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Complete Electric Dipole Response in ^{120}Sn and ^{208}Pb and Implications for Neutron Skin and Symmetry Energy

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Abstract. Polarized proton scattering at energies of a few 100 MeV and extreme forward angles including 0° has been established as a new tool to extract the complete E1 response in nuclei up to excitation energies of about 20 MeV. A case study of ^{208}Pb demonstrates excellent agreement with other electromagnetic probes. From the information on the B(E1) strength one can derive the electric dipole dipole polarizability, which is strongly correlated to the neutron skin and to parameters of the symmetry energy. Recently, we have extracted the polarizability of ^{120}Sn with a comparable precision. The combination of both results further constrains the symmetry energy parameters and presents a challenge for mean-field models, since the relativistic and many Skyrme parameterizations cannot reproduce both experimental results simultaneously.

1 Introduction

The electric dipole (E1) response of nuclei is dominated by the giant dipole resonance (GDR), a collective mode at high excitation energy which exhausts most of the energy-weighted sum rule [1]. Properties of the GDR are fairly well understood but recent interest focuses on evidence for a soft mode in neutron-rich nuclei at lower excitation energies termed pygmy dipole resonance (PDR). For a recent review see Ref. [2]. Because of the saturation of nuclear density, excess neutrons are expected to concentrate on the surface forming a skin whose oscillations against an isospin-saturated core should give rise to a low-energy E1 mode [3]. Therefore, the PDR may shed light onto the formation of neutron skins in nuclei [4]. Another quantity related to nuclear E1 modes is the symmetry energy acting as restoring force. The E1 strength distribution carries information on its magnitude and density dependence [5]. The neutron matter equation of state in turn is a key ingredience for the modeling of the equilibrium properties of neutron stars [6].

A case of special interest is the doubly magic nucleus ^{208}Pb. Studies of energy density functionals (EDFs) using Skyrme forces or a relativistic framework suggest the nuclear dipole polarizability α_D as an observable carrying information on both neutron skin and symmetry energy [7]. The polarizability is related to the photoabsorption cross section σ_{abs} by [8]

$$\alpha_D = \frac{\hbar c}{2\pi^2 e^2} \int \frac{\sigma_{abs}}{\omega^2} \, d\omega, \qquad (1)$$

where ω denotes the photon energy. Because of the inverse energy weighting knowledge of the E1 strength at low energies – despite its smallness – is crucial for determining the polarizability.

The centroid of the PDR in heavy nuclei typically lies in the vicinity of the neutron emission threshold S_n. Data on the PDR in very neutron-rich nuclei are still scarce [9–12]. Stable nuclei at different shell closures have been explored with the (γ,γ') reaction [2]. Most of the experimental techniques sensitive to the E1 strength provide data either below or above S_n only. This contribution discusses a novel approach, viz. polarized proton scattering at angles close to and including 0°, allowing to extract the *complete E1 response in nuclei* covering the excitation region of PDR and GDR. Here, besides published data on ^{208}Pb first results for ^{120}Sn are shown and the impact of the combined results on EDFs is explored.

2 Experiments

The experimental techniques are described in Ref. [13] and details of the ^{208}Pb measurement in Ref. [14]. Spectra of the ^{120}Sn(p,p′) reaction at $E_0 = 295$ MeV and forward angles are displayed in Fig. 1. They are dominated by the broad GDR peak centered at about 15 MeV. Towards larger angles the differential cross sections exhibit a fast fall-off characteristic for Coulomb excitation. Between 5 and 9 MeV a structured bump is visible, whose cross sections also decrease with angle. It is expected to contain the PDR but also contributions from spin-flip M1 excitations. For proton energies of 200 – 400 MeV the nuclear cross sections at small momentum transfers are dominated by isovector spinflip-M1 transitions [15], whose cross sections also peak at 0° because of the $\Delta L = 0$ angular momentum transfer.

