PHOTOEXCITATION OF THE STABLE Tl ISOTOPES BELOW THE NEUTRON SEPARATION ENERGY*

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Although the systematics of the Pygmy Dipole Resonance was established in several stable even–even nuclei, the collectivity of this mode, explained in a macroscopic picture as an oscillation of a neutron skin against an isospin symmetric proton–neutron core, is still not well understood. In order to guide the theoretical models, we investigated the heavy odd mass, stable isotopes ^{203,205}Tl using unpolarized bremsstrahlung photon beams at the S-DALINAC facility at TU Darmstadt. The NRF experiments were complemented by measurements at the High Intensity γ-ray Source (HIγS) at the Triangle Universities Nuclear Laboratory (TUNL) in Durham, NC, USA, with a fully linearly polarized quasi-monoenergetic photon beam. Between 4 and 7 MeV, a concentration of dipole strength is observed in the odd-mass nuclide ^{205}Tl. For the ^{203}Tl isotope, two ground-state transitions around 5 MeV could be resolved in the spectra. In this report, the obtained results will be presented. The results for the proton-odd nuclide ^{205}Tl will be compared to the ones for the neighbouring even–even nucleus ^{206}Pb.

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1. Introduction

In the last decades, high resolution Nuclear Resonance Fluorescence (NRF) experiments shed light on a new mode of excitation in many even–even stable nuclei (see, *e.g.*, Ref. [1]). This mode referred to as Pygmy Dipole Resonance (PDR) is manifested as an accumulation of electric dipole transitions on the low-energy tail region of the Giant Dipole Resonance (GDR). The enhancement of dipole strength in the vicinity of the neutron separation threshold considerably affects stellar reaction rates [2]. The systematic study in different mass region showed a correlation of the summed strength in the PDR region to the excess of neutrons in the nucleus. Therefore, the PDR mode is often interpreted as an oscillation of the excess neutrons against a proton–neutron core (see, *e.g.*, Ref. [3]). However, recently the study of the complete chain of calcium isotopes [4] revealed that this behaviour has to be reviewed and much more information is needed to better understand this excitation mode. A part of the information could be obtained from the study of stable odd-mass nuclei which will complete the systematics in isotopic and isotonic chains, respectively. Up to now, it has been reported only in very few nuclides [5–8]. From this point of view, the present paper reports on NRF measurements of the stable odd-proton isotopes ^{203}Tl and ^{205}Tl (ground-state spin $J_0^\pi = 1/2^+$). Since the NRF technique [9] is mainly selective to dipole excited states (due to the low-momentum transfer of real photons to the atomic nucleus), it is well suited to study low-lying dipole strength. The Tl nuclei can be considered as best to reveal the proton–hole contribution to the PDR mode in the mass region near the $Z = 82$ and $N = 126$ shell closures, therefore characterizing the particle–core coupling [10].

2. Experimental setup

The photoexcitation of the stable thallium isotopes was carried out at the Darmstadt High Intensity Photon Setup (DHIPS) [11] at the superconducting electron linear accelerator S-DALINAC at Technische Universität Darmstadt. Figure 1 displays a schematic drawing of DHIPS. A natural Tl target (2060.0 mg) and a target enriched to 99.9% in ^{205}Tl (1938.4 mg) have been irradiated by an unpolarized bremsstrahlung beam with an endpoint energy of 7.5 MeV. Both measurements lasted for about 80 hours. The bremsstrahlung was produced by stopping an electron beam of 7.5 MeV kinetic energy and an average current of 16 μA and 31 μA respectively in a thick copper radiator. Both targets have been sandwiched between two boron disks with a total mass of 240.8 mg (natural) and 394.3 mg (enriched to 99.5% in ^{11}B), respectively. The comparison of the corresponding spectra allows us to identify ground-state transitions of ^{203}Tl. The detection

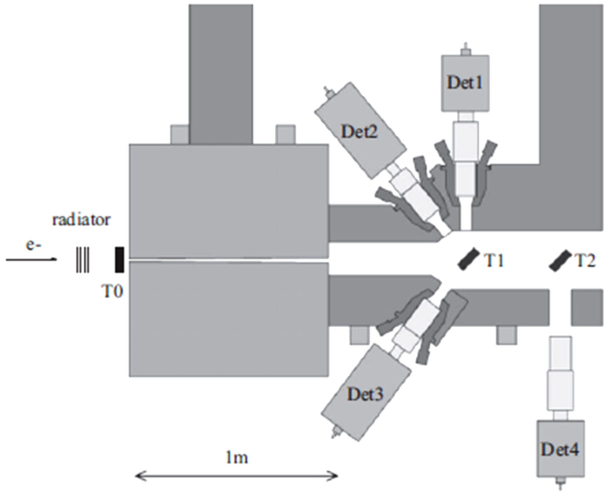

Fig. 1. The NRF setup DHIPS at the S-DALINAC at Technische Universität Darmstadt [11].

