EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

Study of the odd-A, high-spin isomers in neutron-deficient trans-lead nuclei with ISOLTRAP

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Abstract:

We propose to measure the excitation energy of the $\frac{13}{2}^+$ isomers in the neutron-deficient isotopes ^{193,195,197}Po with the ISOLTRAP mass spectrometer. The assignment of the low- and high-spin isomers will be made by measuring the energy of the α particles emitted in the decay of purified beams implanted in a windmill system. Using α-decay information, it is then also possible to determine the excitation energy of the similar isomers in the α-daughter nuclei ^{189,191,193}Pb, α-parent nuclei ^{197,199,201}Rn, and α-grand-parent nuclei ^{201,203,205}Ra.

The polonium beams are produced with a UC_X target and using the RILIS.

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

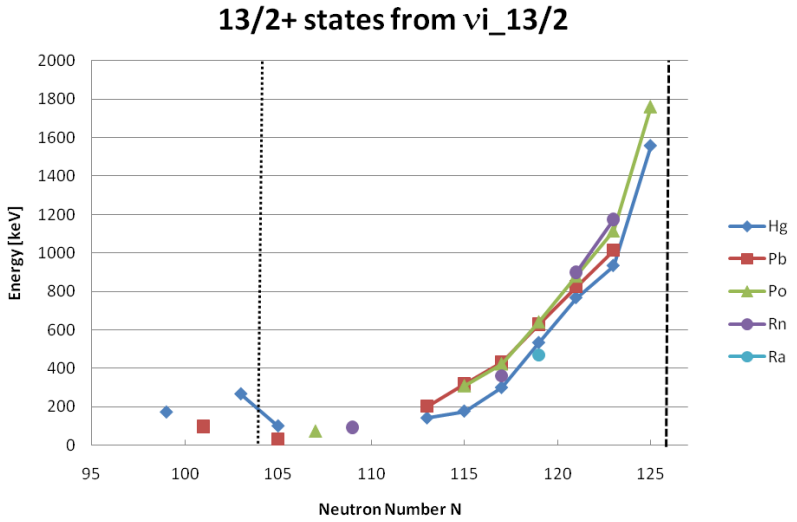

Figure 1: Systematic of the $\frac{13}{2}^+$ energy levels in the neutron-deficient mercury, lead, polonium, radon, and radium isotopes relative to their respective ground state [19].

1 Physics motivation

The phenomenon of shape coexistence is very prominent in the region of the neutron-deficient lead isotopes and has resulted in extensive experimental and theoretical studies [1-18]. It is also the subject of numerous experiments at the ISOLDE facility (IS407, IS440, IS452, IS456, IS465, IS471, IS479, IS494) and of a large research program for HIE-ISOLDE.

Deformed shapes, coexisting at low energy with the spherical one, in the neutron-deficient mercury ($Z = 80$) to radium ($Z = 88$) isotopes, are of great interest to improve our understanding of nuclear structure. Two approaches are mostly used to describe this phenomenon. First, in the spherical shell model of the nucleus, one represents those excited levels as proton pairs scattering across the $Z = 82$ shell closure into the $\pi h_{9/2}$ orbital to form multiple particle-hole configurations [1, 2]. In ^{186}Pb, where triple shape coexistence has been observed in the form of three 0^+ states below 700 keV [4], the ground state is believed to be 0p-0h, the first excited 0^+ state 2p-2h, and the second 0^+ state 4p-4h.

Another picture in which this phenomenon is described is the mean field approach. By projecting the mean-field wave functions on the deformation parameter q, one can assign a shape to the ground and excited states [9]. Using such calculations, it was suggested that the ground state of ^{186}Pb is spherical, while the first excited 0^+ state is oblate and the second excited 0^+ state is prolate. The shape of the ground state was later confirmed as being spherical in the study of the mean-square charge radii [14].

In either approach, the effect is largest when the number of valence neutrons is maximal, which is at $N = 104$, mid way between $N = 82$ and $N = 126$. This is confirmed by the case of ^{186}Pb$_{104}$, which is to date the nucleus in which the shape coexistence phenomenon is the most pronounced. At this neutron number, the $\nu i_{13/2}$ orbital is partly filled and

Table 1: Measured (cf. ENSDF [19]) and predicted (#, based on the AME2003 mass evaluation [20]) excitation energy of the $\frac{13}{2}^+$ state in the lead, polonium, radon, and radium isotopes relative to their respective ground state.