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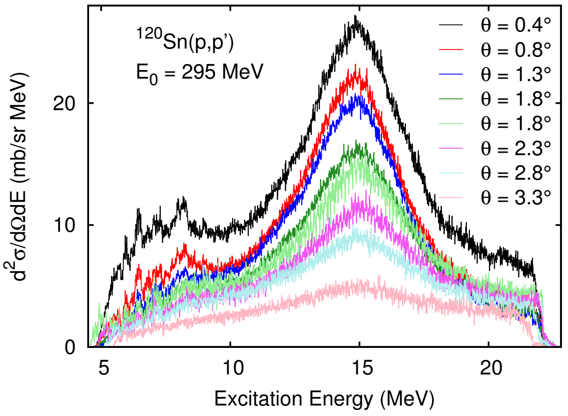

Figure 1. Differential cross sections of the ^{120}Sn(p,p′) reaction at $E_0 = 295$ MeV and very forward angles.

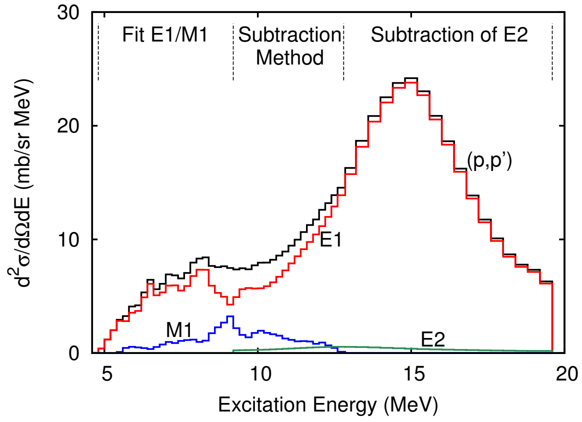

Figure 2. Result of the multipole decomposition for ^{120}Sn into E1 and M1 cross sections. E2 cross sections have been calculated with the code DWBA07 using the experimental strength distribution of Ref. [19] and the Love-Franey effective interaction [18] and subtracted prior to the MDA.

3 Decomposition of E1/M1 cross sections

An extraction of the cross sections due to M1 and E1 excitations was performed in two independent ways based on a multipole decomposition of cross section angular distributions (MDA) and on the measurement of polarization transfer observables (PTA). The MDA is explained in detail in Refs. [16, 17]. It is based on model calculations using the code DWBA07, microscopic transition densities from the quasiparticle-phonon model (QPM), and the Love-Franey proton-nucleus effective interaction [18]. Unlike the case of ^{208}Pb, in ^{120}Sn no individual transitions could be resolved at low excitation energy despite the good energy resolution of about 25 keV due to the higher level density. Therefore the MDA was performed in energy bins of 200 keV (400 keV above 12 MeV). Under such conditions no sizable contributions to the cross sections from multipoles other than E1 or M1 are indicated by the experimental angular distributions except the excitation of the isoscalar giant quadrupole resonance (GQR). Its contributions to the cross sections were determined by normalizing the QPM predictions for the GQR to the experimental isocalar E2 strength distribution taken from Ref. [19] and subtracting the resulting cross sections from the spectra at all angles prior to the MDA. The decomposition into E1 and M1 cross sections is shown in Fig. 2 together with the E2 cross sections resulting from the above described procedure.

Alternatively, the measurement of the polarization transfer coefficients D_{SS}, D_{NN}, and D_{LL} can be used for the decomposition, where S, N, and L denote sidewards, normal, and longitudinal polarization spanning a coordinate system defined with respect to the moving incident proton. The combination of these polarization transfers observables takes specific values for spinflip (−1) and non-spinflip (+3) transitions [20]. At 0°, D_{SS} and D_{NN} are indistinguishable and it suffices to measure one of them (D_{SS} in the present case). The relation of Ref. [20] can then be rearranged to introduce a total spin transfer Σ

$$\Sigma = \frac{3 - (2D_{SS} + D_{LL})}{4}, \tag{2}$$

which takes a value of 0 for $\Delta S = 0$ (non-spinflip) and 1 for $\Delta S = 1$ (spinflip) transitions. The different reaction mechanisms allow an idenfication of spinflip with M1 and non-spinflip with E1 transitions, respectively.