system consisted of three High Purity Germanium (HPGe) detectors with efficiencies of 100% relative to a standard NaI detector mounted at polar angles of 90°, 95° and 130° relative to the incident beam, respectively. The detectors were surrounded by active anti-Compton Schield made of bismuth germanate (BGO) scintillators and shielded against the low-energy part of the background radiation, using aluminium and lead absorbers in front of each detector. Using GEANT4, the efficiency of the detectors was simulated then checked and normalised with a ^{56}Co source.

An additional experiment has been carried out at the High Intensity γ-ray Source at the Triangle Universities Nuclear Laboratory to measure possible decay branches (see below). There, the natural thallium target was exposed to a nearly monoenergetic linearly polarized γ-ray beam (FWHM $\approx$ 3%) for about three hours. The scattered γ-rays from the target have been counted by four HPGe detectors positioned at angles perpendicular to the incoming beam. A typical schematic setup can be found in Ref. [12].

3. Analysis and results

Spectra of the scattered photons on the natural (upper panel) and the enriched thallium (lower panel) target, respectively, measured at DHIPS are shown in Fig. 2. One can notice that besides transitions originating from ^{11}B(γ, γ') a concentration of transitions from ^{205}Tl is visible in the energy range between 5 MeV and 7 MeV. The most pronounced ground-state transitions are the ones of the doublet at 4961.1 and 4967.8 keV excitation

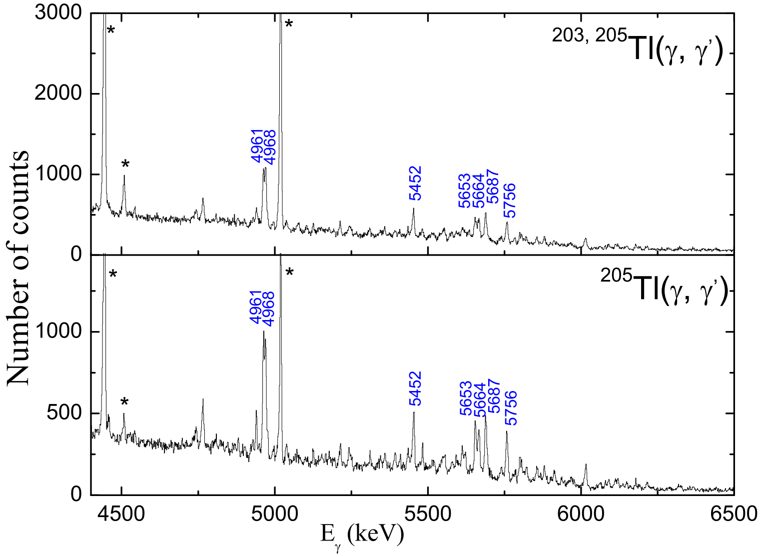

Fig. 2. Part of the photoexcitation spectrum of ^{203,205}Tl (upper part) and ^{205}Tl measured at 130° at an end point-energy of 7.5 MeV with a natural and enriched thallium target, respectively. Peaks marked by asterisks correspond to ^{11}B and their escape lines.

energy. The integrated elastic cross section $I_{i,0}$ associated to the decay of an excited state E_x to the ground state is derived from the peak area $A_{i,0}$ in the spectrum

$$I_{i,0} = \frac{A_{i,0}}{N_{\mathrm{T}}\, N_\gamma(E_i)\, \epsilon(E_i)\, W(\theta)}\,. \tag{1}$$

Here, N_{T} is the number of target nuclei, N_γ the absolute photon flux irradiating the target, ϵ the absolute detector efficiency, and $W(\theta)$ is the angular distribution of the photons emitted during the transitions. The product $N_\gamma\, \epsilon$ is calibrated using the ground-state transitions in ^{11}B knowing their integrated cross section from the literature. The transition strength quantified by the ground-state transition width Γ_0 can be extracted from the measured integrated elastic cross section $I_{i,0}$

$$I_{i,0} = \pi^2 \left(\frac{\hbar c}{E_x}\right)^2 g\, \frac{\Gamma_0^2}{\Gamma}\,, \tag{2}$$

