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Nuclear Resonance Fluorescence off ^{54}Cr: The Onset of the Pygmy Dipole Resonance

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Abstract. Low-lying electric and magnetic dipole excitations (E1 and M1) below the neutron separation threshold, particularly the Pygmy Dipole Resonance (PDR), have drawn considerable attention in the last years. So far, mostly moderately heavy nuclei in the mass regions around $A = 90$ and $A = 140$ were examined with respect to the PDR. In the present work, the systematics of the PDR have been extended by measuring excitation strengths and parity quantum numbers of $J = 1$ states in lighter nuclei near $A = 50$ in order to gather information on the onset of the PDR. The nuclei ^{50,52,54}Cr and ^{48,50}Ti were examined via bremsstrahlung produced at the DArmstadt Superconducting electron Linear ACcelerator (S-DALINAC) with photon energies up to 9.7 MeV with the method of nuclear resonance fluorescence. Numerous excited states were observed, many of which for the first time. The parity quantum numbers of these states have been determined at the High Intensity Gamma-ray Source (HIγS) of the Triangle Universities Nuclear Laboratory in Durham, NC, USA. Informations to the methods and the experimental setups will be provided and the results on ^{54}Cr achieved will be discussed with respect to the onset of the PDR.

1. Introduction

The Pygmy Dipole Resonance (PDR) [1] is one of three components of the $E1$ transition strength below and around the neutron separation threshold besides two-phonon states [2] and the Giant Dipole Resonance (GDR). It is usually associated with an accumulation of isolated $E1$-transitions in contrast to the continuous distribution of the GDR above the particle separation threshold. Given that the GDR has been subject of intensive research since the 1940's, it is well known and is interpreted as an oscillation of the neutrons against the protons [3]. On the other hand the nature of the PDR is not yet understood. It is usually interpreted as an oscillation of an $N = Z$ core against a skin of excess neutrons. However, this notion is under current debate.

Since the PDR does not occur in the calcium isotopes [4] and is fully developed already in heavier nickel isotopes [5], the A≈50 mass region may provide crucial information on the PDR. With the investigation of this mass region, we complete a systematic trend of the PDR over several mass regions from its onset to well-developed cases. In order to provide the necessary experimental data, measurements on stable even-even chromium and titanium nuclei were conducted. Here, the $B(E1)$ values were determined via the nuclear resonance fluorescence method, which has proven to be an effective means in the past.

2. Experiment

2.1. Nuclear resonance fluorescence

In the Nuclear Resonance Fluorescence method (NRF) [6] incident photons are used to populate resonantly excited states. These states decay typically within femto- to picoseconds either direct to the ground-state, which is called elastic scattering, or through intermediate states, called inelastic scattering. The emitted photons are detected and their energy, intensity and angular distribution allow conclusions regarding cross sections, transition strength, parity and spin quantum numbers as well as branching ratios. High-resolution photon scattering experiments are feasible only below the particle threshold, where discrete states can be observed.

The experiments were performed at two facilities: at the Darmstadt High Intensity Photon Setup (DHIPS) [7] located at the S-DALINAC of the Institut für Kernphysik, TU Darmstadt, Germany and at the High Intensity γ-ray Source (HIγS) [8] at the Duke Free Electron Laser Laboratory of the Triangle Universities Nuclear Laboratory in Durham, NC, USA. The experiments will be exemplified through the nucleus ^{54}Cr, which was examined through NRF for the first time.