Figure 3 presents a comparison of the results from MDA and PTA in the excitation energy region up to 12.5 MeV (at higher E_x the M1 contribution is negligible). Good agreement of the two independent methods is obtained except for the energy region between 8 and 9 MeV, where the PTA yields somewhat larger $\Delta S = 1$ cross sections although both methods still agree within error bars.

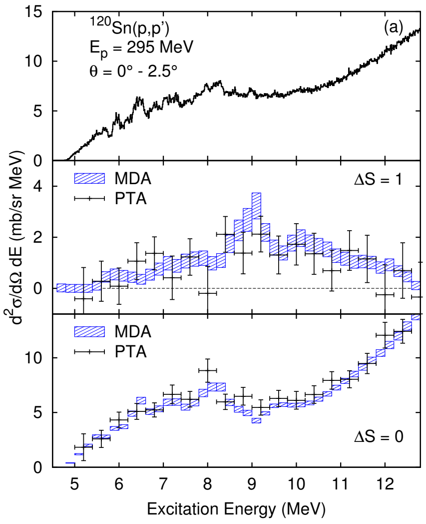

Figure 3. Comparison of the decomposition of E1/M1 cross sections for ^{120}Sn using MDA and PTA.

4 Polarizability

The E1 cross sections of Fig. 2 can be converted into reduced B(E1) transition strengths with the aid of the semiclassical model of Coulomb excitation [21]. The electric dipole polarizability of ^{120}Sn can then be determined using Eq. (1). Additional data from excitation energy regions not accessible in the present experiment were also considered. Below 5 MeV, the E1 strength was taken from the (γ,γ') data [22]. Above 29 MeV, photoabsorption cross sections from a natural Sn target [23] were taken into account assuming that the absolute cross sections and energy dependence are equal for all stable tin isotopes. In the giant resonance region, photoabsorption cross sections deduced from the present work were averaged with data from $(\gamma$,n) [24] and $(\gamma$,xn) [25, 26] experiments.

The resulting polarizability of ^{120}Sn is plotted in Fig. 4 versus the polarizability of ^{208}Pb. The yellow bands indicate the respective experimental uncertainties. The predictions of a variety of EDFs based on Skyrme forces for these two quantities a shown in comparison. A description of SV-min and SV-Bas can be found in Ref. [27]. The open circle shows the results from latest attempt of the UNEDEF collaboration aiming at the determination of an optimal EDF [28]. References to the other forces are summarized in Ref. [29].

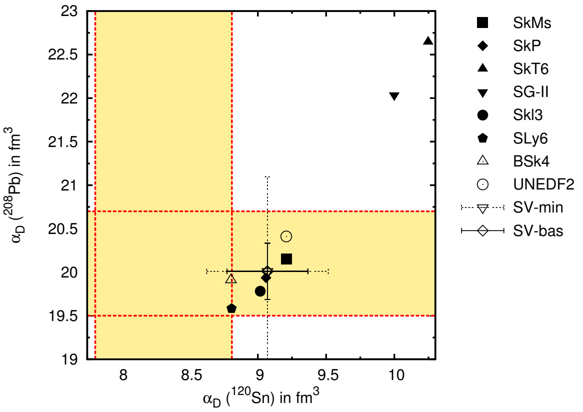

Figure 4. Polarizabilites of ^{208}Pb and ^{120}Sn in comparison to EDFs based on Skyrme forces.

