EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Letter of Intent to the ISOLDE and Neutron Time-of-Flight Committee

Development of neutron-rich Tl beams for nuclear structure studies beyond ^{208}Pb

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Abstract

We ask for the development of $^{210\text{-}216}$Tl beams. This will pave the way for future studies of the structure of neutron-rich nuclei beyond ^{208}Pb, by means of isomer and beta-decay spectroscopy at the IDS decay station. Availability of Tl beams will also open the possibility for nuclear radii, moments and masses in this relatively unexplored region.

Requested shifts: 9 (one per isotope)

Introduction

The region east and north-east of ^{208}Pb (trans-lead region) has been difficult to access as only very specific production techniques can be applied here. Isotopes in this region can be effectively produced by ^{238}U fragmentation at high energy. The only facilities in the world with such capabilities are GSI-FAIR and ISOLDE, at the present time. After LS2, ISOLDE will provide a unique opportunity to study the beta decay (and isomer decay) of neutron rich Tl and Pb isotopes. The present LoI originates from the previous IS584 proposal, which was approved but never run. It was finally cancelled by the INTC given the absence of Tl beam development, asking to present a new LoI and recognising the physics case is well motivated.

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. Over the years, other techniques have been used to explore this region. At GSI-FAIR fragmentation reactions have provided an effective mean to reach this unexplored region [1,2,3,4,5].

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.

At ISOLDE spectroscopic studies of $^{215-218}Bi$, ^{215}Pb and $^{214-218}Po$ have been carried out successfully at IDS [7,8]. Heavy Hg, Bi, At were also produced [9] and studied [10-15]

Physics Case

<u>Long-lived isomers in $^{210,211,213}Tl$ and β-decay of $^{211-216}Tl$</u>

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. [16] 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 [17]. 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 [17] 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 [18]). 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 [16]. 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.

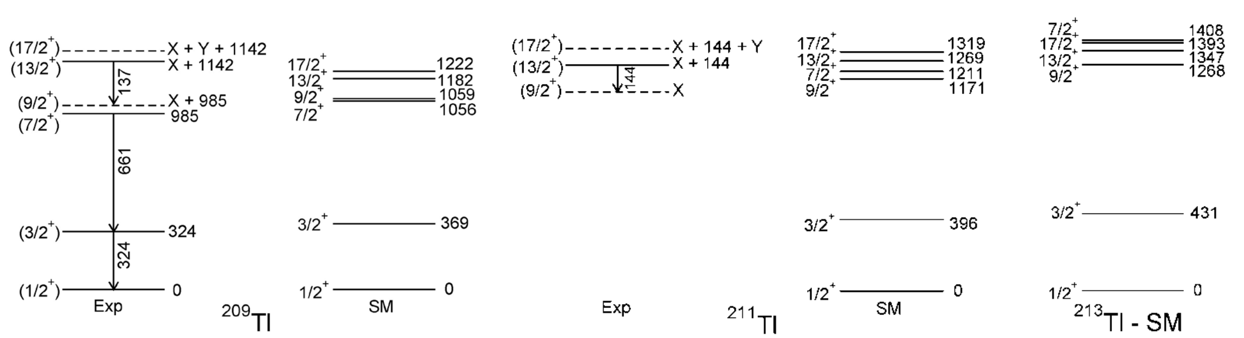

Fig. 1: The experimental and theoretical level schemes for the odd-even Tl isotopes beyond N=126. Data are taken from [4,16].

Beta-delayed gamma spectroscopy of $^{211-216}Tl$ will also help to detect low-spin states in odd-even Pb isotopes which are not populated in fragmentation reactions. Fast-timing techniques will allow one to measure the 4^+ and 6^+ lifetimes of $^{212-214(216)}Pb$, relevant for effective three-body forces [3]. We remark here that in a recent work, the existence of a long-living isomer was also hypothesised in ^{210}Tl [19].

The scope of neutron-rich Tl beams will not be limited to decay spectroscopy at IDS.

Nuclear radii and moments of $^{208-216}$Tl

Yielding to a long tradition, measurements of nuclear radii and moments via laser spectroscopy has been a major subject of activity at ISOLDE. Nuclear radii are known only up to ^{208}Tl. The main goal would be to probe the shell effect near N=126. At the moment, we have only limited information about the kink in radii at N=126: Pb, Bi and, recently, Hg chains. At the same time the problem of the kink description became rather urgent: different theoretical approaches are competed in this field [20,21]. Therefore, the extension of the corresponding experimental data is of a primary importance. The isomer shift for ^{208}Tl was measured previously for a different atomic transition and, as the result, uncertainty of d<r^2> proves to be large and analysis of the kink is hampered. One needs to remeasure ^{208}Tl, and to measure ^{209}Tl. For heavier Tl isotopes, the increasing neutron number should induce large matter radii that should in turn determine large charge radii in n-rich Tl isotopes, due the isoscalar interaction and the low angular momentum (s and d waves) of protons below the Z=82 shell closure. Combined measurements of nuclear radii and moments will help to extract information on the proton wave function and nuclear deformation in this exotic region until ^{214}Tl, maybe ^{216}Tl.

Masses of $^{212-216}$Tl

Mass measurements stops at Tl the ^{211}Tl isotope. New mass measurements until the ^{216}Tl isotope will help to validate models that are then used to extrapolate towards the r-process nuclei.

Experimental details

In the present LoI, we ask for the production of neutron rich Tl isotopes in the mass range 211-216. If successful we plan a following proposal to populate states in Pb and to investigate the existence of long-living isomers in ^{211,216}Tl at Isolde Decay Station (IDS) setup.

The $^{211-216}$Tl beams are produced from a UC_x target using RILIS. We expect a laser ionization efficiency of 27% for Tl.

Due to the large Fr contamination, neutron rich Tl beams in the mass range 211-213 are very difficult to produce at ISOLDE. Therefore, 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 – 10^6 as demonstrated in previous tests [22]. 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.

A loss in intensity for the elements of interest if we use the LIST is foreseen. The on-line runs in 2012 and off-line investigation showed a loss factor between 20 and 50 compared to standard RILIS operation. In the 2018 run, this factor was 25 (for Mg), and the maximum measured suppression factor for contaminations reaches even 10^6 (Na). This is the state-of-the-art knowledge on isotope production and contaminant suppression with the LIST.

For the heavier masses A=214-216, 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 $^{211-213}$Tl.

We request one shift per isotope (nine in total: A=208-216) to measure production yields and beam purity.

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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)*