	Pb		Po		Rn		Ra	
N	A	E [keV]	A	E [keV]	A	E [keV]	A	E [keV]
103	185	#						
105	187	33(13)						
107	**189**	**90(60)**#	191	74(21)				
109	**191**	**50**#	**193**	**100(30)**#	195	93(26)		
111	**193**	**165**#	**195**	**230**#	**197**	#		
113	195	202.9(7)	**197**	**204**#	**199**	**180(70)**#	**201**	#
115	197	319.31(11)	199	310(2)	**201**	#	**203**	#
117	199	430(7)	201	424.1(23)	203	362(5)	**205**	#
119	201	629.1(3)	203	641.68(17)	205	#	207	470(10)
121	203	825.2(3)	205	880.31(7)	207	899(1)	209	#
123	205	1013.85(3)	207	1115.076(16)	209	1173.98(13)		
125	207	4761(4)	209	1760.96(9)				

the interaction with the proton pairs in the $\pi h_{9/2}$ orbital is largest. In order to clearly identify the exact role played by the $\nu i_{13/2}$ orbital in this region of the nuclear chart, one needs to know its single particle energy. This information is, however, very difficult to access, though it should eventually be available with transfer reactions at the HIE-ISOLDE facility. Meanwhile, a first order approach is to measure the excitation energy of the $\frac{13}{2}^+$ states in even-Z, odd-A isotopes as it should be mostly of single-particle nature. The study of those states in mercury ($Z = 80$), lead ($Z = 82$), polonium ($Z = 84$), radon ($Z = 86$), and radium ($Z = 88$) has been systematically tackled, helped greatly by their isomeric nature in many isotopes. Unfortunately, as can be seen in Fig. 1, this information is scarce in the region of $104 < N < 114$ where it is most needed. In some of those isotopes, it is not even known whether the low-spin (typically $\frac{3}{2}^-$) or the high-spin ($\frac{13}{2}^+$) state is the ground state. The current predictions for the unmeasured isotopes are shown in bold in Table 1.

Since the polonium isotopes present the best compromise between all the experimental constraints (production rates, resolution), we propose to use the ISOLTRAP mass separator to measure the excitation energy of the isomers in the odd-A polonium isotopes ^{193,195,197}Po and to identify which state is the ground state using decay spectroscopy on samples purified with the high mass resolving power of ISOLTRAP.

2 Experimental procedure

We propose to measure the mass of the long-lived (i.e. those coming out of the target), low- and high-spin isomers in the isotopes ^{193,195,197,199}Po, as they present the best compromise between production rates and required resolving power, as compared to the Pb or Rn isotopes. The half-lives of those isotopes are presented in Table 2. The excitation energy

Table 2: Half-lives, main α-decay energies [23], and yields [24] of the polonium ($Z = 84$) isotopes of interest using RILIS. The yields were measured with the Cu-vapour lasers; the Nd:YAG lasers, currently in use at the RILIS, deliver higher power and an increase of at least $\times 2$ with respect to the published values has been observed during experiment IS456.

A	N	I	$T_{1/2}$ [s]	E_α [MeV]	Yield $\left[\frac{\text{ions}}{\mu\text{C}}\right]$
193	109	$(\frac{3}{2}^-)$	0.45	6949	$7{\cdot}10^1$
		$(\frac{13}{2}^+)$	0.24	7004	$1{\cdot}10^2$
195	111	$\frac{3}{2}^-$	4.64	6606	$2.5{\cdot}10^4$
		$\frac{13}{2}^+$	1.92	6699	$5.5{\cdot}10^4$
197	113	$\frac{3}{2}^-$	53	6282	$5.8{\cdot}10^5$
		$\frac{13}{2}^+$	25.8	6385	$2{\cdot}10^6$
199	115	$\frac{3}{2}^-$	312	5952	$>{\cdot}10^6$
		$\frac{13}{2}^+$	252	6059	$>{\cdot}10^6$

