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MEASUREMENT OF THE γ DECAY FROM THE ENERGY REGION OF THE PYGMY DIPOLE STATES EXCITED IN THE ^{208}Pb$(p,p'\gamma)$ REACTION AT CCB*

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For a few years, the medical cyclotron Proteus C-235 at the Cyclotron Centre Bronowice in Kraków, Poland has been regularly used for nuclear structure experiments. One of the ongoing studies is focused on the γ decay of collective states populated in $(p,p'\gamma)$ reactions. In a recent experiment, γ decays of excited states in the energy region of the Pygmy Dipole States in ^{208}Pb have been observed. Good efficiency and energy resolution provided by the PARIS clusters and LaBr$_3$:Ce scintillators facilitate a comparison of the obtained energy spectra with previous measurements of pygmy states in this nucleus.

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1. Introduction

Studies of the E1 strength distribution in the region of the so-called Pygmy Dipole States (PDS) represent an important topic in the nuclear structure research [1, 2]. The pygmy states are observed as an increase of the E1 excitation strength in the region of the low-energy tail of the Isovector Giant Dipole Resonance (IVGDR), around the neutron separation threshold. The total strength of these states constitutes several per cent of the total IVGDR strength.

The pygmy states were successfully populated in various nuclear reactions, such as inelastic scattering of γ rays [3, 4], protons [5], alpha particles [6] and heavy ions [7, 8] or in β decay [9]. The electric dipole transition strength distribution obtained with various probes display striking differences. It is particularly noticeable in the comparison of results obtained with the inelastic scattering of α particles and γ rays. In the first reaction (recognised as the best isoscalar probe available), states at visibly lower excitation energy than in the second one (which is an isovector probe) are populated. This indicates that the PDS has two components: isovector and isoscalar.

The ^{208}Pb nucleus is an important reference point, as it is the heaviest doubly magic stable isotope, providing an insight into the behaviour of heavy neutron-rich nuclei. In the study of γ decay of the collective modes induced via the $^{208}\mathrm{Pb}(p,p'\gamma)$ reaction performed at the Cyclotron Centre Bronowice (CCB) in Kraków, Poland, excited states in the region of PDS were populated. The coincidence measurement of energies of inelastically scattered protons and emitted γ rays enabled observation of γ-ray energy spectra corresponding to the γ decay to the ground state (g.s.) in ^{208}Pb. These data can be compared with those from previous measurements.

2. Experiment

The experimental set-up dedicated to the coincidence measurement of charged particles and γ rays has been meticulously tested at CCB [10]. It has been proven to produce, for the studies of collective excitations, scientifically relevant results [11]. Last year, the set-up was upgraded to improve the energy resolution of the measurement. The new set-up (Fig. 1) consisted of 18 KRATTA array detectors [12] placed inside a vacuum chamber coupled to two clusters of PARIS detectors [13] and four cylindrical single-crystal $\mathrm{LaBr_3}$:Ce scintillators in the commonly used size of 3.5″ in diameter and 8″ in length [14].

The KRATTA detectors were grouped in columns of three detectors each, with two groups of three columns placed symmetrically on both sides of the beam axis. The centres of the detectors in the middle of the columns were

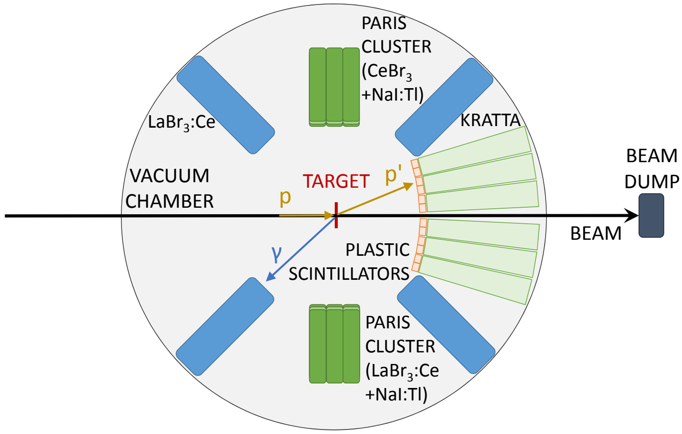

Fig. 1. A schematic view of the experimental set-up.

positioned at angles: $\vartheta = 6^\circ$, $\vartheta = 12^\circ$ and $\vartheta = 18^\circ$ in respect to the beam axis (see Fig. 2), at 40 cm from the target. At the front of each KRATTA detector, allowing a more precise time and position measurement, four fast plastic scintillators were installed. The γ-ray detectors were installed outside the vacuum chamber in dedicated sockets (see Fig. 2), setting them at a distance of 25 cm from the target. In respect to the beam axis, the PARIS clusters were placed at $\vartheta = 90^\circ$ and the $LaBr_3$:Ce detectors at $\vartheta = 45^\circ$ and $\vartheta = 135^\circ$.

