CERN-INTC-2019-021 / INTC-SR-078
23/09/2019

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

REPORT ON IS584

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

21 September 2013

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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. 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. The measurement was never made because the beam was not developed.

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

Introduction

The measurement was not run, because the request beams were not developed. Anyway, the physics case is still valid, and there is a window of opportunity at ISOLDE after LS2 before the operation of the FEAR facility at Darmstadt. We are not aware of any other facility able to study such heavy nuclei. Therefore, after LS2, ISOLDE will provide a unique opportunity to study the beta decay of neutron rich Tl and Pb isotopes. The physics motivations detailed below remain intact, also considering the puzzling first spectroscopic data on ^{213}Pb [8, soon to be submitted to Phys. ReV. C]. We thus ask for the development of neutron-rich Tl and Pb beams.

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, representing the particle-hole sector surrounding ^{208}Pb, are critical for understanding effects of seniority, the onset of proton-neutron configuration mixing that drives collectivity and nuclear deformation.

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 [1]. More recently 40 new neutron-rich isotopes have been identified with the same technique [2]. 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 [3] and in ^{208}Hg and ^{209}Tl [4], and lifetime of a number of beta-decaying isotopes were reported [5].

Very recently, multi-nucleon transfer reactions using neutron-rich unstable beams accelerated by HIE-ISOLDE have been proposed by J. Valiente-Dobon and collaborators [6] to populate ^{212,214}Pb and ^{208,210}Hg. The proposal has been accepted by the INTC committee as this approach might open new experimental possibilities.

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 [7] including the measurement of the half-life and a proposed level scheme for the daughter ^{215}Bi nucleus. However, the data do not allow to extract direct information on the spin and parity of the ground state both of the parent and daughter nuclei.

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 $s_{1/2}$ orbital and coupling to the 2^+,4^+,6^+,8^+ levels $(g_{9/2})^2$ from neutron pairs breaking. While this is true in ^{209}Tl, the isomeric decays observed in ^{211,213}Tl do not follow this trivial prediction. In Ref. [8] it is shown how the structure of ^{211,213}Tl differs from the one in ^{209}Tl, reported in Ref. [4]. Figure 1 presents a comparison between measured and calculated levels, using the code ANTOINE [9]. The Shell Model (SM) space consists of the neutron orbitals $g_{9/2}$, $i_{11/2}$ and $j_{15/2}$ above the closed N=126 shell, while the proton(-hole) space is made of $s_{1/2}$, $d_{3/2}$, $h_{11/2}$, $d_{5/2}$, below the Z=82 closed shell. The Kuo-Herling interaction [10] is used which has been proved to be effective in this region [3,4]. 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 give origin to 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 [11]). The observed 144-keV gamma ray would fit well into this scenario. The situation for ^{213}Tl is less clear: one gamma transition at 380 keV has been observed but it has not been placed [8]. 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. This 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.

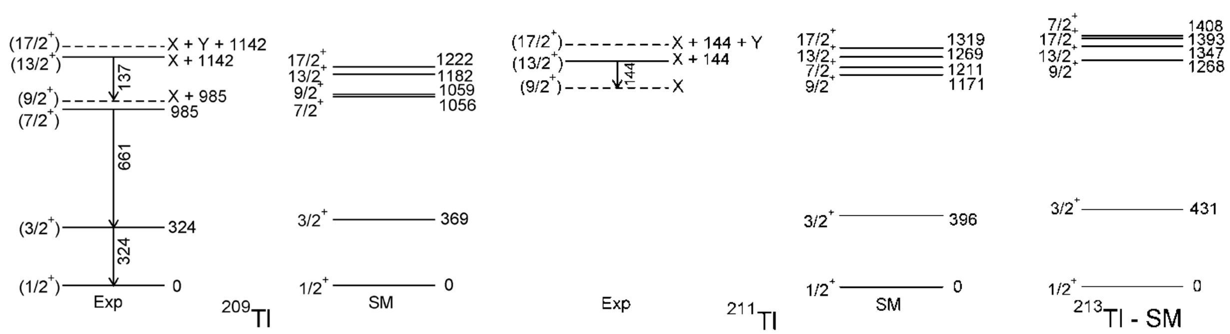

Fig. 1: The experimental and theoretical level schemes for the odd-even Tl isotopes beyond N=126. Data are taken from [4,8].

