EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Proposal to the ISOLDE and Neutron Time-of-Flight Committee

Beta-decay study of neutron-rich Tl and Pb isotopes

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Abstract

It is proposed to study the structure of neutron-rich nuclei beyond ^{208}Pb. The one-proton hole $^{211-215}$Tl and the semi magic ^{213}Pb will be produced and studied via nuclear and atomic spectroscopy searching for long-lived isomers and investigating the beta-delayed gamma emission to build level schemes. Information on the single particle structure in $^{211-215}$Pb, especially the position of the $g_{9/2}$ and $i_{11/2}$ neutron orbitals, will be extracted along with lifetimes. The beta-decay will be complemented with the higher spin selectivity that can be obtained by resonant laser ionization to single-out the decay properties of long-living isomers in ^{211,213}Tl and ^{213}Pb.

Requested shifts: [21] shifts, (split into [2] runs over [1] years)

Introduction

The neutron rich Hg, Tl, Pb and Bi isotopes are of exceptional interest to map the evolution of the nuclear structure and single particle levels away from the double magic nucleus ^{208}Pb (Z=82, N=126) towards the neutron-rich side of the nuclear chart.

Despite the wealth of experimental data available for the doubly magic nucleus ^{208}Pb (Z=82, N=126) and its closest neighbours, the more neutron-rich quadrant defined by Z<=82 and N>126 remains poorly explored. Yet, such nuclei are critical for understanding the onset of proton-neutron configuration mixing that drives collectivity and nuclear deformation. In particular, at the moment the tests of the nuclear interaction in this region are scarce, while there are already indications of unexplained features of the nuclear structure in the region "southeast" of ^{208}Pb[1]. Single-particle energies and life-time measurements are basic ingredients required for the prediction of the properties of more complex configurations.

The reason for the limited spectroscopic information lies in the experimental difficulties to access this region of the nuclear chart. The synthesis of neutron-rich trans-lead nuclei in fusion-evaporation reactions is experimentally problematic due to the strong competition with fission; on the other hand, spallation reactions suffer from high contamination levels from more abundantly produced isobars. However over the years other techniques have been used to explore this region. At FRS-GSI M. Pfützner and collaborators demonstrated that fragmentation reactions offer a promising new means to reach this unexplored region [2]. More recently 40 new neutron-rich isotopes have been identified with the same technique [3]. By using a high-sensitivity gamma-detection array as the RISING setup, isomeric decays in very neutron-rich lead isotopes were studied up to ^{216}Pb [4] and in ^{208}Hg and ^{209}Tl [5], and lifetime of a number of beta-decaying isotopes were reported [6].

Multi-nucleon transfer reactions on ^{238}U target were used for studying high-spin excited states in ^{211}Pb [7] and, recently, they have been proposed [8] to populate states in ^{212,214}Pb and ^{208,210}Hg by using neutron-rich unstable beams accelerated by HIE-ISOLDE.

At ISOLDE spectroscopic studies of $^{215\text{-}218}$Bi and ^{215}Pb have been carried out successfully. The combination of the resonance ionization laser ion source (RILIS) and the pulsed release method has paved the way to reach these isotopes by efficiently suppressing the otherwise huge isobaric contamination. Results on ^{215}Pb have been recently reported [9] including the measurement of the half-life and a proposed level scheme for the daughter ^{215}Bi nucleus. Very recently, the development of a new technique, namely the Laser Ionization Source Trap (LIST) target [10], has given access to the study of decay properties of ^{219}Po.

Physics Case

Long-lived isomers in ^{211,213}Tl and β-decay of $^{211\text{-}215}$Tl

Naively, one would expect the thallium isotopes to follow the seniority scheme of the lead isotopes, with the proton-hole being a spectator in the $s_{1/2}$ – $d_{3/2}$ orbitals and coupling to the 0^+, 2^+,4^+,6^+,8^+ levels $(g_{9/2})^2$ from neutron pairs breaking. Large scale Shell Model (SM) calculations using the ANTOINE code [12] have been performed in ^{209,211,213}Tl. The model space consists of the neutron orbitals $g_{9/2}$, $i_{11/2}$ and $j_{15/2}$ above the closed N=126 shell and proton orbitals $s_{1/2}$, $d_{3/2}$, $h_{11/2}$, $d_{5/2}$, below the Z=82 closed shell. The Kuo-Herling interaction [13] is used: this interaction has already been proved to be effective in the region closer to stability [4,5]. The comparison with the experimental data [5,11] obtained from isomeric decay studies using relativist projectile fragmentation of primary ^{238}U beam is shown in Fig.1. For ^{209}Tl the agreement is very good, while for the more exotic isotopes the comparison is less clear. For ^{211}Tl the SM calculations suggest an inversion of the $7/2^+$ and $9/2^+$ levels, which could originate a spin trap with a long-lived $9/2^+$ isomeric state decaying by M3/E4 (order of ms to s lifetime, as in ^{215}Bi [14]). One observed gamma ray at 144-keV in ^{211}Tl could be assigned to the $(13/2^+)$ → $(9/2^+)$ transition and it would fit well into this scenario.

