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Deformation dependence of the isovector giant dipole resonance: The neodymium isotopic chain revisited

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ABSTRACT

Proton inelastic scattering experiments at energy $E_p = 200$ MeV and a spectrometer scattering angle of 0° were performed on ^{144,146,148,150}Nd and ^{152}Sm exciting the IsoVector Giant Dipole Resonance (IVGDR). Comparison with results from photo-absorption experiments reveals a shift of resonance maxima towards higher energies for vibrational and transitional nuclei. The extracted photo-absorption cross sections in the most deformed nuclei, ^{150}Nd and ^{152}Sm, exhibit a pronounced asymmetry rather than a distinct double-hump structure expected as a signature of K-splitting. This behaviour may be related to the proximity of these nuclei to the critical point of the phase shape transition from vibrators to rotors with a soft quadrupole deformation potential. Self-consistent random-phase approximation (RPA) calculations using the SLy6 Skyrme force provide a relevant description of the IVGDR shapes deduced from the present data.

1. Introduction

Giant resonances represent a prime example of collective modes in the nucleus. A smooth mass-number dependence of the resonance parameters is characteristic of all nuclear giant resonances and, as such, a study of them yields information about the non-equilibrium dynamics and the bulk properties of the nucleus [1]. The oldest and best known giant resonance is the IVGDR owing to the high selectivity for isovector E1 excitation in photo-absorption experiments. The properties of the IVGDR have been studied extensively using (γ, xn)-type experiments, particularly in the Saclay [2] and Livermore [3] laboratories. These sets of experiments are a major source of information with respect to the γ-strength function [4] above the neutron threshold – an important quantity used in statistical reaction calculations relevant to

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applications like astrophysical large-scale reaction networks [5,6], reactor design [7], and even nuclear waste transmutation [8].

Recently, a new experimental technique for the extraction of electric dipole-strength distributions in nuclei via relativistic Coulomb excitation has been developed [9,10]. It utilises proton inelastic scattering with energies of a few hundred MeV at scattering angles close to 0°. Although many of these experiments focus on establishing the strength below and around neutron threshold and its contribution to the dipole polarisability [11–16], such data also provide information on the photo-absorption cross sections in the energy region of the IVGDR.

The chain of stable even–even neodymium isotopes is known to comprise a transition from spherical to deformed ground states for heavier isotopes and thus represents an excellent test case to study the influence of deformation on the properties of the IVGDR. A (γ,xn) experiment at Saclay [17] revealed that the width increases with deformation evolving into a pronounced double-hump structure in the most deformed nuclide ^{150}Nd, considered to be a textbook example [18] of K-splitting owing to oscillations along the different axes of the quadrupole-deformed ground state. Here, we report new photo-absorption cross sections for ^{144,146,148,150}Nd extracted from 200 MeV proton scattering experiments with results differing significantly from Ref. [17]. In particular, no double-hump structure is observed in the most deformed ^{150}Nd nucleus. This finding is confirmed in a further measurement of the comparably deformed ^{152}Sm nucleus, again in contrast to a (γ,xn) measurement at Saclay [19]. This unexpected result may be related to the special structure of these two nuclei which are predicted to lie near the critical point [20] of a shape phase transition from spherical to quadrupole-deformed ground states [21].

2. Experiment and analysis

The proton inelastic scattering experiments were performed at the iThemba Laboratory for Accelerator Based Sciences (iThemba LABS) in South Africa. The K600 magnetic spectrometer, positioned at 0° with the acceptance defined by a circular collimator having an opening angle $\theta_{\mathrm{lab}} = \pm 1.91°$, was used to analyse a scattered 200 MeV dispersion-matched proton beam delivered from the Separated Sector Cyclotron of iThemba LABS. The self-supporting ^{144,146,148,150}Nd and ^{152}Sm targets were all isotopically enriched to values $> 96\%$ (except ^{148}Nd enriched to 90%) with areal densities ranging from 1.8 to 2.6 mg/cm^2. The corresponding ground-state deformation parameters β_2 are given in the second column of Table 1. The beam preparation and the detector setup are described in Ref. [10]. Details regarding the data extraction and analysis of the present measurements can be found in Ref. [22].

