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EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Status Report to the ISOLDE and Neutron Time-of-Flight Committee

IS456
Study of polonium isotopes ground-state properties by simultaneous atomic and nuclear spectroscopy

September 25, 2019

E. Ahmed[1], A. Algora[2], B. Andel[1], A.N. Andreyev[3], S. Antalic[4], A.E. Barzakh[5], B. Bastin[6], M. Bissell[7], M. Borge[8], K. Chrysalidis[9], T.E. Cocolios[1], B. Cooper[7], J. Cubiss[3], H. De Witte[1], K. Dockx[1], D.V. Fedorov[5], V.N. Fedosseev[9], K.T. Flanagan[7], S. Franchoo[10], L. Fraile[11], H. Fynbo[12], L. Ghys[13], L.J. Harkness-Brennan[14], R. Heinke[15], D.S. Judson[14], J. Konki[16], U. Köster[17], I. Lazarus[18], N. Lecesne[6], R. Lica[19], N. Marginean[19], B.A. Marsh[9], C. Mihai[19], P.L. Molkanov[5], E. Nacher[8], A. Negret[19], J. Ojala[20], R.D. Page[14], J. Pakarinen[20], A. Perea[8], H. Perrett[7], L. Popescu[13], V. Pucknell[18], C. Ricketts[7], S.R. Rothe[9], H. Savajols[6], M.D. Seliverstov[5], S. Sels[16], C. Sotty[19], M. Stryjczyk[1], O. Tengblad[8], J. Van de Walle[13], P. Van den Bergh[1], P. Van Duppen[1], M. Vandebrouck[21], V. Vedia[11], M. Venhart[22], S. Viñals[8], R. Wadsworth[3], N. Warr[23], K.D.A. Wendt[14], S.G. Zemlyanoy[24]

[1] *KU Leuven Instituut voor Kern- en Stralingsfysica, BE-3001 Heverlee, Belgium*
[2] *Institut de Física Corpuscular, Universitat de València, ES-46980 Valencia, Spain*
[3] *Department of Physics, The University of York, York Y010 5DD, United Kingdom*
[4] *Department of Nuclear Physics and Biophysics, Comenius University, SK-84248 Bratislava, Slovakia*
[5] *Petersburg Nuclear Physics Institute, RU-188350 Gatchina, Russia*
[6] *Grand Accélérateur National d'Ions Lourds (GANIL), FR-14076 Caen, France*
[7] *School of Physics and Astronomy, The Univeristy of Manchester, Manchester M13 9PL, United Kingdom*
[8] *Instituto de Estructura de la Materia, CSIC, ES-28006 Madrid, Spain*
[9] *EN Department, CERN, CH-1211 Geneva, Switzerland*
[10] *Institut de Physique Nucéaire, Université Paris-Saclay, FR-91406 Orsay Cedex, France*
[11] *Nuclear Physics Group, Complutense Univeristy of Madrid, ES-28040 Madrid, Spain*
[12] *Institut for Fysik og Astronomi, Aarhus Universitet, DK-8000 Aarhus C, Denmark*
[13] *Belgian Nuclear Research Centre SCK-CEN, BE-2400 Mol, Belgium*
[14] *Department of Physics, Oliver Lodge Laboratory, University of Liverpool, Liverpool L69 7ZE, United Kingdom*
[15] *Intitut für Physik, Johannes Gutenberg Universität, DE-55122 Mainz, Germany*
[16] *EP Department, CERN, CH-1211 Geneva, Switzerland*

[17] *Institut Laue-Langevin, FR-38042 Grenoble, France*
[18] *Science and Technology Facilities Council, Daresbury WA4 4AD, United Kingdom*
[19] *IFIN Horia Hulubei, RO-077126 Bucharest-Magurele, Romania*
[20] *Accelerator Laboratory, University of Jyväskylä, FI-40014 Jyväskylä, Finland*
[21] *Commissariat à l'Energie Atomique et aux Energies Alternatives (CEA), FR-91191 Gif-sur-Yvette Cedex, France*
[22] *Slovak Academy of Sciences, SK-84511 Bratislava, Slovakia*
[23] *Institut für Kernphyzik, Universität zu Köln, DE-50937 Köln, Germany*
[24] *Joint Institute of Nuclear Research, RU-141980 Dubna, Moscow Region, Russia*

