EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Proposal to the ISOLDE and Neutron Time-of-Flight Committee
(Following HIE-ISOLDE Letter of Intent I-110)

Structure of intruder states in ^{190}Pb probed with transfer reactions

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Abstract

The scientific aim of this proposal is to investigate the underlying structure of the intruder states in the neutron-deficient Pb region. This can be assessed using direct reactions employing heavy radioactive ion beams in inverse kinematics, only available at HIE-ISOLDE, CERN. We propose to use the ^{7}Li(^{186}Hg,t)^{190}Pb reaction studied with the Miniball+T-REX set up, which will allow the intruder states in ^{190}Pb to be probed via α-particle transfer into a ^{186}Hg nucleus impinging on a ^{7}Li target at 3.5MeV/u. The present proposal is part of our experimental program to study the shape coexistence phenomenon in this region. Nucleon transfer reactions are essentially the only feasible technique to unambiguously determine the intrinsic configuration of the intruder states and provide complementary information that can not be extracted from experiments employing Coulomb excitation or fusion-evaporation reactions.

Requested shifts: 15 shifts, (split into 1 runs over 1 years)
Beamline: MINIBALL + T-REX

1 INTRODUCTION

In the atomic nucleus, the interplay between single-particle motion, collectivity and pairing is seen as a rich tapestry of coexisting nuclear shapes and exotic excitations, often associated with so called **intruder states**. One of the richest regions is formed by very neutron-deficient nuclei with proton number Z close to the magic 82 and neutron number N close to 104 (mid-shell) [1,2]. Shape coexistence in this region was first established in the early 1970s in laser spectroscopy experiments, in which a sudden change in nuclear charge radii was observed between the isotopes ^{187}Hg and ^{185}Hg [3]. Since then a whole arsenal of spectroscopic techniques has been developed to study this phenomenon. For example, rotational bands based on different potential energy minima have been investigated via in-beam γ-ray spectroscopy [4,5], α-decay fine structure measurements have probed the location of different minima [6] and lifetime measurements have shed light on the collectivity of yrast transitions [7]. However, there are still many **open questions and problems related to intruder states** that also address key questions in the field:

1) **Confirmation of three different shapes in the same nucleus.**
2) **Underlying structure of intruder states in the Z≈82 and N≈104 region.**
3) **Onset of deformation in even-mass Z>82 nuclei with decreasing N.**
4) **The role and behaviour of the multiproton multihole (*np-mh*) excitations in odd-Z nuclei with Z>82.**
5) **Systematic behaviour of mixing between different shape coexisting structures.**

In order to verify and understand shape coexistence phenomena it is important to determine what drives the nucleus into deformation, what are the underlying structures of nuclear states with different shapes, and what are the roles of pairing, the proton-neutron interaction and configuration mixing in this picture. In this endeavour, germanium detector arrays, electron spectrometers and particle detectors have been important tools for decades. However, these devices can provide only partial information on nuclear de-excitation processes, the underlying structure of states populated or which orbitals were involved.

The underlying structure can be addressed with direct nuclear reactions (or "transfer reactions"). They can be used to determine nuclear properties from basic level spectroscopy to structural characteristics such as single-particle, pairing and cluster properties. Transfer reactions are important as they exhibit an inherent selectivity connecting initial and final states in a single step accessing a particular degree of freedom. The reaction mechanism in which one or two nucleons are transferred is well studied and understood, allowing a transparent connection of experimental observables with underlying physics. For example, single-nucleon transfer reactions have been particularly important in establishing single-particle models in near-stable nuclei. The advent of post-accelerated radioactive ion beams (RIB) has also brought cluster transfer reactions in inverse kinematics within reach using state-of-art instruments.

2 OBJECTIVES

The scientific aim of the present proposal is to initiate an experimental program employing transfer reactions, and subsequently provide **unambiguous determination of the structure of intruder states** in the neutron-deficient Pb region. This will be addressed by studying the population, non-population and depopulation of these states in transfer reactions. These reactions can only be accessed with heavy radioactive beams in inverse kinematics, currently only available at HIE-ISOLDE. The objectives of the research program are:

1) **Probe excited states in nuclei in the neutron-deficient Pb region using transfer reactions**
2) **Determine the structure of the intruder states in nuclei in the neutron-deficient Pb region**

The first objective marks a new approach to studying the neutron-deficient Pb region. It will provide direct measurement of transferred angular momentum and enable the single-particle states involved in the transfer to be probed. In fact, these are the only measurements that can directly address the second objective, which remains unresolved regardless of extensive experimental and theoretical efforts.

The results obtained in the scope of this proposal will enable stringent tests of existing theoretical calculations and provide new data for development of better nuclear models.

