THE LOW-SPIN STRUCTURE OF ^{206}Tl STUDIED BY γ-RAY SPECTROSCOPY FROM THERMAL NEUTRON CAPTURE REACTION*

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(Received January 4, 2018)

The low-spin structure of the ^{206}Tl nucleus has been investigated with the FIPPS prompt γ-ray spectrometer of ILL making use of the $^{205}\mathrm{Tl}(n,\gamma)^{206}\mathrm{Tl}$ reaction and the γ-coincidence technique. A large number of excitations up to the neutron binding energy (at 6.5 MeV) in ^{206}Tl were observed. Preliminary results of the data analysis provided the information on the decay scheme of the capture state in ^{206}Tl and on the multipolarities of a number of γ rays. The comparison of the experimental data with shell-model calculations will help describing the proton–hole and neutron–hole couplings near the doubly magic core ^{208}Pb, benchmarking single-particle levels and two-body matrix elements of the residual interaction in this important region of the nuclear chart.

DOI:10.5506/APhysPolB.49.561

1. Introduction

The ^{206}Tl nucleus has only one proton hole and one neutron hole with respect to the best-known doubly-magic core: ^{208}Pb. Such nuclei, situated in the vicinity of doubly-closed shells, are the source of information on both the nucleonic single-particle energy levels and the two-body matrix elements of the effective nuclear interactions. Therefore, the structure of ^{206}Tl nucleus

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* Presented at the XXXV Mazurian Lakes Conference on Physics, Piaski, Poland, September 3–9, 2017.

is an ideal testing ground for various types of calculations based either on the shell-model approach or taking into account couplings between single particles/holes excitations and excitations of the core (such as vibrations) [1–5].

In the past, the thermal capture reactions on ^{205}Tl [6, 7] were used to study the low-spin structure of ^{206}Tl populated by primary γ rays from the capture state at 6.5 MeV. Such state, being in fact composed of a number of unresolved individual levels [8], has two J^{π} components as the coupling of the captured neutron spin, $1/2\ \hbar$, to the ^{205}Tl ground state spin, $1/2\ \hbar$, may result in the 0^{+} and 1^{+} spin values. In thermal neutron capture reactions, a large number of levels within a few units of spin were observed. However, due to the limited experimental setup available at that time, only very tentative spin-parity assignments were proposed for a series of excitations.

In this paper, we present preliminary results of the $^{205}\mathrm{Tl}(n,\gamma)^{206}\mathrm{Tl}$ experiment, performed at the Institut Laue-Langevin (Grenoble, France). The structure of ^{206}Tl was studied by γ-coincidence measurements with the newly constructed HPGe array — FIPPS. This multidetector setup has allowed to perform precise γ-spectroscopy measurements, thus, providing detailed information on the decay scheme of the capture state in ^{206}Tl.

2. Experiment

The low-spin states in ^{206}Tl were investigated in a thermal neutron capture experiment performed at the ILL in Grenoble. After the collimation to a halo-free pencil beam, the capture flux on target was $10^{8}\ n/(\mathrm{s}\times\mathrm{cm}^{2})$. The ^{205}Tl target was 99.9% enriched with total weight of 1938.4 mg. The γ decay of ^{206}Tl was measured with the newly constructed array — FIPPS (FIssion Product Prompt γ-ray Spectrometer). FIPPS is a system composed of 8 HPGe clovers (for a total of 32 HPGe crystals), arranged in annular geometry at every 45° around the target. The digital electronics was used to collect and process the signals from the detectors. The events were stored trigerless. Each event contained information on γ-ray energy, time (with a time stamp every 10 ns) and identification number of the specific detector that fired. The data were sorted offline into a $\gamma\gamma$-coincidence matrix and a $\gamma\gamma\gamma$-coincidence cube with the time window of 300 ns.

3. Data analysis and results

3.1. The level scheme

Thanks to the purity of the target, the only product of the reaction was ^{206}Tl (apart from a small number of contaminations — lines from, *e.g.*, ^{7}Li, ^{28}Al, ^{28}Si, ^{56}Fe, ^{116}Sn, and Ge isotopes). Owing to the large number of primary γ rays feeding numerous states in ^{206}Tl, the γ-ray spectrum was very complex and γ-coincidence techniques were applied in the analysis, using as gating transitions already known lines.