of the long-lived isomer will be measured in the ISOLTRAP mass spectrometer [21], which has already resolved isomers in the $A = 200$ mass region down to 50 keV [22].
The beam treatment will be done in the typical fashion of ISOLTRAP: the beam is first slowed down, injected into the ISOLTRAP RFQ cooler-buncher, extracted in bunches, possible isobaric contaminants are separated in the Multi-Reflection Time-of-Flight (MR-ToF) isobar separator, and the bunches are finally cooled in the gas-filled Penning trap before being injected in the precision Penning trap. The bunches are excited in that last trap and the time of flight (ToF) to a microchannel plate detector is measured [25]. Alternatively, the ions can be transferred to decay-spectroscopy setup [26]. The total efficiency of the setup in that mass region is typically 0.1%. The full layout of the ISOLTRAP setup can be seen in Fig. 2 and more information is given in the recent ISOLTRAP proposals [27]. The isomer excitation energy can be determined from the frequency difference in the ToF spectrum for each isomer with sufficient accuracy [22]. Using 3-4s excitation cycles, which are routinely achieved, the expected resolving power is 100 keV, which is sufficient for the excitation energy range of ^{193,195,197,199}Po.
In the study of the isotope ^{187}Pb in Ref. [22], the RILIS scheme allowed an unambiguous selection of the low- and high-spin states. Unfortunately, such a separation is not possible in the case of the polonium isotopes (see e.g. ^{195}Po in Ref. [17]) as the hyperfine structures completely overlap on the whole frequency range. The use of the relative production rates between the two isomers (see yields and Ref. [24]), though a good indication, is not sufficient for an unambiguous assignment either. Instead, it becomes necessary to clean one of the two isomers in the Penning trap and to identify it beyond the mass measurement setup, as described for experiment IS463 [28].
In the case of the most neutron-deficient polonium isotopes, however, it is preferable to use the characteristic α decay of each isomer, as they provide a clear identification (see Table 2), and high efficiency is achievable. The idea would be to replace the current ISOLTRAP

