\mathbf{R}^{\mu\nu} \\
&+\frac{1}{2}m_\rho^2\boldsymbol{\rho}^2 + \frac{1}{2}(\partial\boldsymbol{\pi})^2 - \frac{1}{2}m_\pi^2\boldsymbol{\pi}^2 - \frac{1}{4}\mathrm{F}_{\mu\nu}\mathrm{F}^{\mu\nu} - g_\sigma\bar{\psi}\sigma\psi \\
&-g_\omega\bar{\psi}\gamma\cdot\omega\psi - g_\rho\bar{\psi}\gamma\cdot\boldsymbol{\rho\tau}\psi - \frac{f_\pi}{m_\pi}\bar{\psi}\gamma_5\gamma^\mu\boldsymbol{\tau}\psi\cdot\partial_\mu\boldsymbol{\pi} \\
&-e\bar{\psi}\gamma\cdot A\frac{(1-\tau_3)}{2}\psi + \frac{e\kappa_i}{4m}\bar{\psi}\sigma^{\mu\nu}\mathrm{F}_{\mu\nu}\psi.
\end{aligned}
\tag{1}
$$

m, m_σ, m_ω, m_ρ and m_π are the masses of the nucleon and mesons, respectively. ψ, σ, ω, ρ and π are the corresponding field operators and A_μ denotes the electromagnetic field. g_σ, g_ω, g_ρ, and f_π are the effective meson-nucleon coupling constants. $e^2/4\pi = 1/137$, $\kappa_\pi = 1.79$, $\kappa_\nu = -1.91$. U(σ) is the nonlinear σ self-interaction, and $\Omega^{\mu\nu}$, $\mathbf{R}^{\mu\nu}$, $F^{\mu\nu}$ denote the field tensors for the vector mesons and electromagnetic field, respectively. The pion-nucleon interaction is chosen in a pseudovector form. The Euler-Lagrange coupled equations are derived from the Lagrangian density (1):

$$
\begin{aligned}
i\partial_t\psi_i = &(\boldsymbol{\alpha}(-i\nabla - g_\omega\boldsymbol{\omega} - g_\rho\boldsymbol{\tau\rho} - e\frac{(1-\tau_3)}{2}\mathbf{A}) \\
&+\beta(m+g_\sigma\sigma) + \beta\frac{f_\pi}{m_\pi}\gamma_5\gamma^\mu\boldsymbol{\tau}\cdot\partial_\mu\boldsymbol{\pi} + g_\omega\omega_0 + g_\rho\boldsymbol{\tau\rho}_0 \\
&+e\frac{(1-\tau_3)}{2}A_0 - \frac{e\kappa_i}{4m}\beta\sigma^{\mu\nu}\mathrm{F}_{\mu\nu})\psi_i
\end{aligned}
\tag{2}
$$

$$
\left(\partial_t^2 - \Delta + m_\sigma^2\right)\sigma = -g_\sigma\rho_s - g_2\sigma^2 - g_3\sigma^3 \tag{3}
$$

$$
\left(\partial_t^2 - \Delta + m_\omega^2\right)\omega_\mu = g_\omega j_\mu \tag{4}
$$

$$
\left(\partial_t^2 - \Delta + m_\rho^2\right)\boldsymbol{\rho}_\mu = g_\rho\mathbf{j}_\mu \tag{5}
$$

$$
\left(\partial_t^2 - \Delta + m_\pi^2\right)\boldsymbol{\pi} = \frac{f_\pi}{m_\pi}\partial_\mu\left(\bar{\psi}\gamma_5\gamma^\mu\boldsymbol{\tau}\psi\right) \tag{6}
$$

$$
\left(\partial_t^2 - \Delta\right)A_\mu = ej_\mu^{em}. \tag{7}
$$

The quantum field theory is treated in the lowest order in the *mean-field* approximation: the meson field operators are replaced by their expectation values, i.e. the meson fields behave as classical fields. The sources of the meson fields are defined by the nucleon densities and currents. In the description of ground-state properties of nuclei the *no-sea* approximation is usually applied. The contributions to the meson sources coming from the Dirac sea of antiparticle states are neglected.