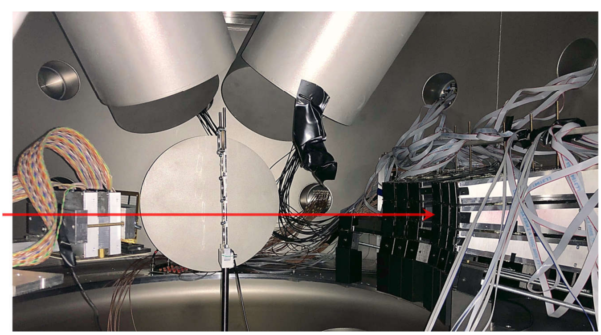

Fig. 2. A photo of the interior of the vacuum chamber. To the right, KRATTA detectors with plastic scintillators are visible. In the centre, surrounding a target ladder, sockets in which γ-ray detectors were placed can be seen. The beam direction is marked with an arrow.

In the measurement, a self-supporting, 48 μm thick ^{208}Pb target of 99.98% enrichment was used. The target was irradiated by a 155 MeV proton beam. As in the previous measurements, the data were collected in the coincidence mode, employing the Multi-Branch System [15]. Data acquisition was triggered by signal detection in at least one γ-ray detector and one plastic scintillator. Contrary to the previous experiment, both KRATTA detectors and γ-ray detectors had a digital read-out.

3. Results

During the experiment, γ rays from the decay of excited ^{208}Pb nuclei were measured in coincidence with scattered protons. The data were processed with the method described in Ref. [10]. The obtained matrix of detected γ-ray energy *versus* excitation energy (deduced from the measured proton energy) is presented in the left panel of Fig. 3. The most prominent line in the matrix corresponds to the transition from the first excited 3^- state to the ground state. The cut-off at the neutron separation energy (S_n = 7.368 MeV) is visible.

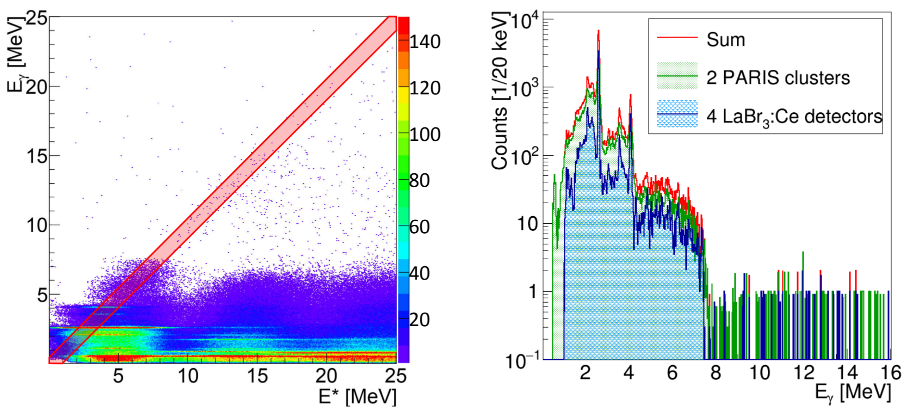

Fig. 3. (Colour on-line) Left panel: an E_γ *versus* E^* matrix measured with the $LaBr_3$:Ce+PARIS+KRATTA set-up. The γ decay to the ground state is represented graphically as a grey/red polygon. Right panel: γ-ray energy spectra corresponding to γ decay to the g.s. in ^{208}Pb measured by $LaBr_3$:Ce detectors (patterned dark grey/blue) and PARIS clusters (dashed light grey/green). The sum spectrum of both types of γ detectors is shown in grey/red.

Events fulfilling a requirement: $E_\gamma + 0.5 \geqslant E^* \geqslant E_\gamma - 1$ [MeV], were selected as corresponding to the γ decay to the ground state. The γ-ray energy spectra obtained with this condition are shown in the right panel of Fig. 3. The spectrum containing all measured events of the γ decay to the ground state (grey/red line) is presented together with the separate spectra measured by $LaBr_3$:Ce detectors (filled black/blue area) and PARIS cluster (dashed light grey/green area). In the reported experiment, the combined efficiency of the two employed PARIS clusters was estimated to be twice as large as that of the four $LaBr_3$:Ce detectors which were used.

