Nuclear-structure experiments at iThemba LABS to investigate discrepancies between (p,p') and $(\gamma, x\mathrm{n})$ data

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Abstract. The iThemba Laboratory for Accelerator Based Sciences (iThemba LABS) is a centre of expertise and innovation in the field of nuclear-structure physics and is a leader in several high-impact studies. One of the highlights of these nuclear-structure experiments is the study of the broad structure of the IsoVector Giant Dipole Resonance (IVGDR) in the rare-earth region. Proton inelastic scattering experiments with $E_{\mathrm{p}} = 200$ MeV were performed on the even-even Nd isotope chain and ^{152}Sm at very forward scattering angles including zero degrees with the K600 magnetic spectrometer. The evolution of the shape of the IVGDR in the transition from spherical to deformed nuclei was investigated. One of the goals of this highlighted study was to confirm the K-splitting observed in previous photo-absorption measurements from Saclay. Significant discrepancies were found between the direct $(\gamma, x\mathrm{n})$ data obtained at Saclay and the equivalent photo-absorption cross sections obtained using $(\mathrm{p}, \mathrm{p}')$ data from the K600. Furthermore, discrepancies exist for several nuclei between photo-absorption data taken at the Saclay and Livermore laboratories. These discrepancies, possible reasons for them and future investigations will be presented and discussed.

1. Introduction

Photo-absorption is a powerful tool for understanding aspects of nuclear structure, in particular the IsoVector Giant Dipole Resonance (IVGDR). The behaviour of the IVGDR provides information on the symmetry energy of nuclear matter which has applications for the nuclear equation of state in neutron stars [1]. The location and strength of the IVGDR is also crucial in determining nucleosynthesis in the *s*-, *r*-, and *p*-processes [2; 3]. Data on photo-absorption cross sections are also used in the design of nuclear reactors, neutron shielding, radioisotope production from electron accelerators, and radiation therapy [4]. It is, therefore, clear that accurate photo-absorption data are critical for the entire nuclear-data community. In fact, because of the importance of this information, there was an International Atomic Energy Agency (IAEA) project to generate a new database for strength functions and to update existing photo-nuclear data [5; 6].

In recent years, an experimental technique for the extraction of electric-dipole strength distributions in nuclei via relativistic Coulomb excitation has been developed [7; 8]. It utilises proton inelastic scattering with energies of a few hundred MeV at scattering angles close to zero degrees. Under these kinematic conditions, the background from nuclear processes in heavy nuclei has been found to be small and its contribution can easily be subtracted [9–13]. Although many of these experiments aim to establish the strength below and around the neutron threshold and its contribution to the dipole polarisability [9–12; 14; 15], the data contain information on the photo-absorption cross sections in the energy region of the IVGDR. This technique is an alternative to direct measurements of the photo-absorption cross sections by either the detection of the outgoing neutrons produced in $(\gamma, x\mathrm{n})$ reactions, or by observation of the decay of the unstable nucleus resulting from the activation of the target sample.

2. Discrepancies in existing photo-absorption data

2.1. Photo-absorption studies at Saclay and Livermore

Owing to the numerous applications of photo-absorption reactions, they have been extensively studied, typically using $(\gamma, x\mathrm{n})$-type experiments, and particularly in the Saclay [16] and Livermore [17] laboratories. However, it has long been known that inconsistencies in the cross sections and relative contributions of the $(\gamma, 1\mathrm{n})$ and $(\gamma, 2\mathrm{n})$ components exist in the Saclay and Livermore data [18]. Re-evaluations of the photo-neutron cross sections for various nuclides [19; 20] suggest that the multiplicity-sorting method used to distinguish the various $(\gamma, x\mathrm{n})$ channels may have led to systematic biases, shifting events from the $(\gamma, 2\mathrm{n})$ to the $(\gamma, 1\mathrm{n})$ channel owing to, among other factors, the neutron background in the detectors, and the neutron energy distribution when there are competing (γ, n), $(\gamma, 2\mathrm{n})$, and (γ, np) reactions. Gheorghe *et al.* [21] applied a new method of Direct Neutron Multiplicity (DNM) sorting to new $^{209}\mathrm{Bi}(\gamma, x\mathrm{n})$ data and the results corroborate this perspective. This measurement is one of those studied by the PHOto-Excitation and Neutron emIssion cross [X] section (PHOENIX) collaboration, which performed a $(\gamma, x\mathrm{n})$ measurement of, amongst others, ^{159}Tb using the DNM sorting method in 2018 [6].