Spokesperson: Thomas Elias Cocolios, thomas.elias.cocolios@cern.ch
Contact person: Reinhard Heinke, reinhard.heinke@cern.ch

Abstract:
The aim of this experiment remains unchanged from its standing addendum. We propose to complete the study of the ground-state and long-lived isomeric-state properties in ^{211,212,219,220}Po isotopes, which studies at ISOLDE are usually prevented by the preponderant isobaric Fr contamination. To overcome this problem, the RILIS in the LIST mode will be utilized. The new data will be used to delineate the region of charge-radii odd-even staggering reversal for $Z > 82$, $N > 126$; to study the properties of high-spin states with longer half-lives in the vicinity of $N = 126$; and to study the systematic α-decay properties in neutron-rich pre-actinide nuclei to test calculations from density functional theory in the region.

Requested shifts: 22.5 shifts, (split into 1 run over 1 year)
This Status Report follows from document INTC-P-222-ADD-2.

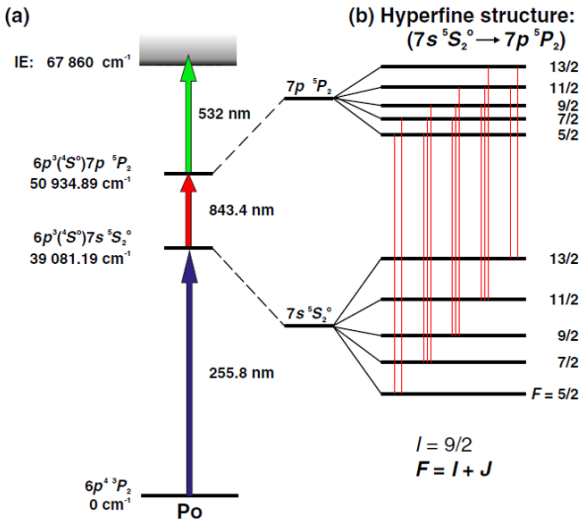

Figure 1: (a) Resonance ionization scheme in the atomic polonium. (b) Hyperfine components of the 843 nm transition for a nuclear spin $I = 9/2$.

1 Motivation and technique

The region of the $Z = 82$ shell closure is rich in subtle nuclear structure effects that are reflected in both the microscopic and macroscopic properties of these nuclei. For example, the shape coexistence observed in nuclei around ^{186}Pb [1] yields to extreme shape staggering in the mercury isotopes in the same region with two protons less [2], while the polonium isotopes with two protons more exhibit a slow yet steady onset of deformation [3]. In the most extensive nuclear shell model calculation ever, the relevance of the proton and neutron high-j orbital occupations have been highlighted [2]. At $N \geq 126$, the crossing of the shell closure is reflected in the abrupt change in the trend of the changes in the mean-square charge radii, see e.g. [4]. While the effect is not peculiar to $N = 126$ [5], its magnitude has been a challenge for nuclear theory but points as well to a question of high-j orbital occupation [6, 7]. Finally, beyond $N = 132$, the phenomena of odd-even staggering reversal in the charge radii and of reflexion asymmetry of the nucleus [8] coincide, though their relationship remain under question [9].

Throughout the IS456 experimental campaigns, we have investigated the ground-state properties of the polonium isotopes by means of combined in-source resonance ionization spectroscopy and decay spectroscopy. The laser frequency of one of the resonant atomic transitions in the ion source is scanned across the hyperfine structure and isotope shifts, while the rate of ionization is monitored by measurement on a Faraday cup, or via decay spectroscopy at a dedicated α-decay station (the Windmill) or at the ISOLDE identification station. From the schemes originally developed for this program [10], the one retained features 3 transitions, from the ground state to an excited state at 255 nm, then to a further excited state with a transition at 843 nm, and eventually with non-resonant ionization with intense 532 nm light (see Fig. 1). The original fluorescence work by Kowalewska et al [11] used the 255 nm transition, while the IS456 campaigns scanned

