LOW-SPIN STRUCTURES OF THE ^{205}Pb AND ^{207}Pb NUCLEI STUDIED BY γ-RAY SPECTROSCOPY IN THERMAL NEUTRON CAPTURE REACTIONS*

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The low-spin structures of the ^{205}Pb and ^{207}Pb isotopes, populated by thermal-neutron capture, have been studied by the γ-ray coincidence technique with the FIPPS HPGe array at the Institut Laue-Langevin (Grenoble, France). Preliminary results of the data analysis provided information on the decay schemes of the capture states located at 6.7 MeV in both nuclei. The spins of several states in ^{205}Pb have been established owing to $\gamma\gamma$-angular correlations analysis.

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1. Introduction

The structure of nuclei around doubly-closed cores provides an excellent ground for studying two types of couplings: (a) between valence nucleons/holes and (b) of the valence nucleons/holes with core excitations. The

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former are the source of information on the effective nucleon–nucleon interaction, while the latter may be used as a unique test of various effective interactions employed in mean-field based models.

Recently, we have performed a complete spectroscopy investigation of low-spin states in the ^{206}Tl and ^{210}Bi nuclei, lying two-holes and two-particles away from the doubly-closed core ^{208}Pb, respectively, which allowed for testing the quality of realistic shell-model predictions [1]. The ^{205}Pb nucleus, being a three-neutron-hole system with respect to the ^{208}Pb core, should provide even more demanding probes for the realistic shell-model calculations. In the past, the energy levels arising from the excitations of valence holes located on the $p_{1/2}$, $f_{5/2}$, $p_{3/2}$, $i_{13/2}$, and $f_{7/2}$ orbitals in ^{205}Pb were observed up to the $J^{\pi} = 33/2^{+}$ state at 5162 keV [2–4], corresponding to the stretched $\nu i_{13/2}^{-3}$ configuration. Moreover, several states involving the promotion of the neutron particle through the energy gap to the $g_{9/2}$, $i_{11/2}$, $j_{15/2}$, $d_{5/2}$, $s_{1/2}$, $g_{7/2}$, and $d_{3/2}$ orbitals up to spin $37/2^{+}$ were traced as well [4]. The low-spin states in ^{205}Pb have been studied in the past by using thermal neutron capture reaction [5, 6]. However, due to the limitation of the setup used at that time, only the most intensely populated levels could be identified and assignments of the spin-parity quantum numbers to the excited states could be done only tentatively.

In turn, the ^{207}Pb isotope has only one neutron hole with respect to the doubly-closed ^{208}Pb core. Therefore, it could serve as a testing case for a newly developed microscopic "hybrid" model [7, 8], aiming at describing the entire excitation spectrum of one-valence-particle/hole nuclei, including states arising from the coupling of the valence nucleon/hole with excitations of the doubly-magic core. Thus far, the experimental data on the single-hole excitations in ^{207}Pb, involving the $p_{1/2}$, $f_{5/2}$, $p_{3/2}$, $i_{13/2}$, $f_{7/2}$, and $h_{9/2}$ orbitals, have been collected in various reactions [9]. Additionally, members of the multiplets characterized by more complex structures, *i.e.*, the couplings of neutron hole in the $p_{1/2}$, $f_{5/2}$, $i_{13/2}$, or $f_{7/2}$ orbitals, with the excitations of the ^{208}Pb core, 3^{-}, 5^{-}, 2^{+}, 4^{+}, 6^{+}, 8^{+}, 10^{+}, or 12^{-}, have been identified [10–12]. However, despite rather large amounts of experimental data collected in previous studies, the low-spin structure of ^{207}Pb has never been studied, so far, by thermal neutron capture reactions. Therefore, our investigation is the first to provide γ-ray spectroscopy data from the ^{206}Pb$(n,\gamma)^{207}$Pb reaction.

In this paper, we present the preliminary results of the ^{204}Pb$(n,\gamma)^{205}$Pb and ^{206}Pb(n,γ)^{207}Pb experiments carried out at the Institut Laue-Langevin (Grenoble, France). The multidetector HPGe array FIPPS [13] was used for precise γ-ray coincidence measurements, providing detailed information on the decay schemes of the capture states in ^{205,207}Pb isotopes.