Therefore, it would be important to confirm the existence of a long-lived isomeric state in ^{211}Tl and to assess the likely existence of another one in ^{213}Tl, since this will provide a test of validity of the interaction matrix elements between proton-holes and neutron-particles below Z=82 and beyond N=126 used in the calculations. This measurement would be possible at ISOLDE by in-source laser spectroscopy, i.e. by analysing the dependence of observed gamma-rays on the frequency of the first or second laser step.

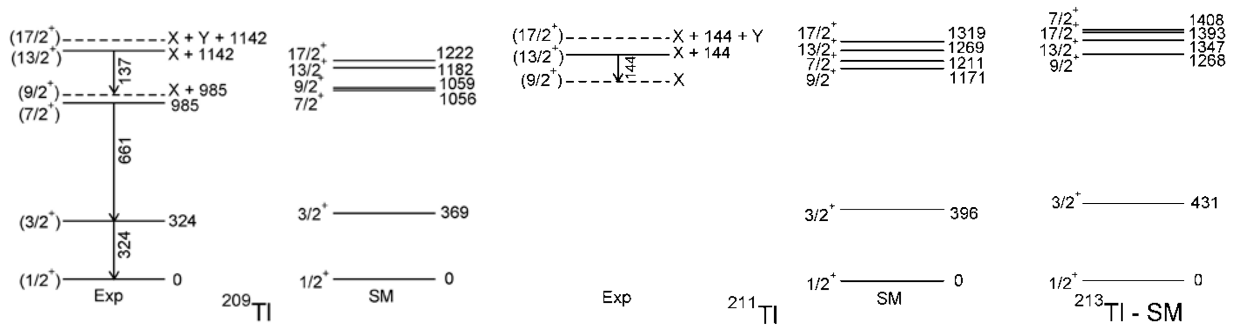

Fig. 1: Experimental and theoretical level schemes for the odd-even Tl isotopes beyond N=126. Data are taken from [5,11].

Moreover, we propose to measure the beta decay of Tl in the mass range 211-215. Lifetime measurements for $^{211\text{-}212\text{-}213}$Tl have been reported [6,15] with relative uncertainties in the order of 50% to 100%. For ^{214,215}Tl isotopes no spectroscopic information are available.

Our aim is to decrease the uncertainty of the half-lifes of $^{211\text{-}212\text{-}213}$Tl down to 10%, measure the half-life of ^{214,215}Tl, and build a more detailed level scheme in the daughter Pb nuclei which, up to know, have never been populated by β^--decay. The lifetime of the neutron-rich Tl isotopes is a fundamental benchmark for the models which then aim at predicting the beta lifetimes of the more exotic (out of reach at the moment) nuclei involved in the rapid nucleosynthesis process. State-of-the-art theoretical calculations generally underestimate the half-lives for heavy neutron-rich nuclei ([6] and Ref. therein). If this situation persists for even more exotic systems, it will have implications on the nucleosynthesis path. From Fig. 4 in Ref. [6] it is clear that a higher precision is needed for a better comparison with different theoretical predictions, as well as data on more exotic isotopes, as it is aimed at in this proposal.

Long-lived isomers in ^{213}Pb

The odd-even lead nuclei are expected to follow the textbook-case seniority scheme observed for the even-even isotopes. The isomeric decay of ^{213}Pb has been also investigated at GSI following relativistic fragmentation [11]. The observed decay spectrum is shown in Fig.2 together with the level scheme of ^{211}Pb [7] deduced from multi-neutron transfer reactions. The level scheme of ^{213}Pb is expected to be very similar to ^{211}Pb, as confirmed also by shell-model calculations. The observed gamma-line above 700 keV might correspond to the $(13/2^+)$→$(9/2^+)$ transition at 734 keV in ^{211}Pb but the placement of the other transitions is not clear. The two most intense gamma-rays are in coincidence, but they have different intensities and the corresponding $(17/2^+)$→$(13/2^+)$ transition at 322 keV in ^{211}Pb is too far in energy from the gamma-ray in Fig.2 which slightly below 500 keV. This would imply a large structural change with respect to ^{211}Pb, in sharp contrast with theoretical expectations and systematics. Therefore, no firm conclusion on the isomeric decay of ^{213}Pb could be drawn.