the second transition at 843 nm for practical reasons (the Doppler contribution to the measurement of isotope shifts and hyperfine splitting of the intermediate level $7s\ ^5S_2$ is less by a factor of 3.3 at this transition, the laser at a fundamental frequency is more stable for scanning). The nuclear electromagnetic moments were extracted from the $7s\ ^5S_2^\circ$ state which is common to both transitions, so that the data are nicely complementary. The extraction of the changes in mean-square charge radii from isotope shifts required an additional study of the atomic parameters [12].
In this proposal, we propose to study the $N = 126$ shell closure by the measurement of the nuclear state properties of the high-spin isomers in ^{211m}Po ($T_{1/2} = 25.2$ s, $E^* = 1462$ keV, $I = (25/2^+)$) and ^{212m}Po ($T_{1/2} = 45.1$ s, $E^* = 2922$ keV, $I = (18^+)$). The study of their nuclear magnetic dipole moment will be used to determine the dominant configuation occupied by the valence nucleons, while the isomer shift will help shed light on how the interplay between these particles affect the shape of the nucleus in this region.
We shall also explore the heavier polonium isotopes beyond $N = 132$. Through our previous studies, the isotopes ^{216,217,218}Po have been studied [3, 13], allowing a first insight into the region. However, it would be essential to complete this picture with the heavier isotopes ^{219,220}Po, from which the trend in odd-even staggering in the charge radii could be determined, and the limit of the region of odd-even staggering reversal addressed. Moreover, these two isotopes have so far eluded basic spectroscopy, due to their long half-life of the order of > 10 min, which is too long for the typical discovery studies performed at in-flight separation facilities, while the beams are difficult to produce and heavily contaminated at ISOL facilities.
Our previous studies have highlighted the relevance of our measurements in comparison to many nuclear models, such as density functional theory, the interacting boson model, and most recently with large-scale Monte Carlo shell model calculations [2, 3, 14, 15]. The data collected in this work will offer new opportunities to challenge the latest nuclear models, in particular with new calculations from density functional theory [15].
The main hindrance to the study of these isotopes are the large isobaric contamination of surface ionized francium and radium isotopes, with yields exceeding 10^7 particles per second and decaying with high α activity. Under those conditions, it is nearly impossible to rely on the beam gate for purification, as was done for ^{216,218}Po, and the high activity saturates the detectors very quickly. In order to remove this isobaric contamination, we propose to make use of the Laser Ion Source and Trap (LIST) [16] to repel the unwanted surface ions while ionizing the atoms of interest in a separate region.

2 Achievements and progress

The IS456 experimental campaign has been very successful in delivering high-quality data on the polonium isotopic chain [3, 10, 12, 13, 17, 18, 19, 20, 21], as well as the subject of 2 PhD theses and 1 MSc thesis [22, 23, 24].
Since the approval of the addendum to IS456 concentrating specifically on the use of the LIST to complete the overal program, a full analysis of the performance of the previous LIST unit from 2012 has been performed [13, 16, 19]. It revealed that the high deposition rate of radioisotopes on the rods of the LIST, coupled with electron-impact

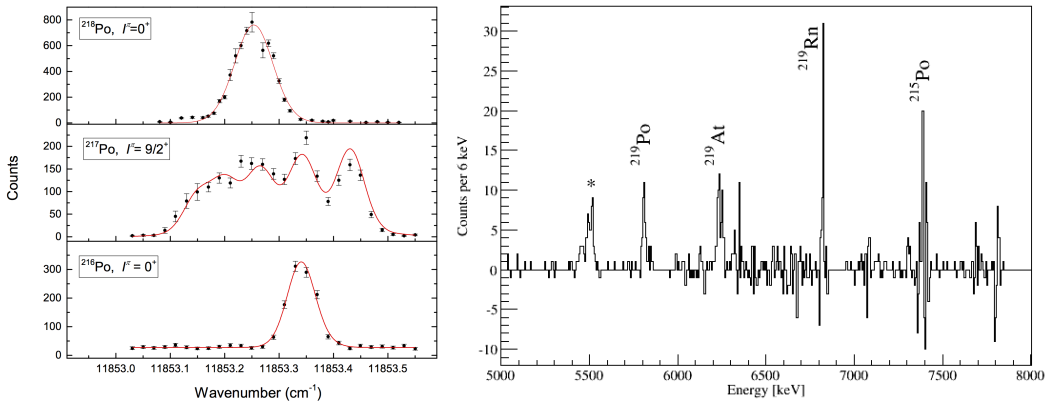

Figure 2: (Left) Resonance ionization spectroscopy scans of $^{216-218}$Po revealing the isotope shifts between each isotope and the hyperfine structure of ^{217}Po [13]. (Right) Laser-ON-OFF subtracted α-decay spectrum of ^{219}Po [13].

