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# PARTICLE-CORE COUPLINGS CLOSE TO NEUTRON-RICH DOUBLY-MAGIC NUCLEI*

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Preliminary results are presented from a recent campaign of experiments, performed at the PF1B cold-neutron facility at ILL (Grenoble, France), in which $\gamma$-ray spectroscopy of neutron-rich nuclei produced in neutron induced fission on $^{235}$U and $^{241}$Pu targets was performed. By using the EXILL array, consisting of EXOGAM, GASP and ILL-Clover detectors, and a digital triggerless data acquisition system, $\gamma$ coincidences over several microseconds time windows were studied. This allowed to obtain new information on nuclei around $^{132}$Sn, such as $^{132}$Te, $^{133}$Sb and $^{130}$Sn, in which microsecond isomeric states occur. Preliminary results on $^{210}$Bi, populated by cold-neutron capture, are also shown. The data offer the possibility to investigate the couplings between core excitations and valence particles, around the doubly magic nuclei $^{132}$Sn and $^{208}$Pb.

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## 1. Introduction

In doubly-magic nuclei, in general, the lowest excited states exhibit a high degree of collectivity. For example, in $^{208}$Pb, the lowest excitation (at 2615 keV) is the $3^-$ octupole vibration with a large transition strength of 34 W.u. In $^{132}$Sn, the first three excitations, $2^+$, $3^-$ and $4^+$ are placed between 4 and 4.5 MeV and show a sizable collectivity with a transition probability of about 7 W.u. for the $2^+$ and $4^+$ and $> 7$ W.u. for the $3^-$ phonons, respectively.

As a consequence, nuclei with one or two particles outside of a doubly-closed core play a crucial role not only in determining the nucleonic single-particle energy levels and the two-body matrix elements of the effective nuclear interactions. They are also important to understand the couplings between phonon excitations and valence particles, which give rise to a series of multiplets [1]. The identification of these multiplets can provide precise, quantitative information on the phonon–particle couplings. In fact, the energy and transition probability for states belonging to phonon–particle multiplets can be calculated within mean-field based models and comparisons with experiment can provide a unique test of various effective interactions like Skyrme, Gogny, *etc.* From a broader perspective, understanding the coupling of a single particle to core excitations, in particular vibrations, is of primary importance, as this coupling is responsible for the quenching of spectroscopic factors [2]; it is also the key process at the origin of the damping of giant resonances [3].

In this respect, the regions around doubly magic $^{132}$Sn and $^{208}$Pb are particularly attractive as these nuclei are considered the best doubly closed cores. $^{209}$Bi (one-proton nucleus with respect to the $^{208}$Pb core) is the only case where the complete set of states arising from phonon–particle coupling is known: it is the $3^- \otimes \pi h_{9/2}$ multiplet, consisting of states with spins ranging from $J^\pi = 3/2^+$ to $15/2^+$ [1]. In other nuclei around $^{208}$Pb, states originating from couplings of the $3^-$ phonon with single particles/holes have been located as well, although these are mostly only the highest spin members of the multiplets. The examples include $^{206-209}$Pb, $^{206,207}$Tl and $^{206}$Hg [4, 5]. Several indications of states of particle–phonon nature have also been found around other doubly-magic and semi-magic nuclei lying near the stability valley [6–14], while searches for particle–phonon coupled states away from the stability valley, as, for example, in neutron-rich nuclei, are expected to provide information on the robustness or softness of nuclear collectivity which can be measured with the purity of single-nucleon excitations on top of core vibrations.

In the present contribution, preliminary results from a high-efficiency and high-resolution $\gamma$-spectroscopy campaign at ILL (Grenoble) are presented. They concern neutron-rich $^{132}$Te, $^{133}$Sb and $^{130}$Sn nuclei (located around the doubly-magic $^{132}$Sn core), which were populated by cold-neutron induced fission on $^{235}$U and $^{241}$Pu targets. In addition, low-spin spectroscopic study of $^{210}$Bi, produced by a cold-neutron capture reaction, is presented. The results are then discussed from the perspectives of two theoretical approaches: the shell model and the particle–phonon coupling model.