2.2. Darmstadt High-Intensity Photon Setup

At DHIPS the electron beam provided by the S-DALINAC is used to produce bremsstrahlung photons, impinging on a copper or gold radiator. In order to reduce the contribution of low-energy photons a beam hardener made of aluminium is placed behind the radiator. Through a massive copper block with a 12 mm bore, photons are collimated on the target located between three HPGe detectors. These are positioned at 90°, 93° and 130° polar angle with respect to the incoming photon beam. At these angles the ratio of the count rate between 90° and 130° differs the most for the spin sequences $0 \to 1 \to 0$ and $0 \to 2 \to 0$, respectively. Since only $J = 1$ and $J = 2$ states are observed, it is possible to determine the spin quantum numbers of the excited states from this counting ratio. Additional active BGO-shielding is used around the HPGe detectors to reduce Compton background in the spectra. Figure 1 shows a schematic of DHIPS. For further details on the setup, see Ref. [7]. Two energy settings for the S-DALINAC were used to produce bremsstrahlung spectra with 9.7 and 7.5 MeV endpoint energy for approximately 125 and 100 h, respectively. The target consisted of 1500 mg ^{54}Cr enriched to 95.58 %, bound in chromium monoxide and enclosed in 191.8 and 207.5 mg ^{11}B, respectively, which is used for energy and photon flux calibration.

2.3. High Intensity γ-ray Source

At HIγS photons are produced in a free electron laser utilizing electrons provided by a linac and booster synchrotron. These photons are reflected inside the laser resonator cavity and are boosted to energies suitable for NRF via Compton back scattering off the oncoming electrons. After passing a collimator, a quasi-monochromatic photon beam is provided for the experiments. For details see Ref. [8]. Since Compton scattering preserves the polarisation of the primary laser photons, the beam has nearly 100 % polarization. This allows a determination of the excited states' parity quantum numbers [9]: For positive parity the intensity of the emitted photons has a maximum in the polarization plane of the incident photons and a minimum perpendicular to it and vice versa for negative parity. Due to the quasi-monochromatic energy profile the beam has been tuned to several energy settings. Twenty settings between 5.5 and 10 MeV were

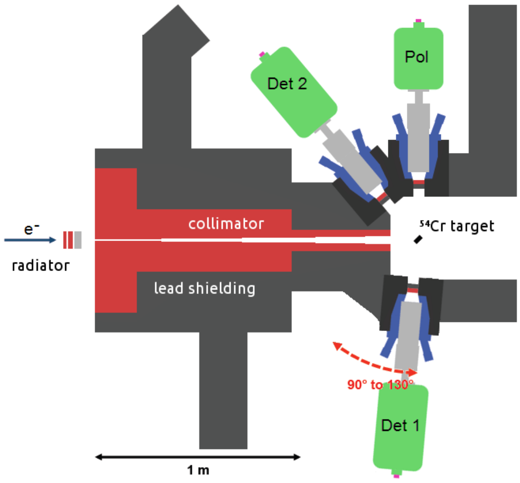

Figure 1. Schematic display of DHIPS. Lead shielding, BGO-shielding and copper collimator are shown in grey, blue and red. Figure adapted from Ref. [10]

measured, each for 4 to 5 hours. The same target of ^{54}Cr as at DHIPS was used, but without boron enclosure.

3. Analysis

In order to determine the parity quantum number of the excited states, an asymmetry ε is defined according to Ref. [9]:

$$\varepsilon = \frac{N_{\|} - N_{\perp}}{N_{\|} + N_{\perp}}\,, \tag{1}$$

where $N_{\|}$ and $N_{\perp}$ are the γ-ray intensities in and perpendicular to the polarization plane. The analysing power of the NRF reaction and hence the ideal asymmetry equal either +1 or -1. Because of the finite opening angle of the detectors this sensitivity is not fully reached. Nevertheless, a clear assignment of parity quantum numbers is possible.

The spin quantum numbers are determined through the measurements at DHIPS via the ratio w of intensities N at 90° and 130°:

$$w = \frac{N(90^\circ)}{N(130^\circ)}\,. \tag{2}$$

Detection efficiencies for both experiments have been obtained from a measurement of a ^{56}Co calibration source and extrapolated to 10 MeV photon energy using the detector responses simulated with the Monte-Carlo-tracking simulation tool GEANT4 [11]. The expected values for w are 2.26 for quadrupole and 0.71 for dipole transitions. The assignment of spin quantum numbers is complemented by known values taken from Ref. [12] and by the parity measurement. Since almost exclusively $E1$, $M1$ and $E2$ transitions are excited by real photons, spin $J = 1$ has been assigned to all states with negative parity.