2. Experimental setup

The ^{205}Pb and ^{207}Pb nuclei were produced in two separate experiments performed at the ILL in Grenoble [14, 15]. The targets of ^{204}Pb (229.75 mg, 66% enriched) and ^{206}Pb (3.9317 g) were placed in the centre of the detection system and irradiated by the collimated pencil-shaped thermal neutron beam with a capture flux of 10^8 n/(s$\times$cm^2). The γ rays from the decays of the capture states in ^{205}Pb and ^{207}Pb were measured with the FIPPS (FIssion Product Prompt γ-ray Spectrometer) array, composed of 8 HPGe clovers (for a total of 32 HPGe crystals), arranged in annular geometry at every 45° around the target in the plane perpendicular to the beam. Additionally, seven clovers (for a total of 28 HPGe crystals), provided by IFIN-HH (Bucharest), were placed forward and backward at 45° with respect to the beam-line.

In both cases, the signals from the detectors were processed digitally and the events were stored triggerless. Each event contained information on γ-ray energy and time, as well as the identification number of the specific HPGe crystal that fired. Next, the data were sorted offline into a $\gamma\gamma$-coincidence matrix and a $\gamma\gamma\gamma$-coincidence cube with a time window of 300 ns. The time-random coincidences were negligible in these cases due to the moderate count rate during the experiments.

3. ^{205}Pb data analysis and results

From the neutron capture state at 6732 keV in ^{205}Pb, the decay proceeds via primary (mainly E1) γ-ray transitions of several MeV, populating in a statistical way numerous excitations below the neutron binding energy. Owing to a large number of decay paths, the measured γ-ray spectrum was very complex. In order to resolve it and obtain the information on the ^{205}Pb level scheme, the γ-ray coincidence techniques were applied in the analysis. The already known strong primary and secondary γ rays were used in the $\gamma\gamma$ matrix as gating transitions to obtain clean spectra and, thus, identify new lines and locate the new energy levels in ^{205}Pb. A representative example of such a spectrum, gated on the 261 keV, $3/2^- \rightarrow 1/2^-$ transition, is shown in Fig. 1. This spectrum is zoomed on the high-energy region, where the peaks corresponding to primary γ rays from the capture state in ^{205}Pb may be expected.

In the course of the analysis, 27 primary γ rays (13 new) and $\sim$115 secondary γ-ray transitions ($\sim$ 90 new) were established. The decay from the capture state ($J^\pi = 1/2^+$) to the ground state ($J^\pi = 5/2^-$) allowed to populate 33 (9 newly observed) low-spin (J from 1/2 to 7/2) excited states. They are shown together with the primary γ rays in Fig. 2 (a), where the new findings are marked in red/gray. The levels not populated directly from

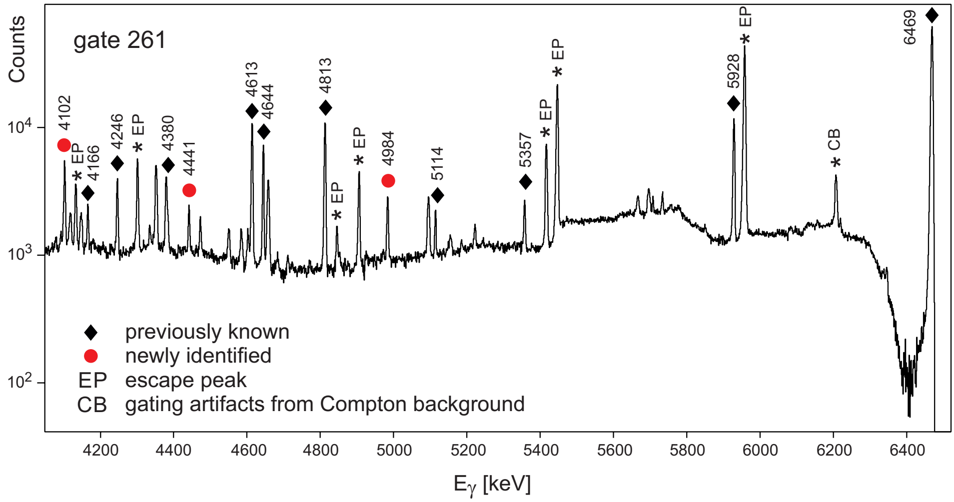

Fig. 1. (Color online) Representative coincidence spectrum of ^{205}Pb gated on the 261 keV, $3/2^- \to 1/2^-$ γ-ray transition from the thermal neutron capture reaction $^{204}\mathrm{Pb}(n,\gamma)^{205}\mathrm{Pb}$.

the capture state, *i.e.*, 576, 703, 762, 1044, and 1265 keV, were established owing to the feeding by the secondary transitions, which were not included in Fig. 2 (a) due to lack of space.