Moreover, we propose to measure the beta decay of Tl in the mass range 211-215. Lifetime measurements for $^{211-212-213}$Tl have been reported [5,12] with relative uncertainties in the order of 40%. For $^{214-215}$Tl isotopes no spectroscopic information are available.

Our aim is to decrease the uncertainty of half-life's measurements on $^{211-212-213}$Tl, measure the half-life of $^{214-215}$Tl, and build a more detailed level scheme in the daughter Pb nuclei.

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. Figure 2 shows the level scheme of ^{211}Pb and the isomeric decay spectrum observed in ^{213}Pb [8], which is expected to have a level scheme almost identical to ^{211}Pb.

While the 722-keV line might correspond to the $13/2^+$ -> $9/2^+$ transition at 734 keV in ^{211}Pb, the placement of the other transitions is not clear. The gamma-gamma coincidences show that the 488 keV gamma-ray is in coincidence with the 722 keV gamma-line, but the corresponding $17/2^+$ -> $13/2^+$ transition at 322 keV in ^{211}Pb is too far in energy. This would imply a large structural change with respect to ^{211}Pb, in sharp contrast with theoretical expectations and systematics. Therefore, the author in [8] concluded that the observed isomeric decay is not from the seniority isomer $21/2^+$.

This hypothesis is also supported by the fact 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.

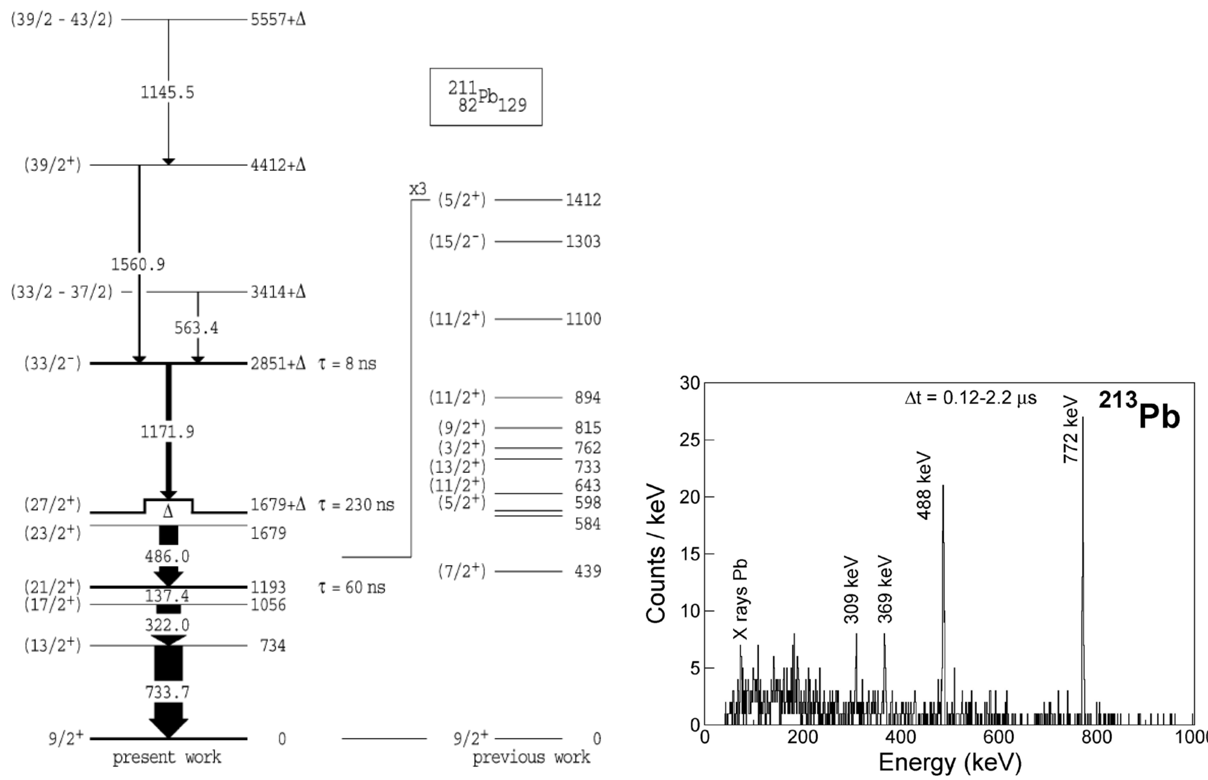

Fig. 2: Left panel: experimental level scheme for the odd-even ^{211}Pb isotope taken from [13]; right panel: experimental spectrum of ^{213}Pb from [8].

