Pygmy dipole resonance in $^{208}$Pb

I. Poltoratska,1 P. von Neumann-Cosel,1,2 A. Tamii,3 T. Adachi,3,4 C. A. Bertulani,5 J. Carter6 M. Dozono7 H. Fujita,2 K. Fujita,7 Y. Fujita,3 K. Hatanaka,2 M. Itoh,8 T. Kawabata,9 Y. Kalmykov,1 A. M. Krumbholz,1 E. Litvinova,10 H. Matsubara,11 K. Nakahashi,11 R. Neveling,12 H. Okamura,2 H. J. Ong,2 B. Ozcel-Tashenov,13 V. Yu. Ponomarev,1 A. Richter,1,14 B. Rubio,15 H. Sakaguchi,1 Y. Sakemi,3 Y. Sasamoto,11 Y. Shimbara,21 Y. Shimizu,17 F. D. Smit,12 T. Suzuki,2 Y. Tameshige,18 J. Wambach,1 M. Yosoi,2 and J. Zenihiro1

1Institut für Kernphysik, Technische Universität Darmstadt, D-64289 Darmstadt, Germany
2Research Center for Nuclear Physics, Osaka University, Ibaraki, Osaka 567-0047, Japan
3Department of Physics, Osaka University, Toyonaka, Osaka 560-0043, Japan
4Kernfysisch Versneller Instituut, University of Groningen, Zernikelaan 25, NL-9747 AA Groningen, The Netherlands
5Department of Physics and Astronomy, Texas A&M University-Commerce, Commerce, Texas 75429, USA
6School of Physics, University of the Witwatersrand, Johannesburg 2050, South Africa
7Department of Physics, Kyushu University, Fukuoka 812-8581, Japan
8Cyclotron and Radioisotope Center, Tohoku University, Sendai, 980-8578, Japan
9Department of Physics, Kyoto University, Kyoto 606-8502, Japan
10ExtreMe Matter Institute EMMI and Research Division, GSI Helmholtzzentrum für Schwerionenforschung, D-64291 Darmstadt, Germany
11Center for Nuclear Study, University of Tokyo, Bunkyo, Tokyo 113-0033, Japan
12iThemba LABS, Somerset West 7129, South Africa
13GSI Helmholtzzentrum für Schwerionenforschung, D-64291 Darmstadt, Germany
14ECT*, Villa Tambosi, I-38123, Villazzano (Trento), Italy
15Instituto de Fisica Corpuscular, CSIC-Universidad de Valencia, E-46071 Valencia, Spain
16Department of Physics, Niigata University, Niigata 950-2102, Japan
17RIKEN Nishina Center, Wako, Saitama 351-0198, Japan
18National Institute of Radiological Sciences, Chiba 263-8555, Japan

(Received 9 March 2012; published 20 April 2012)

Scattering of protons of several hundred MeV is a promising new spectroscopic tool for the study of electric dipole strength in nuclei. A case study of $^{208}$Pb shows that, at very forward angles, $J^+ = 1^-$ states are strongly populated via Coulomb excitation. A separation from nuclear excitation of other modes is achieved by a multipole decomposition analysis of the experimental cross sections based on theoretical angular distributions calculated within the quasiparticle-phonon model. The $B(E1)$ transition strength distribution is extracted for excitation energies up to 9 MeV; that is, in the region of the so-called pygmy dipole resonance (PDR). The Coulomb-nuclear interference shows sensitivity to the underlying structure of the $E1$ transitions, which allows for the first time an experimental extraction of the electromagnetic transition strength and the energy centroid of the PDR.

