Nature of Low-Energy Dipole Strength in Nuclei: The Case of a Resonance at Particle Threshold in ^{208}Pb

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A high-resolution (γ, γ') study of the electric dipole response in ^{208}Pb at the S-DALINAC reveals a resonance structure centered around the neutron emission threshold. Microscopic quasiparticle phonon model calculations in realistic model spaces including the coupling to complex configurations are able to describe the data in great detail. The resonance is shown to result from surface density oscillations of the neutron skin relative to an approximately isospin-saturated core. It also forms an integral part of a toroidal $E1$ mode representing an example of vortex collective motion in nuclei.

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Although low-energy electric dipole resonances in stable nuclei have been known for a long time [1], their nature and systematic features remain under discussion. Experimentally, these modes are typically found in the vicinity of the particle emission threshold, but with varying widths and centroid energies. They are commonly termed pygmy dipole resonances (PDR) since their cross sections are small compared to the main portion of $E1$ response in nuclei, viz., the isovector giant dipole resonance (GDR). Theoretical interpretations of the PDR have been attempted utilizing a variety of sometimes conflicting models ranging from hydrodynamical descriptions [2,3], neutron excess surface density oscillations [4–6], fluid-dynamical approaches [7–9] to local isospin breaking in heavy nuclei by clustering [10]. Recent work has focused on microscopic nonrelativistic [11,12] and relativistic [13–15] random phase approximation (RPA) calculations which predict a strong isoscalar $E1$ mode well below the GDR with toroidal current distributions [16].

Besides resolving the long-standing problem on the structure of the PDR, an improved understanding of its properties is important since it affects two subjects of current interest. Strong soft $E1$ modes are experimentally observed in exotic, very neutron-rich isotopes (see, e.g., [17,18]) and it is an obvious question whether these modes are generated by the same mechanisms as for nuclei close to the valley of stability or whether their structural features change for extreme neutron-to-proton ratios. Furthermore, an $E1$ resonance close to particle threshold has important astrophysical implications because the thermal equilibrium of (γ, n) and (n, γ) reactions in explosive nucleosynthesis scenarios [19] could be considerably modified.

The present work details a representative case, ^{208}Pb. Indeed, the resonance fluorescence (NRF) experiment reported below was triggered by the concluding remarks of one of the latest papers on the PDR problem discussing the example of ^{208}Pb [15]: *"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."* We here report on the observation of a PDR in this excitation energy window with a centroid energy right at the neutron emission threshold ($E_{\mathrm{th}} =$ 7.37 MeV). Evidence for $E1$ transitions in this energy region has been presented in previous work including NRF [20], but only the high experimental sensitivity of a modern NRF setup allows for a full extraction of the PDR.

Most experimental information on the PDR has been derived from γ-strength functions which provide only global features. The high-resolution data presented below exhibit the resonance fine structure and thus provide details which put important constraints on various models. A theoretical interpretation is given using the microscopic quasiparticle phonon model (QPM) which goes beyond the RPA and includes the coupling to more complex configurations. The results describe the measured $E1$ response in ^{208}Pb from the lowest energy to the GDR with remarkable precision. This, in turn, permits one to extract the salient features of the $E1$ mode at threshold. It should be noted that many of the conclusions inferred from the QPM are also evident in some of the theoretical approaches previously mentioned, as discussed in detail below. However, we focus here on a comparison of our experimental results solely with those obtained from the QPM in order to provide a unified framework for the discussion and to present a coherent picture.

The ^{208}Pb(γ, γ') experiment was performed at the Darmstadt superconducting electron linear accelerator S-DALINAC. Electrons with an energy $E_0 = 9.0$ MeV and a current of about 20 μA impinged on a Cu disk of sufficient thickness (14 mm) to stop them completely. The generated bremsstrahlung was guided through a Cu collimator to a 1.2 g enriched ^{208}Pb target (99% purity). The decay of states excited by resonant photoabsorption was measured by two HPGe detectors placed at scattering angles of 90° and 130° with an efficiency of 100% each relative to a $3'' \times 3''$ NaI crystal. The lead target was sandwiched between boron disks with a total weight of 1.54 g which provide well-known transitions for an absolute calibration of the photon flux. Details of the experimental setup are described in [21].

The top part of Fig. 1 displays a representative photon scattering spectrum measured at $\Theta_\gamma = 130°$. Ground-state transitions are clearly visible up to photon energies of 8 MeV, about 700 keV above the neutron threshold. This finding, which is the result of our highly sensitive and almost background-free detection system, is nevertheless somewhat surprising since the experimental cross section is proportional to Γ_0^2/Γ, where Γ_0 denotes the g.s. and Γ denotes the total decay width. Above particle threshold, typically $\Gamma_0 \ll \Gamma$ because of the dominance of particle decay widths, and accordingly the (γ, γ') cross sections become very small.