In the following we assume that nucleon single-particle states do not mix isospin. Charge conservation guarantees that only the 3-components of the isovector $\boldsymbol{\rho}$ and $\boldsymbol{\pi}$ contribute. The fields ρ^{μ}_{+}, ρ^{μ}_{-}, π_{+} and π_{-} vanish and there are no meson-contributions to the isospin current.

In the description of nuclei with equally occupied time-reversed ($\pm\Omega$) single-particle states, the pion field does not contribute to the stationary solutions of the system of equations (2) - (7) at the Hartree level. For time-dependent problems, Eqs. (2) - (7) propagate the nuclear system in time for a given set of initial parameters (stationary solution for the ground-state, initial deformations, initial velocities of proton and neutron densities). Calculations are simplified by neglecting the time derivatives in the Klein-Gordon equations for the meson fields. This means that retardation effects for the meson fields are neglected, and this is justified by the large masses in the meson propagators causing a short range of the corresponding meson exchange forces. The time-dependent model is described in detail in Ref. [4].

In Refs. [3, 4] we have investigated the dynamics of isoscalar and isovector collective motion in spherical nuclei. In the limit of small amplitude motion, collective oscillations correspond to giant resonances. We have found that for isovector dipole, isovector and isoscalar quadrupole excitations, the model reproduces reasonably well the experimental data on energies of giant resonances for light nuclei. Initial conditions for the time-evolution of the nuclear system were chosen in such a way that there was no contribution of the pion field. Let us consider, for example, isovector dipole motion. A well-defined excitation mechanism is provided by the electromagnetic interaction in relativistic heavy-ion collisions [8]. In a simplified picture, the initial conditions for isovector dipole motion are: at $t' = 0$ (in the center of mass system) all protons start moving in the $+z$ direction with velocity v_π, and all neutrons start moving in the $-z$ direction with velocity $v_\nu = \frac{Z}{N} v_\pi$. The initial proton and neutron spinors in the center of mass system are constructed by a homogeneous Lorentz transformation of the spherical static spinors [4].

Although the boost breaks rotational symmetry, the densities, fields and potentials are invariant with respect to a rotation around the z-axis (axial symmetry). The isovector motion is described in cylindrical coordinates. The static Dirac spinor takes the form

$$\psi(\mathbf{r}, \Omega, s, t_3) = \frac{1}{\sqrt{2\pi}} \begin{pmatrix} f^{+}(z, r_\perp)\, e^{i(\Omega-1/2)\phi} \\ f^{-}(z, r_\perp)\, e^{i(\Omega+1/2)\phi} \\ i g^{+}(z, r_\perp)\, e^{i(\Omega-1/2)\phi} \\ i g^{-}(z, r_\perp)\, e^{i(\Omega+1/2)\phi} \end{pmatrix} \chi_\tau(t_3), \quad (8)$$

where $\Omega > 0$ denotes the projection of the total single-particle angular momentum $\mathbf{j} = \mathbf{l} + \mathbf{s}$ on the symmetry axis. For each spinor with positive Ω, the time-reversed spinor with the same energy is [9]

$$\psi(\mathbf{r}, -\Omega, s, t_3) = \frac{1}{\sqrt{2\pi}} \begin{pmatrix} -f^{-}(z, r_\perp)\, e^{i(-\Omega-1/2)\phi} \\ f^{+}(z, r_\perp)\, e^{i(-\Omega+1/2)\phi} \\ i g^{-}(z, r_\perp)\, e^{i(-\Omega-1/2)\phi} \\ -i g^{+}(z, r_\perp)\, e^{i(-\Omega+1/2)\phi} \end{pmatrix} \chi_\tau(t_3), \quad (9)$$

