The γ-ray spectroscopy studies of low-spin structures in [210]Bi and [206]Tl using cold neutron capture reactions

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Abstract.

The γ-coincidence studies of low-spin structures of [210]Bi and [206]Tl are presented. The [210]Bi nucleus, populated in thermal neutron capture reaction, was investigated using EX-ILL HPGe array at Institut Laue-Langevin in Grenoble. The experimental results were compared to the shell-model calculations allowing to draw the conclusions on the nature of the low-spin excitations populated below the neutron binding energy in [210]Bi (4.6 MeV). It has been found that some levels cannot be described by the valence proton and neutron couplings, but may arise from couplings of valence particles to the 3⁻ octupole phonon of the doubly magic [208]Pb core. Moreover, preliminary results of a low-spin structure measurements of [206]Tl by the γ-coincidence technique, making use of the [205]Tl(n,γ)[206]Tl reaction at the FIPPS prompt γ-ray spectroscopy facility of ILL are shown. The population of a large number of excited states of [206]Tl above the ground state up to the neutron binding energy (at 6.5 MeV), within a few units of spin is expected. The analysis involving double and triple γ-coincidences and γγ-angular correlations will allow to significantly extend the experimental information on the energy and spin-parity of the levels in [206]Tl. This will help shedding light on the proton-hole and neutron-hole couplings near the doubly magic core [208]Pb.

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1 Introduction

Nuclei from vicinity of doubly-closed shells play an important role in studying both: a) the couplings between valence nucleons, thus being a source of information on the effective nucleon-nucleon interaction and, b) couplings of the valence nucleons with core excitations. In this way they provide a unique opportunity of testing various effective interactions used in mean-field based models, like Skyrme, Gogny, etc. From a broader perspective, the particle-phonon couplings are at the origin of quenching of spectroscopic factors [1] or damping of giant resonances [2]. The vibrational phonons are best known from the spectroscopic studies of doubly-magic nuclei in which they appear, in general, as the lowest excited states. For example, in ^{208}Pb, the lowest excitation (at 2615 keV) is the 3^- octupole vibration with a large $E3$ transition strength of 34 W.u. As this excitation is known to influence the structure of neighboring nuclei having ^{208}Pb as core, one expects to observe states of particle-phonon nature in the structures of ^{210}Bi and ^{206}Tl, being only one-proton one-neutron-particle and one-proton one-neutron-hole away from ^{208}Pb core.

The lowest lying excitations of the ^{210}Bi nucleus arise from the fully identified multiplet $\pi h_{9/2} \nu g_{9/2}$ [3], with the $J^\pi = 1^-$ ground state and the member of this multiplet with maximum spin, i.e., $J^\pi = 9^-$ excitation, lying only 271 keV above. The level structure of ^{210}Bi below ~2 MeV, should origin exclusively from couplings of a proton on the $1h_{9/2}$, $2f_{7/2}$, $1i_{13/2}$, $2f_{5/2}$, $3p_{3/2}$, $3p_{1/2}$ and a neutron on the $2g_{9/2}$, $1i_{11/2}$, $1j_{15/2}$, $3d_{5/2}$, $4s_{1/2}$, $2g_{7/2}$, $3d_{3/2}$ orbitals. In addition, in the higher energy region the couplings between valence particles and the 3^- phonon vibration of ^{208}Pb core should be observed.

An amount of experimental data on ^{206}Tl has already been accumulated as well. The ground state of ^{206}Tl is a member of the doublet arising from the $\pi s_{1/2} \nu p_{1/2}$ configuration [4]. Moreover, members of the multiplets involving a proton hole on the $3s_{1/2}$ and $2d_{3/2}$ orbitals and a neutron hole on the $3p_{1/2}$, $3p_{3/2}$, and $2f_{5/2}$ orbitals, with a total number of 8 states, have been identified (although, some of them are not completely assigned) [5]. At higher excitation energies, the members of multiplets with a proton hole occupying the $1h_{11/2}$ orbital, and a neutron hole on the $1i_{13/2}$ orbital have been found as well. In addition, four excitations involving the promotion of a neutron through the energy gap separating neutron shells at $N = 126$ have been located at 4.2-4.5 MeV in the ^{205}Tl(d,p)^{206}Tl reaction [6], i.e., the members of the $\pi s_{1/2}^{-1} \nu d_{5/2}^{+1}$ configurations. Measurements using the thermal neutron capture reaction on ^{205}Tl [7, 8] reported a series of states populated by primary γ rays from the capture state at 6.5 MeV in ^{206}Tl, however, in these works only very tentative spin-parity assignments were proposed. The presence of two components of the capture state (0^+ and 1^+) was deduced as well.

