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Structure and evolution of electric dipole strength in ^{204,206,208}Pb below the neutron emission threshold ☆

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Abstract

The electric dipole strength distributions below threshold in stable even-mass Pb isotopes have been extracted from photon scattering experiments at the superconducting Darmstadt electron linear accelerator S-DALINAC. Between 4 and 6.5 MeV excitation energy a resonance-like clustering of strength is observed. A strong evolution of a fragmentation of the dipole strength with opening the neutron shell is found. The fine structure of the strength is compared to microscopic quasiparticle-phonon model calculations that quantitatively reproduce the data quite well and explain the fragmentation of the dipole strength. Models suggesting the oscillation of excess neutrons with respect to an $N \simeq Z$ core as a possible origin of low-lying E1 strength are critically examined. © 2000 Elsevier Science B.V. All rights reserved.

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The electric dipole (E1) response represents a benchmark test for experimental and theoretical structure investigations in atomic nuclei. It is dominated by the isovector giant dipole resonance (IVGDR) at high excitation energy above the particle emission threshold. At low excitation energies, the E1 strength is typically suppressed by several orders of magnitude with respect to the single-particle estimate. During the past years considerable experimental and theoretical efforts have been devoted to an elucidation of the structure of the lowest-lying 1^- state in heavy nuclei [1]. In spherical nuclei it can be interpreted to result from the coupling of quadrupole and octupole vibrations (see [2,3] and Refs. therein), whereas in deformed nuclei the E1 transitions into low-lying states populate the band heads of the $K = 0,1$ octupole rotational bands [4].

The energy region between the two-phonon quadrupole-octupole mode and the IVGDR is still not very well studied and represents a challenge both to experiment and theory, although being a long-standing problem with a first systematic survey given already about 30 years ago [5]. Local accumulations of electric dipole strength [6] are observed which are often referred to as 'pygmy' resonance, and their underlying structure is not clarified. It is of special interest to learn whether this resonant mode – if it is one – is due to a collective effect or not. Theoretical approaches in hydrodynamic or schematic models [7–11] suggest for nuclei with $N > Z$ an oscillation of the neutron excess with respect to the $N \simeq Z$ core, somewhat similar to strong low-lying E1 modes in light halo nuclei [12]. Alternatively, Iachello pointed out the possible dipole moment generated e. g. by α clustering within a nuclear 'environment' of finite isospin [13]. Schematic random phase approximation calculations of Ref. [14] also predict a fragmented local dipole mode below threshold, but its relation to macroscopic model predictions is not worked out yet.

Photon scattering [1] using highly efficient high-resolution Germanium detectors is sensitive to the excitation of dipole modes that have a large branching ratio to the ground state (g. s.). This technique – also called nuclear resonance fluorescence (NRF) – is therefore especially well suited to study the fine structure of E1 strength up to the particle threshold. A systematic study over a wide mass and energy region can help in determining the structure of the low-lying E1 strength in general. Of particular interest are investigations along isotopic or isotonic chains where either the N/Z ratio varies or the effects of a shell closure can be studied.

Recent experiments provided systematic information about E1 strength below threshold on the Sn isotopes [15] and $N = 82$ isotones [16,17]. These results compare well with the quasiparticle-phonon model (QPM), even in detail, and information about the underlying excitation mechanism could be extracted from the structure of the wave functions in the model predictions. The present work is aiming at an extension of the systematic study of the pygmy resonance to the Pb isotopes, thereby improving previous results [18] on ^{206,208}Pb in new state-of-the-art experiments. The high sensitivity of present day NRF setups allows one also to study for the first time the dipole strength in ^{204}Pb which due to its low natural abundance of about 1.4% is commercially available with moderate enrichment and small target mass only. This allows us to investigate the evolution of the E1 strength with a gradual opening of the $N = 126$ shell closure.