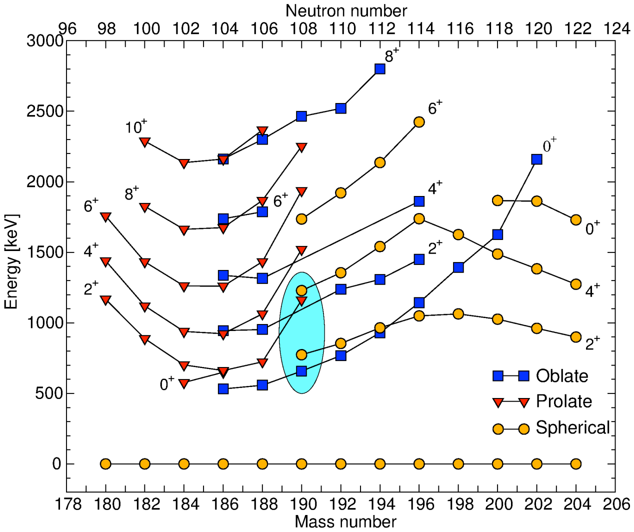

Figure 1: Level energy systematics of the neutron-deficient Pb isotopes [5]. The different configurations have been labelled and the states of interest in the present proposal are highlighted.

The occurrence of excited 0^+ states in this region is generally associated with multiproton excitations across the closed Z=82 shell [1,8,9,10]. As shown in Figure 1, in the Pb isotopes the 0^+ states intrude down in energy toward the spherical ground states when approaching the neutron mid-shell at N=104 [6,8,11,12,13]. A complementary view of these 0^+ states is provided by mean-field methods in which the different shapes are associated with energy minima. The first calculations of quadrupole potential energy surfaces were performed within the Strutinsky approach [14,15,16,17]. The existence of a spherical ground state with low-lying oblate and prolate minima has been confirmed by self-consistent mean-field approaches based on effective Skyrme [18,19] and Gogny [20] interactions. In a truncated shell-model approach, these oblate and prolate mean-field configurations can be associated with proton *2p-2h* and *4p-4h* excitations, respectively, forming a unique system of three different shapes.

3 METHODS

Different types of transfer reactions will be used to address the objectives of the physics program. They pose different challenges and can be better suited for different instruments, such as Miniball+T-REX or the ISOLDE Solenoidal Spectrometer (ISS), but can also be complementary to each other. Essential for these studies are high beam energies the HIE-ISOLDE can provide as sensitivity to the angular momentum transfer increases with increasing beam energy. These are described in general terms together with examples below.

One neutron transfer reactions (stripping or pick-up) from the even-mass Hg isotopes will populate states that are connected to the low-spin ($1/2^-$) shape isomer or the high-spin ($13/2^+$) ground state of the Hg isotopes (e.g. ^{184}Hg(d,p)). The relative population of these states can supply information on the different components in the ground state of the even-mass nuclei. Alternatively, one could use an isomerically pure beam of odd-mass Hg (produced using laser ionization of specific hyperfine components) starting from e.g. the $1/2^-$ shape isomers in the odd-mass Hg isotopes, the one-neutron transfer reaction can populate low-spin (0^+, 2^+, 4^+) states in the even-mass Hg. Assuming that the neutron acts as a spectator, the relative cross section contains information on the intruder contribution to these states. In a similar manner, the neutron (non-)occupancy in the light Pb isotopes can be studied using **two-neutron transfer reactions**.

It has been suggested that the driving mechanism behind shape-coexistence are proton-pair excitations across the Z=82 proton shell closure, although the experimental confirmation is still pending. For example, the relative population of the excited 0^+ states via **two-proton transfer reactions** (^{3}He(^{184}Hg,^{186}Pb)n, ^{16}O(^{184}Hg,^{186}Pb)^{14}C and ^{6}Li(^{196}Po,^{194}Pb)^{8}B) may shed light on this.

An exploratory experiment has been performed at REX-ISOLDE to investigate **cluster-transfer reactions** with radioactive beams in inverse kinematics [21]. The aim was to test the potential of cluster-transfer reactions at the Coulomb barrier as a mechanism to explore the structure of exotic neutron-rich nuclei. The reactions ^{7}Li(^{98}Rb,αxn) and ^{7}Li(^{98}Rb,txn) were studied through particle-γ coincidence measurements. The results indicate that cluster-transfer reactions can be well described as a direct process and that they can be an efficient method to investigate the structure of neutron-rich nuclei at medium-high excitation energies and spins. We will extend these studies to neutron-deficient Pb isotopes using reactions such as ^{7}Li(^{184}Hg,txn) and ^{7}Li(^{185}Tl, αxn).

We propose to start the experimental program by studying ^{190}Pb via the ^{7}Li(^{186}Hg,t)^{190}Pb reaction at 3.5MeV/u. The beam energy has been chosen to match the optimum reaction Q value and to ensure the reaction takes place below the fusion barrier. The ^{190}Pb nucleus is an ideal starting point to assess the proposed physics case. It is located in the transitional region where the intruder configurations start to come down in energy close to the ground state (see Figure 1 and Figure 2). Our focus is to measure the structure of the low-lying 2^+ states at 774keV and 1163keV, tentatively assigned as having near-spherical and prolate shapes, respectively. The population of higher lying states can bring added value to the proposed work. The sensitivity to observe particle-γ coincidences is needed to distinguish between the 2^+ states and the ground and other low-lying states (e.g. the 0_1^+ state at 658keV and the 4_1^+ state at 1229keV). Moreover, sensitivity to observe γ-rays also enables possible beam impurity issues to be overcome. Therefore, the Miniball+T-REX set-up is best suited for this study.