It is easy to show that

$$\psi\,(z, r_\perp, \varphi, -\Omega) = i\, S\, \psi\,(z, r_\perp, -\varphi, \Omega)\,. \quad (10)$$

where the unitary operator $S = \gamma^5 \gamma^2$ corresponds to a reflection with respect to the (x, z) plane, or equivalently, to the transformation $\varphi \to \varphi' = -\varphi$. The corresponding expression for the adjoint spinors is

$$\overline{\psi}\,(z, r_\perp, \varphi, -\Omega) = -i\, \overline{\psi}\,(z, r_\perp, -\varphi, \Omega)\, S^{-1}\,. \quad (11)$$

The Dirac Hamiltonian in Eq. (2) commutes with the operator S only if the pion field and the φ-components of the vector fields vanish. Using relations (10) and (11), and the fact that $\left[S, \gamma^5\right]_+ = 0$, it can be shown that in the case where for every $+\Omega$-state the corresponding $-\Omega$-state is also occupied, the pion field and the φ-components of the vector fields vanish, since the corresponding nucleonic sources vanish

$$\sum_{\Omega > 0} \left[\overline{\psi}\,(\Omega)\, \Gamma\, \psi\,(\Omega) + \overline{\psi}\,(-\Omega)\, \Gamma\, \psi\,(-\Omega)\right] = 0.$$

where Γ represents the φ-components of vector operators γ_μ and $\gamma_\mu \gamma_5$. This is not restricted only to the static case, but is true for any motion of the system which fulfills (10). In the case of isovector dipole motion, the operator of a Lorentz boost along the z-axis commutes with S

$$\left[e^{-\frac{\omega}{2}\,\alpha_3}, S\right]_- = 0\,. \quad (12)$$

For our choice of initial conditions, the spinors after the Lorentz boost

$$\psi'(\mathbf{r}', \Omega, s, t_3, t' = 0) = e^{-\frac{\omega}{2}\,\alpha_3}\, \psi(\mathbf{r}, \Omega, s, t_3), \quad (13)$$

where primes indicate the c.m. system, satisfy relation (10). No pion field or φ-currents are generated by the Lorentz boost at $t' = 0$, and therefore they vanish at all later times. These initial conditions are, of course, very schematic, but allow a description of the basic dynamics of isovector motion. The actual excitation mechanism, especially when hadron probes are involved, is much more complex. In order to generate the pion field dynamically, collective motion has to be started in such a way that relation (10) is no longer valid for time-dependent spinors. Excitations of this type can be produced, for example, in $(\mathbf{p}, \mathbf{p}')$ inelastic reactions using polarized beams. To describe the resulting collective motion in our time-dependent model, a schematic choice of initial conditions is one in which nucleons with $\Omega > 0$ and nucleons with $\Omega < 0$ are boosted in opposite directions.

In Fig. 1a we display the time-dependent dipole moment

$$d_z(t) = \langle \Phi(t) | \hat{d}_z | \Phi(t) \rangle = \langle \Phi(t) | \sum_{i=1}^{A} r_i Y_{10}(i) \tau_3(i) | \Phi(t) \rangle \quad (14)$$

and the corresponding Fourier power spectrum for an illustrative calculation. $|\Phi(t)\rangle$ is the time-dependent Slater determinant of occupied states. The nucleus is ^{48}Ca. In the calculation of the ground-state the parameter set NL-SH [10] has been used: m = 939.0 MeV, m_σ = 526.059 MeV, m_ω = 783.0 MeV, m_ρ = 763.0 MeV,g_σ = 10.444, g_ω = 12.945, g_ρ = 4.383, g_2 = −6.9099 fm^{-1}, g_3 = −15.8337. At t' = 0 in the c.m. system, all protons and half of the neutrons (those with $\Omega < 0$) are boosted in the $+z$ direction with velocity 0.03 c. All neutrons with $\Omega > 0$ start moving in the $-z$ direction with velocity 0.0729 c. This corresponds to an energy transfer of 50 MeV. For the properties of the system that we