2.2. $(\mathrm{p}, \mathrm{p}')$ *and* $(\gamma, x\mathrm{n})$ *measurements*
Photo-absorption studies have been a particular focus of experimental work using the K600 magnetic spectrometer at the iThemba Laboratory for Accelerator Based Sciences (iThemba LABS) using the $(\mathrm{p}, \mathrm{p}')$ reaction with $E_\mathrm{p} = 200$ MeV at zero degrees [13; 22; 23]. The advantage of using the $(\mathrm{p}, \mathrm{p}')$ reaction mechanism for photo-absorption studies is that it is an inclusive measurement relying on the relativistic Coulomb excitation of the target nucleus by the exchange of virtual photons [24]. It does not require the detection of any specific decay mode of the IVGDR. The measurement of each excitation energy is taken with the same probe - inelastic proton scattering - obviating concerns such as changing detection efficiency for neutrons as is present in photo-neutron experiments.

The analysis of $(\mathrm{p}, \mathrm{p}')$ data taken at the Research Center for Nuclear Physics (RCNP) [9; 12; 14; 15] shows fair agreement with $(\gamma, x\mathrm{n})$ and total photo-absorption data in spherical nuclei (^{208}Pb, ^{120}Sn, ^{40,48}Ca) and slight deviations for the moderately-deformed ^{96}Mo nucleus, thus indicating the reliability of the energy dependence of the virtual-photon spectrum. There may be limitations to the $(\mathrm{p}, \mathrm{p}')$ approach when accurate scattering-angle information related to the non-dispersive direction is unavailable (which is the case at iThemba LABS but not at RCNP). It should be noted that this limitation means that *absolute* cross sections are difficult to obtain, but the distribution of the IVGDR in excitation energy is not compromised. That being said, fair agreement has been obtained between data taken at iThemba LABS and real-photon experiments for medium-mass nuclei. Internal consistency of normalisation (0.6 ± 0.1 down to (γ, abs)) was achieved using the virtual-photon method on $(\mathrm{p}, \mathrm{p}')$ data [25].

A recently published study on the IVGDR for selected neodymium and samarium isotopes obtained using the K600 magnetic spectrometer [13] found non-trivial disagreements with respect to the distribution of the IVGDR strength between the extracted photo-absorption information from iThemba LABS and pre-existing $(\gamma, x\mathrm{n})$ data from Saclay [26; 27] (see Fig. 1). However, in line with the concerns raised in Refs. [19; 20] about potential systematic biases in the data from Saclay and Livermore, this disagreement may result from the processing of the photo-neutron data and does not necessarily indicate problems with the indirect method used in the analysis of the K600 data (see Ref. [13] for details). It is important, however, to understand the unexpected discrepancies observed for deformed nuclei.

3. Delving deeper into discrepancies between $(\mathrm{p}, \mathrm{p}')$ and $(\gamma, x\mathrm{n})$ measurements
In order to further investigate the above-mentioned discrepancies, we will obtain the photo-absorption cross sections of ^{90}Zr and ^{159}Tb using the inelastic scattering of 200 MeV protons at very forward scattering angles with the K600 magnetic spectrometer. Whilst these nuclei are disparate in mass, their selection is deliberate: first, photo-neutron data were collected at both Saclay and Livermore for both nuclei and second, the IVGDR in ^{90}Zr is dominated by the $(\gamma, 1\mathrm{n})$ channel whereas that in ^{159}Tb has contributions from both the $(\gamma, 1\mathrm{n})$ and $(\gamma, 2\mathrm{n})$ channels. In ^{90}Zr, the two-neutron threshold lies at high excitation energy, above the main peak

of the IVGDR (see Fig. 2), and the (γ, p) cross section is thought to be weak in the peak of the IVGDR [28].

