Pygmy dipole resonances in relativistic random phase approximation

Vretenar, Dario; Paar, Nils; Ring, Peter; Lalazissis, G. A.

Pygmy dipole resonances in the relativistic random phase approximation

D. Vretenar,[1,2] N. Paar,[1] P. Ring,[1] and G. A. Lalazissis[1,3]
[1]Physik-Department der Technischen Universität München, D-85748 Garching, Germany
[2]Physics Department, Faculty of Science, University of Zagreb, 10000 Zagreb, Croatia
[3]Physics Department, Aristotle University of Thessaloniki, Thessaloniki GR-54006, Greece
(Received 7 November 2000; published 28 February 2001)

The isovector dipole response in ^{208}Pb is described in the framework of a fully self-consistent relativistic random phase approximation. The NL3 parameter set for the effective mean-field Lagrangian with nonlinear meson self-interaction terms, used in the present calculations, reproduces ground state properties as well as the excitation energies of giant resonances in nuclei. In addition to the isovector dipole resonance in ^{208}Pb, the present analysis predicts the occurrence of low-lying $E1$ peaks in the energy region between 7 and 11 MeV. In particular, a collective state has been identified whose dynamics correspond to that of a dipole pygmy resonance: the vibration of the excess neutrons against the inert core composed of an equal number of protons and neutrons.

DOI: 10.1103/PhysRevC.63.047301 PACS number(s): 21.60.Jz, 24.30.Cz, 24.30.Gd

The multipole response of nuclei with large neutron excess has been the subject of many theoretical studies in recent years. Exotic nuclei with extreme neutron to proton ratio exhibit many interesting and unique structure phenomena. In addition to exotic ground state properties, the onset of low-energy collective isovector modes has been predicted and experimental evidence for these modes in light nuclei has been reported [1]. Catara *et al.* have studied the low-lying components in strength distributions of weakly bound neutron-rich nuclei [2], and the effect of large neutron excess on the dipole response in the region of the giant dipole resonance in O and Ca isotopes [3]. They have shown that the neutron excess increases the fragmentation of the isovector giant dipole resonance (GDR) and that the radial separation of proton and neutron densities leads to nonvanishing isoscalar transition densities to the GDR states. The fragmentation of the isoscalar and isovector monopole strength in neutron rich Ca isotopes has been studied in Ref. [4], and in [5] the onset of pygmy dipole resonances in Ca isotopes has been analyzed.

The pygmy dipole resonance, which is also the subject of the present study, results from the excess neutrons oscillating out of phase with a core composed of equal number of protons and neutrons. A number of theoretical models have been applied in studies of the dynamics of pygmy dipole resonances. These include: the three-fluid hydrodynamical model (the protons, the neutrons of the same orbitals as protons, and the excess neutrons) [6], the two-fluid (the core fluid and the neutron excess fluid) Steinwedel-Jensen hydrodynamical model [7], density functional theory [5], and the Hartree-Fock plus random phase approximation (RPA) with Skyrme forces [3,8]. More recently, large scale shell model calculations have been performed in studies of pygmy and dipole states in O isotopes [9], and dipole and spin-dipole strength distributions in ^{11}Li [10].

There is also experimental evidence for possible pygmy dipole states in ^{208}Pb. Studies of the low-energy spectrum by elastic photon scattering [11], photoneutron [12], and electron scattering [13] have detected fragmented $E1$ strength in the energy region between 9 and 11 MeV. The fine structure exhausts between 3 and 6 % of the $E1$ sum rule. The relationship between coherent neutron particle-hole (p-h) excitations and the onset of dipole pygmy resonances in ^{208}Pb has been investigated in the Hartree-Fock plus RPA model [8]. A concentration of strength has been found around 9 MeV exhausting 2.4% of the $E1$ sum rule. In particular, two pronounced peaks have been calculated at 8.7 and 9.5 MeV, which appear as likely candidates to be identified as pygmy resonances. The exact location of the calculated pygmy states will, of course, depend on the effective nuclear interaction. Therefore, it would be important to compare the predictions of various nuclear effective forces with experimental data. ^{208}Pb is a particularly good example, since all nuclear structure models have been tested in the description of ground and excited state properties of this doubly magic spherical nucleus. The pygmy dipole resonance can be directly related to the neutron excess, and therefore the splitting between the GDR and the pygmy resonance represents a measure of the neutron skin. Precise information on neutron skin in heavy nuclei is essential for the quantification of the isovector channel of effective nuclear forces.

