BRIEF REPORTS

Brief Reports are short papers which report on completed research or are addenda to papers previously published in the **Physical Review.** *A Brief Report may be no longer than four printed pages and must be accompanied by an abstract.*

Fine structure of the giant isoscalar quadrupole resonance in ^{208}Pb observed in high-resolution (e,e') and (p,p') experiments

S. Kamerdzhiev,[1,2] J. Lisantti,[3] P. von Neumann-Cosel,[4] A. Richter,[4] G. Tertychny,[1,2] and J. Wambach [4,5]
[1]*Institut für Kernphysik, Forschungszentrum Jülich, D-52428 Jülich, Germany*
[2]*State Scientific Centre, Institute of Physics and Power Engineering, 249020 Obninsk, Russia*
[3]*Centenary College of Louisiana, Shreveport, Louisiana 71134*
[4]*Institut für Kernphysik, Technische Hochschule Darmstadt, D-64289 Darmstadt, Germany*
[5]*Department of Physics, University of Illinois at Urbana-Champaign, Urbana, Illinois 61801*
(Received 4 September 1996)

High-resolution (e,e') and (p,p') spectra for the isoscalar giant quadrupole resonance in ^{208}Pb are presented. Fine structure that has been observed hitherto in (e,e') is now also seen in (p,p') and found to be very similar in both experiments. Comparison with results from model calculations reveals the coupling of the random phase approximation modes to surface vibrations as a main source of this fine structure. [S0556-2813(97)02004-9]

PACS number(s): 24.30.Cz, 21.10.Re, 21.60.Jz, 27.80.+w

The isoscalar giant quadrupole resonance (GQ_0R) is one of the best studied giant resonances. By now its systematics are comparable to that of the giant dipole resonance (GDR), the most prominent collective vibrational mode in nuclei [1]. In particular the GQ_0R in ^{208}Pb, which is a most valuable testing ground for theoretical models on heavy nuclei, has been investigated rather thoroughly, both experimentally and theoretically. It has long been shown by many different experiments to have some intermediate structure consisting of four peaks, each a few hundred keV wide. However, the remarkable claim of a fine structure of the GQ_0R based on high-resolution (e,e') results [2,3] constitutes a long-standing problem yet unresolved [4]. The resolution of most hadron scattering experiments was not sufficient to examine this question. Proton scattering with a resolution close to the one achieved in the (e,e') work (for the latest example see Ref. [5]) displays fluctuations of the cross sections, but no attempts were made to distinguish whether these are of statistical nature or reflect the fine structure of the resonance strength. The purpose of this Brief Report is to show that the fine structure observed in electron scattering is confirmed, in great detail, by high-resolution (p,p') experiments and is also consistent with state-of-the-art microscopic calculations.

The ^{208}Pb(e,e') experiments performed at the DALINAC accelerator in Darmstadt are described in detail in Refs. [2,3]. Data were taken for incident energies $E_0=30$–50 MeV and scattering angles between 93° and 165°. Typical energy resolutions were $\Delta E=35$–50 keV. The momentum transfer range was selected such that contributions of multipolarities $\lambda>2$ to the spectra could be neglected. Figure 1 displays a spectrum taken at $E_0=50$ MeV and $\Theta_e=93°$ where $E2$ transitions should be enhanced. The backgrounds due to the radiative tail and due to contributions from other low-multipolarity giant resonances ($E0$,$E1$) are subtracted in the excitation region of interest [3]. The background shape was determined with a fluctuation analysis technique [6] and its basic correctness is assured by the good correspondence of the derived GQ_0R energy-weighted sum rule (EWSR) with results from an $(e,e'n)$ coincidence experiment [7].

The ^{208}Pb(p,p') experiment was performed at the IUCF cyclotron in Bloomington. Protons with incident energies $E_0=200$ MeV scattered to angles $\theta_p=8°$, 10°, 12°, and 15° were detected by the K600 magnetic spectrometer. The average energy resolution in the region of interest was $\Delta E=40$ keV. In Fig. 1 the $E_x=8$–12 MeV region of the spectrum taken at 8° is shown. This scattering angle corresponds to the maximum of the $L=2$ angular distribution where contributions from other multipolarities are significantly suppressed. The underlying continuum background, which is hard to determine precisely, is not subtracted, but the spectrum is plotted with a constant offset to ease a detailed comparison. Further experimental details can be found in Ref. [9].