The present experiment was performed at the superconducting Darmstadt electron linear accelerator S-DALINAC [19]. An endpoint energy of 6.75 MeV, i. e. well below common neutron thresholds, was used in order to avoid the production of neutrons from (γ,n) reactions in the bremstarget and the surrounding material. Such photoneutrons would lead to a significant increase of background in the γ spectra due to subsequent neutron capture reactions. The collimated bremsstrahlung impinged on lead targets with masses between some 100 mg and several g. For the photon flux calibration in the ^{208}Pb(γ,γ') reaction, some 100 mg of boron powder were used. For ^{204,206}Pb the cross sections have been extracted relative to transitions from ^{208}Pb which was contained in the respective targets in small amounts. The scattered γ-rays were measured with two Euroball-Cluster detectors [20] placed at angles of 94° and 132° with respect to the incident beam. Further details of the setup, the data acquisition and analysis are given elsewhere [17,21–23].

The measured photon scattering spectra are displayed in Fig. 1. Arrows indicate transitions to the ground state. Note the different scales which result

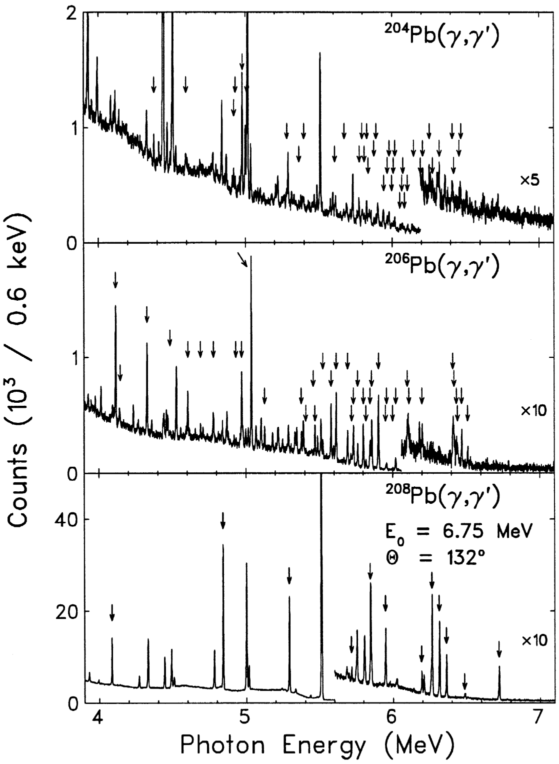

Fig. 1. Photon scattering spectra from ^{204,206,208}Pb taken with a Euroball-Cluster detector placed at 132° with respect to the incident beam. Transitions to the ground states are marked with arrows. Note the different scales.

from different target masses (3 g, 7.1 g, 230 mg) and data acquisition times (131 h, 15 h, 95 h) for the experiments on ^{208}Pb, ^{206}Pb, and ^{204}Pb, respectively. In contrast to the highly enriched ^{208}Pb target (> 99%), materials of lower enrichments were used in the case of ^{206}Pb (88%) and ^{204}Pb (67%).

For the determination of excitation strengths, the multipolarity of the transition to the g. s. must be known. The multipole order (dipole or quadrupole) can be extracted in NRF from angular distribution measurements, and the multipole character from the measurement of the linear polarisation of the scattered radiation. The multipole order could be determined for the body of the transitions, but the extraction of the parities was limited to the lowest excitations in ^{208}Pb. The experimental procedure is described in [17,22]. Our results for the lowest $J = 1$ states in ^{208}Pb at 4842 keV, 5292 keV, and 5512 keV are consistent with negative parity and thus corroborate previous findings [24].

Below 6.7 MeV, only one M1 excitation is experimentally found in ^{208}Pb [25] and ^{206}Pb [26] which is interpreted as an ‘isoscalar’ mode because of the symmetry of the proton and neutron degrees of freedom in the wave function [27,28]. All other dipole transitions observed in the present experiment are assumed to have E1 character. If one would assume an M1 strength in ^{204}Pb comparable to ^{206,208}Pb, our results on the summed electric dipole strength would change by at most 10%. Low-lying spin M1 excitations with sizable excitation strengths are experimentally observed below 3 MeV in the open-shell Pb isotopes. Their transition strengths can be well understood in shell-model calculations [29] which suggest that spin M1 modes between 4 and 7 MeV are weak and can therefore be neglected here. The E2 excitations in ^{208}Pb extracted from the present experiment have been discussed elsewhere with respect to a possible two-octupole phonon structure [23].