In a recent experiment [14] the electric dipole strength distributions below threshold in ^{204,206,208}Pb have been extracted from photon scattering spectra. In particular, a resonancelike clustering of strength is observed between 4 and 6.5 MeV excitation energy. Both the increasing fragmentation of the $E1$ strength and the shift of the centroid of the low-lying strength to higher energies with the opening of the neutron shell, are reproduced by microscopic calculations based on the quasiparticle-phonon model with three-phonon configurations resulting from the coupling of phonons with $J^{\pi}=0^{\pm}$ to $6^{\pm}$. It has been concluded, therefore, that the $E1$ strength found in ^{204,206,208}Pb below 6.5 MeV cannot be attributed to an oscillation of the excess neutrons against the inert core.

In the present study the isovector dipole response in ^{208}Pb is described in the framework of a fully self-consistent relativistic random phase approximation (RRPA). The same effective Lagrangian generates the Dirac-Hartree single-particle spectrum and the residual particle-hole interaction.

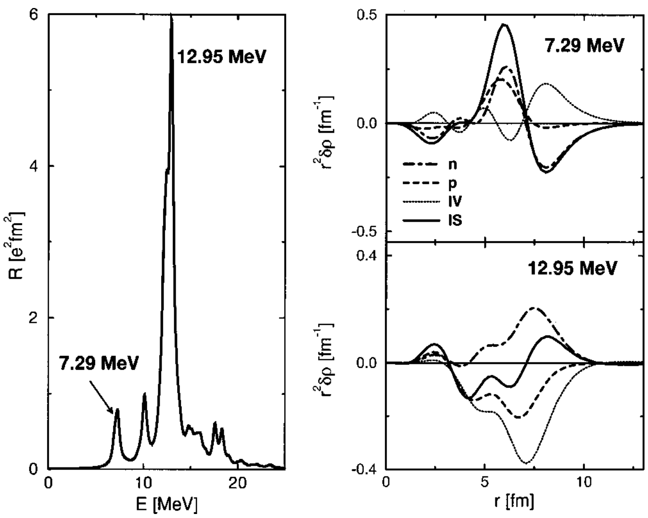

FIG. 1. Isovector dipole strength distribution in ^{208}Pb (left panel), and transition densities for the two peaks at 7.29 and 12.95 MeV (right panel). Both isoscalar and isovector transition densities are displayed, as well as the separate proton and neutron contributions. All transition densities are multiplied by r^2.

The RRPA response functions with nonlinear meson terms have been derived in Ref. [15], and applied in studies of isoscalar and isovector giant resonances. However, the model configuration space did not include the negative energy Dirac states, and therefore model calculations did not reproduce the results obtained with the time-dependent relativistic mean-field model [16,17]. The contribution of pairs formed from occupied positive-energy states and empty negative-energy states (in the no-sea approximation), is essential for current conservation and the decoupling of the spurious state [18]. In addition, configurations which involve negative-energy states give an important contribution to the collectivity of excited states. In a recent study [19] we have employed a fully self-consistent RRPA, including configuration spaces with negative-energy Dirac states, to calculate the isoscalar dipole resonance structure in ^{208}Pb. Two basic isoscalar dipole modes have been identified, and the discrepancy between the calculated strength distribution and current experimental data has been analyzed.

In Fig. 1 we display the isovector dipole strength distribution in ^{208}Pb (left panel), and the corresponding transition densities to the two states at 7.29 and 12.95 MeV (right panel). The calculations have been performed within the framework of self-consistent Dirac-Hartree plus relativistic RPA. The effective mean-field Lagrangian contains nonlinear meson self-interaction terms, and the configuration space includes both particle-hole pairs and pairs formed from hole states and negative-energy states. The discrete spectrum of RRPA states has been folded with a Lorentzian distribution with a width of 0.5 MeV.

The strength distribution has been calculated with the NL3 [20] parameter set for the effective mean-field Lagrangian. This force has been extensively used in the description of a variety of properties of finite nuclei, not only those along the valley of β stability, but also of exotic nuclei close to the particle drip lines. Properties calculated with NL3 indicate that this is probably the best effective interaction so far, both for nuclei at and away from the line of β stability. In particular, in Ref. [17] it has been shown that the NL3 ($K_{\mathrm{nm}}=271.8$ MeV) effective interaction provides the best description of experimental data on isoscalar giant monopole resonances. The calculated energy of the main peak in Fig. 1 $E_p=12.95$ MeV has to be compared with the experimental value of the excitation energy of the isovector giant dipole resonance: 13.3 ± 0.1 MeV [21]. In the energy region between 5 and 11 MeV two prominent peaks are calculated: at 7.29 and 10.10 MeV. In the following we will show that the lower peak can be identified as the pygmy dipole resonance.