The fact that in Ref. [8] it was not possible to clearly identify the decay from this isomer could hint at a very long half-life, much larger than the 100 µs, time window in that experiment. 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 $^{211\text{-}213}Tl$, 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 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 [14]) 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 $^{211-215}$Tl beam and ^{213}Pb beam are produced from a UC_x target using RILIS. On the basis of a measured rate of 47pps for ^{215}Pb at the experimental setup from Ref.[7], we could estimate yields for those isotopes.

The values are reported in Table 1. (*Rates are estimated from various predicted/extrapolated cross-sections and scaled using the 47pps measured rate of ^{215}Pb. Still waiting for other estimation from Thierry, if never*)

Isotope	Rate on tape /s	Time	Expected n. counts
^{211}Tl	540	1h→ 1shift	19000 (1 10^5)
^{212}Tl	225	1h→ 1shift	8100 (6 10^4)
^{213}Tl	90	1h→ 1shift	3240 (3 10^4)
^{214}Tl	36	1h →3 shifts	1300 (3 10^4)
^{215}Tl	12	1h →6 shifts	432 (2 10^4)
^{213}Pb	250	1h →3 shifts	9000 (2 10^5)
^{215}Pb Reference	47 (*) [7]		

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 [15]. We cannot neglect that the $^{211-213}$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 in to account the laser ionization efficiencies of 27% for Tl ad 6% for Pb, 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 expect the 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. 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
[if relevant, name fixed ISOLDE installation: COLLAPS, CRIS, ISOLTRAP, MINIBALL + only CD, MINIBALL + T-REX, NICOLE, SSP-GLM chamber, SSP-GHM chamber, or WITCH]	☒ 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.

Additional hazards:

Hazards	*[Part 1 of the experiment/equipment]*	*[Part 2 of the experiment/equipment]*	*[Part 3 of the experiment/equipment]*
Thermodynamic and fluidic			
Pressure	[pressure][Bar], [volume][l]		
Vacuum			
Temperature	[temperature] [K]		
Heat transfer			
Thermal properties of materials			
Cryogenic fluid	[fluid], [pressure][Bar], [volume][l]		
Electrical and electromagnetic			
Electricity	[voltage] [V], [current][A]		
Static electricity			
Magnetic field	[magnetic field] [T]		
Batteries	☐		
Capacitors	☐		

Ionizing radiation			
Target material	[material]		
Beam particle type (e, p, ions, etc)			
Beam intensity			
Beam energy			
Cooling liquids	[liquid]		
Gases	[gas]		
Calibration sources:	☐		
• Open source	☐		
• Sealed source	☐ [ISO standard]		
• Isotope			
• Activity			
Use of activated material:			
• Description	☐		
• Dose rate on contact and in 10 cm distance	[dose][mSV]		
• Isotope			
• Activity			
Non-ionizing radiation			
Laser			
UV light			
Microwaves (300MHz-30 GHz)			
Radiofrequency (1-300MHz)			
Chemical			
Toxic	[chemical agent], [quantity]		
Harmful	[chemical agent], [quantity]		
CMR (carcinogens, mutagens and substances toxic to reproduction)	[chemical agent], [quantity]		
Corrosive	[chemical agent], [quantity]		
Irritant	[chemical agent], [quantity]		
Flammable	[chemical agent], [quantity]		
Oxidizing	[chemical agent], [quantity]		
Explosiveness	[chemical agent], [quantity]		
Asphyxiant	[chemical agent], [quantity]		
Dangerous for the environment	[chemical agent], [quantity]		
Mechanical			
Physical impact or mechanical energy (moving parts)	[location]		
Mechanical properties (Sharp, rough, slippery)	[location]		
Vibration	[location]		
Vehicles and Means of Transport	[location]		
Noise			
Frequency	[frequency],[Hz]		
Intensity			
Physical			
Confined spaces	[location]		
High workplaces	[location]		
Access to high workplaces	[location]		
Obstructions in passageways	[location]		
Manual handling	[location]		
Poor ergonomics	[location]		

0.1 Hazard identification

3.2 Average electrical power requirements (excluding fixed ISOLDE-installation mentioned above): *(make a rough estimate of the total power consumption of the additional equipment used in the experiment)*