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Direct determination of ground-state transition widths of low-lying dipole states in ^{140}Ce with the self-absorption technique

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ABSTRACT

The technique of self absorption has been applied for the first time to study the decay pattern of low-lying dipole states of ^{140}Ce. In particular, ground-state transition widths Γ_0 and branching ratios Γ_0/Γ to the ground state have been investigated in the energy domain of the pygmy dipole resonance. Relative self-absorption measurements allow for a model-independent determination of Γ_0. Without the need to perform a full spectroscopy of all decay channels, also the branching ratio to the ground state can be determined. The experiment on ^{140}Ce was conducted at the bremsstrahlung facility of the superconducting Darmstadt electron linear accelerator S-DALINAC. In total, the self-absorption and, thus, Γ_0 were determined for 104 excited states of ^{140}Ce. The obtained results are presented and discussed with respect to simulations of γ cascades using the DICEBOX code.

1. Introduction

Atomic nuclei represent enormously complex quantum objects. Their quantum states can correspond to collective modes, to non-collective single-particle excitations or to mixtures of both. This leads to complex decay patterns, in particular for collective modes situated at excitation energies where multiple lower-lying levels open alternative decay channels. However, those channels do not yet fully dominate the entire decay pattern. An important example for such a collective mode is the Pygmy Dipole Resonance (PDR) [1]. It is a resonance-like concentrated enhancement of $E1$-excitation strength in the vicinity of the particle-separation threshold. Typically, the PDR is attributed to the out-of-phase oscillation of excess neutrons against an isospin-saturated core. Recently, the PDR attracted a great deal of attention because of its fundamental character, its impact on nuclear astrophysics [2–4], and its sensitivity to properties of nuclear matter [5,6]. However, up to now the detailed structure of the PDR is not well settled (see, *e.g.*, Refs. [1,7–9] and the references therein).

Up to now, the PDR has mainly been investigated exploiting the method of Nuclear Resonance Fluorescence (NRF) (see, *e.g.*, Refs. [9–12]). NRF uses real photons to probe nuclear structure [13,14]. Owed to the low-momentum transfer of photons, they induce mainly dipole and, to a lesser extent, electric quadrupole transitions. Thus, NRF measurements are perfectly suited to study low-lying dipole states in nuclei such as states in the PDR region.

However, NRF measurements are sensitive to the product $\Gamma_0 \cdot \Gamma_0/\Gamma$ of the ground-state transition width Γ_0 and the branching ratio Γ_0/Γ to the ground state. Even though the individual transition widths Γ_i to low-lying excited states are much weaker than the branch to the ground state (*i.e.*, $\Gamma_0 \gg \Gamma_i$) this might not be the case for their sum $\sum \Gamma_i$ which is relevant for the size of Γ_0/Γ. The latter needs to be known in order to experimentally determine Γ_0 from NRF data. If, for a given state, decays to lower-lying excited states have not been observed, appropriate assumptions, *e.g.*,

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$\Gamma_0/\Gamma = 1$, are commonly applied. Otherwise, calculations within the statistical model can be used to estimate mean branching ratios to the ground state which has been done in NRF experiments to extract averaged properties from the spectra in an alternative analysis method (see, *e.g.*, Refs. [9,15,16]). However, a statistical approach does not help in the analysis of isolated individual states. In addition, this method has to rely on the validity of the statistical model in the investigated energy region including a reasonable description of the nucleus using level density and photon-strength functions, *i.e.*, the results are model dependent.

Recently, NRF measurements with quasi-monoenergetic photons at the High Intensity γ-Ray Source (HIγS) [17,18] at Triangle Universities National Laboratory (TUNL) in Durham, NC, USA gave experimental insight in mean decay properties of dipole excited states in the energy region of the PDR [12,19–23]. All of these measurements demonstrate that the decay via intermediate states cannot be neglected, however, the data do not answer the question how individual states behave. Recent studies also revealed that the mean branching ratio $\langle b_0 \rangle$ to the ground state cannot completely be described within the statistical model [20,22,23], demonstrating the need to study Γ_0 directly.

One opportunity to study Γ_0 is provided by inelastic proton scattering at forward angles. $B(E1)$ strengths have been extracted for individual states of ^{208}Pb below the separation threshold from (p, p') measurements [24]. However, the extraction of reduced transition strength values is model dependent. Furthermore, the energy resolution of (p, p') experiments of about 25 keV is worse than in NRF, where the resolution accounts to a few keV. Thus, the investigation of individual states in energy regions with rather high level density is difficult, especially since states with $J \neq 1$ can also strongly be excited by this mechanism.

In contrast, the method of self absorption [13,25] provides a model-independent measurement of absolute values for the ground-state transition width Γ_0, the total transition width Γ, and, therefore, also of the branching ratio to the ground state for individual states. Since self-absorption measurements are basically a combination of two NRF measurements, the excellent energy resolution of γ-ray detectors can be exploited at the same time.