In order to check the previously known level scheme of ^{206}Tl and extract new spectroscopic information, a large number of coincidence spectra was inspected — representative examples are shown in Fig. 1 (a) and (b).

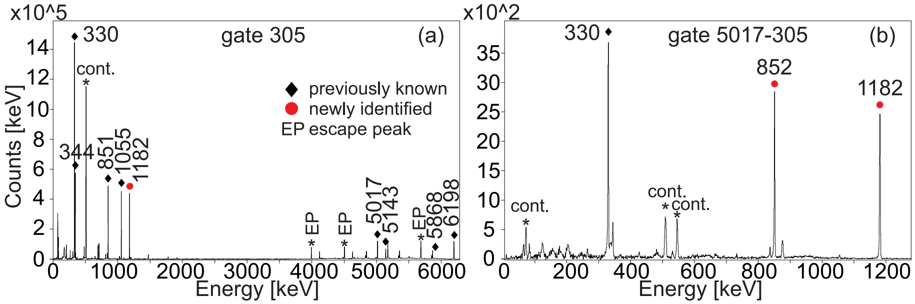

Fig. 1. (Color online) Representative coincidence spectra of ^{206}Tl from the thermal neutron capture reaction ^{205}Tl$(n,\gamma)^{206}$Tl: (a) the spectrum gated on the 305-keV transition and (b) the spectrum double-gated on the 5017- and 305-keV transitions.

The first information on the decay scheme of ^{206}Tl from neutron capture reaction resulting from the preliminary analysis of the γ-coincidence data is shown in Fig. 2 (a). The gates were set in the $\gamma\gamma$-matrix and in the $\gamma\gamma\gamma$-cube on strong primary and secondary γ rays to obtain clean spectra and identify the main paths of the decay. The levels and transitions marked in black were known from the earlier studies (the energies were taken from NNDC [9]), while the transitions marked in thick black/red were found in the present investigations.

In the spectrum gated on the 305-keV, an intense γ ray feeding the ground state (see Fig. 1 (a)), a series of peaks were identified as corresponding to transitions in ^{206}Tl. The line of 1182 keV (marked by circle (red) in Fig. 1 (a)) was not reported in previous works. A further inspection of single- and double-gated spectra allowed to associate this transition with the decay of the state at 1486 keV which was not observed thus far. For example, the spectrum gated on the 305- and 5017-keV transitions shown in Fig. 1 (b) allows to identify two branches of the 1486-keV state's decay: *(i)* through the previously mentioned 1182-keV line and *(ii)* through a new transition of 852 keV populating the 635-keV level. Further, it was observed that this newly established state decays via 6 branches in total, namely, the 1221-, 1182-, 852-, 837-, 488-, and 370-keV γ rays.

In a similar analysis, new branches were found, depopulating the 1844-keV level (1844-, 1578-, 1209-, 1195-, and 1042-keV γ rays) and the 1118-keV excitation (1118-, 881-, 482-, and 467-keV γ rays).