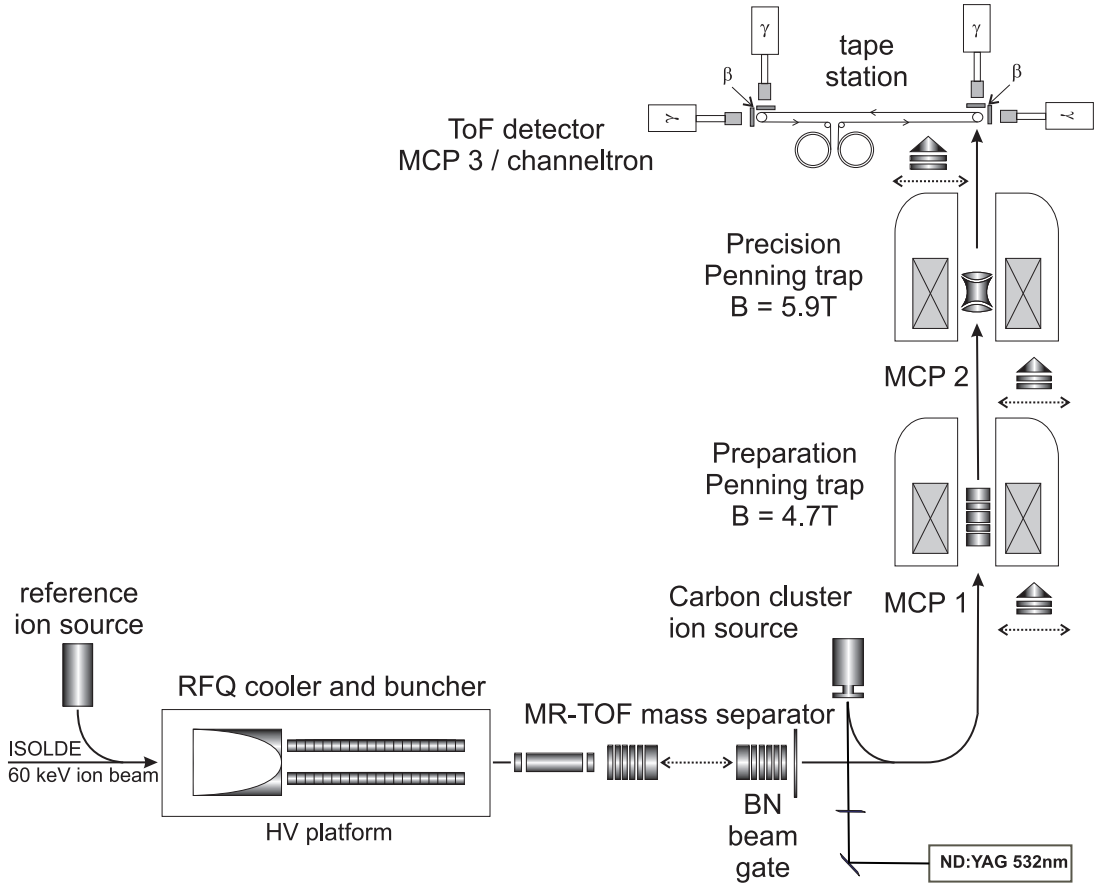

Figure 2: Layout of the ISOLTRAP facility.

decay detection chamber and tape transport system by an 'α-windmill', either as used in the study of the polonium isotopes during experiment IS456 [17], or as currently under study by the CRIS Collaboration [29]. A new device is also under design by a Paisley-Leuven collaboration. All those devices are however similar in essence. The beam ejected from the Penning trap is re-accelerated to an energy of 10-15 keV, as for the standard ISOLTRAP Tape Station, and implanted in one of ten ultra-thin C foils (thickness 20 μg per cm^2), mounted on a rotating wheel. A Si detector is placed behind the foil at the implantation position to measure the energy of the emitted α particles (typical solid angle is 20%, typical energy resolution at ISOLDE is 25 keV [17]). The wheel is then rotated to offer a fresh sample. When a used foil comes back, the short-lived α-decaying isotopes have all decayed and the foil can be re-used. Thanks to the low background conditions and a clear separation of the peaks, very few counts are needed to identify the isotopes of interest. Considering the lowest yield ($\sim$ 100/s), the low transport efficiency (0.1%), and the detection efficiency (20%) a total time of 14 hours is required to collect 1000 events. Once the polonium study is complete, one can use the precise Q_α values extracted from α-decay studies in the literature to determine the energy level in the complete α-decay chains that involve those nuclei. In that way, all the energy levels highlighted in Table 1 for lead, radon, and radium could be determined.

3 Beam production and shifts estimate

3.1 RILIS beam

The beams of polonium are produced by irradiating an ISOLDE UC_X target with the PS-Booster 1.4 GeV proton beam. The atoms diffuse and effuse from the target to the atomizer where they are then irradiated with the ISOLDE RILIS lasers for selective resonant ionization [24] and mass separated with either the GPS or HRS separator. The measured yields are shown in Table 2. Note that those yields were measured with the Cu-vapour pump lasers and, as the final ionization step is non-resonant, the additional power available with the RILIS Nd:YAG pump laser gives an increase in the ionization efficiency (as observed in the second run of experiment IS456). There are no special requirements on the transfer line or on the surface of the atomizer cavity. For the setting of the RILIS lasers, one (1) on-line shift should be considered for each run as there are no possible stable marker for the polonium isotopes.

RILIS | 1 shift per run

Possible contaminants in the beam are surface-ionized thallium ($Z = 81$) and lead ($Z = 82$). The yields of the thallium isotopes are $\sim 10^5$ ions per μC for all the masses of interest. The recent experiment on Coulomb excitation of ^{200}Po with MiniBall at REX-ISOLDE (IS479) reported on $\sim 1\%$ contamination with ^{200}Tl [30], which is comparable to that estimate. The recent study of $^{193-195}$Tl at ISOLTRAP (IS463) using the surface ion source reached yields of $\sim 10^4$ ions per μC [31]. As for the possible lead contamination, the yields are not tabulated for the surface ion source. Isobaric contaminants were however identified in low amounts during the recent study at ISOLTRAP (IS463) and successfully separated before injection to the precision Penning trap.

3.2 Mass measurement of ^{193,195,197,199}Po

For each isotope, one (1) shift is devoted to the identification of possible isobaric contaminants and their separation using either one of the Penning traps or the recently installed MR-ToF isobar separator. Depending on the projected yields with respect to those of the isobaric contaminants, between two (2) and five (5) shifts are foreseen for the mass measurement. Finally, one (1) to two (2) shifts are necessary to send the beam to the windmill decay station and identify the species of interest.
We propose to use ^{199}Po as a bench mark in that study as the yields will allow to easily identify the contaminants and their separation from the beam of interest. It is also perfectly suited for the development of the beam transport to the new α-decay setup. For that purpose, we request two (2) shifts.