It has also to be mentioned that, in a very simple shell model picture, ^{213}Pb corresponds to the middle of the $g_{9/2}$ shell and, according to the seniority scheme, its $21/2^+$ isomeric state should have a very long half-life, much larger than the 100 μs time window applied in the experiment reported in [11].

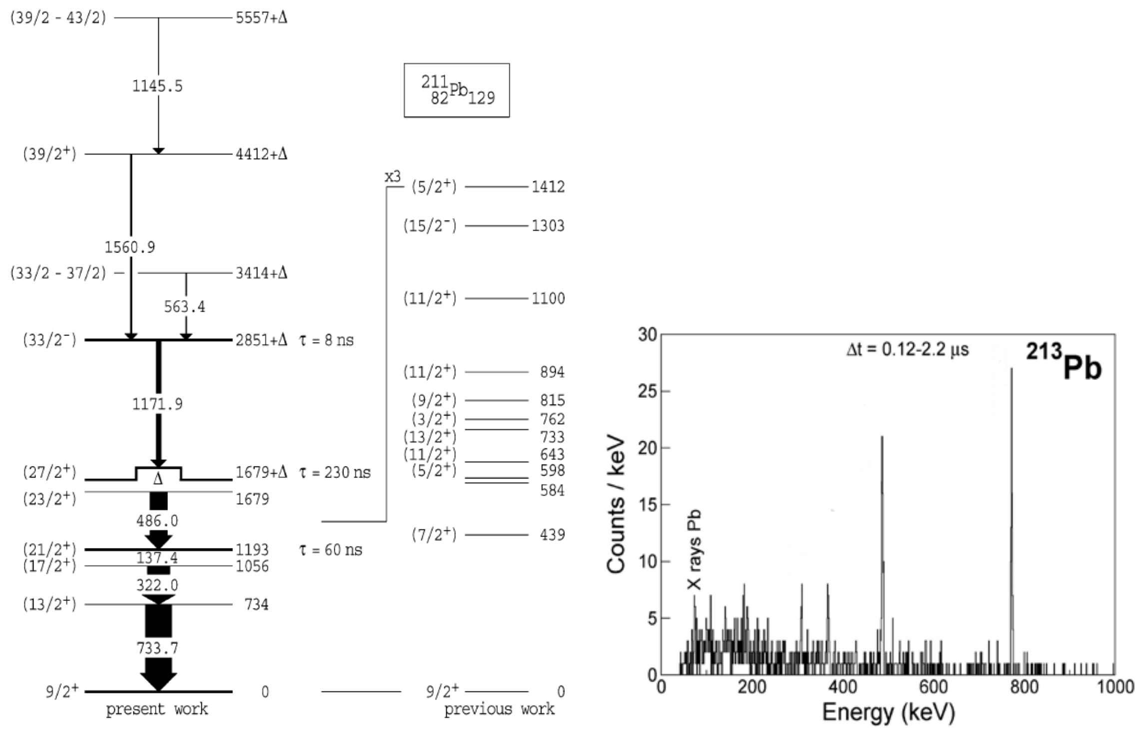

Fig. 2: Left panel: experimental level scheme for the odd-even ^{211}Pb isotope taken from [7]; right panel: experimental spectrum of ^{213}Pb from [11].

Also, it is likely that the $27/2^+$ level will continue to be yrast isomers in ^{213}Pb, either an E2-decaying isomers like in ^{211}Pb or, should it move below the $23/2^+$ state, very long lived.

In this picture it is interesting to verify the possible existence of long-lived isomers in the ^{213}Pb isotope. Similar to the case of ^{211,213}Tl, we would make use of the in-source resonant laser ionization technique in narrow band mode in order to separate radiation originating from different isomers in the same isotope.

Experimental details

In the present proposal we intend to study the beta-decay of neutron rich Tl isotopes in the mass range 211-215 to measure half lives, to populate states in Pb and to investigate the existence of long-living isomers in ^{211,213}Tl and ^{213}Pb. We intend to use the new Isolde Decay Station (IDS) setup in the phase I configuration.

In this preliminary configuration the tape station from KULeuven will be used in combination with 4 Clover HpGe detectors and 3 Miniball crystals (or one Miniball triple cluster [16]) for gamma detection. According to GEANT4 simulations (C. Sotty, private communication) the total geometrical efficiency of the gamma-array detector is estimated to be around 42%. Assuming an intrinsic detection efficiency of 2% at 1.3 MeV, the total photo-peak efficiency will be 8-9% at 1.3 MeV. Around the implantation point, plastic scintillators coupled to fast photomultipliers will provide an efficient beta trigger with a geometrical efficiency of 60% of 4π. The use of β-γ and β-γ-γ coincidence technique will substantially reduce background effects and enable detailed decay schemes to be constructed.