The E1 strength distributions of ^{204,206,208}Pb are displayed in the upper part of Fig. 2. In all three nuclei two bumps of concentrated E1 strength around 5 and 6 MeV can be seen. A few $J = 1$ states show up below 4 MeV in ^{204,206}Pb which can be interpreted to arise from octupole coupling. For E1 excitations above 4 MeV an increasing fragmentation from the doubly closed shell at ^{208}Pb to the neighbouring isotopes ^{206}Pb and ^{204}Pb is observed. In ^{208}Pb 9 levels carry a summed E1 strength of $\sum B(\mathrm{E1})\uparrow = 944(76) \cdot 10^{-3}\ \mathrm{e^2 fm^2}$ whereas for ^{206}Pb 37 levels have been measured with a total strength of $\sum B(\mathrm{E1})\uparrow = 391(67) \cdot 10^{-3}\ \mathrm{e^2 fm^2}$. Finally, for the 40 detected excitations in ^{204}Pb a dipole strength of $\sum B(\mathrm{E1})\uparrow = 235(73) \cdot 10^{-3}\ \mathrm{e^2 fm^2}$ is found. In terms of the energy-weighted electric dipole sum rule, these numbers correspond to an exhaustion of 0.705(58)%, 0.300(52)%, and 0.193(59)% in ^{208}Pb, ^{206}Pb, and ^{204}Pb, respectively.

In comparison to previous photon scattering work (see [18] and Refs. therein), an increase of sensitivity by more than one order of magnitude could be achieved in the present experiment. Whereas in earlier experiments as e. g. [18,25,26] a threshold of about $B(\mathrm{E1}) \geq 10^{-2}\ \mathrm{e^2 fm^2}$ could be achieved between 5 and 6 MeV in ^{206,208}Pb, the present experi-

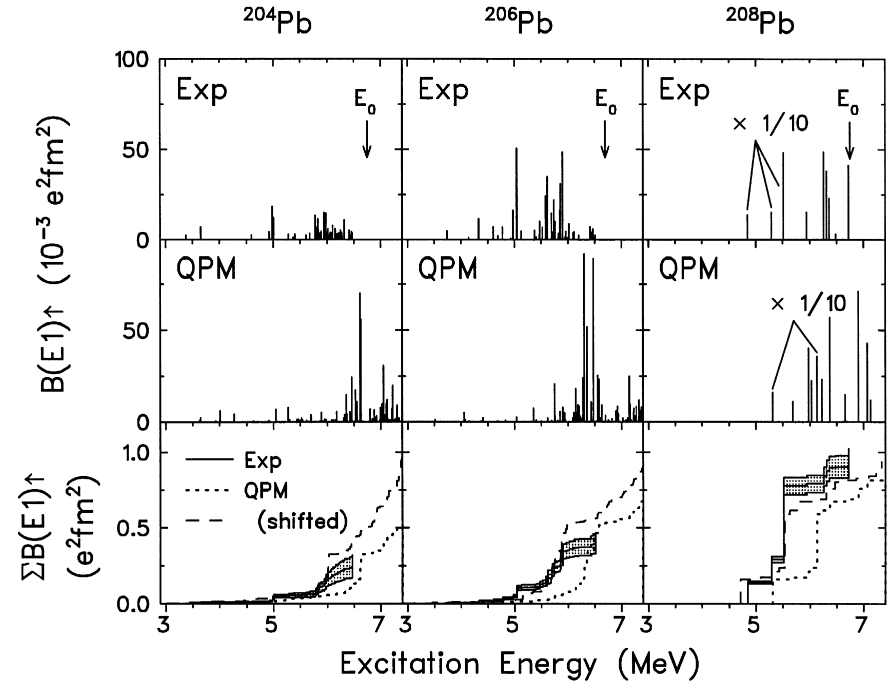

Fig. 2. E1 strength distributions in ^{204,206,208}Pb (left to right). Top row: Experimental strength distribution up to the endpoint energy of 6.75 MeV (indicated by arrows). Middle row: Predictions from the quasiparticle-phonon model. Bottom row: Running sum from the experiment (solid histogramme) and the QPM (short-dashed: original calculation; long dashed: energy shifted by 600 keV).