The transition densities to the states at 7.29 and 12.95 MeV are displayed in the right panel of Fig. 1. The proton and neutron contributions are shown separately; the dotted line denotes the isovector transition density and the solid line has been used for the isoscalar transition density. As it has been also shown in Ref. [3], although the isoscalar $B(E1)$ to all states must identically vanish, the corresponding isoscalar transition densities to different states need not to be identically zero. The transition densities for the main peak at 12.95 MeV display a radial dependence characteristic for the isovector giant dipole resonance: the proton and neutron densities oscillate with opposite phases; the total isovector transition density is much larger than the isoscalar component; at large radii they both have a similar radial dependence. A very different behavior is observed for the transition densities to the state at 7.29 MeV: the proton and neutron densities in the interior region are not out of phase; there is almost no contribution from the protons in the surface region; the isoscalar transition density dominates over the isovector one in the interior; the large neutron component in the surface region contributes to the formation of a node in the isoscalar transition density. In Ref. [3] it has been shown that this last effect is also characteristic for very neutron-rich systems. The transition densities to the state at 10.10 MeV display a radial behavior which is intermediate between those shown in Fig. 1, but closer to the isovector giant dipole at 12.95 MeV. We have also analyzed the RRPA amplitudes of the three states: the neutron p-h excitations contribute 65%, and the proton 35% to the total intensity of the isovector giant dipole at 12.95 MeV, while the neutron contribution is 86% for the state at 7.29 MeV. The proton p-h excitations contribute only 14% to the total RPA intensity of this state. For the state at 10.10 MeV, on the other hand, we find 68% of proton excitations and only 32% is the contribution from neutron p-h configurations. However, 31% of the total intensity comes from a single proton p-h state $g7/2^{-1}h9/2$. We notice that in the study of neutron halos and $E1$ resonances in ^{208}Pb [8], performed in the HF+RPA model with the SGII interaction, it was found that for the pygmy states the neutron response is a factor of 10 larger than the proton response, whereas at energies corresponding to the GDR this ratio is about 1.6 or roughly N/Z.

The phenomenon of low-lying isovector dipole strength was already studied almost thirty years ago in the framework of the three-fluid hydrodynamical model [6]. By using a generalization of the Steinwedel-Jensen model [22] to three fluids: the protons, the neutrons in the same orbitals as protons,

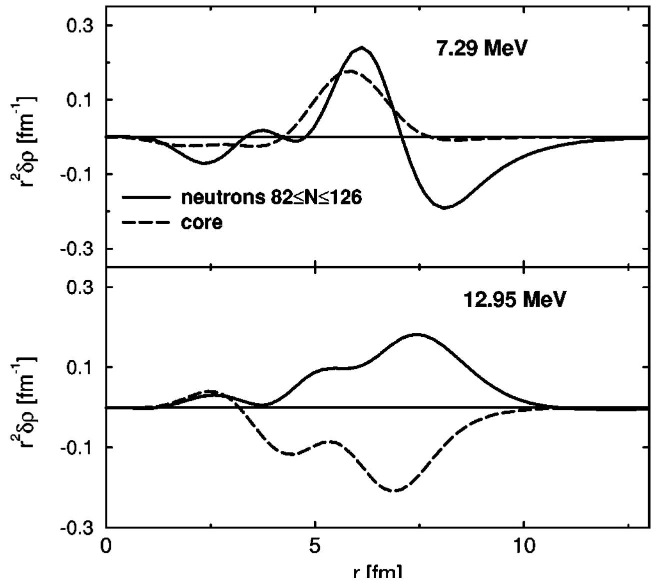

FIG. 2. Isovector dipole transition densities to the 7.29 and 12.95 MeV RRPA states in ^{208}Pb. The contributions of the excess neutrons ($82<N\leqslant126$) (solid), and of the proton-neutron core ($Z,N\leqslant82$) (dashed) are displayed separately. The transition densities are multiplied by r^2.

and the excess neutrons, two normal modes of dipole vibrations were identified: (i) vibrations of the protons against the two types of neutrons and (ii) the vibration of the excess neutrons against the proton-neutron core. In the case of neutron-rich nuclei, the latter mode corresponds to pygmy resonances. For ^{208}Pb, in addition to the GDR state at 13.3 MeV, a low-lying pygmy state at 4.4 MeV excitation energy was found in the analysis of Ref. [6]. The dipole strength of this state, however, was negligible (two orders of magnitude) compared to the GDR state.