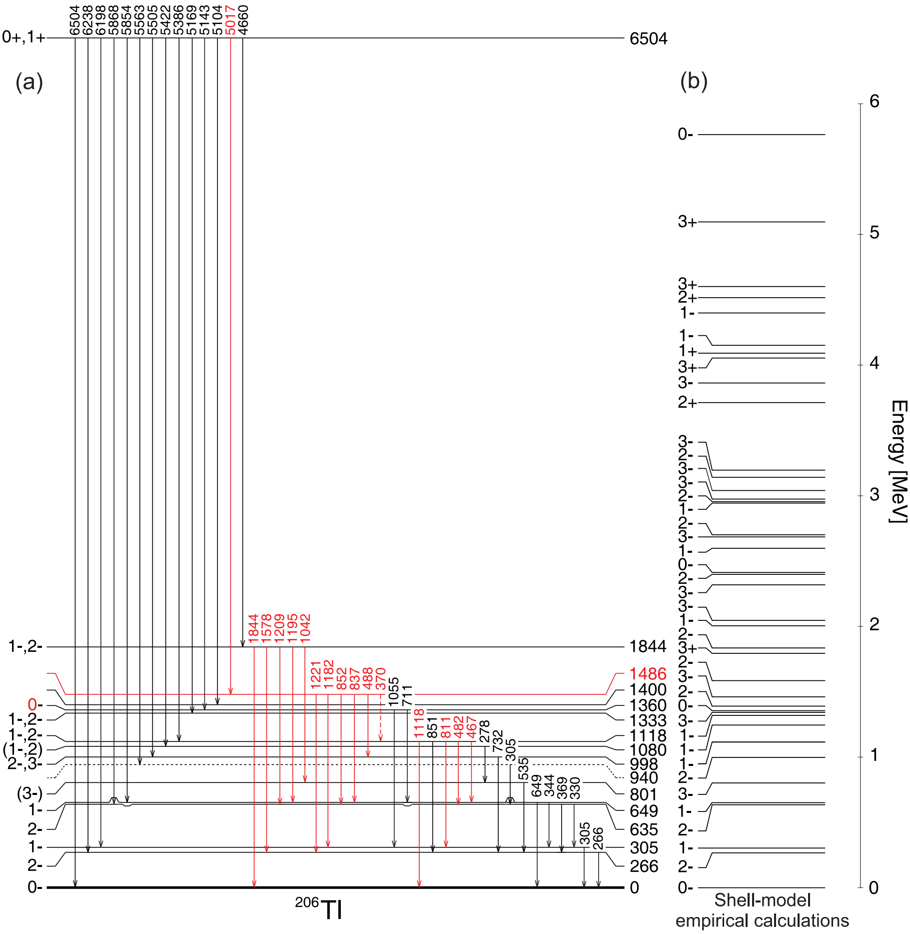

Fig. 2. (Color online) (a) Preliminary level scheme of ^{206}Tl. All new findings are marked in thick black/red. The dashed lines indicate tentatively identified levels and transitions. (b) Theoretical predictions from shell-model calculations (the states for the spin range 0–3 are plotted).

3.2. Angular correlations of γ rays

The setup of the FIPPS clovers allowed us to use the $\gamma\gamma$-angular correlation analysis to extract information about γ-ray multipolarities and spins of the states. A procedure similar to the one described in [10, 11] and standard $\gamma\gamma$-angular correlation formalism were used. As the single crystals were considered as separate detectors, the number of experimental points (calculated angles) is 20.

Figure 3 (a) shows, as an example, the angular correlation function obtained for the 711–649-keV cascade deexciting the 1360-keV level for which the spin value was not assigned precisely so far ($J^\pi = (0,1,2)^-$ [12]). As the M1 multipolarity was previously assigned to the 649-keV, $1^- \to 0^-$, transition, the theoretical curve (dashed/orange line in Fig. 3 (a)) for $0^- \to 1^- \to 0^-$, M1–M1 cascade describes very well the experimental result. This indicates a pure M1 character for the 711-keV line and $J^\pi = 0^-$ for the 1360-keV state. Additionally, the angular correlation function for the 5143–1055-keV cascade (Fig. 3 (b)) going through the intermediate level at 1360 keV supports this scenario. The isotropic distribution suggests spin 0 for this state. Moreover, since there are two possible spin values for the capture state in ^{206}Tl ($J^\pi = 0^+, 1^+$) and the $0 \to 0$ γ decay is forbidden, one can deduce that the 5143-keV primary γ ray deexcites only the 1^+ component of the capture state and thus is most probably of E1 character.

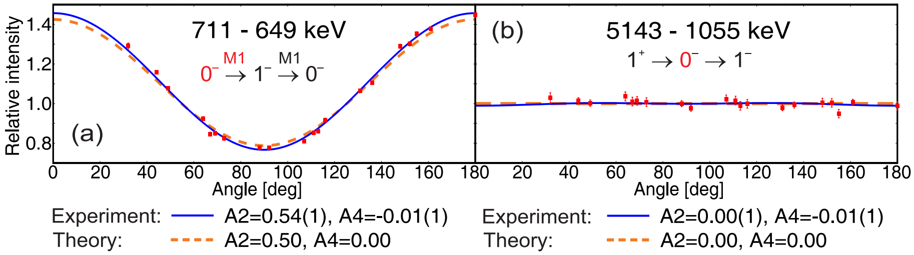

Fig. 3. (Color online) Experimental angular correlation functions of the 5143–1055- and 711–649-keV cascades (solid/blue curve and the A_2 and A_4 coefficients) together with the theoretical curve calculated for pure transitions (dashed/orange line).