The data taken at DHIPS are also used to determine the integrated cross section. Here the essential formula is:

$$I_{j\to i} = \frac{A_{j\to i}}{N_\gamma(E)\cdot N_T\cdot \varepsilon(E)\cdot W_{0\to j\to i}}\,, \tag{3}$$

where the integrated cross section $I_{j\to i}$ is calculated from the peak area $A_{j\to i}$, the photon flux $N_\gamma(E)$, the number of nuclei in the target N_T, the efficiency $\varepsilon(E)$ and the angular distribution

$W_{0\rightarrow j\rightarrow i}$. Because the photon flux is not known, the well known integrated cross sections of the excited states of the calibration standard ^{11}B are used. With that the photon flux at 2125, 4445, 5020, 7286 and 8920 keV can be measured, and after interpolating using the Schiff-formula [13] for bremsstrahlung, the cross sections for the states in ^{54}Cr can be determined. One obtains the transition width Γ from the equation:

$$\frac{\Gamma_0^2}{\Gamma} = \frac{I_{0\rightarrow j\rightarrow 0}}{\pi^2\cdot\left(\frac{\hbar c}{E_r}\right)^2\cdot g} \tag{4}$$

if either the ground state decay branching ratio $\frac{\Gamma_0}{\Gamma}$ has been measured or with the approximation $\frac{\Gamma_0^2}{\Gamma}\approx\Gamma$, where Γ_0 is the ground-state transition width, E_r the excitation energy and $g=\frac{2J_j+1}{2J_0+1}$ a spin dependent statistical factor. In cases where inelastic transitions have been observed, Γ_0 was corrected accordingly. From that the transition strength $B(\lambda L)$ is calculated via

$$\Gamma_0 = 8\pi\sum_{L}^{2L+1}\left(\frac{E_\gamma}{\hbar c}\right)^{2L+1}\cdot\frac{L+1}{L((2L+1)!!)^2}\cdot B(\lambda L)\downarrow\ . \tag{5}$$

In that way, numerous states have been observed for the first time.

4. Discussion

The measured $B(E1)$ values were compared to calculations within the framework of the quasi-particle phonon model. These calculations were capable of satisfactorily reproducing the level density and transition strengths. predicting an isoscalar character of the excited states in the energy region of interest near the neutron separation threshold. This allows a differentiation from the isovector GDR, whereby the properties usually describing the PDR are present. Similar results were already published for the closed-shell neighbouring isotope ^{52}Cr [14].

With the newly acquired data a comparison between the even-even chromium isotopes measured under the same conditions is possible. A common way to do so is the usage of the so-called Thomas-Reiche-Kuhn Energy Weighted Sum Rule (EWSR), which gives an approximation for the summed up electric dipole transition strength as function of proton and neutron number [15]. The ratio of the total observed $E1$ transition strength up to 9.7 MeV to the EWSR is almost constant for the two lighter chromium isotopes ^{50,52}Cr and increases rather drastically to ^{54}Cr as illustrated in figure 2.

This interesting finding hints on one hand at the important role of valence neutrons for the formation of the low-lying $E1$ strength and on the other hand highlights the crucial role of shell structure on the properties of the PDR questioning in its fully collective character.

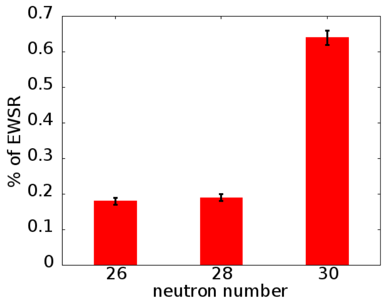

Figure 2. Exhausted percentage of the EWSR for ^{50}Cr, ^{52}Cr, and ^{54}Cr. Beyond the shell-closure at 28 neutrons, the overall strength increases noticeable [14].

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