The FIPPS-IFIN array, whose detectors were arranged at certain angles around the target, allowed us to use the $\gamma\gamma$-angular correlation analysis to extract information about γ-ray multipolarities and excited levels spins. We applied the well-known procedure described for example in Refs. [16, 17]. A series of $\gamma\gamma$-coincidence matrices were sorted according to the relative angle between the detectors that fired, namely, 45°, 60°, 90°, 120°, 135°, and 180°. Due to the differences in geometry and efficiency between the FIPPS and IFIN crystals, three sets of $\gamma\gamma$-coincidence matrices, involving FIPPS-FIPPS, FIPPS-IFIN or IFIN-IFIN combinations, were defined requiring corrections for different attenuation coefficients q_n.

To combine the information from the different detector types, a simultaneous fit of the angular correlation function to the three sets of experimental points was then performed. A more detailed description of this method will be presented in the longer paper summarizing the results of finished analysis. The fitted $W(\theta)$ function was expressed as a sum of Legendre polynomials, $P_n(\cos\theta)$

$$W(\theta) = A_0[1 + q_2A_2P_2(\cos\theta) + q_4A_4P_4(\cos\theta)]\,, \tag{1}$$

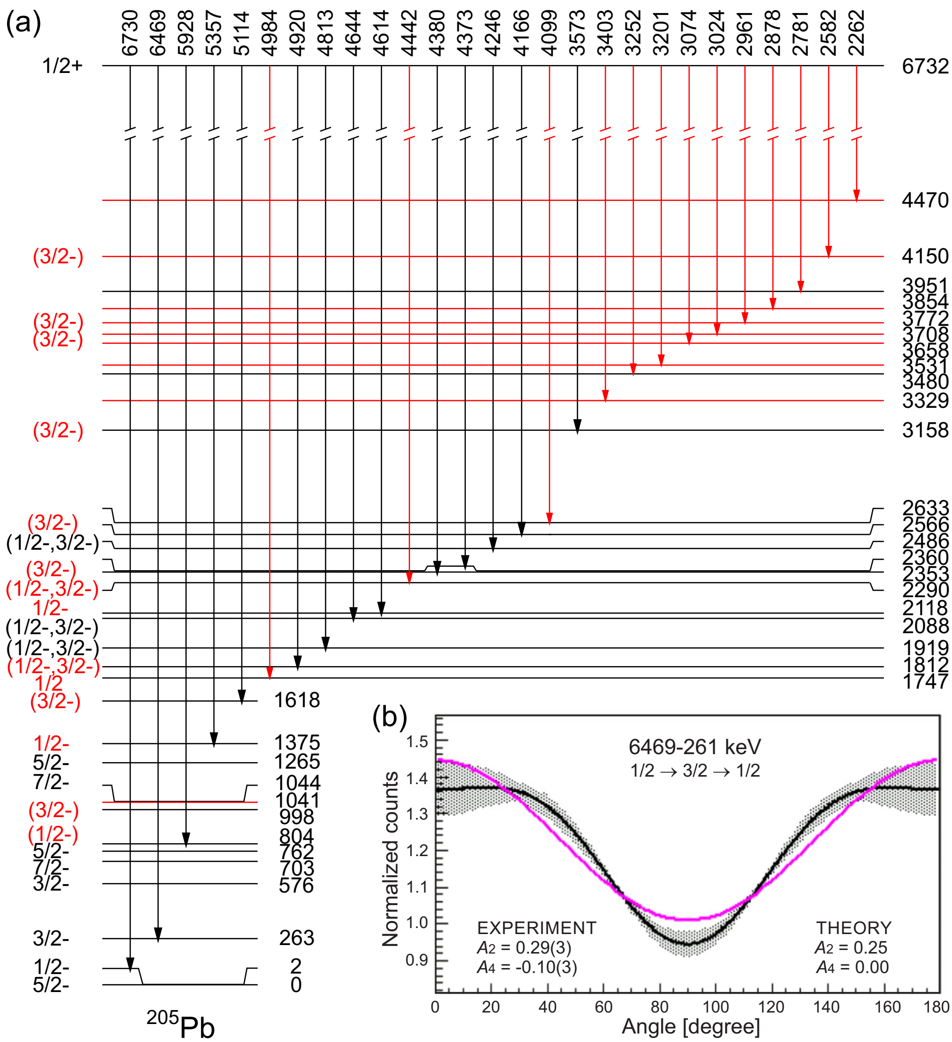

Fig. 2. (Color online) (a) A part of the preliminary level scheme of ^{205}Pb from thermal-neutron capture reaction containing the primary γ rays. The newly found levels and γ-ray transitions are marked in red/gray. (b) A fit of angular correlation function to experimental data obtained for the 6469 and 261 keV pair of γ rays from ^{205}Pb (black curve with the gray band corresponding to the experimental error) together with the theoretical curve calculated for pure transitions (pink/gray line).

with the three sets of different q_n values. As a result, the A_2 and A_4 parameters of the correlation function could be extracted and compared to the theoretical ones.

Figure 2 (b) shows, as an example, the fit of angular correlation function (marked by the black solid line and a gray band representing the experimental error) obtained for the strong 6469–261 keV cascade leading to the 2 keV state in ^{205}Pb. The spin of the initial, intermediate, and final states, $1/2^{+}$, $3/2^{-}$, and $1/2^{-}$, respectively, as well as the M1(+E2) multipolarity of the 261 keV γ ray were previously established. In addition, the rather pure E1 multipolarity, likely for the primary transitions, is expected for the 6469 keV γ ray. The theoretical curve, calculated for the $1/2 \rightarrow 3/2 \rightarrow 1/2$ cascade, assuming the stretched character of involved transitions, is shown by the pink/gray line in Fig. 2 (b). The disagreement between