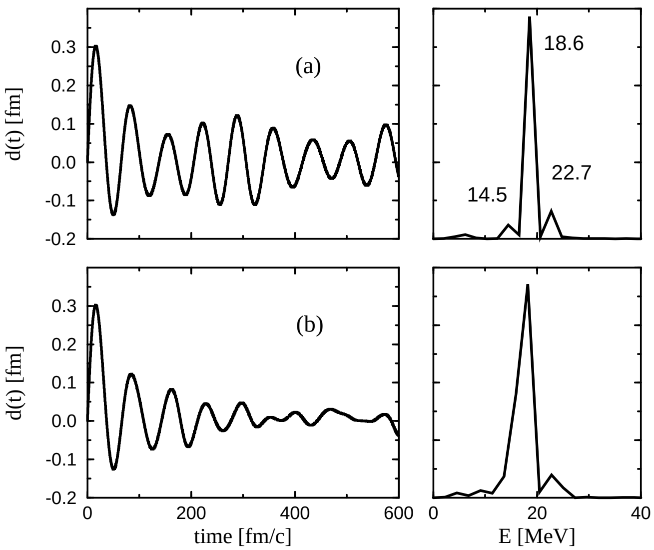

Fig. 1. Time-dependent dipole moments and the corresponding Fourier power spectra for ^{48}Ca. The static solutions are calculated with the NL-SH parameter set. In the calculation for Fig. 1a the pion field is not included. The pseudovector pion-nucleon interaction with m_π = 138 MeV and $f_\pi^2/4\pi$ = 0.08 is used in the time-evolution of Fig. 1b

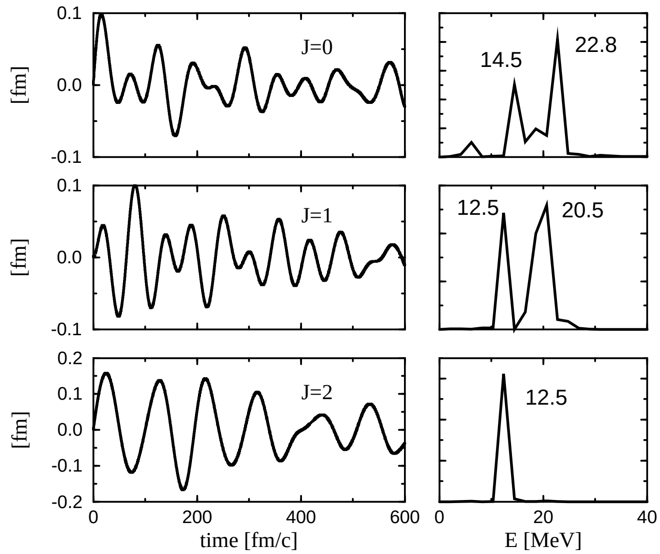

Fig. 2. Time-dependent expectation values and the corresponding Fourier power spectra for the isovector spin-dipole operator (15), for J^π = 0^-, 1^-, and 2^-. The parameters are those from Fig. 1a, i.e. the pion field is not included in the calculation