DOI: 10.1103/PhysRevC.85.041304 PACS number(s): 25.40.Ep, 21.10.Re, 21.60.Jz, 27.80.+w

The electric dipole ($E1$) strength in nuclei is dominated by the isovector giant dipole resonance (GDR), originating from the collective motion of neutrons against protons in the nucleus and located well above the particle emission threshold. The GDR provides basic insight into the isovector properties of the nuclear force and thus was intensively investigated both experimentally and theoretically [1,2]. However, at present the interest is more focused on low-lying dipole strength, well below the GDR energies, referred to as pygmy dipole resonance (PDR). It appears in nuclei with neutron excess and might be pictured macroscopically to result from oscillations of these excess neutrons against an inert core with $N \simeq Z$ (see, e.g., Ref. [3] and references therein). The PDR is predicted in all microscopic calculations based on the random-phase approximation (RPA), but the theoretical central energies and strengths differ considerably, in particular between those based on nonrelativistic and relativistic mean-field approaches (see, e.g., Ref. [4] for an example in the stable tin isotopes).

By its nature, the PDR may shed light onto the formation of neutron skins in nuclei [5–7] and, because of the strong correlation in the RPA models, in turn on the symmetry energy [6,8,9]. Constraints on the magnitude and density dependence of the symmetry energy are important ingredients for the modeling of neutron stars. There is a clear correlation between the total electric dipole polarizability and the neutron skin [9,10]. However, it has been argued that the PDR alone carries independent information [6,9].

The properties of the PDR in stable nuclei have been studied extensively for different neutron and proton shell closures with the $(\gamma,\gamma')$ reaction (see, e.g., Ref. [11] and references therein). Crucial data in exotic neutron-rich nuclei, where the PDR should be enhanced, are still scarce [6,12,13] and suffer from large systematic uncertainties. The heaviest stable doubly magic nucleus $^{208}$Pb has always been a benchmark and the PDR has been studied in various recent $(\gamma,\gamma')$ experiments [14–17]. Theoretically, closed-shell nuclei permit the inclusion

1vnc@ikp.tu-darmstadt.de
of complex degrees of freedom beyond the mean-field level in the microscopic calculations \[14,18\].

While the results of Refs. \[14–17\] agree quite well, the \((\gamma,\gamma')\) reaction in general suffers from two problems: the experimental quantity measured is the ground-state \(\gamma\)-decay width times the ground-state branching ratio. The latter is usually not known and assumed to be 100\% in most analysis. However, statistical model calculations indicate potentially large correction factors (although not for the case of \(^{208}\text{Pb}\)) modifying the resulting PDR strength distributions considerably \[19\]. Furthermore, the dominance of particle over \(\gamma\) decay suppresses the experimental signal above threshold. Another, more general problem is the experimental separation of the PDR from the GDR. While theoretical transition densities provide a signature in the model calculations \[20\], the experimentally determined reduced \(B(E1)\) strengths do not allow such a distinction. A possible experimental approach to the distinction of PDR and GDR is the use of isoscalar probes, and a pioneering \((\alpha,\alpha'\gamma)\) experiment has been performed \[21\], demonstrating a large exhaustion of the isoscalar energy-weighted sum rule by low-energy \(E1\) transitions in \(^{208}\text{Pb}\).

Recently, a new experimental technique utilizing polarized proton scattering at and close to 0° to measure the complete \(E1\) strength in nuclei has been developed \[22\]. It allows, in particular, a consistent extraction of the \(E1\) transition strengths below and above the neutron threshold. At small momentum transfers and incident proton energies of several hundred MeV, the cross sections are dominated by isovector spin-flip \(M1\) transitions (the analog of the Gamow-Teller mode) \[23\] and by Coulomb excitation of non-spin-flip \(E1\) transitions. A separation of these two contributions can be achieved either by a multipole decomposition analysis (MDA) of the angular distributions or by the analysis of polarization transfer observables. In Ref. \[24\], excellent agreement of the two methods was demonstrated for the case of \(^{208}\text{Pb}\). Here we present our results for the \(E1\) strength distribution at energies below the GDR based on the MDA. We also demonstrate that, because of the interference of Coulomb and nuclear interaction, the angular distributions do show sensitivity to the underlying structure allowing for an experimental separation of PDR and GDR contributions.