the calculated $A_2 = 0.25$ and experimental $A_2 = 0.29(3)$ values indicates a mixed M1(+E2) character for the 261 keV line. For the mixing ratio of $\delta = 0.05$, the theoretical value of $A_2 = 0.29$ is in agreement with the one obtained from the fit which validates this approach for the less known pairs of transitions. We note that A_4 coefficient, however within 3 standard deviations almost equal to the calculated one, was observed to be very sensitive to different background subtraction. This issue will be investigated in further analysis.

A similar approach was used for the most intense transitions in the ^{205}Pb capture state's decay. The ongoing analysis allowed for the preliminary spin-parity assignments for several states: nine previously known levels of 804, 998, 1375, 1618, 1747, 2118, 2353, 2566, and 3158 keV and three new excitations at 3708, 3772, and 4150 keV. All of the previously known and newly assigned states are of negative parity character. The presently reported spin-parity assignments were done based on the comparison of the experimental A_2 values with the values calculated for stretched transitions. A detailed discussion of the different scenarios for spin-parity assignments for energy levels and extraction of mixing ratios for considered γ-ray transitions will be done in the future and presented in the final paper.

4. ^{207}Pb preliminary data analysis and first results

Since the γ-ray decay of the neutron-capture state in ^{207}Pb has never been investigated before, our experiment was the first to provide spectroscopic information on the low-spin ^{207}Pb structure populated in thermal neutron capture reaction. The γ-coincidence method was employed to resolve the complex γ-ray spectrum measured with the FIPPS-IFIN array at the ILL, Grenoble. The gates were set in the $\gamma\gamma$ matrix on strong low-lying secondary γ rays to obtain cleaner spectra and identify the new lines and levels. For example, in the spectra gated on the 570 or 898 keV lines, being the intense γ rays feeding the ground state, a series of high-energy peaks were identified as corresponding to primary transitions in ^{207}Pb, namely at 1665, 2349, 2737 3435, 4114, 5840, and 6168 keV. For example, a peak at 2737 keV was associated with the transition from the capture state at 6738 keV to the previously known level of 4000 keV. A further inspection of coincidence spectra, including the spectrum gated on the 2737 keV line shown in Fig. 3 (a), allowed to establish the main paths of the 4000 keV state decay, *i.e.*, through the 3102–898, 1376–1726–898, and 1376–2054–570 keV cascades. The peak at 3102 keV (marked by the red circle in Fig. 3 (a)) was not reported in previous works.