In Fig. 2 we plot the transition densities to the two states at 7.29 and 12.95 MeV. The contributions of the excess neutrons ($82<N\leqslant126$) (solid), and of the proton-neutron core ($Z,N\leqslant82$) (dashed) are displayed separately. By comparing with the transition densities shown in Fig. 1, we notice that there is practically no contribution from the core neutrons ($N\leqslant82$). The reason is, of course, that the p-h configurations which involve core neutrons have much higher excitation energies. For the GDR state at 12.95 MeV the transition densities of the excess neutrons and the core have the same sign in the interior ($r<3$ fm), and opposite phases in the surface region. The overall radial dependence is, however, very similar. The two transition densities have the same sign for the state at 7.29 MeV. The core contribution, however, vanishes for large r and only oscillations of the excess neutrons are observed on the surface of ^{208}Pb.

The difference in the collective dynamics of the two modes is also exemplified in the study of transition currents. In Figs. 3 and 4 we plot the velocity fields for the peaks at 7.29 and 12.95 MeV, respectively. The velocity distributions are derived from the corresponding transition currents, following the procedure described in Ref. [23]. In both figures the velocity field of the proton-neutron core ($Z,N\leqslant82$) (left panel), is separated from the contribution of the excess neutrons ($82<N\leqslant126$) (right panel). To the largest velocity in Figs. 3 and 4 a vector of unit length is assigned. All the other velocity vectors are normalized accordingly. We notice that both the core and the excess neutrons contribute to the velocity field of the giant resonance state (Fig. 4), though the largest velocities correspond to the vibrations of the excess neutrons in the surface region. For the state at 7.29 MeV, on the other hand, the core velocities are much smaller than those of the excess neutrons on the surface. The velocity fields in Fig. 3 corroborate the picture of dipole pygmy resonances as oscillations of the excess neutrons against the inert core of protons and neutrons in the same shell model orbitals.

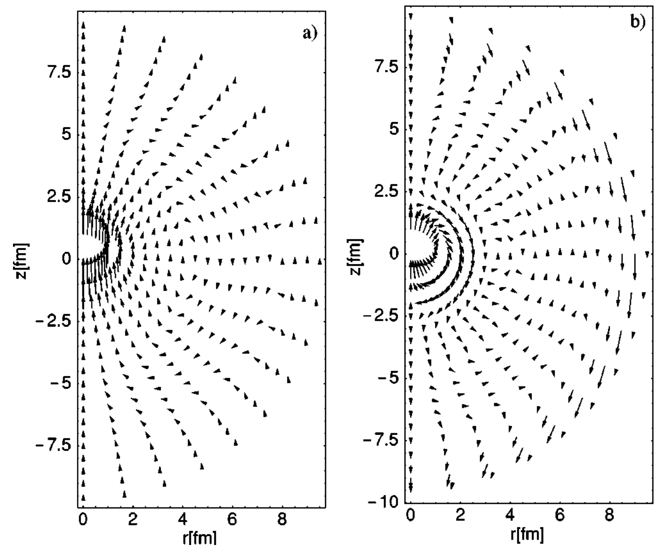

FIG. 3. Velocity distributions for the RRPA state at 7.29 MeV in ^{208}Pb. The velocity field of the proton-neutron core ($Z,N\leqslant82$) (left panel) is separated from the contribution of the excess neutrons ($82<N\leqslant126$) (right panel).

In conclusion, we have used a fully self-consistent relativistic random phase approximation to analyze the isovector

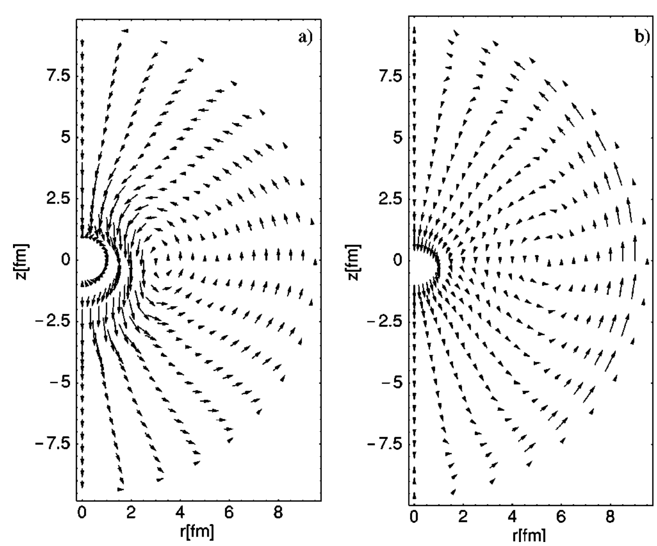

FIG. 4. Same as in Fig. 3, but for the RRPA state at 12.95 MeV in ^{208}Pb.