This allows for the comparison of the shape of the IVGDR determined from the proposed experiment with that determined from the $(\gamma, 1\mathrm{n})$ photo-neutron data without the inclusion of any confounding neutron-multiplicity effects. As a result, a relatively simple direct comparison can be made between the distribution of the IVGDR determined in the proposed experiment and the measured $(\gamma, 1\mathrm{n})$ cross section. By confirming the shape of the IVGDR using data taken with the K600 magnetic spectrometer, we can be sure that the $(\mathrm{p}, \mathrm{p}')$ reaction (in combination with the virtual-photon method) correctly reproduces the IVGDR distribution despite the shortage of vertical scattering-angle information.
Along with the ^{90}Zr data to test the validity of the $(\mathrm{p}, \mathrm{p}')$ method for photo-absorption independently at iThemba LABS, the possible impact of the neutron multiplicity will be investigated using ^{159}Tb. In ^{159}Tb, the IVGDR is predicted to have a bimodal distribution which spans the two-neutron threshold (see Fig. 3). Therefore, we would expect that if the processing of the photo-neutron data does, in fact, cause a transfer of events from the $(\gamma, 2\mathrm{n})$ to the $(\gamma, 1\mathrm{n})$ channel, we should see a similar effect in these data as for the neodymium and samarium data of Ref. [13]. This will allow us to verify that the differences observed between the photo-neutron data and the K600 data are due to the multiplicity-sorting problem. Proton inelastic scattering has been performed at RCNP on ^{154}Sm [29], which is a very similar case to ^{159}Tb. The two-neutron threshold sits roughly between the two IVGDR components. The results of the ^{154}Sm measurement suggest a reduced $K = 0$ component and a different $K = 0/K = 1$ ratio compared to the Saclay [27] results. Therefore, checking another deformed case like ^{159}Tb, where the results seem to depend on the multiplicity sorting into 1n and 2n channels, is important.

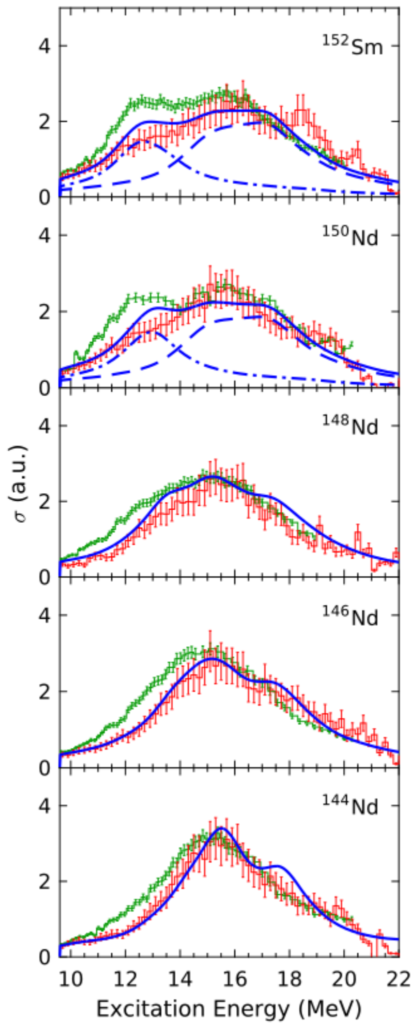

Figure 1. Photo-absorption cross sections obtained at iThemba LABS ([13] - red histograms) normalised to the maximum of the pre-existing $(\gamma, x\mathrm{n})$ results obtained at Saclay ([26; 27] - green histograms). The blue lines show the results of calculations using the Skyrme Separable Random-Phase Approximation [30] with the SLy6 force (solid: full, dash-dotted: $K = 0$ contribution, dashed: $K = 1$ contribution). Taken from Ref. [13].