## 2. Experimental setup and data analysis

The EXILL campaign took place in 2012–2013 at the PF1B [15] cold-neutron facility at Institut Laue-Langevine (Grenoble, France) and lasted two reactor cycles (each $\approx$ 3 months long). The ILL reactor is the world's brightest continuous neutron source with an in-pile flux up to $1.5 \times 10^{15}$ neutrons s$^{-1}$ cm$^{-2}$, providing of the order of $10^8$ neutrons s$^{-1}$ cm$^{-2}$ on target, after collimation. Two detectors setups were used, the first consisting of 8 EXOGAM clovers (at 90° with respect to the beam direction), 6 large coaxial detectors from GASP (at 45°) and 2 ILL-Clover detectors (at 45° and 180° with respect to the beam direction and the GASP detectors, respectively) with a total photopeak efficiency of about 6%. In the second setup, the GASP and ILL detectors were replaced by 16 $LaBr_3$ crystals for lifetime measurements by fast-timing techniques. A digital data acquisition, triggerless, allowed event rates up to 0.84 MHz to be handled [16].

In this contribution, we report on results obtained with the first setup. In particular, in Sec. 2.1 we focus on $\gamma$-spectroscopy studies of neutron rich fission fragments around $^{132}$Sn, populated by neutron induced fission on $^{235}$U and $^{241}$Pu targets, while in Sec. 2.2 preliminary results from the $(n,\gamma)$ reaction on $^{209}$Bi will be presented.

### *2.1. Spectroscopy of neutron-rich nuclei around $^{132}$Sn*

The main part of the EXILL campaign consisted of two long runs of neutron induced fission on $^{235}$U and $^{241}$Pu targets, $\approx$ 1 mg/cm$^2$ thick. A large fraction of the data was taken with the first configuration of the EXILL array, comprising Ge detectors only. The use of a fully digital, triggerless acquisition system (with time stamp intervals of 10 ns) allowed to study coincidences among $\gamma$-transitions over several tens of microseconds. This gave the possibility to investigate nuclei close to the $^{132}$Sn doubly-magic core, in which microsecond isomers were identified in previous works. This is the case of $^{132}$Te, $^{133}$Sb and $^{130}$Sn [4, 18–21]. The analysis was based on double and triple $\gamma$-coincidence histograms constructed either requiring correlations among $\gamma$-rays prompt with fission events (an event with $\gamma$-ray fold larger than 4 recorded within 200 ns was considered a fission event) or requesting correlations between prompt and delayed transitions (a transition was considered delayed if it occured within 200 ns and 20 $\mu$s after the prompt event and was not associated with multiplicity higher than 3). Examples of $\gamma$-ray fold distributions, as a function of time, for Ge events collected over a 20 $\mu$s time interval are given in Fig. 1.

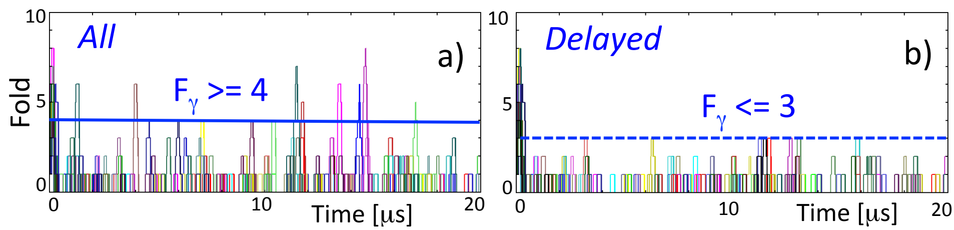


Fig. 1. (a) Ge fold distributions for 10 sequences of events in a 20 $\mu$s time window, after a prompt fission event (see the text for details). It is seen that in this time range $\approx 50\%$ probability exists for a new prompt fission event (with fold $F_\gamma \geq 4$). (b) Ge fold distributions for 10 events in a 20 $\mu$s time window, after a prompt fission event, which satisfy the condition $F_\gamma \leq 3$ for delayed transitions in the interval 200 ns up to 20 $\mu$s. This allows to reject more than 85% fission events in the delayed time window.

