Complete dipole strength distributions in $^{208}$Pb from high-resolution polarized proton scattering at $0^\circ$

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Abstract. Small-angle polarized proton scattering including $0^\circ$ at incident energies of a few 100 MeV/nucleon is established as a new spectroscopic tool for the study of E1 and M1 strength distributions. Experiments of this type have been realized recently at RCNP, Osaka, Japan with high energy resolution of the order 25 - 30 keV (FWHM). Using $^{208}$Pb as an example, the physics potential of such data is discussed. It includes information on the properties of the Pygmy Dipole Resonance but also on complete E1 and M1 strength distributions and thus the gamma strength function. The E1 polarizability can be extracted with a precision of about 4% providing important experimental constraints on the neutron skin thickness in $^{208}$Pb.

1. Introduction
The electric dipole (E1) response of nuclei is dominated by the giant dipole resonance (GDR), a highly excited collective mode above the particle emission threshold [1]. Its properties are well understood but recent interest focusses on evidence for a soft mode in neutron-rich nuclei below the GDR termed pygmy dipole resonance (PDR). Because of the saturation of nuclear density, excess neutrons might form a skin whose oscillations against an isospin-saturated core should give rise to a low-energy E1 mode [2]. Therefore, the PDR may shed light onto the formation of neutron skins in nuclei [3]. Another quantity related to nuclear E1 modes is the symmetry energy acting as restoring force. The E1 strength distribution carries information on its poorly known magnitude and density dependence [4], indispensable ingredients for the modeling of the equilibrium properties of neutron stars [5].

A case of special interest is the doubly magic nucleus $^{208}$Pb. In a measurement of parity-violating elastic electron scattering at JLAB, the PREX collaboration [6] aimed at the first model-independent determination of the neutron skin thickness in $^{208}$Pb. However, the recent result $r_{\text{skin}} = 0.34^{+0.15}_{-0.17}$ fm suffers still from limited statistics. Studies of energy density functionals (EDFs) [7] using Skyrme forces [8] or a relativistic framework [9] suggest the nuclear dipole polarizability $\alpha_D$ as an alternative observable constraining both neutron skin and symmetry energy. The polarizability is related to the photoabsorption cross section $\sigma_{\text{abs}}$ [10]

$$\alpha_D = \frac{hc}{2\pi^2e^2} \int \frac{\sigma_{\text{abs}}}{\omega^2} d\omega,$$

(1)

where $\omega$ denotes the photon energy. Because of the inverse energy weighting, $\alpha_D$ depends on the E1 strength at low energies.
The centroid of the PDR lies typically in the vicinity of the neutron emission threshold \((S_n)\). Data on the PDR in very neutron-rich nuclei are still scarce [11, 12, 13]. Stable nuclei at different shell closures have been explored with the \((\gamma, \gamma')\) reaction (Ref. [14] and refs. therein). While this technique provides important information on the fine structure of the PDR, it is essentially limited to excitation energies up to \(S_n\), and unobserved branching ratios of the \(\gamma\) decay to excited states may require corrections for the total strength [15]. Measurements of decay neutrons are constrained to energies \(E_x > S_n\) and uncertainties in the vicinity of \(S_n\) are large. This contribution discusses a novel approach viz. polarized proton scattering at angles close to and including \(0^\circ\), to provide the complete \(E1\) response in nuclei up to excitation energies well above the region of the GDR. At proton energies of 200 – 400 MeV the cross sections at small momentum transfers are dominated by isovector spinflip-M1 transitions (the analog of the Gamow-Teller mode) and by Coulomb excitation of non-spinflip \(E1\) transitions [16, 17]. A separation of these two contributions, necessary for an extraction of the \(E1\) response, is achieved by two independent methods: a multipole decomposition analysis of the angular distributions (MDA) and the measurement of polarization transfer (PT) observables.

2. Experimental and analysis

The experimental techniques are described in Ref. [18] and details of the \(^{208}\text{Pb}\) measurement in Ref. [19]. A spectrum measured at \(0^\circ\) spectrometer angle is displayed in Fig. 1. Besides strong transition at low excitation energies, in the giant resonance region prominent excitation of the GDR is observed. Because of the excellent energy resolution \(\Delta E = 25 – 30\) keV (FWHM) pronounced fine structure is visible, a phenomenon now established as a global feature of giant resonances [20, 21]. The grey line indicates the experimental background mainly due to small-angle scattering in the target. It is determined from the focal-plane position distribution in non-dispersive direction achieved by operating the spectrometer optics in an underfocus mode [18].

For an extraction of the cross sections due to M1 and E1 excitations, two independent methods are used. The first one is based on the measurement of the polarization transfer coefficients \(D_{NN}, D_{SS}\) and \(D_{LL}\), where \(N\) (normal), \(S\) (sideways), and \(L\) (longitudinal) define a coordinate axis.
system in the frame of the moving proton. A complete set of these observables permits a unique identification of the spinflip character of a transition [22]. At 0°, $D_{NN} = D_{SS}$. This allows the definition of the total spin transfer $\Sigma$

$$\Sigma \equiv \frac{3(2D_{SS} + D_{LL})}{4},$$  \hspace{1cm} (2)

which takes values $\Sigma = 1$ and 0 for spinflip and non-spinflip transitions, respectively. Figure 2 presents a decomposition of the total cross sections (top) into $\Delta S = 1$ (middle) and $\Delta S = 0$ (bottom) parts for the $^{208}$Pb data. In the giant resonance region $\Sigma \approx 0$ is found as expected from the non-spinflip character of the GDR. In general, the spinflip part of the cross section is small except for the region $E_x \simeq 7 – 9$ MeV, where the spinflip M1 resonance was observed previously [23].