In a similar analysis, a new level fed by the 1665 keV primary γ ray was established at 5073 keV. The spectrum gated on the 1665 keV transition shown in Fig. 3 (b) helped to identify three branches of the 5073 keV state's decay, namely, through the transitions of 4175, 4503, and 5073 keV, to the 898, 570 keV, and ground state, respectively. Furthermore, the 6738 keV transition feeding directly the ground state from the capture level was observed in a single γ-ray spectrum.

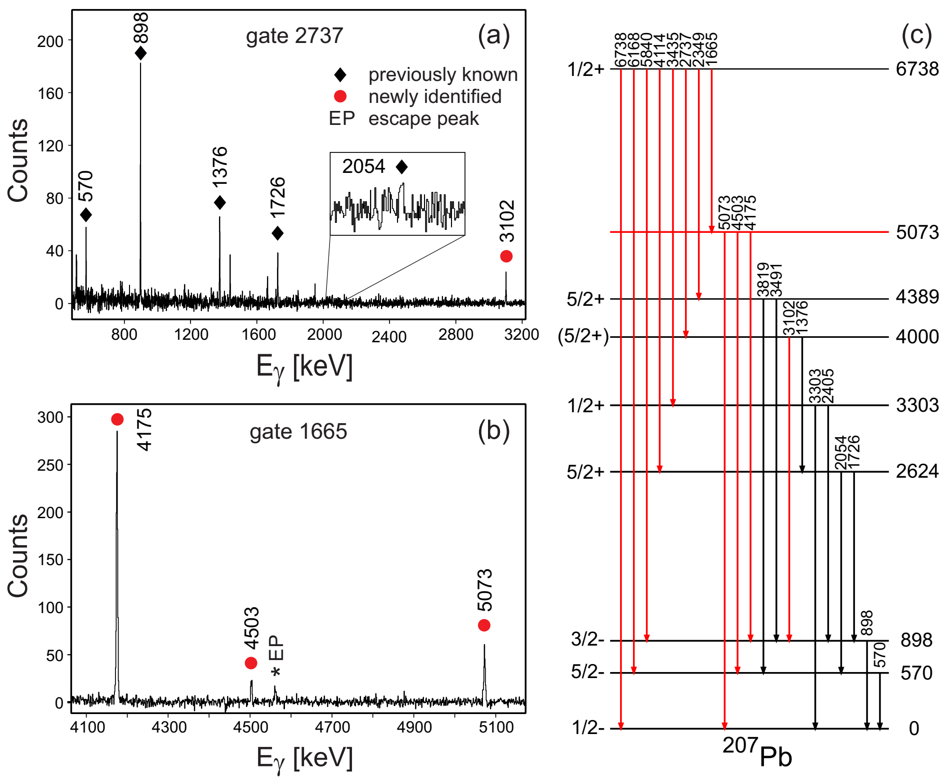

Fig. 3. (Color online) Representative coincidence spectra of ^{207}Pb gated on the (a) 2737 keV and (b) 1665 keV γ-ray transitions from the thermal neutron capture reaction ^{206}Pb$(n,\gamma)^{207}$Pb. (c) The preliminary level scheme of ^{207}Pb — newly found level and γ-ray transitions are marked in red/gray.

The first information on the decay scheme of ^{207}Pb from neutron capture reaction resulting from the preliminary analysis of the γ-ray coincidence data is shown in Fig. 3 (c), where the levels and transitions found in the present investigations were marked in red/gray.

5. Summary

The γ-ray spectroscopy studies of ^{205}Pb and ^{207}Pb, populated by thermal-neutron capture, were performed with a high-efficiency HPGe FIPPS-IFIN array. A series of new γ rays were observed and new levels were identified in both isotopes. The first results of the $\gamma\gamma$-angular correlations analysis allowed to assign spin-parity values of several states in ^{205}Pb. Further analysis will allow to extend experimental information on the level scheme of ^{207}Pb, including spin-parity assignments for the most intensely populated new states. The newly established excited structures may be used as an excellent probe for different theoretical calculations, *e.g.*, shell-model predictions with realistic nucleon–nucleon interactions (^{205}Pb), as well as new models aiming at describing particle/hole–phonon couplings on a microscopic basis [7, 8] (^{207}Pb).

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