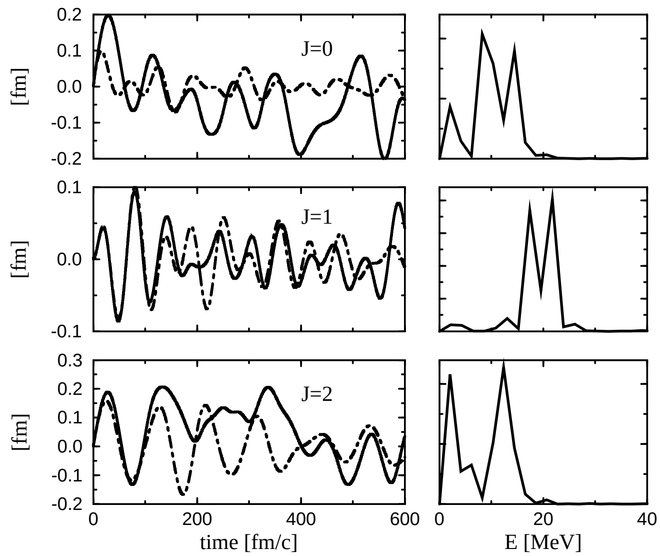

Fig. 3. Same as in Fig. 2, but the pseudovector pion-nucleon interaction with m_π = 138 MeV and $f_\pi^2/4\pi$ = 0.08 is included in the time-evolution. The dashed lines are the spin-dipole moments from Fig. 2, calculated without the pion field

want to discuss, this schematic choice of initial conditions represents all situations in which collective motion is started in such a way that particles in time-reversed orbits move in opposite directions (for example, excitations produced in reactions with polarized hadron probes). Of course, we could boost all $\Omega > 0$ nucleons opposite to all $\Omega < 0$ nucleons, but then the dipole moment vanishes. For the dipole moment in Fig. 1a the pion field is not included in the calculation, i.e. f_π = 0. The Fourier spectrum displays three distinct peaks with energies of 14.5, 18.6, and 22.7 MeV. These should be compared to the experimental value for the centroid energy of the giant dipole resonance in ^{48}Ca: 19.5(5) MeV [11]. Of course the structure of the Fourier spectrum does not depend on the choice of initial conditions. The power spectrum in Fig. 1a has the same structure as that obtained in the case when all protons move opposite to all neutrons [4]. By analyzing the transition densities, we found that the lowest frequency mode represents an oscillation of the interior region (bulk mode), while the peaks at 18.6 and 22.7 MeV correspond to surface modes of Goldhaber - Teller type. The damping of the dipole moment in Fig. 1a is caused by the coupling to the continuum (escape width), and there are also contributions to the width coming from the damping via the mean field (Landau damping). The width of the main peak in Fig. 1a is $\approx$ 2 MeV. The experimental value for the width of the isovector giant resonance in ^{48}Ca is $\approx$ 4 MeV.

For the choice of initial conditions described above, not only spatial degrees of freedom of the nucleons, but also isovector spin-dipole degrees of freedom are excited. Experimental information on isovector spin-dipole resonances (ΔL = 1, ΔS = 1, ΔT = 1) is rather sparse. Properties of these resonances have been investigated theoretically in the framework of non-relativistic RPA calculations [12, 13]. In particular, the energy splitting of the triplet of spin-dipole states J^π = 0^-, 1^-, 2^-, and the mixing of the J^π = 1^- component with the isovector giant dipole resonance. In Fig. 2 we display the time dependent expectation values and the corresponding Fourier power spectra for the isovector spin-dipole operator

$$-(-i)^J \langle \Phi(t) | \sum_{i=1}^{A} r_i \left[Y_1(i) \times \boldsymbol{\sigma}(i) \right]_{J0} \tau_3(i) | \Phi(t) \rangle \tag{15}$$

for J = 0, 1, and 2. The coupling constants, masses and initial conditions are the same as for the dipole moment in Fig. 1a, i.e. there is no contribution from the pion field. The collective oscillations should correspond to isovector spin-dipole resonances in ^{48}Ca. The largest amplitudes of oscillation are observed for the state J^π = 2^-. The average energy of the 0^- excitations is the highest (main peak at