The comparison between the newly obtained ^{159}Tb data will be made with photo-neutron data for the same nucleus (Ref. [33]) and with the corrected photo-neutron data given in Ref.

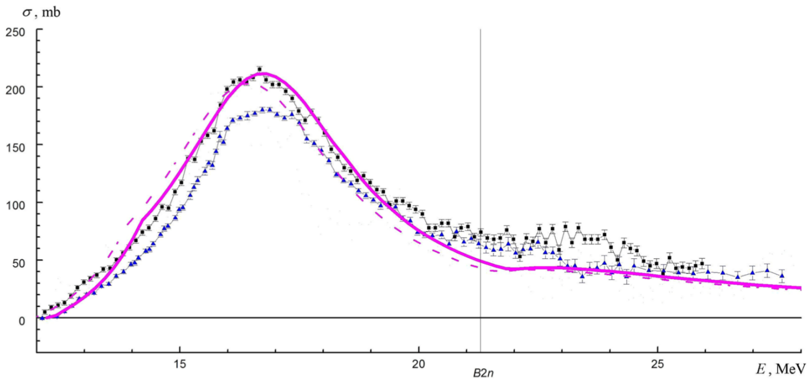

Figure 2. The comparison (taken from Ref. [19]) of the experimental cross sections $\sigma(\gamma, xn)$ obtained for ^{90}Zr at Livermore ([31] - blue triangles) and Saclay ([32] - black squares). The pink lines (dotted before and solid after correction) illustrate the result of calculations in the frame of the combined photo-nucleon reaction model. As can be seen, the main part of the IVGDR falls below the two-neutron threshold and is, therefore, dominated by single-nucleon emission.

[20] to determine whether the same relative effect is observed (i.e. the relative change in the cross sections of the $(\gamma, 1n)$ and $(\gamma, 2n)$ reactions). In addition, the newly obtained ^{159}Tb data from iThemba LABS will be compared to the results of the earlier-mentioned measurements by the PHOENIX collaboration after the application of the new DNM sorting method [34].

These comparisons will allow for confirmation that the discrepancies observed between the data of Ref. [13] and those of Refs. [26; 27] are, in fact, owing to the multiplicity unfolding of the photo-neutron data.
Further studies will allow us to clearly demonstrate that the application of the virtual-photon method to proton inelastic scattering data results in the extraction of reliable photo-absorption information. Given the importance of photo-absorption data in industrial applications, nuclear astrophysics, and nucleosynthetic studies, as well as studies of basic nuclear properties like the symmetry energy, it is vital that accurate and high-quality data are available to the nuclear-data community. This investigation provides a method for confirming that the photo-absorption information obtained from proton inelastic scattering data is valid and should be included in nuclear data evaluations of the photo-absorption strength.

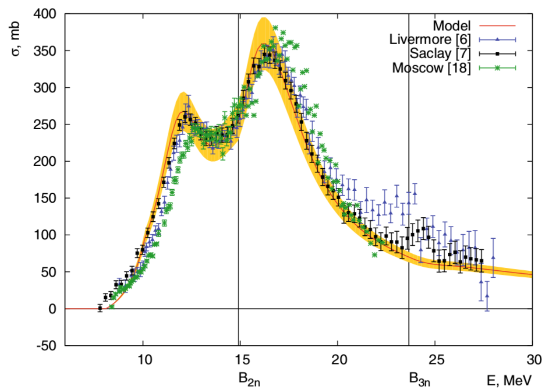

Figure 3. The calculated neutron yield for the ^{159}Tb(γ, xn) reaction (line, normalised) compared with experimental data taken at Livermore ([35] - blue triangles) and Saclay ([33] - black squares) and using Bremsstrahlung at Moscow State University ([36] - green stars, normalised). Taken from Ref. [20].

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