Physics Letters B 727 (2013) 361–365

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Constraining nuclear photon strength functions by the decay properties of photo-excited states

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A R T I C L E   I N F O

Article history:
Received 29 August 2013
Received in revised form 15 October 2013
Accepted 16 October 2013
Available online 22 October 2013
Editor: W. Haxton

Keywords:
Photon strength function
Pygmy dipole resonance
Nuclear resonance fluorescence
Gamma-spectroscopy

A B S T R A C T

A new approach for constraining the low-energy part of the electric dipole Photon Strength Function ($E1$-PSF) is presented. Experiments at the Darmstadt High-Intensity Photon Setup and the High Intensity $\vec{\gamma}$-Ray Source have been performed to investigate the decay properties of ^{130}Te between 5.50 and 8.15 MeV excitation energy. In particular, the average γ-ray branching ratio to the ground state and the population intensity of low-lying excited states have been studied. A comparison to the statistical model shows that the latter is sensitive to the low-energy behavior of the $E1$-PSF, while the average ground state branching ratio cannot be described by the statistical model in the energy range between 5.5 and 6.5 MeV.

1. Introduction

In complex quantum systems with high level density a statistical treatment is often used to describe average quantities of the system. In nuclear physics, e.g., this is the case for describing the nucleus at sufficiently high excitation energies within the so-called statistical model. In nuclear astrophysics this approach is used in Hauser–Feshbach calculations [1] to calculate reaction rates and properties of atomic nuclei relevant for the nucleosynthesis of the elements [2–4]. A crucial input in these statistical model calculations are Photon Strength Functions (PSF), that describe the average radiative transition probabilities between nuclear levels as a function of the γ-ray energy involved [5]. It has been shown, that the low-energy behavior of the $E1$-PSF may have an important impact on reaction rates in astrophysical calculations [6–8]. The statistical model is also used in the analysis of different experimental approaches, i.e. to correct for unobserved branching transitions [9], where the low-energy region of the PSF is of particular importance. However, so far very little experimental information is available in this energy region on the PSF or the validity of the statistical approach in general. In this Letter we present an experimental approach which is based on the method of Nuclear Resonance Fluorescence (NRF) [10] with quasi-monochromatic photon beams to constrain the low-energy dependence of the relevant PSF, exemplarily, for the case of ^{130}Te. In addition, we show that the decay properties of photo-excited states in the energy range from 5.5 to 6.5 MeV cannot be reproduced by the statistical model, which

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0370-2693/$ – see front matter
http://dx.doi.org/10.1016/j.physletb.2013.10.040

points to a violation of the Brink–Axel hypothesis [11]. Nuclear structure effects thus seem to play an important role in the description of the photoresponse of medium-heavy atomic nuclei even up to 6.5 MeV excitation energy.

Several approaches have been used in the past to determine the energy dependence of PSF at low γ-ray energies. While the photoabsorption cross section from NRF experiments probes the PSF in relation to transitions to the ground state and a few observed decays to lower-lying excited levels, other methods, based on the study of nuclear decay [12–15], provide an insight into the PSF between excited states. However, the results from different approaches are in some cases very contradictory [16].

The most relevant PSF is the $E1$-PSF, that is dominated at high γ-ray energies by the well-known Giant Dipole Resonance (GDR) [17–19]. In the last decades, at lower excitation energies another structure has been observed in NRF experiments [20,21,9,22–24], Coulomb Excitation experiments [25–27] as well as in decay spectroscopy experiments probing the $E1$-PSF [13,28,29]. This additional strength has been denoted as Pygmy Dipole Resonance (PDR) [30]. The results indicate that the extrapolation of the GDR using a Standard Lorentzian (SLO) parametrization do not offer an appropriate description of the $E1$-PSF at low γ-ray energies. However, at these energies experimentally verified information is very scarce, thus, input from experiments on the qualitative behavior of the relevant PSF is highly mandatory.

In this manuscript, we present a new approach which allows for constraining the low-energy behavior of the $E1$-PSF and testing the applicability of the statistical model by an analysis of the decay pattern from NRF experiments with continuous-energy bremsstrahlung and quasi-monochromatic photons.

2. Experiments

The first experiment took place at the Darmstadt High-Intensity Photon Setup (DHIPS) [31] using continuous-energy bremsstrahlung to determine the spin quantum numbers and the integrated cross sections of individual excited states relative to the calibration standard ^{11}B, see e.g. Refs. [9,23]. No information on parity quantum numbers and therefore on the transition character was accessible from this measurement. Hence, a second experiment was performed using a quasi-monochromatic, nearly 100% linearly polarized photon beam at the High Intensity $\vec{\gamma}$-Ray Source (HI$\vec{\gamma}$S) facility [32] at Triangle Universities Nuclear Laboratory. The linear polarization of the incoming photons enabled the assignment of parity quantum numbers to excited states [33] in the energy region from 5.5 MeV to 8.5 MeV. All observed states were assigned to have negative parity, thus, indicating that $E1$ strength is dominant in this energy regime. For the main part of this work we want to concentrate on average decay properties, which are essential for the statistical model.