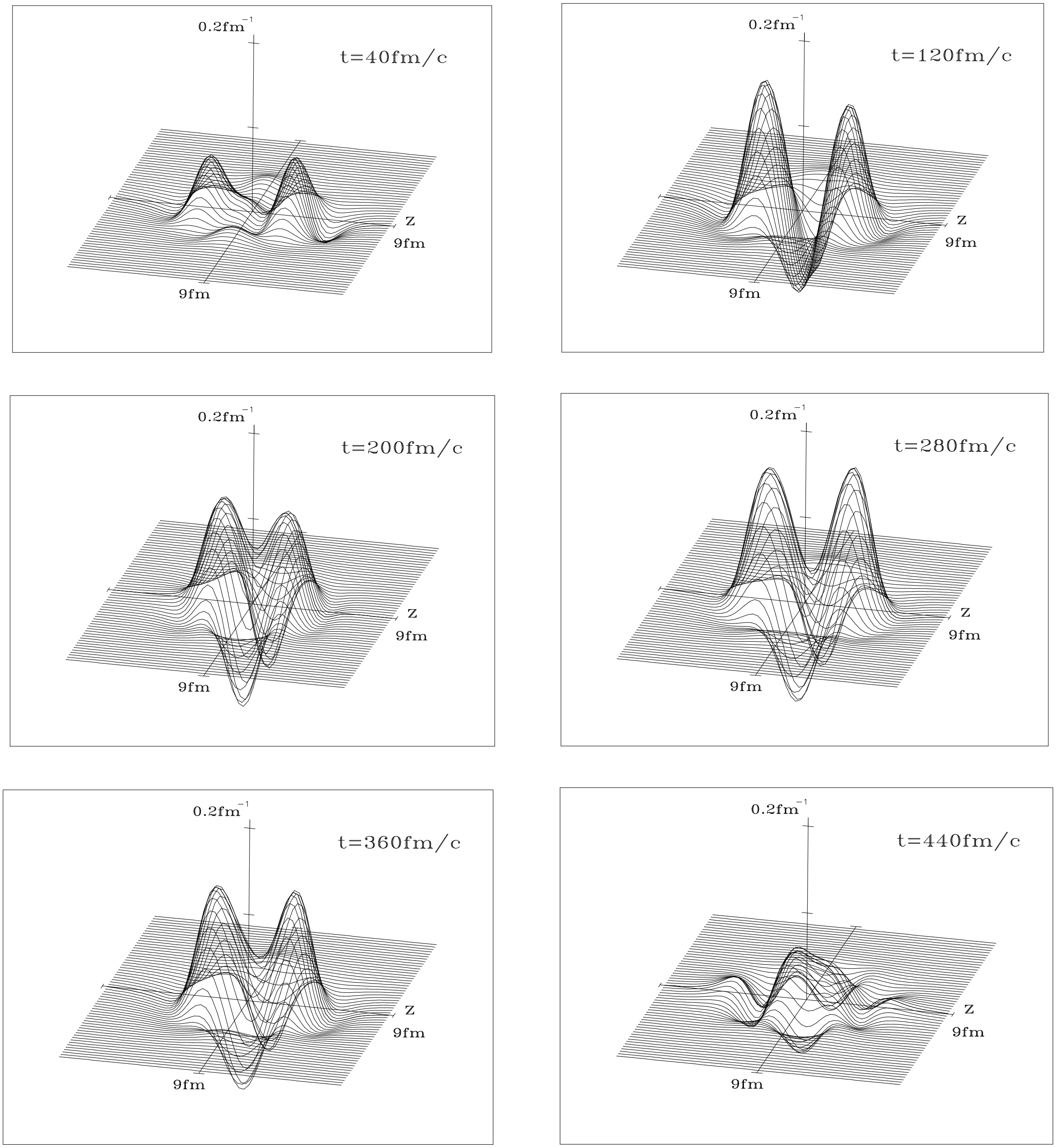

Fig. 4. Time-evolution of the pion field for ^{48}Ca. The field corresponds to the isovector dipole and spin-dipole oscillations shown in Fig. 1b and 3, respectively

22.7 MeV, an additional peak at 14.5 MeV), and that of the 2^- excitation (12.4 MeV) is the lowest. The splitting of the triplet of spin-dipole states is in agreement with the results of Ref. [12], where the structure of isovector spin excitations in nuclei is investigated in the framework of continuum Hartree-Fock RPA. The splitting of spin-dipole states is attributed to the spin-orbit interaction, and results in the lowest J state having the highest energy. The average energy of the spin-dipole 1^- in Fig. 2 (peaks at 12.4 and 20 MeV), is close to that of the nonspin-dipole 1^- (Fig. 1a). However, comparing the oscillations for the two 1^- states in Figs. 1a and 2, it appears that the two modes do not couple. This would be in agreement with shell model calculations of Ref. [13], where it was shown that very little mixing is to be expected between spin-dipole and nonspin-dipole resonance 1^- states.