dipole resonance structure in ^{208}Pb. In particular, we have investigated the relationship between the neutron particle-hole excitations at low energy and the onset of dipole pygmy resonances. For the effective interaction we have used the set of nonlinear parameters NL3. This interaction has been used in many recent applications of the relativistic mean field model, both in stable nuclei and in nuclei far from the valley of β stability, including drip-line systems. In the particular case studied in this paper, model calculations reproduce the excitation energy of the isovector giant dipole resonance in ^{208}Pb. In addition, low-lying $E1$ peaks are calculated in the energy region between 7 and 11 MeV . While some of these represent the fine structure of the giant resonance, a collective state has been identified whose dynamics correspond to that of a dipole pygmy resonance. By analyzing transition densities and velocity distributions, we have related the onset of pygmy resonance at 7.29 MeV to the vibration of the excess neutrons against the inert core composed of protons and neutrons in the same shell model orbitals. Experimental information on the fragmentation of $E1$ strength in ^{208}Pb is, however, only available in the energy window 8–12 MeV [11–13], and below 6.5 MeV [14]. In order to test the predictions of the present analysis, it would be important to obtain experimental data also in the energy region between 6 and 8 MeV.

This work was supported in part by the Bundesministerium für Bildung und Forschung under Project No. 06 TM 979, by the Deutsche Forschungsgemeinschaft, and by the Gesellschaft für Schwerionenforschung (GSI) Darmstadt.

[1] T. Aumann *et al.*, Nucl. Phys. **A649**, 297c (1999).
[2] F. Catara, C. H. Dasso, and A. Vitturi, Nucl. Phys. **A602**, 181 (1996).
[3] F. Catara, E. G. Lanza, M. A. Nagarajan, and A. Vitturi, Nucl. Phys. **A624**, 449 (1997).
[4] I. Hamamoto, H. Sagawa, and X. Z. Zhang, Phys. Rev. C **56**, 3121 (1997).
[5] J. Chambers, E. Zaremba, J. P. Adams, and B. Castel, Phys. Rev. C **50**, R2671 (1994).
[6] Radhe Mohan, M. Danos, and L. C. Biedenharn, Phys. Rev. C **3**, 1740 (1971).
[7] Y. Suzuki, K. Ikeda, and H. Sato, Prog. Theor. Phys. **83**, 180 (1990).
[8] J. P. Adams, B. Castel, and H. Sagawa, Phys. Rev. C **53**, 1016 (1996).
[9] H. Sagawa and Toshio Suzuki, Phys. Rev. C **59**, 3116 (1999).
[10] Toshio Suzuki, H. Sagawa, and P. F. Bortignon, Nucl. Phys. **A662**, 282 (2000).
[11] R. D. Starr, P. Axel, and L. S. Cardman, Phys. Rev. C **25**, 780 (1982).
[12] Z. W. Bell, L. S. Cardman, and P. Axel, Phys. Rev. C **25**, 791 (1982).
[13] G. Kühner, D. Meuer, S. Müller, A. Richter, E. Spamer, O. Titze, and W. Knüpfer, Phys. Lett. **104B**, 189 (1981).
[14] J. Enders *et al.*, Phys. Lett. B **486**, 279 (2000).
[15] Z. Y. Ma, N. Van Giai, H. Toki, and M. L'Huillier, Phys. Rev. C **55**, 2385 (1997).
[16] D. Vretenar, H. Berghammer, and P. Ring, Nucl. Phys. **A581**, 679 (1995).
[17] D. Vretenar, G. A. Lalazissis, R. Behnsch, W. Pöschl, and P. Ring, Nucl. Phys. **A621**, 853 (1997).
[18] J. F. Dawson and R. J. Furnstahl, Phys. Rev. C **42**, 2009 (1990).
[19] D. Vretenar, A. Wandelt, and P. Ring, Phys. Lett. B **487**, 334 (2000).
[20] G. A. Lalazissis, J. König, and P. Ring, Phys. Rev. C **55**, 540 (1997).
[21] J. Ritman *et al.*, Phys. Rev. Lett. **70**, 533 (1993).
[22] H. Steinwedel and J. H. D. Jensen, Z. Naturforsch. A **5**, 413 (1950).
[23] F. E. Serr, T. S. Dumitrescu, Toru Suzuki, and C. H. Dasso, Nucl. Phys. **A404**, 359 (1983).