3. Analysis and results

In the low-energy part of the measured spectra peaks originating from decays of the lowest 2^+ excited states are observed in the HI$\vec{\gamma}$S experiment. Since these states cannot be excited directly by the quasi-monochromatic photon beam, they can only be populated by decay cascades of the primary excited states. The feeding occurs through different cascades, each too weak to be observed. However, the lowest-lying excited states collect most of the total intensity of non-direct ground state transitions of photo-excited states, which, in the following, we denote as inelastic decay.

The analysis of the population intensities of these lowest excited states thus allows for measuring the average inelastic cross section $\sigma_{\gamma\gamma'}$ for each beam energy, which has been demonstrated

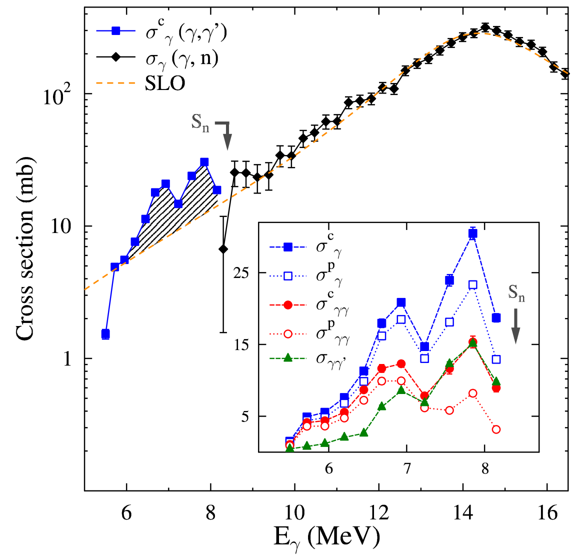

Fig. 1. (Color online.) Total photoabsorption cross sections from (γ,γ') and (γ,n) experiments [35]. Blue squares: total photoabsorption cross section; red dots: elastic cross section; green triangles: inelastic cross section. The hatched area corresponds to 0.83(6)% of the TRK sum rule. For details see text.

in Ref. [22]. Together with the elastic cross section $\sigma_{\gamma\gamma}$ the total photoabsorption cross section is given by $\sigma_\gamma = \sigma_{\gamma\gamma} + \sigma_{\gamma\gamma'}$.

Two different values for the elastic cross section are investigated: The cross section stemming from the analysis of resolved peaks in the spectra is denoted as $\sigma^p_{\gamma\gamma}$. The value indicated as $\sigma^c_{\gamma\gamma}$ takes into account the contribution of strength that might be hidden in the continuum of the spectra as pointed out earlier in [9,34]. This value is determined by integrating the total intensity observed in the spectra in the energy range between $E_b - 1\sigma_b$ and $E_b + 2\sigma_b$, where E_b is the mean photon beam energy and σ_b the standard deviation of the spectral photon flux distribution, respectively. An asymmetric energy range has been selected to minimize the effect of the detector response which has not been taken into account. This intensity has been corrected for cosmic background and converted into the cross section $\sigma^c_{\gamma\gamma}$ by normalizing to resolved transitions in this energy interval. Since no contribution of non-nuclear scattering processes and detector response have been subtracted the values of $\sigma^c_{\gamma\gamma}$ represent an upper limit of the cross section. In contrast, $\sigma^p_{\gamma\gamma}$ can be assigned to be a lower limit. Thus, the actual value of $\sigma_{\gamma\gamma}$ should be found between these two limits. The corresponding total photoabsorption cross sections are labeled as σ^p_γ and σ^c_γ, respectively.

Fig. 1 shows the photoabsorption cross section determined in the present experiments together with results from a former (γ,n)-experiment [35] above the neutron separation threshold S_n. An enhancement of the $E1$ strength below S_n compared to the SLO extrapolation of the GDR between 6 MeV and 8.5 MeV is apparent which corresponds to 0.83(6)% (1.82(5)%) of the Thomas–Reiche–Kuhn (TRK) sum rule [36,37] after (before) subtraction of the extrapolated SLO contribution. The additional strength shows two distinct maxima at 6.82 MeV and 7.85 MeV. Similar double structures of the low-lying $E1$ strength have been reported before in the neighboring $N = 82$ nuclei [38,22,39]. In experiments using the $(\alpha,\alpha'\gamma)$ method [40] different underlying structures could be assigned to the two accumulations of $E1$ strength in ^{140}Ce, ^{138}Ba [41,42] and ^{124}Sn [43,44].

Two additional observables have been extracted from the experimental data. Using the experimental cross sections the average ground state branching ratio $\langle b_0\rangle = \sigma_{\gamma\gamma}/\sigma_\gamma$ can be determined,