The dipole moment in Fig. 1b is calculated for the same set of initial parameters, but now also the pion field is in-

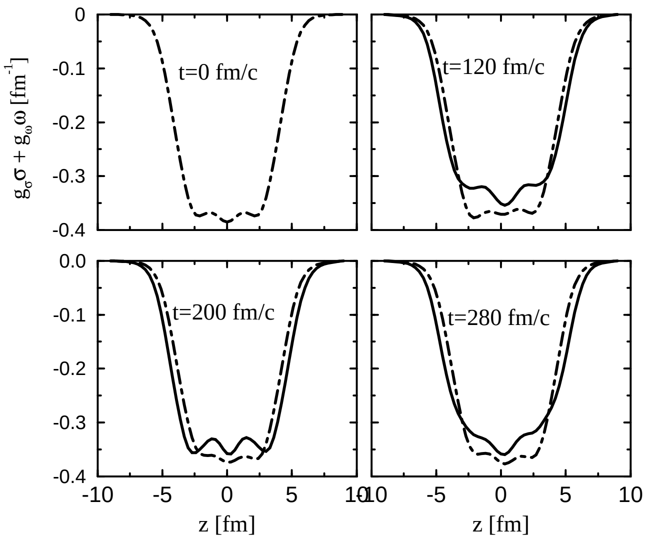

Fig. 5. Effective potential $(g_\sigma \sigma + g_\omega \omega)$ $[fm^{-1}]$ at t = 0, 120, 200 and 280 fm/c, without (dashed line), and with (solid line) the pion field included in the time evolution

cluded. The pion mass m_π = 138 MeV, and for the πN coupling constant we take the experimental value $f_\pi^2/4\pi$ = 0.08. The main effect of the inclusion of the pion field is the strong damping of the isovector dipole oscillation. The pion field is generated dynamically. It builds up, damps the oscillation and then gradually disappears. Correspondingly, a larger width ($\approx$ 3.5 MeV) of the resonance is observed in the Fourier power spectrum in Fig. 1b. For ^{48}Ca approximate values for the total energies of the fields (equations (51)-(54) of Ref. [4]) are: $E_\sigma \approx$ 6500 MeV, $E_\omega \approx -5500$ MeV, $E_\rho \approx -10$ MeV, $E_{Coulomb} \approx -50$ MeV. The energy of the pion field as a function of time has a quasi-parabolic form. It starts from zero, increases to a maximum $\approx$ 180 MeV at $t \approx$ 280 fm/c, and decreases to $\approx$ 10 MeV at $t \approx$ 460 fm/c (by that time the oscillation is almost completely damped). The effect of the pion field on spin-dipole oscillations is shown in Fig. 3. Time-dependent spin-dipole moments and the Fourier spectra are calculated for $f_\pi^2/4\pi$ = 0.08. For comparison we have also included the spin-dipole moments from Fig. 2, calculated without the pion field (dashed lines). The inclusion of the pion field has relatively little effect on the spin-dipole 1^- excitation, and again, no coupling between the spin-dipole and nonspin-dipole (Fig. 1b) 1^- oscillations is observed. On the other hand, the 0^- and 2^- spin-dipole oscillations are strongly perturbed by the inclusion of the pion field. The effect is especially pronounced between $t \approx 200$ fm/c and $t \approx 400$ fm/c. For the 2^-, in addition to the peak at 12.4 MeV, a low-lying mode appears in the Fourier spectrum. The most drastic effect is observed for the 0^- spin-dipole excitations. The eigenmodes are shifted to lower frequencies, and there are no peaks in the Fourier spectrum above 15 MeV.

