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IS566 Status report to the ISOLDE and Neutron Time-of-Flight Committee
(Following Proposal to the ISOLDE and Neutron Time-of-Flight Committee
IS494 and HIE-ISOLDE Letters of Intent I-107 and I-110)

Probing intruder configurations in ^{188}Pb using Coulomb excitation

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Abstract

Coulomb excitation measurements to study the shape coexistence, mixing and quadrupole collectivity of the low-lying levels in the neutron-deficient ^{188}Pb nucleus are proposed. The HIE-ISOLDE beam of ^{188}Pb nuclei will be delivered to MINIBALL+SPEDE set-up for simultaneous in-beam γ-ray and conversion electron spectroscopy. The proposed experiment will allow the sign of the quadrupole deformation parameter to be extracted for the two lowest 2^+ states in ^{188}Pb. Moreover, the advent of SPEDE will allow probing of the bandhead 0^+ states via direct measurements of E0 transitions. Unlike in the original proposal, in this status report we do not address the ^{186}Pb case as it was not approved by the INTC in May 2013.

Requested shifts: 12 shifts, (split into 1 run over 1 year), beam development to improve Pb/Tl ratio, none of the shifts approved for IS566 have been used.
Beamline: MINIBALL + SPEDE + CD

1 Introduction

The interplay between single-particle motion, collectivity, and pairing in light Pb nuclei is manifested as a rich gamut of coexisting nuclear shapes and exotic excitations [1 and references therein]. One of the goals of modern nuclear physics research is to understand the origin of these structures and their relation to the fundamental interactions between the nuclear constituents. These subjects can be investigated particularly well in the Pb isotopes close to neutron mid-shell, where a relatively small proton shell gap, together with a large valence neutron space, provides fertile ground for studies of shape transitions within a small energy range. In α-decay studies, the first two excited states of the mid-shell nucleus ^{186}Pb were observed to be 0^+ states [2]. On the basis of α-decay hindrance factors, the 0^+_2 state was associated with mainly π(2p–2h) configuration, whereas the 0^+_3 state was associated with a π(4p–4h) configuration. Consequently, together with the spherical ground state [3], the three 0^+ states with largely different structures establish a unique shape-triplet in ^{186}Pb. Similarly, the three different structures have been manifested in the form of isomeric states associated with different shapes in ^{188,190}Pb [4-7]. Recently, rotational bands built on these states in ^{186,188}Pb were observed by in-beam γ-ray measurement [5,8] and their collectivity confirmed in lifetime measurements [9,10].

A complementary view of these 0^+ states is provided by mean-field methods in which each local minimum of the potential energy surface is associated with a different collective shape. The first calculations of quadrupole potential energy surfaces were performed within the Strutinsky approach [11-13]. The existence of a spherical ground state with low-lying oblate and prolate minima has been found in self-consistent mean-field approaches based on effective Skyrme [14-16] and Gogny [17] interactions. In a truncated shell-model approach, these oblate and prolate mean-field configurations can be associated with π(2p − 2h) and π(4p − 4h) excitations, respectively, forming a unique system of the three different shapes. Although much experimental effort has been put into investigating light Pb nuclei, the information obtained is still rather scarce. It remains a challenge for both theoretical and experimental studies to obtain a consistent and detailed description of the observed phenomena.

We propose to carry out the investigations of nuclear collectivity and mixing of the low-lying states in the neutron-deficient Pb nuclei, namely the isotopes ^{188}Pb, employing the Coulomb excitation (Coulex) technique at the HIE-ISOLDE facility. In Fig. 1, the level energy systematics of even-mass Pb isotopes is shown. The 0^+ states of the predominantly π(2p–2h) configuration, associated with the oblate shape, intrude down in energy close to the spherical ground state when approaching the neutron mid-shell at N = 104 and becomes the first excited state already at A = 194. The onset of prolate deformation, mainly associated with a π(4p–4h) configuration, can be seen around A = 190 for states with $I^\pi \leq 4^+$. The prolate states with $I^\pi \geq 4^+$ form the yrast band at A = 188. Thus, light Pb isotopes provide a unique laboratory to study the three competing structures of different shapes around 1 MeV.