ments' sensitivity limits amounted to $B(\mathrm{E1}) \geq 10^{-3}$ e^{2}fm^2 for ^{206}Pb and $B(\mathrm{E1}) \geq 5 \cdot 10^{-4}$ e^{2}fm^2 for ^{208}Pb, see also Ref. [23]. The overall agreement with the previous results is good. The determination of excited states and strengths due to the moderate enrichment of the target in the ^{204}Pb (γ,γ') reaction was complicated by the presence of a rather high density of levels from ^{206,207}Pb which resulted in an increase of the mean detection threshold. A detailed comparison of the NRF results presented here with other spectroscopic investigations must be restricted to ^{208}Pb since the information for individual states in $_{206}$Pb is rather sparse and nothing at all is known about $J = 1$ states in the studied energy window in ^{204}Pb. The excitation of low-lying 1^- states in ^{208}Pb by (α,α') reactions proves an isoscalar character of these transitions [30]. No common underlying structure is suggested for the 1^- states observed in the present experiment from proton scattering and transfer reactions [31,32]: For some states a single one-particle one-hole (1p1h) configuration dominates, while other states exhibit more complex wave functions with mixing of many 1p1h couplings.

We now focus on possible interpretations of the origin of the E1 strength detected below 7 MeV. In a first step, one may assume that the detected strengths represent the low-energy tail of the IVGDR with some local fluctuations. If one takes a realistic, energy-dependent width of the Lorentzian parametrising the IVGDR as suggested in [6] for spherical nuclei, the IVGDR clearly cannot account for the experimental results. This is depicted in Fig. 3 where the gross structure of our measured strength (binned in 200 keV steps) is compared to the extrapolation of the IVGDR [6]. Fig. 3 reveals a further feature of the measured E1 strengths: By opening the neutron shell, the centroid of the low-lying strength is shifted to higher excitation energies. However, from the present experiment one cannot draw phenomenological conclusions: The shift could be related either to a

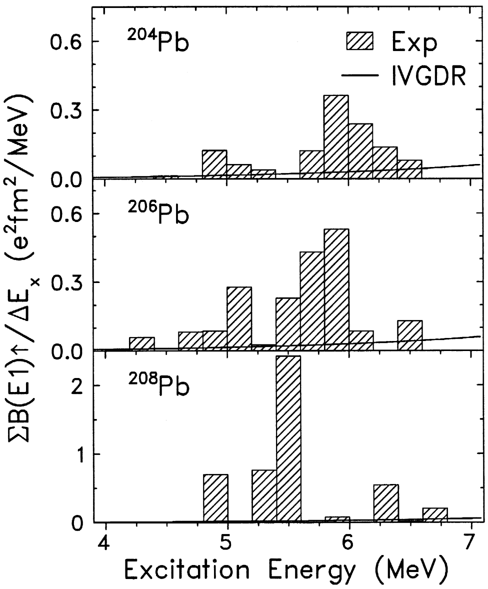

Fig. 3. Comparison of the measured strength distributions (hatched histogrammes) with the extrapolation of the isovector giant dipole resonance (IVGDR). For the parametrisation of the IVGDR a Lorentzian with energy-dependent width was assumed according to the description of [6].

mass dependence (e. g. $\propto A^{-1/3}$ as for the IVGDR) or to the change in the N/Z ratio (as would be expected for neutron skin oscillations [9,10]).

For the description of electric dipole excitations below the particle threshold several interpretations have been given. In the doubly magic nucleus ^{208}Pb the authors of [11] predict an oscillation of the excess neutrons with respect to an $N \simeq Z$ core. Such a soft dipole mode is predicted at roughly 9 MeV, and its expected strength is about as large as that found experimentally at 5–6 MeV. A possible adjustment of the parameters of the residual interaction used in [11] to lower the centroid would deteriorate the good description of the IVGDR. The hydrodynamical approach of Ref. [7] expects a soft dipole mode at 4.5 MeV with about one third of the measured strength in contrast to the data. Both models do not discuss the consequences of a variation of the N/Z ratio and the opening of the neutron shell on the E1 strength distribution. Local isospin breaking as discussed in [13] provides an alternative explanation of low-lying E1 strength. The experimentally determined centroids are consistent with expectations from such a model [33], but up to now no quantitative predictions are available.