While some models (SKT6, SG-II) predict too large values of α_D for both nuclei, most Skyrme forces are capable of reproducing the experimental result for ^{208}Pb but find a somewhat too large value for ^{120}Sn. Exceptions are SLy6 and BSK4 which predict polarizabilities compatible with both values. There is no estimate of the theoretical uncertainties except for SV-min and SV-bas, where a corresponding procedure is decribed in Ref. [27]. By way of construction the errors are much larger for SV-min than for SV-bas. However, for both models there is some overlap with the experimental data point for ^{120}Sn taking these error bars into account.

Figure 5 depicts the same correlation as Fig. 4 but in comparison to relativistic mean-field models. Specifically, results for PC (full symbols) [30], DD-ME2 (open symbols) [31] and FSU (cross) [4] are shown. In the relativistic models one can study the dependence on the symmetry energy by varying its magnitude described by the parameter J (or a_0) [5]. The summary of presently available results favor a value $J \simeq 30-35$ MeV [32]. The effect of a variation between $J = 28$ and 36 MeV is demonstrated in Fig. 5. All results approximately fall on a straight line, i.e., a proportionality of both α_D values with J is observed. For ^{208}Pb, such a correlation was already established by Roca-Maza et al. [33]. However, the absolute value of J needed to describe $\alpha_D(^{208}\mathrm{Pb})$ differs for the PC and DD-ME2 forces. Furthermore, all three models fail to describe both polarizabilities simultaneously. This implies that the density dependence of the symmetry energy predicted by the relativistic models is not correct.

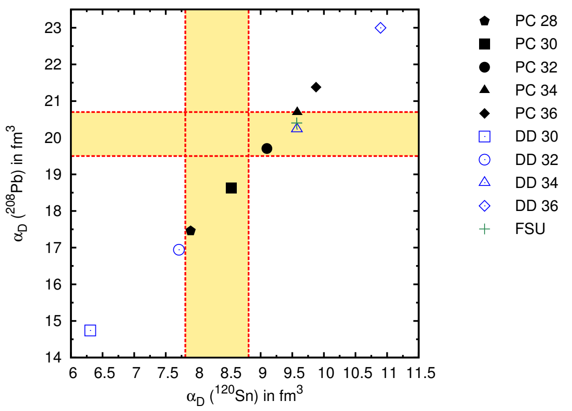

Figure 5. Polarizabilites of ^{208}Pb and ^{120}Sn in comparison to EDFs based on relativistic models.

5 Concluding Remarks

Polarized proton scattering at very forward angles allows to study, with high energy 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 all available data. 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. Since the correlation between polarizability, neutron skin thickness and symmetry energy ($\Delta r_{np} \propto \alpha_D \cdot J$ [34],) is model-dependent, experimental tests in other nuclei are important as a constraint of the poorly determined isovector interaction in EDFs.

The present work presents a first result for the semimagic nucleus ^{120}Sn. The correlation between both polarizabilites reveals a sytematic problem of RMFs, which cannot reproduce both values simultaneously irrespective of the choice of the symmetry energy strength. This points to a problem of RMFs to provide the correct density dependence of the symmetry energy, which is crucial for an extrpolation into the high-density regime of neutron stars. EDFs based on Skyrme forces tend to give a somewhat too large value for ^{120}Sn but the agreement is probably still acceptable taking theoretical uncertainties into account. In any case, in view of these new results a systematic study of the dipole polarizability over a wider range of nuclei is of utmost importance and work along these lines is underway.

The (p, p') data also provide information on other interesting questions not dicussed here because of lack of space. Utilizing isospin symmetry, the M1 cross sections resulting from the MDA and PTA decomposition can be converted into reduced B(M1) transition strengths [35]. This promises systematic information on the hardly explored spin-M1 resonance in heavy nuclei [15, 36]. Excellent agreement with results from eletromagnetic probes [37] is found for ^{208}Pb. Furthermore, because of the high energy resolution fine structure is systematically observed in the excitation region of the GDR. With a wavelet analysis [38, 39] one can extract information on important decay mechanisms of the GDR and the level density of $j^{\pi} = 1^{-}$ states [40].

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