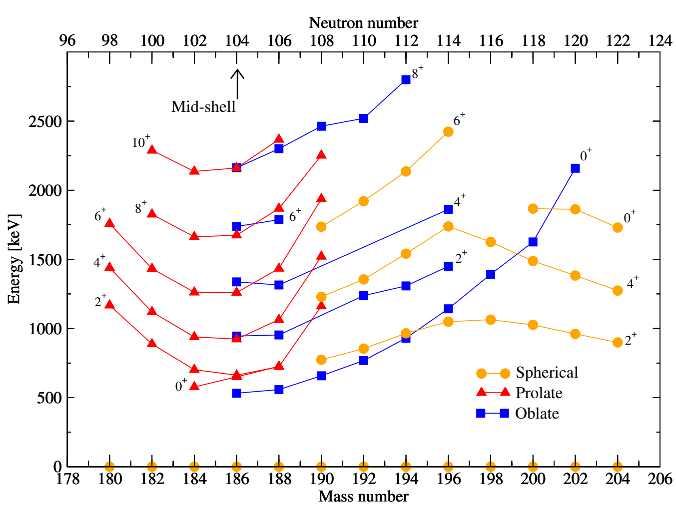

Figure 1. Level energy systematics of the even-mass Pb isotopes.

In order to establish a complete picture of shape coexistence in this region, knowledge of transition probabilities from nuclear states assigned with different shapes is essential. Transition probabilities are very sensitive to the details of a nuclear wave function and, consequently, information about nuclear shape and configuration mixing can be inferred. Furthermore, the knowledge of the nuclear wave functions renders it possible to extract an effective nucleon-nucleon interaction to produce a realistic nuclear potential. So far, collectivity of γ-ray transitions originating from prolate states in ^{186,188}Pb has been established by in-beam lifetime measurements [9,10]. While in-beam lifetime experiments probe mainly yrast states, with Coulex the population of low-lying non-yrast states becomes feasible and, enables a comprehensive study of collectivity, coexisting shapes and their mixing in these nuclei. In our recent IS494 MINIBALL experiment at REX-ISOLDE, the 2^+_1 states were populated in even-mass $^{188-198}$Pb via Coulex. Preliminary analysis suggests that the systematic trend of B(E2) values in these isotopes and the quadrupole moments for $^{188-192}$Pb can be extracted from that data. It is worth noting that a detailed understanding of the competing structures in Pb isotopes will be of direct relevance to developing a fuller picture of the evolution of these phenomena in the neighbouring nuclei such as isotopes of Hg.

2 Update on the physics case and instrumentation since the acceptance of IS566

2.1 Current status of the analysis of the ^{188}Pb SAGE and MINIBALL experiments (IS494)

Recently, we have conducted an in-beam γ-ray and conversion electron spectroscopy experiment to study ^{188}Pb employing stable beams and the SAGE spectrometer at the University of Jyväskylä. While these data are about to be published, it can already be concluded that the conundrum related to the level energies of the excited 0^+ states has been solved. Moreover, branching ratios for the inter-band $2_2^+ \rightarrow 2_1^+$ transition, in particular the conversion electron component, has been directly measured.

The even-mass $^{188-198}$Pb Coulex experiments (IS494) performed at REX-ISOLDE have been partially published, namely for the isotopes ^{196,198}Pb [18]. The analysis of $^{188-192}$Pb isotopes has been on hold until necessary complementary results have been obtained in order to draw firm conclusions. The new SAGE results for ^{188}Pb, once published, provide the missing information for the analysis of the existing (IS494) ^{188}Pb Coulex data.

The new information obtained for ^{188}Pb from the SAGE and IS494 experiments since the acceptance of the IS566 proposal provide important constraints for the future analysis of the IS566 Coulomb excitation data, but do not answer the physics scope of the IS566 proposal. In this way the sensitivity to subtle-order effects, such as Q_{sp} values of the low-lying 2+ states, can be gained. Moreover, HIE-ISOLDE remains the unique facility to conduct this study.

2.2 Instrumentation

The SPEDE spectrometer has been commissioned both at the University of Jyväskylä and at ISOLDE [19]. It has also been successfully employed in the IS641 experiment at IDS in studies $^{182-186}$Tl beta-decay [20]. The MINIBALL electronics upgrade, foreseen to take place during the LS2, will be beneficial for in-beam experiments with SPEDE.