![Figure 2](image_url)

**Figure 2.** Decomposition of non-spinflip ($\Delta S = 0$) and spinflip ($\Delta S = 1$) cross section parts based on the MDA and PT, respectively, in the excitation energy region 5 – 9 MeV. The hatched areas indicate the experimental uncertainties. Excellent agreement between the two completely independent methods is observed.

Alternatively, a decomposition of the cross sections into multipole contributions based on their different angular dependence can be performed. Predictions for the shapes of the angular distributions needed for such an analysis were obtained from calculations with the code DWBA07 [24] using microscopic quasiparticle-phonon model (QPM) wave functions [25] and the Love-Franey effective proton-nucleus interaction [26]. For E1 transitions, the interference of Coulomb and nuclear contributions was taken into account. Although data were available up to 10°, it was decided to limit the angle range to $\Theta \leq 4°$ in order to enhance the selectivity on lower multipoles of interest here at small momentum transfers. This allowed a restriction to transferred angular
momenta $\Delta L = 0$ (M1) and $\Delta L = 1$ (E1), while higher multipoles were subsumed in a $\Delta L = 2$ contribution. In order to account for the model dependence of this assumption, the analysis was repeated replacing $\Delta L = 2$ by $\Delta L = 3$. The $\chi^2$-weighted mean of the fits with all possible combinations of theoretical angular distributions provides the final result. In the GDR region the M1 contribution was zero within error bars and was replaced by a phenomenological background describing the data at high excitation energies.

A direct comparison of both methods is possible under the assumption that all contributions $\Delta L > 0$ in the multipole decomposition are of non-spinflip nature. Figure 2 demonstrates excellent agreement up to $E_x = 9$ MeV. At higher excitation energies the comparison is hampered by the contributions of quasi-free scattering in the spectrum, which are known to contain a non-negligible spinflip part [27] and cannot be distinguished in the multipole analysis. In any case, both methods agree that $\Delta S = 1$ contributions are very small.

3. E1 strength distribution
It can be shown that under the experimental conditions at very small angles ($\Theta < 1^\circ$) E1 transitions arise purely from Coulomb excitation. This allows an extraction of reduced transition strengths using semiclassical theory [28]. The resulting B(E1) strength up to 8.2 MeV is compared in Fig. 3(a) with an average over all available $^{208}$Pb($\gamma, \gamma'$) and $^{207}$Pb($\gamma, n$) data (see [25, 29, 30, 31] and references therein). Excellent agreement is obtained up to $S_n$. The excess strength in the ($p, p'$) data above threshold can be attributed to previously unknown partial neutron decay widths. Figure 3(b) provides a summary of photoabsorption cross section data.
on $^{208}$Pb in the GDR region. Besides the present work, results using positron annihilation in flight [32] and tagged photons [33] are available. Again, very satisfactory agreement of all three measurements is observed.

4. Polarizability
As discussed above, an important quantity, which can be derived from the data, is the electric dipole polarizability. We find $\alpha_D = 18.9(13) \text{ fm}^3/e^2$ for the E1 strength up to 20 MeV. By taking an average of all available data including excitation energies up to 130 MeV [32, 33], a result with further reduced uncertainty $\alpha_D = 20.1(6) \text{ fm}^3/e^2$ is obtained. The covariance ellipsoid of the correlation between $\alpha_D$ and the neutron skin thickness $r_{\text{skin}}$ in the approach of Ref. [8] is shown in Fig. 4. Only with the present precision for $\alpha_D$ (hatched band) one can constrain the neutron skin thickness to $r_{\text{skin}} = 0.156^{+0.025}_{-0.021}$ fm. The hitherto most precise determinations of this quantity for $^{208}$Pb [34, 35] deduced from exotic atoms ($r_{\text{skin}} = 0.18 \pm 0.02$ fm) and hadron scattering ($r_{\text{skin}} = 0.211^{+0.054}_{-0.063}$ fm), respectively, are in excellent agreement with our result based on a totally independent method.

![Figure 4. Extraction of the neutron skin in $^{208}$Pb based on the correlation between $r_{\text{skin}}$ and the dipole polarizability $\alpha_D$ established in Ref. [8]](image)

Recent calculations of neutron matter and neutron star properties [36] in the framework of chiral effective field theory suggest $r_{\text{skin}} = 0.17 \pm 0.03$ fm. The predictions are sensitive to three-nucleon forces, which may be further constrained by the present results. Since the correlation between polarizability, neutron skin thickness and symmetry energy is model-dependent, viz. $r_{\text{skin}} \propto \alpha_D \cdot a_{\text{sym}}$ [37], a systematic study with a variety of EDFs as well as experimental tests in other nuclei would be important.

5. Conclusions and outlook
Polarized proton scattering at very forward angles allows to study, with high resolution, the complete electric dipole response of nuclei from low excitation energies up to the GDR. The E1 strength distribution deduced in a benchmark experiment on $^{208}$Pb is in excellent agreement with available data. It provides, however, new information in the region around the neutron emission threshold where all previous experiments had limited accuracy. A precise value for the E1 polarizability can be extracted with important consequences for a determination of the neutron skin and the symmetry energy in neutron-rich nuclei. Although controversially discussed
\[ r_{\text{skin}} \] may independently be derived from a similar correlation with the PDR strength \([9, 12]\), which is accurately determined by the present data as well.

Beyond these results, the experiment also provides information on the spin-M1 resonance in \(^{208}\)Pb. Furthermore, the fine structure of the dipole modes contains information on level densities \([21]\) and characteristic scales \([20]\), giving insight into their dominant damping mechanisms. Systematic studies of the E1 and spin-M1 response in nuclei are currently underway with this new powerful technique.

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