Figure 2 (a) shows a partial level scheme of $^{132}$Te, focused on the decay of the two longed-lived isomeric states $7^-$ (at 1925 keV, $\tau_{1/2} = 28.1$ $\mu$s) and $10^+$ (at 2723 keV, $\tau_{1/2} = 3.7$ $\mu$s). Transitions known from neutron-induced fission and $\beta$-decay of $^{132}$Sb, reported in Refs. [18, 19], are given in black, while EXILL results from the analysis of the fission data with the $^{241}$Pu target are indicated in gray/pink, thick arrows. The latter were obtained by making use of prompt-delayed $\gamma$–$\gamma$ coincidences, with gates set on known delayed transition depopulating the isomeric states. While the prompt spectrum obtained in coincidence with the strong, delayed, 151 keV line from the $7^-$ isomeric state, shows only known transitions belonging to $^{132}$Te and the $^{104,105,106}$Mo fission partners (panel (b)), the prompt spectrum in coincidence with the delayed 926 keV line, depopulating the $10^+$ isomer, besides the lines from the Mo partners, shows two new transitions of energy 518 and 900 keV (panel (c)).

The excitation energy spectrum of $^{132}$Te, with two valence $g_{7/2}$ protons and two valence $h^{-1}_{11/2}$ neutron holes with respect to the $^{132}$Sn core, can be explained by shell model calculations taking into account interactions among the four valence particles/holes only. Based on shell model calculations, it has been found that all known states up to $10^+$ are given mostly by neutron excitations, while the newly found transitions depopulate states most likely arising from neutron and proton excitations.

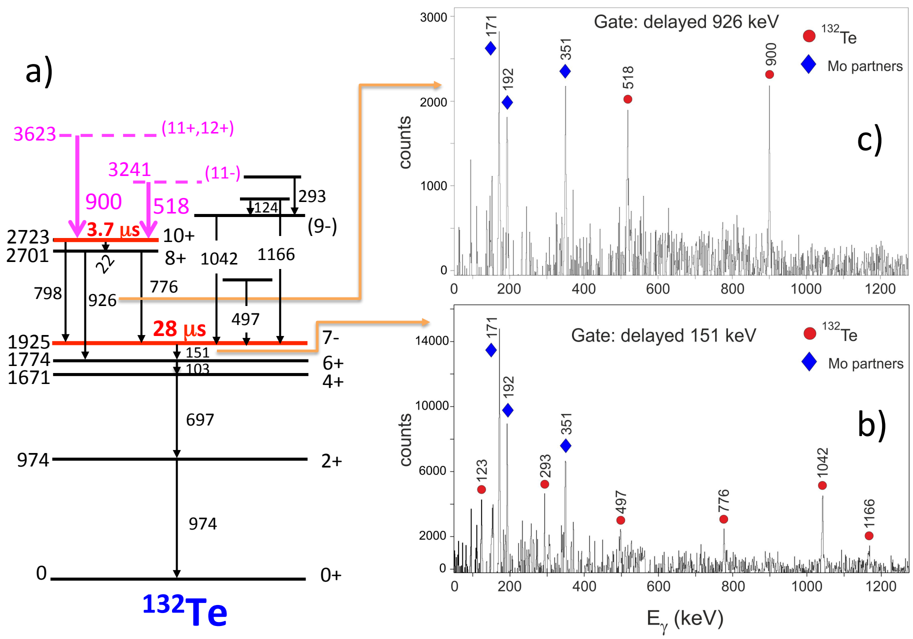


Fig. 2. (a) Partial level scheme of $^{132}$Te showing, in black, the known level scheme below the long lived $7^-$ and $10^+$ isomers and states observed in $\beta$-decay studies [18, 19]. New transitions found in this work are given as gray/pink, thick arrows originating from states with tentative spin assignments. They were observed by studying $\gamma$ coincidences between delayed and prompt transitions, as shown in panels (b) and (c) in the case of gates set on the 151 and 962 keV lines, respectively (see the text for details).

In the $^{133}$Sb nucleus, having one proton outside the doubly magic $^{132}$Sn core, the lowest excited states are single-proton excitations, while around 4 MeV states arising from the coupling between core excitations (in particular $2^+$, $3^-$ and $4^+$ phonons, with a strength of $\approx 7$ W.u.) and the valence proton are expected. With these characteristics, $^{133}$Sb is an ideal playground for testing shell model predictions and/or different approaches taking into account collective excitations, such as phonon excitations of the core. Figure 3 shows the results of a preliminary analysis for $^{133}$Sb. Panel (a) shows (in black) a partial level scheme of $^{133}$Sb, as follows from the $\gamma$-decay of the $21/2^+$ long-lived isomeric state at 4545 keV (with $\tau_{1/2} = 16.6$ $\mu$s), studied in Refs. [20, 21]. By gating on the 1510 and 2792 keV lines, two $\gamma$-rays at 75 and 223 keV were displayed, both feeding the $15/2^+$ state (panel (b)). In turn, by using the prompt-delayed matrix, a gate on the 2792 keV transition showed the 208 and 318 keV lines (panel (c)), feeding the isomeric state. These new transitions are marked in Fig. 3 as gray/pink, thick arrows originating from states with tentative spin assignments.