3 Proposed experiment and data analysis

The isotope of interest in the present proposal is of particular importance as it is placed at the heart of triple shape coexistence; ^{188}Pb and ^{186}Pb are the only isotopes where both (predominantly) prolate and oblate rotational bands have been observed. The measurement of the sign of the quadrupole deformation parameter allows unambiguous confirmation of the shape in a nuclear-model independent manner. SPEDE will not only allow probing of the 0^+ bandhead states, but also to directly measure the enhanced E0 strengths of the inter-band $2_2^+ \rightarrow 2_1^+$ transition arising from mixing between states with same spin and parity, but different deformation.

The ISOLDE facility is currently the only laboratory where these experiments can be carried out. In the following section, the proposed ^{188}Pb experiment is described. In the IS494 experiment, radioactive beams of neutron-deficient Pb isotopes were produced using the UCx primary target and laser ionization (RILIS) [21]. Despite the use of RILIS, isobaric Tl contamination originating from surface ionization was present. In the case of ^{188}Pb, the Pb/Tl ratio was about 50/50. This impurity issue was overcome by means of a laser on/off technique, that enabled us to extract the amount of target excitation arising from Tl contaminants; that information in turn is needed for cross normalization between projectile (Pb) and target excitations. Consequently, a similar scenario for beam production as in IS494 can be used. The required charge state to accelerate ^{188}Pb beams up to 4.2 MeV/u will be obtained with the REX-TRAP/EBIS charge breeder. Accelerated HIE-ISOLDE Pb beams will be delivered to the MINIBALL+SPEDE target position where Pb nuclei will be Coulomb excited in inverse kinematics using various secondary targets. The MINIBALL and SPEDE detector arrays will be exploited for simultaneous detection of both γ rays and conversion electrons, respectively, that de-excite the levels under investigation. Both scattered projectiles and target recoils will be detected using an annular double-sided silicon strip detector (DSSSD) downstream from the secondary target. We propose to use two different beam energies ("low" and "high") and two different targets. This allows us to probe:

1) different scattering angular ranges at which Coulomb excitation takes place,
2) different population of states.

It should be noted, that the low-lying states in the ^{188}Pb have been selectively populated using α- and β-decay and in-beam spectroscopic techniques. In comparison, multistep Coulex is more a powerful technique for the population of non-yrast states. A "low" beam energy can be used to limit the number of multistep Coulomb-excited states. These data can be used to fix the diagonal and transitional matrix elements associated with the low-lying states. The use of "high" beam energies maximizes the Coulex yields, and has been chosen so that the bombarding energy still remains below the so-called "safe" energy. Excitation patterns obtained in "low" and "high" energy measurements will be different and thus combination of both data sets will help constraining the multi-dimensional fit aiming at extraction of the matrix elements from measured γ-ray yields. In addition, each data set will be divided into a few angular ranges to assure sensitivity for diagonal matrix elements. The essential parameters concerning the yield calculations are given in Table 1.

Table 1. Parameters used in the yield calculations.

General parameters	**Value**	**Note**
HIE-ISOLDE transmission	3%	Assumed same as REX-ISOLDE
^{188}Pb HIE-ISOLDE yield	1×10^{6}pps	
^{120}Sn target thickness	2 mg/cm^2	
^{48}Ti target thickness	1 mg/cm^2	
Number of shifts		
^{188}Pb on ^{120}Sn @ 4.2MeV/u	2	Lasers off runs 30% of beam time
^{188}Pb on ^{120}Sn @ 3.5MeV/u	3	--- " ---
^{188}Pb on ^{48}Ti @ 4.0MeV/u	2	--- " ---
^{188}Pb on ^{48}Ti @ 3.5MeV/u	3	--- " ---

A sample γ-ray energy spectrum of ^{188}Pb from experiment IS494 is shown in Fig 2. Most of the γ-ray transitions in ^{188}Tl (black labels) can be distinguished from the ones associated with ^{188}Pb (blue labels). As can be seen, the 953 keV $2_2^+ \rightarrow 0_1^+$ transition was populated as well, although statistics are not sufficient to extract the B(E2) value. Further purification of the energy spectra can be obtained via γ-γ or γ-e^- coincidence analysis. The transitions of interest are shown in a partial level scheme of ^{188}Pb in Fig. 2.