In this paper, we report preliminary results of the γ-coincidence measurements of ^{210}Bi and ^{206}Tl, performed at the Institut Laue-Langevin (Grenoble, France) by employing the thermal neutron capture reaction and the two multidetector germanium arrays: a) EXILL in the ^{210}Bi case [9, 10] and, b) the new FIPPS array for ^{206}Tl.

2 The low-spin structure of ^{210}Bi

2.1 Experimental setup and results

The coincidence measurements of γ rays from the cold-neutron capture in ^{209}Bi were performed at Institut Laue-Langevin (ILL) at Grenoble employing the highly efficient EXILL multidetector array, consisting of 16 HPGe detectors [11]. A ^{209}Bi target, made of small metallic pieces with total weight of 3 g, was placed in the center of the detection system. The data, collected trigerless using digital electronics [12], were sorted offline into a $\gamma\gamma$-coincidence matrix and a $\gamma\gamma\gamma$-coincidence cube with a

coincidence time window of 200 ns. The further details of the performed experiment may be found in [9].

The ^{209}Bi(n,γ)^{210}Bi reaction populates ^{210}Bi in the capture state at 4605 keV, which then decays through emission of γ-ray cascades. The resulting γ spectrum was very complex owing to a large number of decay paths, therefore, the γ-coincidence technique was applied.

The analysis of the γ-coincidence data resulted in significant extension of the ^{210}Bi level scheme, below the neutron binding energy at 4.6 MeV, with the total number of 70 states (33 were newly observed). The spin and parities were proposed based on the γ-ray angular correlations, the decay pattern and the comparison with shell-model calculations. Moreover, from the detailed analysis of angular correlations for strong γ transitions we extracted the upper limit of $\delta = 0.05(2)$ for the mixing ratio of the 320 keV γ-ray transition, which is the main transition populating the ^{210}Bi ground state [10]. This allowed to reduce the uncertainty of the ^{209}Bi(n,γ)^{210}Bi ground-state cross-section estimate, which serves for accurate projections of the ^{210}Po inventory in nuclear reactors and accelerator driven systems using Pb-Bi coolant.

2.2 Searching for excitations arising from the particle-phonon couplings

The detailed comparison of the levels experimentally established in ^{210}Bi with the shell-model calculations involving the excitations of one-valence-proton and one-valence-neutron particles allowed to draw the following conclusions.

All states below 2 MeV may be interpreted as arising from valence-particle excitations and all levels predicted by the shell-model below 1 MeV in ^{210}Bi are populated in cold-neutron capture reaction. This very good correspondence between experiment and calculations in the lower part of the scheme suggests that also in the higher excitation energy region the theory should perform rather well.

In the energy region 1950-2845 keV, all of the calculated levels with spins from $3\hbar$ to $7\hbar$, have found their experimental counterparts. The identified states have configurations which come from neutron and proton excitations to almost all orbitals available above the ^{208}Pb core, allowed by the Kuo-Herling model space [4]. This suggests that in the presented study we approached the complete spectroscopy of low-spin states in the ^{210}Bi nucleus. In contrast, in the energy region above 2 MeV not all observed excitations have corresponding calculated states. Indeed, around the energy of 2.6 MeV one expects to observe several states arising from coupling of the 3^- phonon, to the lowest excitations in ^{210}Bi, i.e., 1^-, 0^-, 9^-, 2^- and 3^-. This coupling would give a number of positive parity levels with spins 2-8 $\hbar$. Most probable candidates for these states are the excitations located at 2007, 2147, 2556, 2726, 2730, 2807, 2883, 2979, 3023, 3047, 3097, and 3120 keV [9].