For an extraction of the ground-state decay width, Γ_0, of levels above threshold, the present results are combined with measurements of Γ [22] and neutron decay widths Γ_n [23]. In an even-even nucleus, NRF selectively excites $J^\pi = 1^+, 1^-$ and to a lesser extent 2^+ states. The spin-1 states can be distinguished from the measured angular distributions. The parities of all but two (assumed to be negative) excited $J = 1$ levels are known. Details of the experimental (γ, γ') results and the analysis are presented elsewhere [24]. The extracted $B(E1)$ strength distribution in ^{208}Pb up to 8 MeV is presented in the middle part of Fig. 1. One observes a group of strong transitions below 6 MeV and a resonancelike structure centered approximately at the neutron threshold which is interpreted as the PDR.

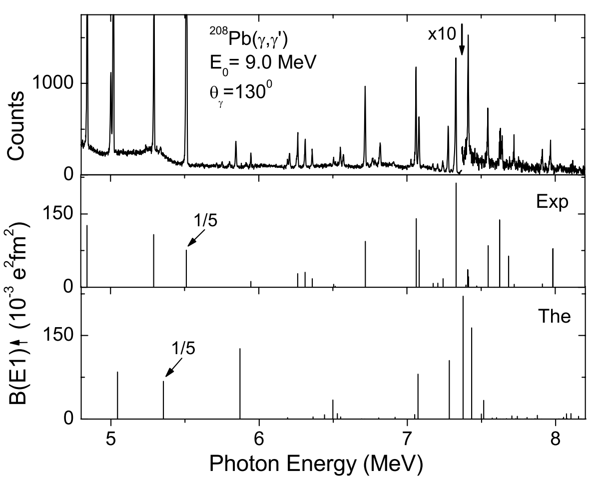

FIG. 1. Top: the spectrum of the ^{208}Pb(γ, γ') reaction at $E_0 = 9.0$ MeV and $\Theta_\gamma = 130°$. Middle: the deduced experimental $B(E1)$ strength distribution below 8 MeV excitation energy. Bottom: the QPM prediction for the $B(E1)$ strength distribution.

Nuclear structure calculations of the properties of low-lying 1^- excited states in ^{208}Pb have been performed within the QPM. Compared to a similar approach [25], here the configuration spaces have been extended considerably, including two- and three-phonon states up to excitation energies of 13 and 16 MeV, respectively. In addition, we have varied the energies of single-particle states near the Fermi level within ± 150 keV to obtain an improved description of the energies of the strongest excitations of 1^- states below 8 MeV. The resulting theoretical $B(E1)$ strength distribution is presented in the bottom part of Fig. 1.

The calculation reproduces well the separation into two groups below and above 6 MeV observed experimentally. Their summed strengths of 0.55 $e^2\,\mathrm{fm}^2$ and 0.72 $e^2\,\mathrm{fm}^2$, respectively, agree closely with the experimental values of 0.52 $e^2\,\mathrm{fm}^2$ and 0.80 $e^2\,\mathrm{fm}^2$. The states below 6 MeV are made up mostly from neutron $1p1h$ configurations, while proton $1p1h$ components and the mixing of $2p2h$ configurations into the wave functions becomes relevant for the transitions to 1^- states above 6.5 MeV.

It is important to test whether the QPM calculations also account globally for the $E1$ response in ^{208}Pb. The density of complex configurations is rapidly increasing with excitation energy which restricted the calculations in the GDR region to wave functions including one- and two-phonon configurations. The result is presented as a histogram with a step width of 200 keV in Fig. 2. The energy centroid of the GDR is 13.25 MeV and the second moment of the strength function (corresponding approximately to the half-width) is 1.91 MeV which may be compared to the experimental values 13.43 MeV and 2.42 MeV, respectively. The slight underprediction of the GDR width can be traced back to the necessary truncation of the model space and the neglect of coupling to the continuum. Nevertheless, the global features of the $E1$ response in ^{208}Pb are fully reproduced. The close agreement