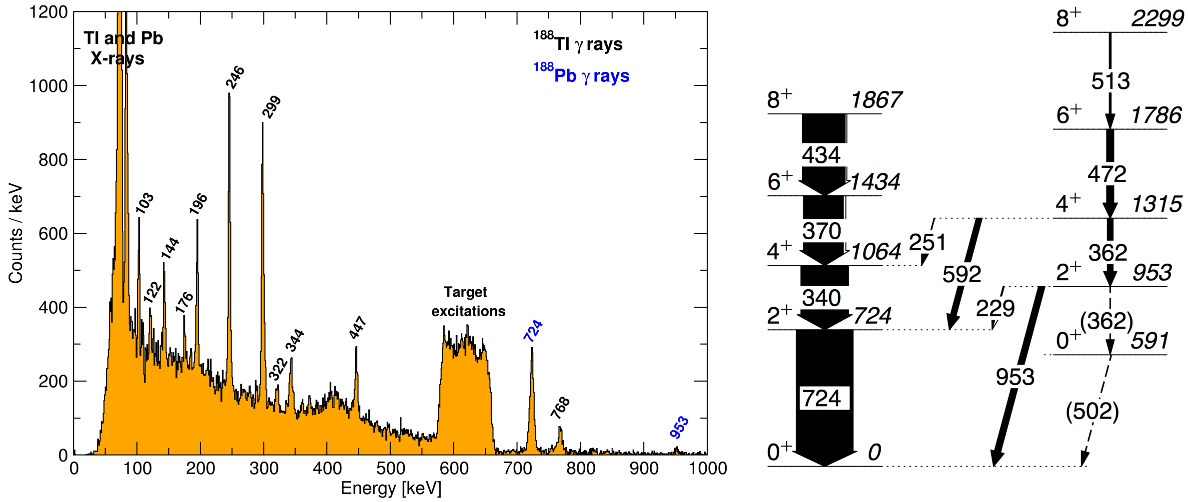

Figure 2. Left: Doppler corrected, background subtracted γ-ray energy spectra obtained in the IS494 experiment. Transitions associated with ^{188}Tl (black) and ^{188}Pb (blue) are labeled. Data include both laser on and off runs. Right: Partial level scheme of ^{188}Pb showing transitions of interest [5]. The $0_2^+ \rightarrow 0_1^+$ transition energy is shown as the K-conversion electron energy.

4 Count rate estimate and beam time request

It has been shown in several experiments that heavy radioactive beams can be exploited in Coulex studies at HIE-ISOLDE. In the present proposal we have used the estimate of 1×10^6pps of ^{188}Pb beam on target (in IS494, the average yield at MINIBALL was 1.6×10^6pps). In Table 2, the γ-ray yield estimates for the proposed ^{188}Pb experiment calculated using the GOSIA code are shown [22]. The matrix elements used in the GOSIA calculation for the yrast band transitions have been extracted from lifetimes measured in Ref. [9], whereas for the non-yrast transitions values extracted from IBM calculations in Ref. [23] are used. Table 2 also lists the MINIBALL γ-ray detection efficiency at the energies of interest together with conversion electron efficiency. In order to obtain sufficient statistics for coincidence analysis, 100000 counts for the $2_1^+ \rightarrow 0_1^+$ transition is estimated to be enough. It should be noted, that figures given in Table 2 are for the whole CD; it is foreseen that CD will be divided in a few angular ranges in the final analysis.

Table 2. Counts obtained for projectile and target excitations in four different beam-target combinations as listed in Table 1 for ^{188}Pb. Beam energies for different reactions are given on top of each column.