3 The low-spin structure of ^{206}Tl

3.1 Experimental setup: the FIPPS array

To investigate the low-spin states in ^{206}Tl, an experiment was performed at the ILL in Grenoble using the ^{205}Tl(n,γ)^{206}Tl reaction and the thermal neutron flux of 10^8 n/(s×cm^2) at target position. The target was a solid, cylindrical piece of 99.9% enriched ^{205}Tl (total weight of 1938.4 mg), placed in the center of the detection system. To measure γ rays we used the newly constructed array FIPPS (FIssion Product Prompt γ-ray Spectrometer), composed of 8 HPGe clovers (giving 32 HPGe crystals in total), in annular geometry around the target.

The signals from the detectors were collected and processed by digital electronics. The events, containing information about γ-ray energy, time of the registration (with a time stamp every 10 ns) and identification number of the specific detector that fired, were stored triggerless.

The γ-coincidence technique was used to resolve the complex spectrum collected from the capture state in ^{206}Tl. The data were sorted offline into a $\gamma\gamma$-coincidence matrix with the time window of 200 ns. The energy calibration was done based on the strong peaks from the ^{152}Eu source, ^{35}Cl(n,γ)^{36}Cl, and ^{48}Ti(n,γ)^{49}Ti reactions.
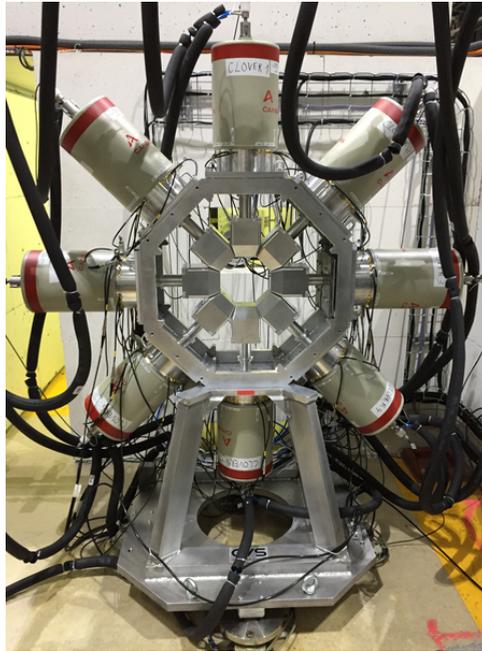

Figure 1. The FIPPS array at ILL Grenoble [13].

3.2 Preliminary data analysis and shell-model interpretation

The gating on the already known, low-lying γ rays in ^{206}Tl made it possible to produce coincidence spectra, the analysis of which will help extending the information on the level scheme of this nucleus below the neutron capture state. Although the only product of the reaction was ^{206}Tl (apart from a small number of contaminants), the collected data contain many γ peaks, owing to many primary γ rays feeding numerous states. Thus, to check and extend the level scheme of ^{206}Tl, the analysis will require identification of various paths of the decay, that is, inspection of a large number of coincidence spectra. The examples of the coincidence spectra are presented in Fig. 2.

The results of the preliminary analysis of the lower part of the level scheme are shown in Fig. 3(a). The levels and transitions marked in black in Fig. 3(a) were known previously (the energies were taken from [14]), while the transitions marked in red were found in the present analysis. The gates were set in the $\gamma\gamma$-matrix on high-energy primary γ rays to obtain clean spectra and identify the main paths of the decay.

In the spectrum gated on the 4660-keV primary transition feeding the 1844-keV state, shown in Fig. 2(b), five peaks were identified as corresponding to new transitions: 1042, 1195, 1209, 1578, 1844 keV. Similarly, by gating on the 5386-keV primary γ ray one can deduce the presence of four new transitions, 1117, 811, 482, 467 keV depopulating the 1117-keV level. Moreover, a new excited
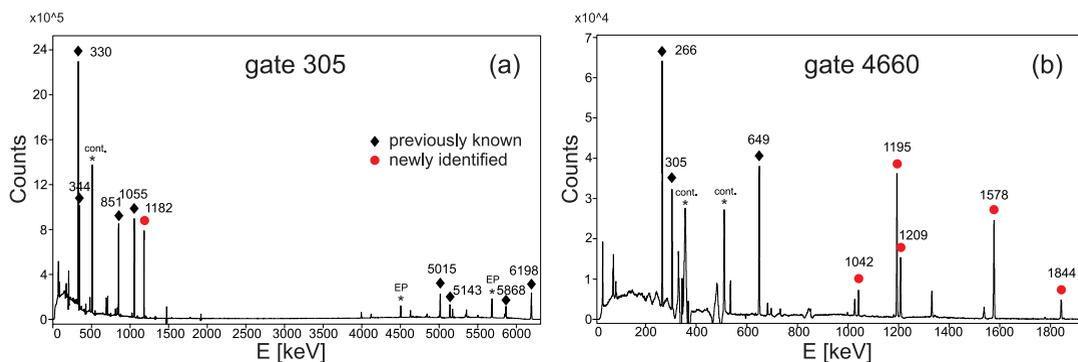
Figure 2. Representative coincidence spectra for ^{206}Tl. (a) Spectrum single-gated on the 305-keV transition; (b) spectrum single-gated on the the 4460-keV primary transition.