In the chosen kinematic conditions, relativistic Coulomb excitation of the target nuclei is the dominant reaction mechanism. The resulting double-differential cross sections (with a systematic uncertainty of ±7%) obtained following the procedures detailed in Ref. [22] are displayed in Fig. 1 for 20 keV energy bins. A typical energy resolution $\Delta E = 45$ keV (FWHM) was achieved. The broad structure visible in all spectra between approximately $E_{\mathrm{x}} = 12$ and 18 MeV corresponds to the excitation of the IVGDR. Statistical errors in this region are of the order of 2–4%. From Fig. 1 it is immediately evident that the width of the IVGDR increases steadily from the nearly spherical ^{144}Nd nucleus through the transition region to the more deformed ^{150}Nd and ^{152}Sm nuclei.

In order to compare to the (γ,xn) data of Carlos et al. [17,19], the (p,p') spectra had to be converted to equivalent photo-absorption cross sections. By way of example, Fig. 2 provides an overview of the conversion process for ^{150}Nd. It can be divided into three distinct stages, namely, background subtraction in the region of the IVGDR, calculation of the virtual-photon spectrum

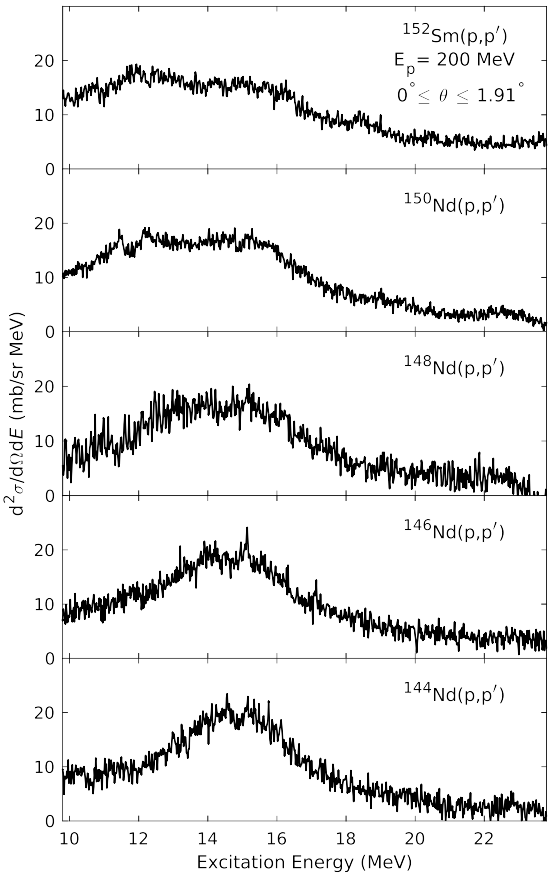

Fig. 1. Experimental double-differential cross sections for the ^{144,146,148,150}Nd(p,p') and ^{152}Sm(p,p') reactions at $E_{\mathrm{p}} = 200$ MeV and $\theta_{\mathrm{lab}} = 0° \pm 1.91°$.

and the division by this spectrum multiplied through by the virtual γ energy to obtain equivalent photo-absorption cross sections. This procedure has been tested for several cases (^{48}Ca, ^{120}Sn, ^{208}Pb) and fair agreement of the resulting shape and absolute values of the photo-absorption cross sections with experiments using real photons was obtained [11–15].

Background from nuclear processes studied in similar experiments at 300 MeV has been found to be small in heavy nuclei [11–14]. It was modelled in the present case by three components. The contributions of the IsoScalar Giant Monopole Resonance (ISGMR, green line) and IsoScalar Giant Quadrupole Resonance (ISGQR, pink line) to the spectrum of Fig. 2(a) were estimated in the following way [13,15]: Computed angular distributions of the ISGMR and ISGQR cross sections were determined by distorted wave Born approximation calculations with the code DWBA07 [23] using quasiparticle phonon model (QPM) transition amplitudes and the Love–Franey effective interaction [24] as input (analogous to Ref. [12]). A representative example of such calculations for Nd and Sm isotopes is shown in Fig. 3.

After averaging over the experimental angular acceptance, these calculations provide a relation between theoretical cross sections and transition strengths under the assumption of a dominant one-step reaction mechanism, which should be well fulfilled at an incident proton energy of 200 MeV. Utilising this proportionality, experimental ISGMR and ISGQR strength distributions can then be converted to (p,p') cross sections in the present spectra. For comparison, the predicted IVGDR cross section is also shown and clearly dominates the spectra. However, the B(E1) transition strengths (and thus the photo-absorption cross sections) cannot be