The \(^{208}\text{Pb}(p,\gamma)\) experiment was performed at the RING cyclotron facility of the Research Center for Nuclear Physics (RCNP), Osaka University. A description of the experimental technique can be found in Ref. \[22\] and details of the present experiment and the polarization transfer measurements can be found in Ref. \[25\]. A proton beam of 295 MeV with intensities 2–10 nA and an average polarization of \(P_0 \approx 0.7\) bombarded an isotopically enriched \(^{208}\text{Pb}\) foil with an areal density of 5.2 mg/cm\(^2\). Data were taken with the Grand Raiden spectrometer \[26\] in an angular range 0°–2.5° and for excitation energies \(E_x \approx 4\) to 22 MeV. Additional data with unpolarized protons were taken at angles up to 10°. Employing dispersion matching techniques, an energy resolution \(\Delta E \approx 25\) keV (full width at half maximum) could be achieved. A spectrum of the \(^{208}\text{Pb}(p,\gamma)\) reaction with the spectrometer set at 0° is shown in Fig. 1 for the excitation energy range 4.5–9 MeV, where the PDR is expected to lie. The arrows indicate the excitation energy of excited states identified in the \((\gamma,\gamma')\) experiments \[14–17\]. Essentially, all prominent dipole transitions observed in the latter experiments are also excited in the present measurements.

Excitation of 1\(^{-}\) states is possible through nuclear and Coulomb interaction, and both contributions add coherently to the cross sections. To verify the assumption of a predominant Coulomb excitation at angles close to 0°, predictions for the angular distributions in \((p,p')\) scattering were calculated based on a semiclassical model \[27\]. As examples, results for the prominent transitions to 1\(^{-}\) states at \(E_x = 5.512\) MeV and 6.720 MeV are shown in Fig. 2. Because of the finite angular resolution of the Grand Raiden spectrometer, the calculated cross section angular distributions were convoluted with Gaussian functions with widths corresponding to the vertical and horizontal angular opening of the detector system.
The shape of the experimental angular distributions is well described and their absolute magnitudes can be reproduced when the calculations are normalized to the average $B(E1)$ strengths deduced from the $(\gamma,\gamma')$ experiments [14–17]. The remaining deviations at angles larger than $2^\circ$ are attributed to effects of Coulomb-nuclear interference and, in the case of the transition to the state at 6.720 MeV, to contributions from unresolved transitions with higher multipoarities.

In order to determine such contributions and to enable a separation from the spin-$M1$ resonance known to set in at $E_x > 7$ MeV [23,28], a MDA was performed. The method, based on model predictions of the angular distribution shapes, is commonly used in the analysis of complex spectra from hadronic reactions; for example, for an extraction of $B(GT)$ strengths in charge-exchange reactions [29] or isoscalar giant resonance strength distributions from inelastic $\alpha$-particle scattering [30], and also for inelastic-electron-scattering form factors of nuclei [31]. Theoretical proton scattering cross sections were calculated using the code DWBA07 [32] with scattering, and also for inelastic electron-scattering form factors of nuclei [31].

Table I summarizes the MDA results for excitation energies $E_x = 4.8$ to 9 MeV integrated over scattering angles $0^\circ$–$0.94^\circ$ and derived $B(E1)$ strengths.