3.3. Shell-model calculations

Shell-model calculations involving excitations of one proton hole and one neutron hole below the ^{208}Pb core were performed and compared with the level structure of ^{206}Tl. The interactions defined in Ref. [13] were used. The lowest states, up to energy of 802 keV, are reproduced very well, however, one should remember that this agreement arises mostly from the fact that the two-body matrix elements of the used interaction were fitted to the energies of levels located in ^{206}Tl in previous investigations. The experiment–theory comparison in the higher part of the ^{206}Tl level scheme will require higher accuracy in spin assignments. This information will be extracted using $\gamma\gamma$-angular correlation technique. Moreover, by making use of the present data we expect to be able to investigate in detail the energy region above 2 MeV, where a large number of states, not observed experimentally so far, is predicted.

4. Conclusions and summary

The results of the preliminary studies of the low-spin structure of the ^{206}Tl nucleus were presented. Gamma–gamma-coincidence data were collected in thermal neutron capture experiment at ILL Grenoble using the FIPPS HPGe array. The first results of the $\gamma\gamma$-angular correlations analysis allowed to assign spin-parity value of 0^- to the 1360-keV level in ^{206}Tl and M1 multipolarity to the 771-keV transition from this state. Further analysis will provide extended information on the level structure of ^{206}Tl, including spin and parity assignments for the majority of the newly found states. Finally, a detailed comparison with shell-model calculations will help extracting key information on the two-body effective interaction from one-proton-hole–one-neutron-hole multiplets. As the ^{206}Tl nucleus is only one-proton-hole and one-neutron-hole away from doubly magic core ^{208}Pb, it is an ideal system for testing the shell-model calculations on odd–odd spherical nuclei. The level structure of ^{206}Tl may be also used as a probe for new models which aim at describing particle–phonon couplings on microscopic basis [15, 16].

REFERENCES

[1] A. Bohr, B.R. Mottelson, *Nuclear Structure*, Vols. I and II, W.A. Benjamin, 1975.

[2] D. Montanari *et al.*, *Phys. Lett. B* **697**, 288 (2011).

[3] D. Montanari *et al.*, *Phys. Rev. C* **85**, 044301 (2012).

[4] G. Bocchi *et al.*, *Phys. Rev. C* **89**, 054302 (2014).

[5] G. Bocchi *et al.*, *Phys. Lett. B* **760**, 273 (2016).

[6] C.C. Weitkamp, J.A. Harvey, G.G. Slaughter, E.C. Campbell, *Bull. Am. Phys. Soc.* **12**, 922, Y10 (1967); Priv. comm. 1970.

[7] G.A. Bartholomew, E.D. Earle, M.A. Lone, *Bull. Am. Phys. Soc.* **15**, 550, EG11 (1970); Priv. comm. 1970.

[8] K.S. Krane, *Introductory Nuclear Physics*, J. Wiley and Sons, 1987.

[9] `http://www.nndc.bnl.gov/`

[10] N. Cieplicka-Oryńczak *et al.*, *Phys. Rev. C* **93**, 054302 (2016).

[11] N. Cieplicka-Oryńczak *et al.*, *Phys. Rev. C* **94**, 014311 (2016).

[12] M.B. Lewis, W.W. Daehnick, *Phys. Rev. C* **1**, 1577 (1970).

[13] B. Szpak *et al.*, *Phys. Rev. C* **83**, 064315 (2011).

[14] L. Rydström, J. Blomqvist, R.J. Liotta, C. Pomar, *Nucl. Phys. A* **512**, 217 (1990).

[15] G. Colò, H. Sagawa, P.F. Bortignon, *Phys. Rev. C* **82**, 064307 (2010).

[16] G. Colò, P.F. Bortignon, G. Bocchi, *Phys. Rev. C* **95**, 034303 (2017).