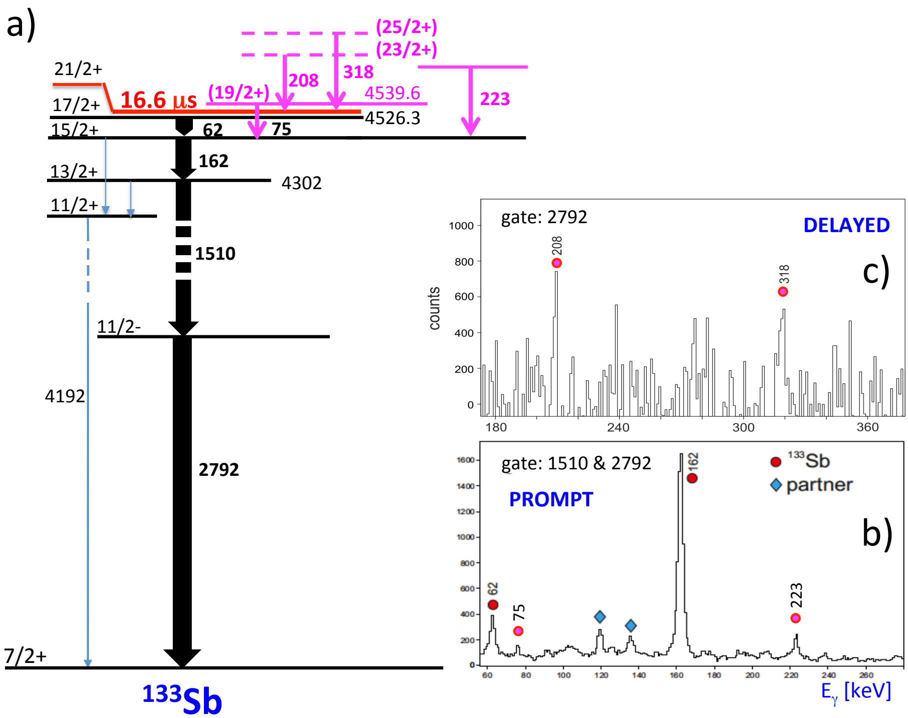


Fig. 3. (a) Partial level scheme of $^{133}$Sb, showing (in black) the known level scheme below the long lived $21/2^+$ isomer [20, 21]. New transitions are given as gray/pink, thick arrows originating from states with tentative spin assignments. They were observed by studying either $\gamma$ coincidences between prompt transitions, as shown in panel (b) or between delayed and prompt ones, as shown in panel (c). Both spectra were taken from the fission data on the $^{235}$U target (see the text for details).

As discussed in Ref. [20, 21], the high spins positive parity states of $^{133}$Sb, shown in Fig. 3 panel (a), may be described as members of the multiplet arising from the coupling of the odd $g_{7/2}$ proton to the $f_{7/2}h^{-1}_{11/2}$ neutron excitations of the core. In that work, shell model calculations based on two-body empirical interactions predicted high spin members of the multiplet (*i.e.* $19/2^+$, $23/2^+$ and $25/2^+$, not yet observed) to be placed above the isomer. The states located in the present work could correspond to those excitations — they are indicated in panel (a) with tentative spin-parity assignments. It is worth noting that a more detailed comparison with theory should be performed, taking into account, in a general scheme, all relevant core excitations, as for example the ones associated with collective phonons of the core. Such calculations, for the specific case of $^{133}$Sb, are under development within a microscopic framework using consistently Skyrme effective interactions [22]. This will represent a significant step forward with respect to paticle–phonon calculations, performed, for many decades, by using the phenomenological model of Bohr and Mottelson [1], based on a weak-coupling approach and on purely phenomenological inputs [11–14].