In this work, we report on the first investigation of ground-state transition widths of low-lying dipole states in the PDR region in ^{140}Ce with the self-absorption technique. In the following the method of self absorption, the experimental setup and the analysis procedure is presented. Afterwards, the results are discussed and compared to simulations exploiting the DICEBOX code [26].

2. Experimental method

Commonly, in 'standard' NRF measurements the target of interest (*scatterer*) is irradiated with a photon beam, *e.g.*, bremsstrahlung, and the *decay* of states excited resonantly from the ground state is investigated. Thus, NRF is sensitive to the product of Γ_0 (excitation) and Γ_0/Γ (decay). In contrast, in self-absorption measurements absorption spectra are analyzed (see, *e.g.*, [13,25]). Hence, the *excitation* process is investigated with this method providing direct sensitivity to Γ_0. Absorption spectra are obtained when a photon beam is transmitted through a thick *absorber*. The resulting spectrum exhibits characteristic absorption lines at the resonance energies of the absorption target: photons with these energies are resonantly absorbed and, thus, missing in the absorption spectrum. The absorption lines are more pronounced for excited states with large Γ_0 so that they are a direct measure for the ground-state transition width. In addition, the transmitted spectrum has a reduced intensity with respect to the original one due to atomic attenuation effects.

Owed to the width of mostly a few eV, the absorption lines cannot be measured directly using high resolution γ-ray spectroscopy. A self-absorption experiment is, thus, usually composed out of at least two measurements. In the first one, a scattering target made of the same material as the absorber is irradiated by the absorption spectrum. With the absorber being removed from the beam line, the second measurement serves as reference measurement. The self absorption is defined as the decrease of scattered photons N_{abs} in the scattering target with respect to the number N_{nrf} of scattered photons in the measurement without absorber:

$$R = 1 - \frac{N_{abs}}{N_{nrf}}. \tag{1}$$

The decrease of scattered photons can be ascribed to resonant absorption and atomic attenuation in the absorber. By correcting R for the atomic attenuation effects, it becomes directly related to Γ_0 and the scatterer serves as high-resolution detector for resonant absorption effects. In earlier self-absorption experiments the atomic attenuation was usually accounted for by using different absorber targets: a resonant absorber (made of the material of interest) and an atomic absorber of similar Z [25,27,28]. The latter was used to measure the contribution of atomic attenuation. In the present work, we used a new approach: both measurements are performed relative to a normalization target which is included to the scattering target and ideally has only few but rather strongly excited states, in our case ^{11}B. The decrease of NRF reactions in ^{11}B is only due to atomic attenuation in the absorber. With the normalization factor $f = N_{abs}^{norm}/N_{nrf}^{norm}$ (with N_{abs}^{norm} and N_{nrf}^{norm} being the number of reactions in ^{11}B in the measurements with and without absorber, respectively) the self absorption can be corrected for the effect of atomic attenuation:

$$R_{\mathrm{exp}} = 1 - \frac{N_{abs}}{f \times N_{nrf}}. \tag{2}$$

At the same time, f also corrects for different measuring times, beam currents, dead times, and any other global normalization factor. Therefore, systematic uncertainties are strongly reduced compared to previous approaches.

For the analysis, the self absorption R has to be calculated as a function of Γ_0 and Γ. The cross section for resonant absorption of a photon corresponding to the excitation of a state j with resonance energy E_j from the ground state and the subsequent decay to a state k is described by a Breit–Wigner cross section convoluted with an energy distribution $w(E')$:

$$\sigma(E) = \int_{-\infty}^{\infty} dE' \, \frac{2\pi \left(\hbar c/E_j\right)^2 g \Gamma_0 \Gamma}{\Gamma^2/4 + (E' - E_j)^2} \times w(E'), \tag{3}$$

with $g = \frac{2J_j+1}{2J_0+1}$ being a spin-dependent statistical factor. The distribution

$$w(E')dE' = \frac{1}{\Delta\sqrt{\pi}} \cdot e^{\left(\frac{E'-E}{\Delta}\right)^2} dE', \tag{4}$$

with Δ being the so-called Doppler width, describes the distribution of effective energies E' in the rest frame of the nucleus of a photon with energy E in the laboratory system. Hence, it accounts for the finite velocities of the target nuclei within the target material and the corresponding Doppler broadening of the excitation cross section. It is used to define the resonance-absorption density

$$\alpha(z, E) = \sigma(E) \times e^{-\sigma(E)z} \tag{5}$$

with z being the penetration depth into the target. It describes the probability for resonant absorption of a photon by an excited state. The exponential term accounts for the decrease of the photon-flux