Indeed, an impressive one-to-one correspondence of the structures observed in both experiments can be established in the energy range up to 11 MeV. Prominent peaks are found at about 8.9, 9.4, 9.6, 10.1, and 10.7 MeV. The detailed comparison indicates a systematic shift of about 50 keV between both spectra for the most pronounced levels. This can probably be traced back to an uncertainty of the (p,p') absolute energy calibration. Above 11 MeV some differences in the gross structure are visible with (e,e') finding the most strength at around 11.5 MeV, while the (p,p') results peak around 11.0 MeV.

For a microscopic theory of nuclear vibrational motion these high-resolution experiments are quite challenging since they reveal very detailed and precise information about the

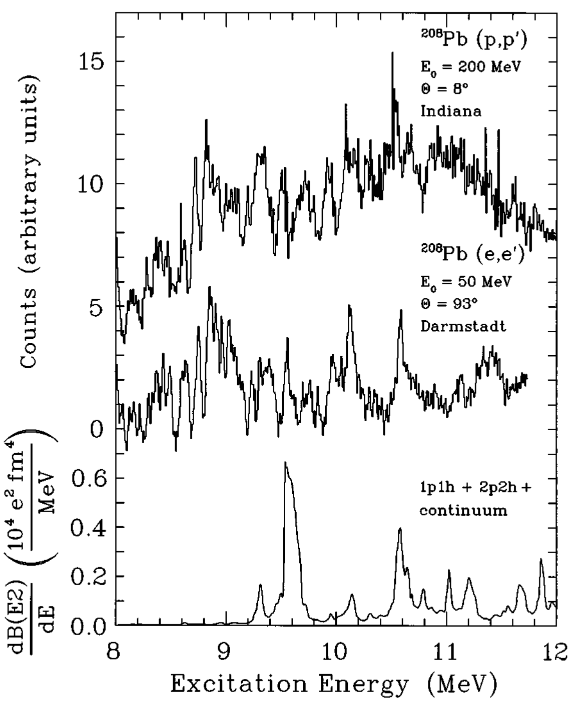

FIG. 1. Top: high resolution ($\Delta E = 40$ keV) spectrum of the ^{208}Pb(p,p') reaction at $E_p = 200$ MeV and $\Theta_p = 8°$ in the excitation region of the GQ$_0$R. The momentum transfer is chosen such that $E2$ transitions are enhanced. Middle: same for the ^{208}Pb (e,e') reaction at $E_e = 50$ MeV and $\Theta_e = 93°$. Bottom: calculation of the $B(E2)$ strength function with the vibrational model described in the text.

coherent motion of nucleons in a collective mode, especially through the observation of the fine structure of such a mode. It has become clear that the random phase approximation (RPA), the simplest microscopic theory of collective motion consistent with basic conservation laws, is only able to describe the mean vibrational frequency of giant resonances and their total ground state transition strength but fails to account for the observed damping width, especially in heavy nuclei [1,8]. The latter originates from two physical effects: (i) single-nucleon emission into the continuum (familiar from ionization in atoms) and (ii) coupling of the single-particle motion to more complex degrees of freedom in the nuclear many-body wave function (leading to dissipative energy loss similar to viscous damping in fluids). Since, in heavy nuclei, particle emission is hindered by the centrifugal and Coulomb barriers, the contribution of (ii) is dominant. Therefore, giant resonances offer a unique testing ground for the interplay between simple and complex motion in a small quantum system.

In the quantitatively most advanced theories the point of view is taken that the main route to complexity is through mixing of the single-particle motion with surface oscillations of the nucleus [10]. When describing these as RPA modes one obtains a theory which includes one-particle–one-hole $(1p1h)$ as well as $1p1h \otimes$phonon excitations of the nuclear ground state. Its most complete version, including continuum effects, has been recently applied in a study of GDR resonances in ^{40,48}Ca and ^{208}Pb with satisfactory description of the damping width [11]. It is also able to describe properties of isoscalar resonances as demonstrated for the case of ^{40}Ca where excellent agreement was obtained [13] with the highly fragmented $E2$ and $E0$ strength distributions extracted from an $(e,e'x)$ experiment [14].