In all three spectra, transitions in the energy range of pygmy states are visible. In the left panel of Fig. 4, a zoom-in of the γ-ray spectrum in this energy region is presented. The identified transitions are labelled with their energies in keV. In the right panel, a spectrum measured in the ^{208}Pb(^{17}O, ^{17}O$'\gamma$) reaction [7] at LNL with the AGATA demonstrator is shown. It is evident, the same transitions have been observed in both experiments.

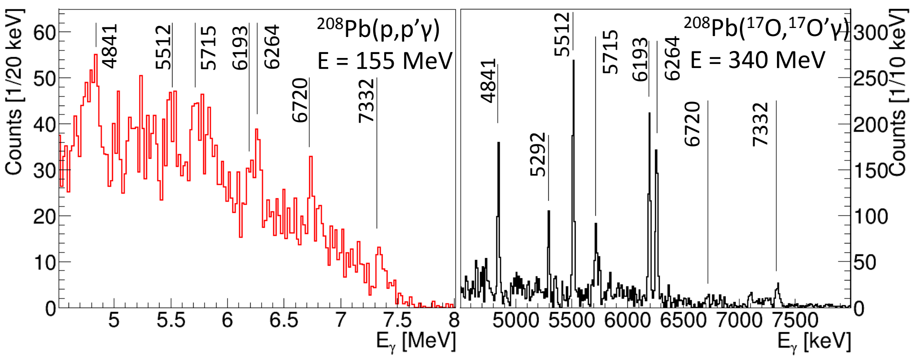

Fig. 4. Left panel: the γ-ray energy spectra corresponding to the decay to the ground state, measured in the ^{208}Pb($p, p'\gamma$) reaction by 4 $LaBr_3$:Ce detectors and 2 PARIS clusters. Right panel: the same spectrum measured in the ^{208}Pb(^{17}O, ^{17}O$'\gamma$) reaction with the use of the AGATA demonstrator [7].

To compare the data quantitatively, relative intensities of the recognised transitions in the PDS energy range were derived. They were calculated following the formula: $I_{\mathrm{rel}}(E_\gamma) = N(E_\gamma)/\sum_{E_i} N(E_i)$, where $N(E_\gamma)$ is a number of counts in the considered peak and $\sum_{E_i} N(E_i)$ is a sum of numbers of counts extracted for each examined transition in the PDS energy region. The obtained relative intensities are presented in Fig. 5. The uncertainties were estimated according to the variance formula. The γ-ray energy spectra measured in both experiments were corrected for the intrinsic detection efficiency.

In the experiment with the ^{208}Pb(^{17}O, ^{17}O$'\gamma$) reaction, the E2 transitions from the 5.72 MeV and 6.19 MeV excited states account for 35(2)% of the observed strength, while in the case of the ^{208}Pb($p, p'\gamma$) reaction, it is 18(4)%. On the other hand, contributions from high-lying 1^- states at 6.72 MeV and 7.33 MeV constitute 27(6)% of the number of counts in the pygmy energy region observed in the measurement performed with the proton beam, whereas in the experiment with the ^{17}O beam, it is only 9(1)%.

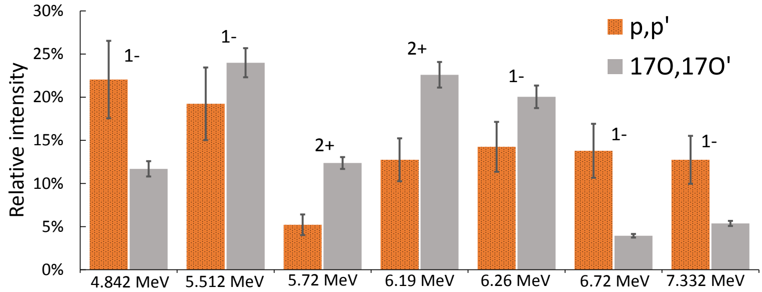

Fig. 5. (Colour on-line) A comparison of the relative intensity of the observed transitions to the ground state in ^{208}Pb in the energy region of Pygmy Dipole States in ^{208}Pb$(p,p'\gamma)$ (dotted grey/orange) and ^{208}Pb$(^{17}$O$,^{17}$O$'\gamma)$ (solid light grey) reactions.

This observation may be explained by the isovector nature of the high-energy component of the pygmy states, which are considered to be more strongly excited in reactions with protons than with heavy ions. To confirm this, an application of an unfolding technique for the γ-ray energy spectra measured at CCB is planned. After that, it is envisaged to compare the results with theoretical calculations.

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