	MR-ToF	Precision Trap	Windmill
^{193}Po	1 shift	5 shifts	2 shifts
^{195}Po	1 shift	2 shifts	1 shift
^{197}Po	1 shift	2 shifts	1 shift
^{199}Po	1 shift	1 shift	1 shift
development		2 shifts	

Summary of requested shifts: We hence request a total of **21 shifts** over 2 runs, one of 9 shifts for ^{197,199}Po and one of 12 shifts for the mass measurements and state identification of ^{193,195}Po. Note that an additional on-line shift for the RILIS setup is required for each run, but could be combined with other polonium experiments (e.g. IS479).

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Appendix

DESCRIPTION OF THE PROPOSED EXPERIMENT

The experimental setup comprises: ISOLTRAP including the tape station system, 2 HPGe detectors, and an α windmill system.

Part of the	Availability	Design and manufacturing
ISOLTRAP	☒ Existing	☒ To be used without any modification
Tape Station	☒ 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
Windmill	☐ Existing	☐ To be used without any modification ☐ To be modified
	☒ New	☐ Standard equipment supplied by a manufacturer ☒ Under design by the CRIS collaboration

HAZARDS GENERATED BY THE EXPERIMENT: Hazards named in the document relevant for the fixed **ISOLTRAP + Tape Station** installation.

Additional hazards:

Hazards	Tape Station [HPGe detectors]	Windmill	[Part 3 of experiment/ equipment]
Thermodynamic and fluids			
Pressure	-	-	
Vacuum	-	-	
Temperature	-	-	
Heat transfer	-	-	
Thermal properties of materials	-	-	
Cryogenic fluid	LN_2 (150L)	-	
Electrical and electromagnetic			
Electricity	4kV, $<$ 1mA	100V, $<$ 1mA	
Static electricity	-	-	
Magnetic field	-	-	
Batteries	-	-	
Capacitors	-	-	
Ionizing radiation			

Target material [material]	-	The C foils where the radioactive samples are implanted are very fragile. Should they break upon opening the Windmill, the pieces are so light that they would become airborne. Great care must be taken when opening the system and removing them (slow pumping/venting, protective equipment: facial mask).	
Beam particle type (e, p, ions, etc)	-	-	
Beam intensity	-	-	
Beam energy	-	-	
Cooling liquids	-	-	
Gases	-	-	
Calibration sources:	☒	☒	
• Open source	□	☒	
• Sealed source	☒	□	
• Isotope	^{60}Co, ^{133}Ba, ^{152}Eu	^{239}Pu, ^{241}Am, ^{244}Cm	
• Activity	few kBq each	1 kBq each	
Use of activated material:	-	-	
• Description	-	-	
• Dose rate on contact and in 10 cm distance	-	-	
• Isotope	-	-	
• Activity	-	-	
Non-ionizing radiation			
Laser	-	-	
UV light	-	-	
Microwaves (300MHz-30 GHz)	-	-	
Radiofrequency (1-300 MHz)	-	-	
Chemical			
Toxic	Pb ($\sim$ 20 bricks)	-	
Harmful	-	-	

CMR (carcinogens, mutagens and substances toxic to reproduction)	-	-	
Corrosive	-	-	
Irritant	-	-	
Flammable	-	-	
Oxidizing	-	-	
Explosiveness	-	-	
Asphyxiant	-	-	
Dangerous for the environment	-	-	
Mechanical			
Physical impact or mechanical energy (moving parts)	The HPGe detectors + Pb shielding are placed on heights and present a risk of falling objects.	The chamber is heavy and needs to be handled with care during installation/removing.	
Mechanical properties (Sharp, rough, slippery)	Corners of the ITEM structure on which the detectors are placed.	-	
Vibration	-	-	
Vehicles and Means of Transport	-	-	
Noise			
Frequency	-	-	
Intensity	-	-	
Physical			
Confined spaces	-	-	
High workplaces	ISOLTRAP 2^{nd} floor around the tape station.		
Access to high workplaces	ISOLTRAP 2^{nd} floor around the tape station.		
Obstructions in passageways	-	-	
Manual handling	-	-	
Poor ergonomics	-	-	

Hazard identification:

Average electrical power requirements (excluding fixed ISOLDE-installation mentioned above): negligible.