The details of the theoretical approach have been given in Refs. [11,12] and will only be sketched here. The starting point is the change of the nuclear density $\delta\rho = \rho - \rho_0$ when applying a local external field V^0. To linear order, $\delta\rho$ satisfies an integral equation

$$\delta\rho(\mathbf{r},\omega) = -\int d^3r' \mathcal{A}(\mathbf{r},\mathbf{r}',\omega)[V^0(\mathbf{r}') + \mathcal{F}(\mathbf{r}')\delta\rho(\mathbf{r}',\omega)], \tag{1}$$

where ω denotes the vibrational frequency and $\mathcal{F}$ is the (local) ph interaction. The coordinate-space propagator $\mathcal{A}$ contains the RPA-like part, including the particle continuum, as well as coupling of the particle and hole states to the surface modes. Having solved for $\delta\rho$ from Eq. (1), the transition strength distribution $S_V(\omega) = \Sigma_n |\langle n|V^0|0\rangle|^2 \delta(\omega - \omega_n)$ is obtained as

$$S_V(\omega) = -\frac{1}{\pi}\mathrm{Im}\int d^3r V^0(\mathbf{r})\delta\rho(\mathbf{r},\omega) \tag{2}$$

and allows for direct comparison with experiment.

The calculations of the electromagnetic quadrupole response $(V^0 = er^2 Y_{2m})$ have been performed for a standard density-dependent Landau-Migdal interaction with parameters listed in Ref. [11] (except that f_0^{ex} has been varied slightly to optimally reproduce the spectrum of the surface modes). In evaluating the propagator $\mathcal{A}$ we have included the low-lying 2_1^+ (4.07 MeV), 3_1^- (2.61 MeV), $5_{1,2}^-$ (3.2,3.7 MeV), 4_1^+ (4.34 MeV), and 6_1^+ (4.40 MeV) surface modes which give the main contribution to the energy region studied in the high-resolution experiments. These modes have been calculated with the RPA using the same interaction parameters.

In principle ground state correlations beyond the RPA are included in this approach with the ''backward going'' diagrams of the quasiparticle-phonon interaction being most important [15]. However, they are neglected in the present calculations due to computational limitations. Their main effect is the appearance of sizable strength at lower excitation energies [13] which is confirmed by experiments on lighter closed-shell nuclei like ^{40}Ca [14,16]. However, the distributions near the maximum of the resonance are little affected, and assuming a similar behavior in ^{208}Pb possible effects should be small for the region of the main GQ$_0$R peak we are concerned with.

The results shown in Fig. 2 indicate the importance of the coupling to the surface modes in the damping [a width of 40 keV has been folded in to account for the experimental resolution in both the (e,e') and (p,p') experiments shown in Fig. 1]. The RPA, with inclusion of continuum emission (dashed line), yields a sharp peak near 10 MeV which exhausts $\sim$17% of the EWSR, $S = (\hbar^2/8\pi m)(50e^2Z)\langle r^2\rangle$, as well as some clusters of weaker strength at higher energy. These results are consistent with previous calculations [17]. Comparison with the experiments in Fig. 1 clearly demonstrates the failure of the RPA. Inclusion of the coupling to surface modes (solid line), on the other hand, leads to a dra-

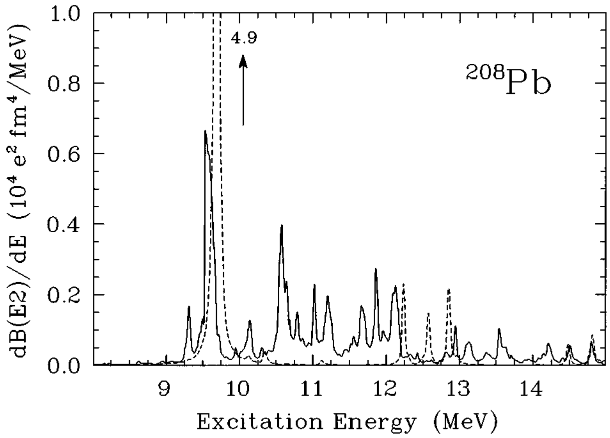

FIG. 2. Theoretical electromagnetic strength distribution in the region of the GQ_0R. The dashed line indicates the RPA result while the solid line includes coupling of the RPA mode to low-lying surface oscillations. A width of 40 keV has been folded in to account for the energy resolution of the experimental spectra shown in Fig. 1.

matic improvement and it can be concluded that a large part of the fine structure is due to this coupling. The main RPA peak is strongly reduced and dispersed over an interval of about 3 MeV starting from ~9 MeV.

The corresponding part of the theoretical distribution is shown in Fig. 1 below the experimental data. A reasonable description is achieved, although the data still exhibit a higher degree of fragmentation. As far as the details of the strength distribution are concerned, correspondence with main experimental maxima at 8.9, 10.1, and 10.7 MeV could be reached by an overall downward shift of about 0.5 MeV. Such a shift could, e.g., be obtained by an approximate 10% increase of the magnitude of the Landau-Migdal parameter f_0^{ex}.