ionization induced by electrons that were extracted from the surface ion source, limited the suppression power of the LIST for the isotopes of interest. It enabled nonetheless the demonstration of the capability of this technique, with the measurement of the hyperfine structure of ^{217}Po and preliminary data on the α decay of ^{219}Po [13] (see Fig. 2).
In the last few years, a **new iteration of the LIST** has been developed by the LARISSA group in Mainz by Reinhard Heinke under the supervision of Prof Dr Klaus Wendt. This new device features a double repeller system that blocks both the surface ions and the electrons, hereby removing the secondary source of ionization that limited the 2012 experimental test without any further reduction on the extraction and ionization efficiency in comparison with the previous LIST [25]. This new iteration of the LIST should allow to complete the measurements proposed in IS456.
To that end, Reinhard Heinke will be hired as post-doc by KU Leuven as soon as he completes his PhD in Mainz (in the course of 2019). He will be appointed on a permanent basis at CERN, where he will take over the **full integration of the LIST** as a standard ISOLDE ion source, and integrate the RILIS team as one of the laser specialists for resonance ionization. These two tasks will allow him to prepare the facility to maximize the chances of success of this campaign at the restart of ISOLDE.
Moreover, the further study of the atomic structure of the polonium atom has allowed the identification of Rydberg series [26]. The ionization scheme does not need to rely on the high-power 532 nm light, which may also be responsible for some unwanted background ionization effect (e.g. temperature increase of the cavity, electron emission from metal surfaces). While less efficient than the original scheme by a factor 10, such a scheme was used during IS513 for it provided higher quality beam at $A = 197$ [27].
Concerning the detection setups, both the Windmill and the ISOLDE identifcation station have been decommissionned since the original campaigns. However, new facilities have also been introduced to the ISOLDE floor. The **ISOLDE Decay Station** has demonstrated its symbiotic capabilities with RILIS [29] and may be used for monitoring specific radioactivity during a laser scan. It will also allow for high-quality decay-spectroscopy

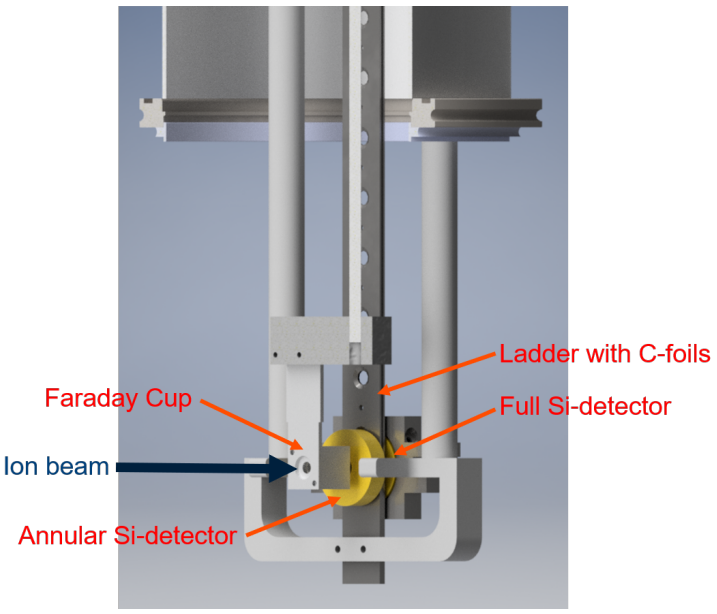

Figure 3: Leuven α-decay spectroscopy setup as designed for IS637 [28]. Up to 10 carbon foils can be mounted on an actuated ladder. A retractable Faraday cup allows for beam tuning. Two Si detectors sandwich the implantation position.