The $^{211\text{-}215}Tl$ beam and ^{213}Pb beam are produced from a UC_x target using RILIS. As the yields of none of these isotopes have been measured, they are estimated from different predicted/extrapolated cross-sections and scaled down using the measured rate of 47pps for ^{215}Pb at the experimental setup from Ref.[9]. We assumed a laser ionization efficiency of 27% for Tl and 6% for Pb. The values are reported in Table 1. From the known half-lifes, decay losses are expected not to be significant.

Isotope	Rate on tape /s	Time	Expected n. counts
^{211}Tl	540	1 shift	$1\cdot10^5$
^{212}Tl	225	1 shift	$6\cdot10^4$
^{213}Tl	90	1 shift	$3\cdot10^4$
^{214}Tl	36	3 shifts	$3\cdot10^4$
^{215}Tl	12	6 shifts	$2\cdot10^4$
^{213}Pb	250	3 shifts	$2\cdot10^5$
^{215}Pb Reference	47 (*) [8]		

Table 1. Expected production rates on target, projected measurement times and number of counts for an average of 7 pulses per supercycle sent to the ISOLDE target. Value marked with asterisk is measured.

Due to the large Fr contamination, neutron rich Tl and Pb beams in the mass range 211-213 are very difficult to produce at ISOLDE. Thus this study would require the use of a quartz line and the HRS mass separator to suppress the Fr contamination up to a factor 10^4. Moreover the use of the Laser Ionization Source Trap (LIST) target, recently developed at ISOLDE, is expected to reduce the contamination up to a factor 10^3 as demonstrated in last year tests [10]. We cannot neglect that the $^{211\text{-}213}Fr$ contaminations are also produced in the β^+ decay of the corresponding surface-ionized Ra isotopes (7-20% branching ratios). However, in such case the selectivity of LIST could be improved by operating the target's hot cavity at lower temperature since the intensity of Fr shows stronger temperature dependence comparing to the standard ion-guide operation mode.

For the heavier masses A=214-215, provided the HRS is used, the isobaric Fr contamination is not expected to be a problem since lifetimes of Fr are in the order of 5 ms or less. In this case we do not need the quartz line, which we expect to slightly affect also the extraction of Tl, and only the pulsed-release technique will be applied. This technique relies on the relatively long lifetimes of the beta-decaying isotopes of interest compared to the significantly shorter lived Fr and Ra and it has been already used in the measurement of neutron rich ^{215}Pb isotopes. No other contaminations are expected and the experiment is feasible despite the low estimated yields compared to $^{211\text{-}213}$Tl.

Taking into account the estimated beta-gamma coincidence efficiency of 5% from GEANT4 simulations and a measurement duty cycle of 20% (ratio between measurement and collection time), we calculated the measurement times and the expected number of counts reported in Table 1.

Summary of requested shifts:

All the proposed isotopes are produced using UC_x target. We ask for the use of the HRS separator. While we require the quartz line and the LIST target for masses 211-213, we are not sure about the effect of the quartz line on the extraction of Tl, which is actually a long-lasting question for the production of neutron-rich Tl beams. We would therefore request to split the run in two parts in the aim to study the production of the masses 214-215 also with the standard UC_x target, the second run being subject to the condition that we do not observe measurable production of ^{214,215}Tl isotopes with the quartz line and the LIST target.

Based on the estimated yields and in order to investigate the beta decay of the proposed isotopes, we ask for 15 shifts. The tuning of the lasers should take up 1 shift for every element. The in-source laser spectroscopy for searching of long-living isomers in ^{211,213}Tl and ^{213}Pb requires extra 4 shifts. The total requested beam time is therefore **21 shifts**.

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Appendix

DESCRIPTION OF THE PROPOSED EXPERIMENT

The experimental setup comprises: *(name the fixed-ISOLDE installations, as well as flexible elements of the experiment)*

Part of the Choose an item.	Availability	Design and manufacturing
New setup IDS (Isolde Decay Station)	☒ Existing	☒ To be used without any modification
[Part 1 of experiment/ equipment]	☐ Existing	☐ To be used without any modification ☐ To be modified
	☐ New	☐ Standard equipment supplied by a manufacturer ☐ CERN/collaboration responsible for the design and/or manufacturing
[Part 2 experiment/ equipment]	☐ Existing	☐ To be used without any modification ☐ To be modified
	☐ New	☐ Standard equipment supplied by a manufacturer ☐ CERN/collaboration responsible for the design and/or manufacturing
[insert lines if needed]		

HAZARDS GENERATED BY THE EXPERIMENT

(if using fixed installation) Hazards named in the document relevant for the fixed [COLLAPS, CRIS, ISOLTRAP, MINIBALL + only CD, MINIBALL + T-REX, NICOLE, SSP-GLM chamber, SSP-GHM chamber, or WITCH] installation.