The EWSR fraction of ~26% of the total EWSR [or 65% of the isoscalar EWSR $(Z/A)S$] exhausted between 8.5 MeV and 13 MeV is not affected by the mixing, however. Similarly, the mean energy $\langle E\rangle = \int d\omega\omega S_V(\omega)/\int d\omega S_V(\omega)$, evaluated over an interval 8.5–13.0 MeV, changes only slightly from 10.1 MeV to 10.2 MeV. The sum rule fraction is in rather good agreement with the recent (e,e') results. While Ref. [3] finds $4.07^{+1.22}_{-0.57}$ $e^2\mathrm{b}^2$ MeV in the region $8.0 \leqslant E_x \leqslant 11.5$ MeV, theory predicts 5.0 $e^2\mathrm{b}^2$ MeV for $8.5 \leqslant E_x \leqslant 13.0$ MeV which is also consistent with the $(e,e'n)$ results of Ref. [7] where 5.4 $e^2\mathrm{b}^2$ MeV have been located in the interval $9.0 \leqslant E_x \leqslant 12.5$ MeV with an uncertainty of about 25%. The calculated strength is also in agreement with heavy-ion Coulomb excitation data [18,19] and the latest (p,p') experiments [5,20,21]. Our theoretical results are similar to previous calculations [22,23] using separable forces and neglecting coupling to the continuum.

To summarize, the presence of fine structure in the GQ_0R first observed in electron scattering, which remained a puzzle for many years, is fully confirmed by recent high-resolution inelastic proton scattering results. In the excitation energy region 8–11 MeV correspondence between the two experiments can be established on a peak-by-peak basis. Some differences are visible at higher energies which might partly be due to admixtures of other multipoles in the data. We note that the fine structure is also indicated in a recent ^{208}Pb(p,p') experiment at $E_p = 65$ MeV with very good energy resolution [24].

The RPA theory clearly fails to describe the observed spreading of the transition strength distribution. After inclusion of coupling to surface modes, however, the calculation agrees quite well with gross features of the observed fine structure. A degree of fragmentation much closer to experiment is attained and prominent peaks can be brought in good agreement to the experiment with a slight variation of the residual interaction strength. One can conclude from the calculation that the interplay of the doorway states and the fine structure compound states is mainly governed by the coupling of the coherent RPA excitations to collective surface modes.

The results presented here emphasize the importance of high-resolution measurements up to high excitation energies and underline the benefit arising from the combination of complementary probes for investigations of the same nuclear states. An experimental step further could be achieved with the new generation of γ-ray facilities of unpredecented sensitivity like the EUROBALL by a measurement of the γ decay of the fine structure states with the (γ,γ') reaction. This should allow a detailed mapping of the hierarchy of the vibrational coupling which can be considered as an example for a nuclear transition from order to chaos [25].

This work was partly supported by the German-Soviet scientific exchange program, by the German Federal Minister of Education, Research and Technology (BMBF) under Contract No. 06DA665I, and by National Science Foundation Grant No. PHY-94-21309. Two of us (S.K. and G.T.) would like to thank J. Speth for the warm hospitality at the IKP in Jülich, where part of this work was performed.

[1] *Electric and Magnetic Giant Resonances in Nuclei*, edited by J. Speth (World Scientific, Singapore, 1991).

[2] G. Kühner D. Meuer, S. Müller, A. Richter, E. Spamer, O. Titze, and W. Knüpfer, Phys. Lett. **104B**, 189 (1981).

[3] G. Kilgus, G. Kühner, S. Müller, A. Richter, and W. Knüpfer, Z. Phys. A **326**, 41 (1987).

[4] A. van der Woude, in Ref. [1], p. 170.

[5] F. E. Bertrand, E. E. Gross, D. J. Horen, R. O. Sayer, T. P. Sjoreen, D. K. McDaniels, J. Lisantti, J. R. Tinsley, L. W. Swenson, J. B. McClelland, T. A. Carey, K. Jones, and S. J. Seestrom-Morris, Phys. Rev. C **34**, 45 (1986).

[6] S. Müller, F. Beck, D. Meuer, and A. Richter, Phys. Lett. **113B**, 362 (1982).