data to be collected on the unstudied isotopes thanks to its large array of high-purity germanium clovers in comparison with the single coaxial germanium detector used at either the Windmill or the ISOLDE identification station in past campaigns of IS456 [17, 18].
In the framework of IS637, a **new high-efficiency α-decay setup** with two Si detectors in sandwich around ultra-thin C foils has been commissioned [28] (see Fig. 3). While reminiscent in its concept of the Windmill, this new chamber offers much better vacuum conditions and more modern operation with respect to its predecessor. Its solid angle coverage is comparable to that the of the Windmill, in excess of 50% and will complement the work performed at IDS for α-emitting isotopes. In the course of 2018, it was used for both campaigns of IS637 so that its integration in terms of safety and radioprotection has now been fully validated.
Following all these developments and investments, IS456 will be ready to take beam and be completed at the restart of ISOLDE after the CERN Long Shutdown 2.

Summary of requested shifts: The yields and performance estimates remain unchanged with respect to the addendum, while the contamination issues have now been addressed. We therefore request to maintain the full **22.5 shifts**, including the commissioning of the LIST and validation of its superior suppression power against francium beams, the laser spectroscopy study of ^{211m,212m,219,220}Po, and their decay spectroscopy study with IDS. Reference measurements of long-lived $^{208-210}$Po will also be performed in Faraday cups, and ^{196}Po at the α-decay setup to benchmark those measurements with the previous ones.

Table 1: Yields and shift request per isotope. The known yield of ^{196} is scaled to account for the LIST loss factor (20 on polonium [13]) and the reduced efficiency of the RILIS narrow band operation. Yields of ^{208}Po are taken from the 2012 IS456 campaign and extrapolated to ^{209,210}Po. Yields for ^{211m,212m,219,220}Po are as tabulated in the original addendum.

Isotope	Half-life	Yield [ions/μC]	Shifts
		LIST test	2
^{196}Po	5.8 s	10^4	0.5
^{208}Po	2.989 y	10^7	1
^{209}Po	102 y	10^7	0.5
^{210}Po	138.38 d	10^7	0.5
^{211m}Po	25.2 s	2×10^4	2
^{212m}Po	45.1 s	2×10^4	2
^{219}Po	620 s	3×10^1	7
^{210}Po	Unknown	10^1	7
		TOTAL	**22.5**

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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	Availability	Design and manufacturing
IDS	☒ Existing	☒ To be used without any modification
Leuven α-decay setup	☒ 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

HAZARDS GENERATED BY THE EXPERIMENT (if using fixed installation:) Hazards named in the document relevant for the fixed **RILIS** and **IDS** installation.

Additional hazards:

Hazards	[Part 1 of experiment/ equipment]	Leuven α-decay setup	[Part 3 of 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		^{241}Am	
• Activity		50 Bq	
Use of activated material:			
• Description	☐		
• Dose rate on contact and in 10 cm distance	[dose][mSV]		
• Isotope		^{196,211m,212m,219,220}Po and progeny	
• Activity		all decays within days	
Non-ionizing radiation			
Laser			
UV light			
Microwaves (300MHz-30 GHz)			
Radiofrequency (1-300 MHz)			
Chemical			
Toxic	[chemical agent], [quantity]		
Harmful	[chem. agent], [quant.]		
CMR (carcinogens, mutagens and substances toxic to reproduction)	[chem. agent], [quant.]		
Corrosive	[chem. agent], [quant.]		
Irritant	[chem. agent], [quant.]		
Flammable	[chem. agent], [quant.]		
Oxidizing	[chem. agent], [quant.]		
Explosiveness	[chem. agent], [quant.]		
Asphyxiant	[chem. agent], [quant.]		
Dangerous for the environment	[chem. agent], [quant.]		
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]		

Hazard identification: the removal of the Leuven α-decay station will be handled with the Radio-Protection services in a similar way to the Windmill and IS637. After a few days of cool down, the chamber will be opened and controled with all relevant participants to declare what may be removed from the ISOLDE experimental hall.

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]