state was established at 1487 keV – decays via the 1221-, 1182-, 852-, 837-, 488-, and 370-keV γ rays. The exact energy of the primary γ ray feeding the 1487-keV level is 5017 keV, so very close to the 5015-keV transition leading to the 1490-keV level, observed previously. Further analysis with the $\gamma\gamma\gamma$ cube will allow to confirm whether in this case we deal with a doublet of states lying very close in energy, or whether the previously reported values need to be corrected.

The shell-model calculations for ^{206}Tl, involving excitations of one proton hole and one neutron hole, are presented in Fig. 3(b) (only the states with spins from 0 to 3 are plotted). They have been performed using the interactions defined in Ref. [15], that is, the Rydstroem interaction [16] with some of the elements adjusted to reproduce better level energies in nuclei with two to four holes in the ^{208}Pb core.

Five lowest states in ^{206}Tl, up to 802 keV of excitation energy, are reproduced very well, however, one should remember that this agreement arises mostly from the fact that the two-body matrix elements of the interaction, which was used here, were fitted to the energies of states which were located in ^{206}Tl in earlier studies. In order to do the proper experiment-theory comparison in the higher part of the ^{206}Tl level scheme, we need higher accuracy in spin assignments. This will be done using γ-angular correlation technique. In the energy region above 2 MeV, the calculations predict a large number of states not observed experimentally so far. By making use of the present data we expect to add a series of new findings in this energy region.

4 Conclusions and summary

An investigation of low-spin states in ^{210}Bi from a cold-neutron capture reaction was performed by employing the γ-coincidence technique and the EXILL HPGe array. The majority of the 70 states established in the present study arises from the one proton- one neutron-particle excitations. However, the presence of states which come from the particle-phonon couplings was also concluded, i.e., the levels located at 2007, 2147, 2556, 2726, 2730, 2807, 2883, 2979, 3023, 3047, 3097, and 3120 keV, which do not have the calculated partners, very likely are candidates for these type of excitations. In fact, within a weak-coupling approach, the couplings of the ground state or the lowest excited states of ^{210}Bi with the 3^- octupole vibration in ^{208}Pb, at 2615 keV, are expected. These couplings would give a number of positive parity states with spins between 2 and 12, located around 2.6 MeV, although a splitting of the order of hundreds of keV is possible [1, 17–20].

Figure 3. (a) The level scheme of ^{206}Tl from ^{205}Tl(n,γ)^{206}Tl reaction and (b) shell-model calculations.

The results of the preliminary γ-spectroscopy study of ^{206}Tl produced in thermal neutron capture were presented. Gamma-coincidence data were collected using the FIPPS HPGe array at ILL Grenoble. Further analysis will provide extended information on the level scheme of ^{206}Tl while the angular correlations of γ rays will allow to determine spin and parity of the states. The detailed comparison with shell-model calculations will help shedding light on the structure of excited states one-proton-hole and one-neutron-hole away from the doubly magic core ^{208}Pb. Key information on the two-body effective interaction will be extracted from one-proton-hole one-neutron-hole multiplets.

The ^{210}Bi and ^{206}Tl nuclei, being two-particle and two-hole nuclei with respect to the best known doubly magic core ^{208}Pb, are ideal systems for testing the shell model calculations on odd-odd spher-

ical nuclei. Their structures may serve also as a very good testing ground for new models which aim at describing particle-phonon couplings on microscopic basis [21].

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