The time-evolution of the pion field is shown in Fig. 4. The absolute values of the field should be compared for instance with the value of the sigma field ($\approx -0.22 fm^{-1}$), or the omega field ($\approx 0.15 fm^{-1}$), in the center of the nucleus. In Fig. 5 we compare the effective potential well $(g_\sigma \sigma + g_\omega \omega)$ $[fm^{-1}]$ at t = 0, 120, 200 and 280 fm/c, with and without the inclusion of the pion field in the time evolution of the nuclear system. The inclusion of the pion field reduces the depth of the potential, and also the shape becomes more complicated. These effects could provide a qualitative explanation for the increased damping of the isovector nonspin-dipole motion. On one hand, the reduced depth of the potential could lead to a larger escape width. However, one would then also expect to observe a stronger damping of the spin-dipole excitations. On the other hand, the complex shape of the potential will increase the mean-field damping. The nucleons are strictly independent (mean-field approximation), and the randomization of their motion proceeds through collisions with the moving boundary of the potential. The rate of dissipation of energy from the collective degrees of freedom into uncorrelated particle motion will depend on the shape of the potential [14]. The rather strong effects the pion field produces on isovector dipole excitations seem to be caused by the long range of the one-pion exchange, or equivalently, by the small mass of the pion. We have performed a calculation identical to the one just described, but with the mass of the pion equal to that of the ρ-meson, i.e. 763 MeV. In that case the pion does not have any effect on the isovector dipole oscillations, and the energy of the pion field does not exceed 1 MeV.

The pseudovector form of the pion-nucleon interaction has become standard in relativistic Hartree-Fock models [6, 7]. Pseudoscalar models yield unrealistic results even for nuclear matter in the HF approximation [15]. Nevertheless, we have also investigated the influence of the pseudoscalar πN interaction on isovector dipole motion. The interaction Lagrangian density is

$$\mathscr{L}_I = -ig_\pi \bar{\psi} \gamma_5 \boldsymbol{\tau} \cdot \boldsymbol{\pi} \psi \tag{16}$$

We have repeated the calculation shown in Figs. 1 and 2, but now with the pseudoscalar pion-nucleon interaction. The pion mass was fixed at m_π = 138 MeV, and the πN coupling constant was $g_\pi^2/4\pi$ = 14.3. We have found that the pion field in this case does not have any effect on the spin-dipole and nonspin-dipole excitations, and that the total energy of the pion field is always below 3 MeV.

In conclusion, we have analyzed the influence of the pion field on isovector dipole and spin-dipole collective motion in a time-dependent model based on relativistic mean field theory. Starting from the Hartree solution for the ground-state, a specific choice of initial conditions excites not only spatial degrees of freedom of the nucleons, but also isovector spin-dipole degrees of freedom. We observe collective oscillations that correspond to isovector giant dipole and spin-dipole resonances. The choice of initial conditions breaks a self-consistent symmetry and generates the pion field dynamically. We find that the inclusion of the pion field has a very pronounced effect on the dynamics of isovector dipole and spin-dipole oscillations. The long range pion-nucleon interaction provides an additional strong damping mechanism for the isovector dipole vibration. The inclusion of the pion field has also a strong effect on energies and widths of spin-dipole vibrations, and in particular on the $J^\pi = 0^-$, 2^- components of the isovector spin-dipole resonance. In the present version of the model we do not have the possibility to include charged meson fields. However, we expect that the inclusion of charged pions would only increase the observed effects. Another approximation that should be mentioned is the fact that we neglect the time derivatives in the equations of motion for the meson fields. For the pion field this approximation is less justified than for the heavier mesons. We expect that retardation effects for the pion field would change our results only quantitatively.

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