Finally, Fig. 4 shows preliminary results on $^{130}$Sn, obtained from the analysis of the combined EXILL fission data on $^{235}$U and $^{241}$Pu targets. Panel (a) gives a partial level scheme of $^{130}$Sn, from the decay of the $10^+$ long-lived isomer at 2435 keV (with $\tau_{1/2} = 1.5$ $\mu$s) [17]. By setting gates on the 96 and 391 keV delayed lines, a high energy transition at 3884 keV has been displayed in the prompt coincidence spectrum, as feeding the isomer. This could be interpreted as the decay from a state with spin $12^-$ or $13^-$, arising from the coupling of the $3^-$ octupole phonon of $^{132}$Sn to two-neutron-hole state $\nu(h_{11/2}^{-2})10^+$. A similar state, originating from the coupling of the $3^-$ phonon of $^{208}$Pb to the two-neutron-hole state $\nu(i_{13/2}^{-2})12^+$ was observed in $^{206}$Pb [4]. This state agreed very well with predictions of the schematic particle–phonon model based on the phenomenological approach of Bohr and Mottelson [1].

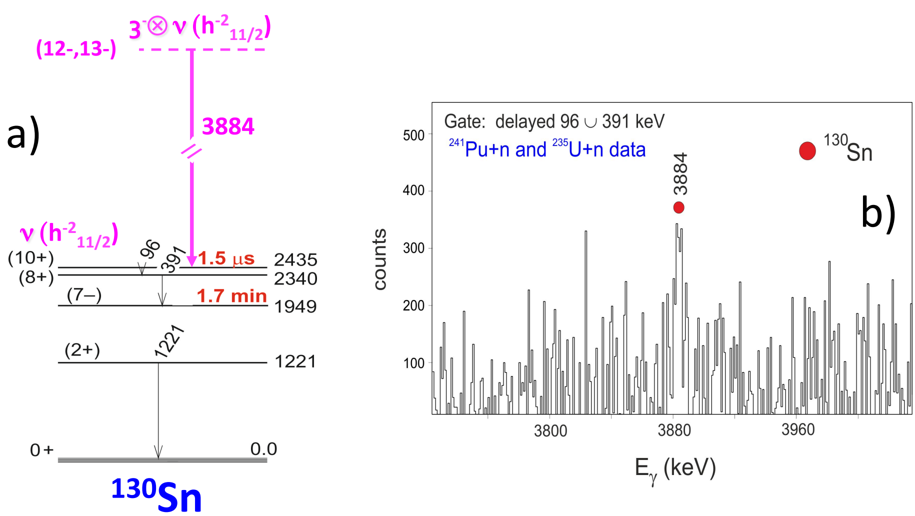


Fig. 4. (a) Partial level scheme of $^{130}$Sn, showing (in black) the known decay below the long lived $10^+$ isomer [17]. Panel (b) shows the spectrum of prompt transitions observed in coincidence with the 96 and 391 keV lines depopulating the isomer. The newly found 3884 keV line, feeding the isomer, is suggested to decay from a state arising by coupling the two-neutron-hole state $\nu(h_{11/2}^{-2})10^+$ to the $3^-$ phonon of the $^{132}$Sn core, similarly to what found in the case of $^{206}$Pb [4] (see the text for details).

### 2.2. The neutron capture reaction $^{209}$Bi(n,$\gamma$)$^{210}$Bi

During the EXILL campaign, several $(n,\gamma)$ experiments were performed with different targets, with both types of configuration for the experimental setup. In this section, preliminary results obtained using a $^{209}$Bi target and the first configuration of the EXILL array (Ge only) are reported. Following the neutron capture on a $^{209}$Bi target, a binding energy state at 4605 keV was populated in $^{210}$Bi. It has been found that the decay from this state proceeds through many paths, feeding a large number of levels. This decay was investigated in great details, for the first time, with high resolution and multi-coincidence $\gamma$-ray techniques [23]. Figure 5 shows a partial level scheme of $^{210}$Bi, with the primary transitions from the capture state only. The newly found levels are marked in gray/red. The analysis established 54 branches from the neutron capture state, of which 31 are new. Moreover, 24 new states populated mainly by primary $\gamma$ rays were also located in the energy range 1900–4220 keV. By using several cascades, the energy of the binding energy state was established at 4605.2(1) keV.