[7] G. O. Bolme, L. S. Cardman, R. Doerfler, L. J. Koester, Jr., B. L. Miller, C. N. Papanicholas, H. Rothhaas, and S. E. Williamson, Phys. Rev. Lett. **61**, 1081 (1988).

[8] J. Wambach, Rep. Prog. Phys. **55**, 989 (1988).

[9] J. Lisantti, E. J. Stephenson, A. D. Bacher, P. Li, R. Sawafta,

P. Schwandt, S. P. Wells, S. W. Wissink, W. Unkelbach, and J. Wambach, Phys. Rev. C **44**, R1233 (1991).
[10] G. F. Bertsch, P. F. Bortignon, and R. A. Broglia, Rev. Mod. Phys. **55**, 287 (1983).
[11] S. Kamerdzhiev, G. Tertychny, and W. Unkelbach, Phys. Lett. B **287**, 293 (1993); S. Kamerdzhiev, J. Speth, G. Tertychny, and V. Tselyaev, Nucl. Phys. **A555**, 90 (1993).
[12] S. Kamerdzhiev and V. I. Tselyaev, Sov. J. Nucl. Phys. **44**, 214 (1986); A. I. Tselyaev, *ibid.* **50**, 780 (1989).
[13] S. Kamerdzhiev, J. Speth, and G. Tertychny, Phys. Rev. Lett. **74**, 3943 (1995).
[14] H. Diesener, U. Helm, G. Herbert, V. Huck, P. von Neumann-Cosel, C. Rangacharyulu, A. Richter, G. Schrieder, A. Staschek, A. Stiller, R. Ryckebusch, and J. Carter, Phys. Rev. Lett. **72**, 1994 (1994).
[15] S. Kamerdzhiev, G. Tertychny, J. Speth, and W. Wambach, Nucl. Phys. **A577**, 641 (1994).
[16] H. Diesener, U. Helm, P. von Neumann-Cosel, A. Richter, G. Schrieder, and S. Strauch, Phys. Lett. B **352**, 201 (1995); F. Zwarts, A. G. Drentje, M. N. Harakeh, and A. van der Woude, Phys. Lett. **125B**, 123 (1983).
[17] J. Wambach, The Nuclear Response in Extended RPA Theories, V.J.A. Swieca Summer School on Nuclear Physics, Campos do Jordao, Brazil, 1991 (unpublished).
[18] J. R. Beene, F. E. Bertrand, D. J. Horen, R. L. Auble, B. L. Burks, J. Gomez del Campo, M. L. Halbert, R. O. Sayaer, W. Mittig, Y. Schutz, J. Barrette, N. Alamanos, F. Auger, B. Fernandez, A. Gillibert, B. Haas, and J. P. Vivien, Phys. Rev. C **41**, 920 (1990).
[19] R. Liguori Neto, P. Roussel-Chomaz, L. Rochais, N. Alamanos, F. Auger, B. Fernandez, A. Gillibert, R. Lacey, A. Mizcaika, D. Pierroutsakou, J. Barrette, S. K. Mark, R. Turcotte, Y. Blumenfeld, N. Frascaria, J. P. Garron, J. C. Roynette, J. A. Scarpaci, A. Van der Woude, and A. M. Van den Berg, Nucl. Phys. **A560**, 733 (1993).
[20] G. S. Adams, T. A. Carey, J. B. McClelland, J. M. Moss, S. J. Seestrom-Morris, and D. Cook, Phys. Rev. C **33**, 2054 (1986).
[21] D. K. McDaniels, J. R. Tinsley, J. Lisantti, D. M. Drake, I. Bergvist, L. W. Swenson, F. E. Bertrand, E. E. Gross, D. J. Horen, T. P. Sjoreen, R. Lijlestrand, and H. Wilson, Phys. Rev. C **33**, 1943 (1986).
[22] P. F. Bortignon and R. A. Broglia, Nucl. Phys. **A371**, 405 (1981).
[23] V. G. Soloviev, Ch. Stoyanov, and V. V. Voronov, Nucl. Phys. **A399**, 141 (1983).
[24] M. Kawabata Y. Mizuno, T. Noro, K. Tamura, H. Togawa, O. Kamigaito, and H. Ikegami, RCNP Annual Report 1992, p. 16.
[25] S. Drożdż, S. Nishizaki, and J. Wambach, Phys. Rev. Lett. **72**, 2839 (1994); S. Drożdż, S. Nishizaki, J. Wambach, and J. Speth *ibid.* **74**, 1075 (1995).