| $E_x$ (MeV) | $\sigma_{E1}$ (mb) | $\sigma_{M1}$ (mb) | $\sigma_{total}$ (mb) | $B(E1)$ ($e^2$ fm$^2$) |
|-------------|-------------------|-------------------|----------------------|------------------------|
| 4.8420 (22) | 2.21 (63)         | 2.21 (63)         | 0.118 (17)           |
| 5.2949 (22) | 1.63 (34)         | 1.65 (34)         | 0.112 (8)            |
| 5.5128 (11) | 5.71 (30)         | 5.76 (33)         | 0.397 (21)           |
| 5.8417 (50) | 0.35 (1)          | 0.43 (2)          |                      |
| 5.9463 (59) | 0.16 (1)          | 0.18 (1)          | 0.013 (1)            |
| 6.2642 (26) | 0.62 (8)          | 1.07 (5)          | 0.057 (17)           |
| 6.3131 (59) | 0.32 (2)          | 0.38 (2)          | 0.032 (2)            |
| 6.3585 (65) | 0.21 (3)          | 0.36 (4)          | 0.020 (3)            |
| 6.4835 (49) | 0.15 (2)          | 0.30 (2)          | 0.015 (2)            |
| 6.7184 (26) | 0.88 (6)          | 0.94 (2)          | 0.095 (6)            |
| 7.005–7.135 | 2.06 (3)          | 2.305 (16)        | 0.206 (14)           |
| 7.135–7.225 | 0.48 (10)         | 0.776 (3)         | 0.015 (2)            |
| 7.225–7.265 | 0.41 (9)          | 0.681 (2)         | 0.028 (4)            |
| 7.265–7.375 | 2.47 (39)         | 4.016 (150)       | 0.254 (23)           |
| 7.375–7.425 | 0.24 (4)          | 0.815 (4)         | 0.021 (3)            |
| 7.425–7.515 | 0.71 (13)         | 1.682 (7)         | 0.053 (12)           |
| 7.515–7.585 | 0.72 (15)         | 1.362 (20)        | 0.061 (13)           |
| 7.590–7.650 | 0.83 (21)         | 1.243 (27)        | 0.109 (25)           |
| 7.655–7.725 | 0.87 (5)          | 1.056 (5)         | 0.104 (6)            |
| 7.730–7.860 | 0.68 (11)         | 1.002 (5)         | 0.072 (18)           |
| 7.865–7.935 | 0.95 (2)          | 1.079 (4)         | 0.120 (18)           |
| 7.935–8.035 | 1.23 (15)         | 1.541 (18)        | 0.167 (18)           |
| 8.040–8.160 | 0.51 (10)         | 0.801 (9)         | 0.055 (13)           |
| 8.160–8.230 | 0.36 (8)          | 0.638 (3)         | 0.052 (12)           |
| 8.230–8.430 | 1.65 (5)          | 1.886 (7)         | 0.242 (15)           |
| 8.430–8.590 | 1.05 (9)          | 1.348 (3)         | 0.145 (20)           |
| 8.595–8.745 | 1.24 (12)         | 1.609 (4)         | 0.191 (25)           |
| 8.750–8.910 | 1.60 (6)          | 1.829 (8)         | 0.277 (23)           |
| 8.910–9.000 | 1.24 (2)          | 1.327 (3)         | 0.215 (24)           |

As discussed in Ref. [14], the QPM calculations used for the present MDA analysis can distinguish between $E1$ transitions to the PDR and GDR by an analysis of the theoretical transition densities. The examples in Fig. 3(a) demonstrate that the resulting $(p, p')$ angular distributions also show significant differences between excitation of these two modes. Thus, $B(E1)$ transition strengths can be directly derived.

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Table I summarizes the MDA results for excitation energies $E_x = 4.8$ to 9 MeV. The partial $E1$ and $M1$ cross sections listed are integrated over a scattering angle range 0°–0.94°, where nuclear contributions to the $E1$ cross sections are on the level of 1% only. Thus, $B(E1)$ transition strengths can be directly derived.
FIG. 3. (Color online) Comparison of theoretical angular distribution shapes used in MDA: (a) $M1$ and representative $E1$ transitions to the PDR and GDR, (b) $E2$ and $E4$, (c) $E3$, $M2$, and $M3$. All curves are normalized at $\Theta_{\text{lab}} = 1.5^\circ$.

$^{208}\text{Pb}$, viz. a centroid energy $E_c = 6.82(2)$ MeV and a strength $\sum B(E1) = 2.18(7)$ $e^2$ fm$^2$. The systematic uncertainty of the MDA approach is estimated to be at most 10% by constructing mixed PDR-GDR angular distributions with given amplitude ratios and studying the variation of $\chi^2$ in the fits.