$I_i^\pi \rightarrow I_f^\pi$ Projectile	$E_{transition}$ [keV]	Det. Eff. [%]	4.3MeV/u ^{188}Pb+ ^{120}Sn	3.5MeV/u ^{188}Pb+^{120}Sn	4.0MeV/u ^{188}Pb+^{48}Ti	3.5MeV/u ^{188}Pb+^{48}Ti
$2_1^+ \rightarrow 0_1^+$	723.5	8.8	126375	107093	3695	4749
$4_1^+ \rightarrow 2_1^+$	340.2	14.1	61877	36737	1890	1607
$6_1^+ \rightarrow 4_1^+$	369.7	13.3	28827	10907	666	359
$8_1^+ \rightarrow 6_1^+$	433.8	12.0	8725	1752	115	35
$2_1^+ \rightarrow 0_2^+$	133.9	7.0	170	455	16	20
$2_2^+ \rightarrow 0_1^+$	952.5	7.5	37970	24846	1341	1380
$4_2^+ \rightarrow 2_2^+$	362.5	13.5	19402	7680	533	345
$6_2^+ \rightarrow 4_2^+$	471.5	11.4	4570	890	70	26
$8_2^+ \rightarrow 6_2^+$	513.0	10.8	812	73	6	1
$2_2^+ \rightarrow 0_2^+$	361.5	13.5	3542	2317	125	129
$2_2^+ \rightarrow 2_1^+$	228.7	18.0	1352	879	47	48
$2_2^+ \rightarrow 2_1^+$	140.2$^{a)}$	8.0	1202	782	42	29
$0_2^+ \rightarrow 0_1^+$	502.5$^{a)}$	8.0	2294	1538	80	83

Target						
$2_1^+ \rightarrow 0_1^+$	^{120}Sn: 1171 ^{48}Ti: 984	6.6 7.3	53153	26619	17241	17875
$4_1^+ \rightarrow 2_1^+$	^{120}Sn: 1023 ^{48}Ti: 1312	7.2 6.1	10795	1640	63	16
$2_2^+ \rightarrow 0_1^+$	^{120}Sn: 2097 ^{48}Ti: 2421	4.2 3.5	71	12	1	0

[a] K-conversion electron energy

Beam development

The beam purity in the IS494 experiment was ~50%. It is clear that IS566 experiment would benefit from beam development as background conditions would be cleaner in the case of a pure Pb beam. A few different methods can be tried to purify the Pb beam from isobaric Tl contamination [24]:

1) Molecular extraction: the PbO molecule can be stabilized vs atomic Pb and a similar approach in other molecular beams have led to 10% molecular sideband formation efficiency.
2) The nanoUCx target (tested at ISOLDE), in conjunction with the GdB_6 low-work-function cavity could reduce non-specific ionization and improve the Pb/Tl ratio.
3) There are ongoing activities to reduce signal/unspecific ions by improving the time structure (bunching) of the produced RILIS ions, and therefore also improving the Pb/Tl ratio.

Summary of requested shifts:

10 shifts of beam time are required for the γ-ray yield measurement of ^{188}Pb (includes laser off runs). A further 2 shifts are required for setting up of HIE-ISOLDE. Thus, **in total we request 12 shifts for ^{188}Pb.**

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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
MINIBALL + only CD	☒ Existing	☒ To be used without any modification
SPEDE	☐ 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 [MINIBALL + only CD, MINIBALL + T-REX] installation.

Additional hazards:

Hazards	*SPEDE*	*[Part 2 of the experiment/equipment]*	*[Part 3 of the experiment/equipment]*
Thermodynamic and fluidic			
Pressure			
Vacuum			
Temperature			
Heat transfer			
Thermal properties of materials			
Cryogenic fluid			
Electrical and electromagnetic			
Electricity	4000V, *negligible* A		
Static electricity			
Magnetic field			
Batteries	☐		
Capacitors	☐		
Ionizing radiation			
Target material			
Beam particle type (e, p, ions, etc)	^{188}Pb ions		
Beam intensity	10^{6} pps		
Beam energy	<4.2MeV/u		
Cooling liquids	[liquid]		
Gases	[gas]		
Calibration sources:	☐		
• Open source	☒ electron source		
• Sealed source	☐		
• Isotope	^{133}Ba, ^{207}Bi		
• Activity			
Use of activated material:			
• Description	☐		

• Dose rate on contact and in 10 cm distance			
• Isotope			
• Activity			
Non-ionizing radiation			
Laser	RILIS, scheme for Pb		
UV light			
Microwaves (300MHz-30 GHz)			
Radiofrequency (1-300MHz)			
Chemical			
Toxic			
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)			
Mechanical properties (Sharp, rough, slippery)			
Vibration			
Vehicles and Means of Transport			
Noise			
Frequency			
Intensity			
Physical			
Confined spaces			
High workplaces			
Access to high workplaces			
Obstructions in passageways			
Manual handling			
Poor ergonomics			

0.1 Hazard identification

The secondary target will be applied in high tension (<4000V) for reduction of delta-electrons.

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)

Negligible