where Γ is the total decay width and $g = (2J_i{+}1)/(2J_0{+}1)$ is the spin factor. In NRF experiments, the branching ratio Γ_0/Γ to the ground state can only be obtained, if all branching transitions to lower-lying states (so-called inelastic transitions) have been observed. However, due to the high radiation background in NRF experiments using continuous bremsstrahlung as photon source, in particular small branching ratios to lower-lying states are difficult to measure. Another difficulty are the nearly isotropic angular distributions of the photons emitted in the γ-decay of odd-mass nuclei that, in our case, did not allow to assign spin quantum numbers to the observed excited states. In order to decide weather the peak observed in the spectra at 4764.1 keV corresponds to a transition from the 4967.8 keV level to the first excited state at 203.7 keV ($J^\pi = 3/2^+$) or to a ground-state transition (difference excitation energy considerations), the photon beam at HIγS has successively been tuned to 4.7 and 4.9 MeV mean beam energy. In the measurement at $E_{\mathrm{beam}} = 4.7$ MeV no peak was observed at 4764 keV. However, in the second measurement at $E_{\mathrm{beam}} = 4.9$ MeV, in which the state at 4967.8 keV was populated, also a peak at 4764 keV was observed. Thus, there is no excited state of ^{205}Tl at 4764 keV and the level at 4967 keV has a significant branching to the $3/2^+$.

Figure 3 summarizes the experimental dipole strength distribution of ^{205}Tl (upper part (a)) measured in the present experiments and, for comparison, the one observed for its even–even neighbour ^{206}Pb (lower part (b)) in the PDR energy region. For ^{203}Tl, two transitions at 5076.5 and 5102.3 keV were identified in the spectra measured with a natural thallium target. As the spin and parity quantum numbers of the excited states of ^{205}Tl are unknown, the product $g\,\frac{\Gamma_0^2}{\Gamma}$ is plotted. For ^{206}Pb, the parities are

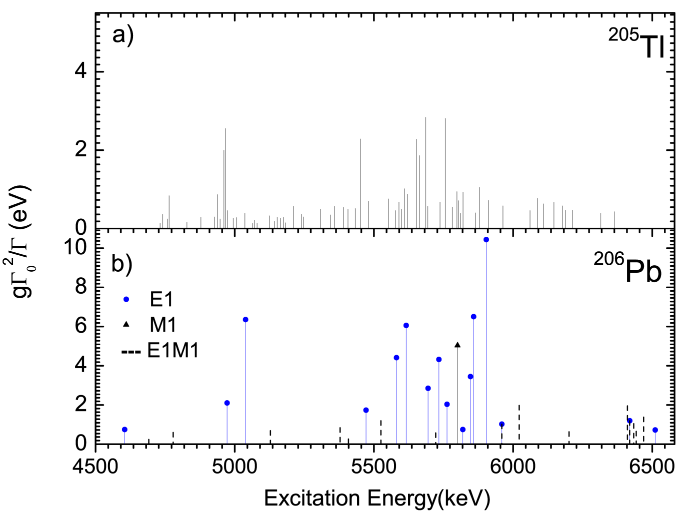

Fig. 3. Extracted dipole strength distribution of ^{205}Tl (a) compared to the neighbouring even–even nucleus ^{206}Pb (b). The data for ^{206}Pb are taken from Ref. [6]. The scale in ^{205}Tl is multiplied by a factor of 2.

taken from NRF polarization measurements in Ref. [6]. Two strong strength concentrations around 5 MeV and 5.7 MeV are noticeable in the proton-odd nuclide ^{205}Tl similar to the ones of the even–even nucleus ^{206}Pb but more fragmented and reduced (for the data on ^{205}Tl, notice that the scale is multiplied by a factor of 2). This behaviour seems to resemble the one at lower excitation energy for the M1 scissors mode [14] and the $[2_1^+ \bigotimes 3_1^-]_1^-$ two-phonon state [15] in odd-mass nuclei. One can see a small shift in the odd-mass ^{205}Tl of the strength mean excitation energy relatively to the even–even mass ^{206}Pb which has also been observed in ^{207}Pb [6]. The doublet of excited states observed at 4964.5 keV in ^{205}Tl could be associated to a doublet at 5543.6 keV identified in ^{207}Pb [10]. The combined strength $\sum(g\,\frac{\Gamma_0^2}{\Gamma})$ of 4.6 eV for ^{205}Tl which is comparable to 5.8 eV for the even–even core ^{206}Pb suggests a weak-coupling of the proton hole $\pi(3s_{1/2}^{-1})$ to the 1^- core excitation in ^{206}Pb although the excitation energy in ^{205}Tl is shifted to lower energies. Theoretical analysis of the present data is in progress within the Quasiparticle Phonon Model.

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