Figure 6 compares the electric dipole strength distribution up to $E_x = 9$ MeV extracted from the present experiment [Fig. 6(a)] with previous results combining $(\gamma,\gamma')$ [14–17] and $^{207}\text{Pb}(n,\gamma)$ [35] data up to 8 MeV with a $^{208}\text{Pb}(e,e')$ measurement [36] at higher excitation energies [Fig. 6(b)]. The agreement is excellent up to the neutron separation energy ($S_n = 7.33$ MeV). Above threshold the present work shows additional, previously unobserved strength. This can most likely be attributed either to unknown neutron partial decay widths of the excited states. Above 8 MeV, $E1$ strength from

FIG. 4. (Color online) Examples of the MDA fits for two adjacent energy bins in the energy region of overlapping levels.

FIG. 5. (Color online) Best $\chi^2$ values in the MDA using either PDR- or GDR-type angular distributions for excitation energies $E_x = 7$ to 9 MeV and bins defined in Table I.

FIG. 6. (Color online) $E1$ strength distributions in $^{208}\text{Pb}$ between 4.8 and 9 MeV from (a) the present experiment in comparison with (b) previous results and theoretical calculations within the (c) QPM, (d) RTBA, and (e) shell model. Note the scale reduction by a factor of 10 for the RTBA results.
PYGMY DIPOLE RESONANCE IN $^{208}$Pb

PHYSICAL REVIEW C 85, 041304(R) (2012)

too small. The RTBA calculation so far includes beyond the one-particle–one-hole (1p1h) states only configurations of the type $1p1h \otimes$ phonon, and thus the fragmentation is insufficient to describe the data (note the general reduction by a factor of 10 in Fig. 6(d) to bring it on the scale of the other results). The total strength up to 9 MeV is more than a factor two too large. The SM shows a fair agreement for the total strength but the fragmentation is somewhat underpredicted.

It would be interesting to extract from the models the centroid and strength of the PDR in $^{208}$Pb to be compared with the experimental result quoted above. However, we refrain from giving the corresponding values summed over the interval where the PDR is found experimentally. In the models the properties of the PDR are very sensitive to the mean-field description and strength might thus be partially shifted to higher excitation energies. One should rather analyze the theoretical transition densities [20, 39] to select those with a dominant PDR character.

To summarize, high-energy proton scattering at angles close to and including $0^\circ$ is used as a new experimental method to determine the $B(E1)$ strength distribution below the GDR in $^{208}$Pb. Combined with dispersion matching techniques, it provides a novel spectroscopic tool for the study of the electric dipole response in nuclei. The method also overcomes some limitations of other commonly used experimental techniques like $(\gamma, \gamma')$ or $(\gamma, n)$ reactions, which are sensitive to assumptions about decay branching ratios and typically limited to energy regions either below or above the neutron separation energy.

The MDA exhibits sensitivity to the structure of $E1$ transitions in $^{208}$Pb through the difference of Coulomb-nuclear interference contributions to the cross sections of PDR and GDR excitations. This is an important finding because the strength distribution does not allow a distinction between the different modes. Thereby, the electromagnetic transition strength and the centroid energy of the PDR could be determined for the first time, providing an experimental benchmark for the strongly varying theoretical predictions (cf. Fig. 6). The method is not restricted to closed-shell nuclei but can be applied in vibrational and well-deformed nuclei where microscopic calculations provide a good description of nuclear excitations. Possible approaches to extract the PDR content from model calculations of the $E1$ response have been discussed, for example, in Refs. [40, 41]. Alternative information on the PDR structure may be obtained from isoscalar probes [42, 43] as demonstrated by studies of the $(\alpha, \alpha')$ reaction [21, 44].

This work was supported by DFG (contracts SFB 634 and NE 679/3–1) and JSPS (Grant No. 14740154). B. R. acknowledges support by the JSPS-CSIC collaboration program and E.L. by the Helmholtz Alliance EMMI.

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