For a microscopic insight into the nature of the low-lying E1 excitations and the experimentally observed fine structure we have performed calculations within the quasiparticle-phonon nuclear model (QPM). The theoretical background is described in [15–17]. The results are shown in the middle row of Fig. 2. Three-phonon configurations resulting from the coupling of phonons with $J^{\pi} = 0^{\pm}$ to $6^{\pm}$ have been considered up to an excitation energy of 9.5 MeV so that a realistic description of the strength distributions and the fragmentation is achieved up to about 8 MeV. 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 the calculations. The experimentally observed fast evolution of the fragmentation of the dipole strength with opening the neutron shell has a natural explanation in the strongly decreasing excitation energies of the lowest two-phonon states when going from ^{208}Pb to ^{204}Pb and the corresponding increase of the level densities. Furthermore, the interaction between simple and complex configurations responsible for the mixing between them is weaker in the doubly magic nucleus.

However, the E1 strength centroids are systematically predicted at higher excitation energies than found experimentally. The lower parts of Fig. 2 display the running sums of the B(E1) values both for the experiment (solid histogramme with errors) and the model. The predicted strength is shifted with respect to the measured distribution in all three nuclei (short-dashed histogramme), but after an overall correction of 600 keV the agreement is good (long-dashed curves). This discrepancy results from uncertainties in the single-particle spectra of the mean field. For the ones near the Fermi surface we have used experimental values of low-lying excited states in odd neighbors of ^{208}Pb as in [34]. The increasing energy centroid of the strength with opening of the neutron shell is reproduced. It can be explained by larger values for the quasiparticle energies where pairing becomes important when the shell opens up. Concerning absolute values, the total E1 transition strength calculated for ^{208}Pb agrees well with the experiment. For ^{206}Pb and ^{204}Pb the measurements are about 30% below the theoretical expectations. The number of detected levels is in good agreement with the predictions from the QPM if one takes a detection threshold into account which amounts to $B(\mathrm{E1}) \geq 1.7 \cdot 10^{-3}$ e^{2}fm^2 and $B(\mathrm{E1}) \geq 2.5 \cdot 10^{-3}$ e^{2}fm^2 at 5 MeV for ^{206}Pb and ^{204}Pb, respectively (3σ above background). These thresholds explain about half of the differences between QPM and the experiment. It may be noted that within the QPM resonance-like structures occur rather naturally due to the interference of one- and two-phonon contributions to the wave functions [16,17]. The resulting strength distributions depend on the shell structure, and there is no obvious relation to a collective motion of the neutrons.

If one refers to previous experiments [18,25,26] in $_{206,208}$Pb and to the tagged photon work of Ref. [35], one finds indications for a concentration of strength above 7 MeV as predicted by the QPM and visible in Fig. 2. However, the multipole character, especially for weak excitations, is not fully clarified, and recent studies using Laser Compton backscattering [36,37] corroborated the presence of isovector spin-M1 strength in this energy region.

In summary, we have performed an NRF experiment on the stable even-mass Pb isotopes to investigate the E1 response below 6.5 MeV with high detection sensitivity. Strong clustering and fragmentation could be observed with the opening of the neutron shell, and the strength has been found to be shifted to higher energies. Within microscopic QPM calculations the experimental results can be understood quantitatively. The camparison to available models suggests that the E1 strength found in ^{204,206,208}Pb below 6.5 MeV cannot be attributed to an oscillation of the excess neutrons with respect to the remaining core. However, this does not preclude the existence of such a mode at higher excitation energies as predicted e.g. in [11].

The NRF setup at the S-DALINAC has recently been rebuilt. Measurements can now be carried out up to an endpoint energy of about 10 MeV [38]. In a first experiment, the nuclei ^{40,48}Ca have been investigated where evidence for strong E1 excitations in the neutron-rich isotope was found [39]. Further studies of light and medium mass nuclei and the extension of the excitation energy region in heavy nuclei would be important to resolve the nature of low-lying E1 resonances near closed shells.

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