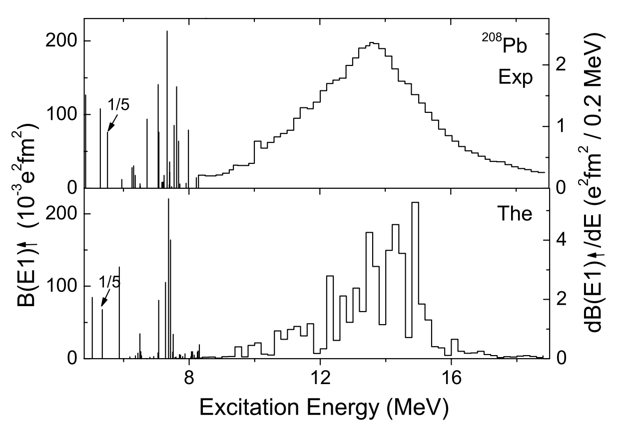

FIG. 2. Experimental $B(E1)$ strength distribution (top) up to 19 MeV compared to the QPM calculation described in the text (bottom). The data above 8 MeV are taken from [26,27]. Note the different scales on the right-hand side for $E_x > 8$ MeV.

of the QPM predictions with the experimental findings permits a rather unique interpretation of the PDR structure features. In Fig. 3 we present the summed transition charge density of proton (dashed lines) and neutron (solid lines) excitations for the group of 1^- states between 7 and 8 MeV (representative for the PDR) in comparison to the one for 1^- states above 8 MeV (the GDR). While for the GDR, protons and neutrons oscillate out of phase as expected, the behavior of the PDR charge transition density is different: in the nuclear interior protons and neutrons move in phase representing a predominantly isoscalar nature of the excitation while at the surface only neutrons contribute, in line with the conclusions of [5,6,15]. However, the latter part dominates the $B(E1)$ strength for the PDR states as the contribution of the isoscalar part is about 8 times smaller. It is therefore suggested that the nature of the pygmy resonance in ^{208}Pb can be interpreted as an oscillation of a neutron skin [28] against a $N \approx Z$ core.

Quantitatively, large differences are observed between the predictions of [5,6,15]. The schematic approach of [5] overestimates the strength by a factor of 20 and the prediction of [6] gives the right strength but an energy of about 9 MeV, while the results of [15] are reasonably close to the data. Of course, none of the models aim at a description of the fine structure provided by the QPM.

Further insight into the nature of the low-energy $E1$ resonance in ^{208}Pb is provided by Fig. 4 which shows a "snapshot" of the velocity distributions for the transitions to the 1^- states in the energy region 6,5–10.5 MeV (left part) and for larger E_x (right part). The velocity fields extracted from the transition currents are plotted in cylindrical coordinates and the length of the vectors is a relative measure of the velocity at a given point. Again, significant differences are visible. The nuclear current of the high-energy mode is directed practically parallel to the z axis. It corresponds to the back-and-forth oscillation of the proton distribution characteristic for the GDR. In contrast, the low-energy mode is dominated by vortex collective motion. Such a toroidal dipole resonance [7,16] corresponds to a transverse "zero sound" wave where the bulk behavior of nuclear matter is that of an elastic medium. Its experimental observation invalidates a hydrodynamical picture [2,3] since no restoring force for such modes exists in an ideal fluid.

A quantitative measure for the role of transverse currents is given by the vorticity strength distribution ν_L,

$$\nu_L = \int_0^\infty r^{L+4} \omega_{LL}(r) dr. \quad (1)$$

It is calculated from the transition vorticity current ω_{LL} introduced in [29]

$$\omega_{LL}(r) = \sqrt{\frac{2L+1}{L}} \left(\frac{d}{dr} + \frac{L+2}{r} \right) j_{LL+1}(r), \quad (2)$$

which is determined by the nuclear transition current density $j_{LL+1}(r)$ for a given multipolarity L. In hydrodynamic collective motion ω_{LL} is strictly zero. Figure 5 displays the normalized vorticity strength distribution as a function of excitation energy. The main concentration is found around $1\hbar\omega$, while contributions in the GDR excitation region are small. Contrary to the $B(E1)$ strength distribution, the energy centroid of the vorticity is practically independent of the strength of the residual interaction. A peak of the vorticity distribution is found at the energy of the PDR, but it clearly does not exhaust the full strength of the toroidal dipole mode.

To summarize, the g.s. dipole response in ^{208}Pb has been studied in a high-resolution (γ, γ') experiment. Combined with the available information on partial neutron and total decay widths, the complete $E1$ response could be extracted up to an excitation energy of 8 MeV. It exhibits a resonance structure centered at the neutron emission threshold and exhausts about 2% of the total $B(E1)$ strength or 4.5% of the σ_{-2} photoabsorption cross