An important part of this work was the analysis of $\gamma$–$\gamma$ angular correlations, in order to firmly establish the spin of the majority of the excited states. The analysis was performed following the formalism of Krane *et al.* [24] and using the EXOGAM clovers only — three relative angles between the detectors, *i.e.* 0°, 45° and 90° degrees were considered. The results of the analysis were compared with shell model calculations performed with the OXBASH code [25] and the Kuo–Herling interactions [26]. The large majority of the experimental states was found to correspond to excitations of one proton and one neutron valence particles, although there are few excitations which could not be assigned to the shell model predictions. It is very likely that they originate from the coupling between the low-lying $3^-$ octupole phonon in $^{208}$Pb, which is known to largely contribute to the structure of the states in neighbouring nuclei, and two valence particle excitations.

## 3. Conclusions

Preliminary results have been presented from a recent campaign aimed at spectroscopic studies of neutron induced fission and $(n,\gamma)$ reactions products, at the cold-neutron facility at ILL (Grenoble). The setup consisted of the high-efficiency Ge array EXILL, which allowed to perform high-resolution $\gamma$-spectroscopy and angular correlation studies of $n$-rich nuclei around the doubly-magic $^{132}$Sn and $^{208}$Pb cores, such as $^{132}$Te, $^{133}$Sb, $^{130}$Sn and $^{210}$Bi. New states, arising from the coupling of valence particles/holes to core excitations, were identified. They provide a testing ground for state of the art theoretical approaches, such as shell model or particle–phonon coupling models.

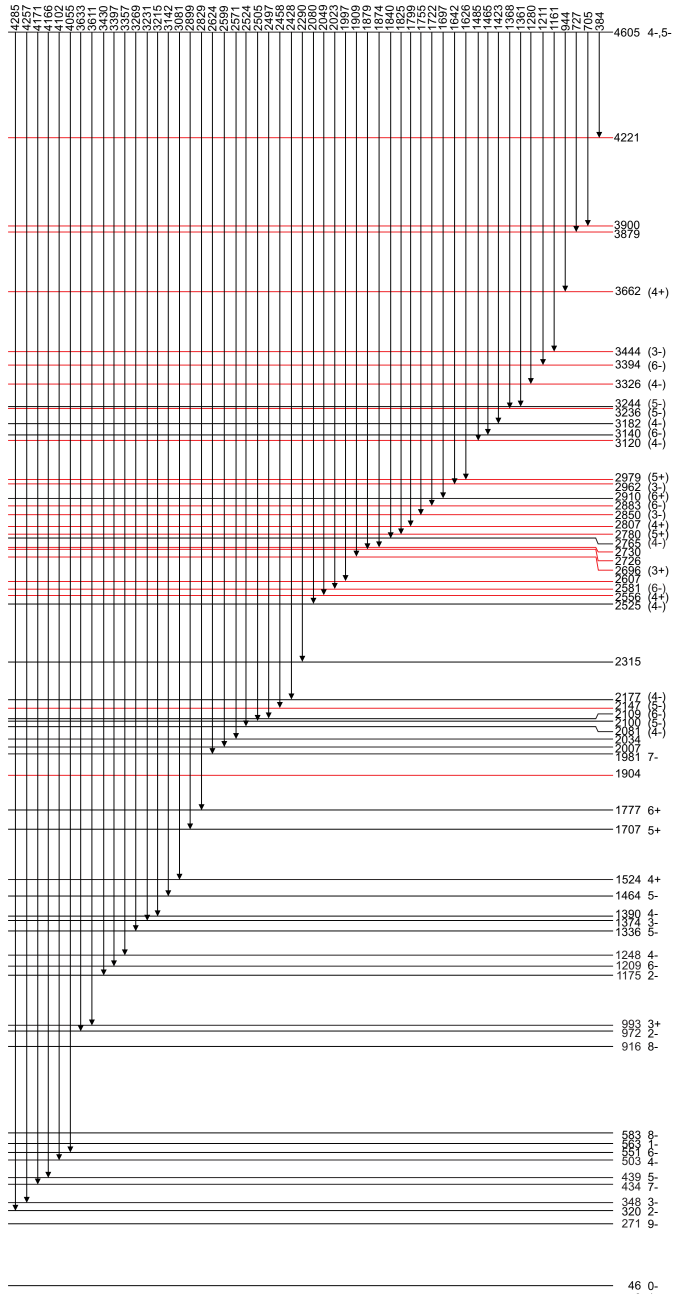


Fig. 5. Partial level schemes of $^{210}$Bi obtained by cold-neutron capture, showing primary decay transitions only. Newly found states are marked in gray/red [23].

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