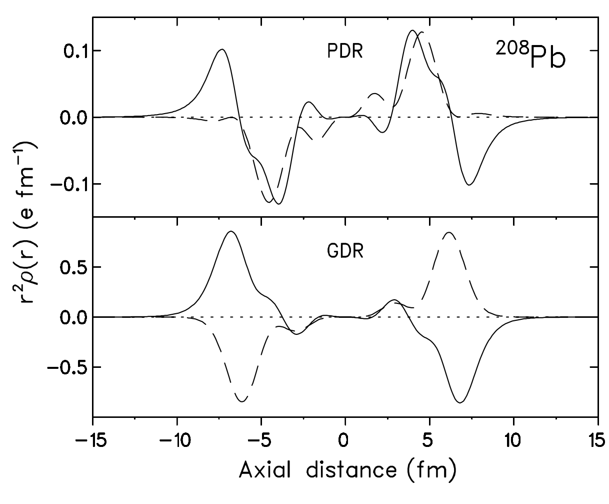

FIG. 3. The averaged transition charge densities of protons (dashed lines) and neutrons (solid lines) for the PDR (upper part) in comparison to those for the GDR (lower part).

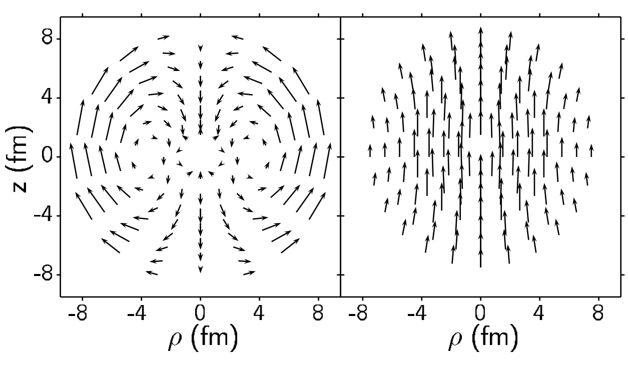

FIG. 4. The QPM prediction for the velocity distributions of $E1$ excitations at $E_x = 6.5$–10.5 MeV (left) and $E_x > 10.5$ MeV (right) in ^{208}Pb.

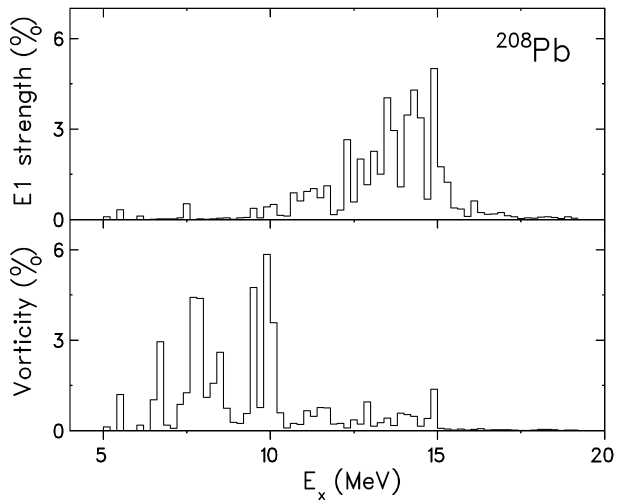

FIG. 5. A comparison of the $E1$ strength (upper part) and the vorticity distribution (lower part) as a function of excitation energy. The latter, as defined in Eq. (1), serves as a measure of transverse current contributions.

section in ^{208}Pb. Because of its relation to the latter [30], the results also imply a considerable modification of the nuclear dipole polarizability. QPM calculations including the coupling up to three phonons provide a very good description of the experiment which in turn allows for a physical interpretation of the data.

The resonance is generated by surface density oscillations of the neutron skin relative to an approximately isospin-saturated core, as qualitatively predicted, e.g., in [5,6,15]. Thus, the present results indicate that the mechanism of a soft $E1$ mode in nuclei does not differ significantly for nuclei close to stability and those with extreme proton/neutron ratios except for halo nuclei with ground-state binding energies close to threshold where the coupling to the continuum makes a genuine contribution [31,32]. A confirmation of the present conclusions by other selected examples is of great importance. High-resolution data of the dipole response have recently been reported for ^{40,48}Ca [33], allowing for a particularly large N/Z variation, and $N = 82$ nuclei showing resonancelike structures at $E_x \approx 6$ MeV [34]. For one of the cases (^{138}Ba), the pure $E1$ nature of the mode has been demonstrated by parity measurements using polarized photons from laser Compton backscattering [35].

The PDR found in ^{208}Pb exhausts approximately 30% of the total strength of a toroidal $E1$ mode, representing an example of vortex collective motion in nuclei [7,16]. Besides the recently identified orbital magnetic quadrupole "twist mode" [36,37] it constitutes another case of an excitation mode whose existence directly invalidates a hydrodynamical interpretation. Because the mode semiclassically corresponds to a purely transverse excitation, inelastic electron scattering at low momentum transfer is the optimum tool to further elucidate its structure and energy distribution. Work along these lines is in progress at the S-DALINAC.

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