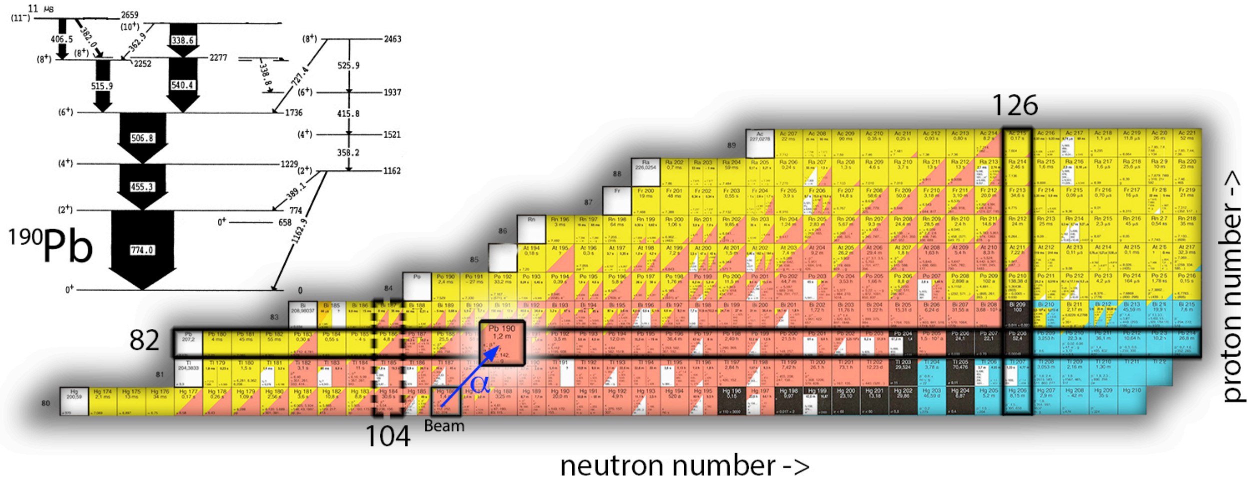

Figure 2: Chart of nuclei around the nuclei of interest and partial level scheme of ^{190}Pb [^{22}]. The proposed α-transfer reaction leading to ^{190}Pb is illustrated with an arrow.

In Table 1, essential parameters used in the yield calculations are listed. The α-particle transfer cross section leading to the ground state is taken from [21], for excited states we assume that to be a factor of 100 lower (similar magnitude to all low-lying states). The cross sections for one-proton and tritium transfer leading to ^{187}Tl and ^{189}Tl nuclei, are a factor of 5 lower and a factor of 5 higher, respectively.

Table 1: Parameters used in yield calculations.

^{186}Hg ISOLDE yield [ions/μC]	^{7}Li target thickness [mg/cm^{2}]	HIE-ISOLDE transmission [%]	^{186}Hg Miniball yield $^{a)}$ [pps]	T-REX coverage [%]	Cross-section to ground state [mb]	Cross-section to excited states $^{b)}$ [mb]
1.0×10^{9}	0.4	5	5×10^{7}	66	5	0.05

$^{a)}$Assuming 2μA proton current from PS Booster, $^{b)}$Assuming the same for each excited state at E_{beam}=3.5MeV/u.

In Table 2, the yield estimates for the ^{7}Li(^{186}Hg,t)^{190}Pb reaction studied with the Miniball+T-REX set up are shown. The estimated t-γ yield will allow for robust ℓ-value assignments through angular distribution analysis. The other key experiments to further address our scientific aim will be identified after results from the proposed experiment have been assessed. As mentioned earlier, ^{187}Tl and ^{189}Tl nuclei are produced as side products via one-proton and tritium transfers, respectively. This is illustrated in Figure 3, where the simulated ΔE-E spectra following the proposed reaction are shown. It should be noted that the states populated in these nuclei do not decay via γ-rays with overlapping energies. Therefore, the γ-rays can be considered as pure tags and consequently the ^{187}Tl and ^{189}Tl data can be taken as a bonus that renders an interesting physics case. For example, these data may shed light on the coupling of an odd-proton to the ^{186}Hg and ^{188}Hg cores.

Table 2: Count rate estimates for ^{7}Li(^{186}Hg,t)^{190}Pb reaction studied with the Miniball+T-REX set up.

Detected radiation	Counts / shift	Counts / 5 days
t-particle (ground state)	167080	2506202
t-particle (excited state)	1671	25062
t-γ coincidences (2_1^+ state)[a)]	140	2105
t-γ coincidences (2_2^+ state) [b)]	110	1654

[a)] γ_{eff} = 8.4%, [b)] γ_{eff} = 6.6%

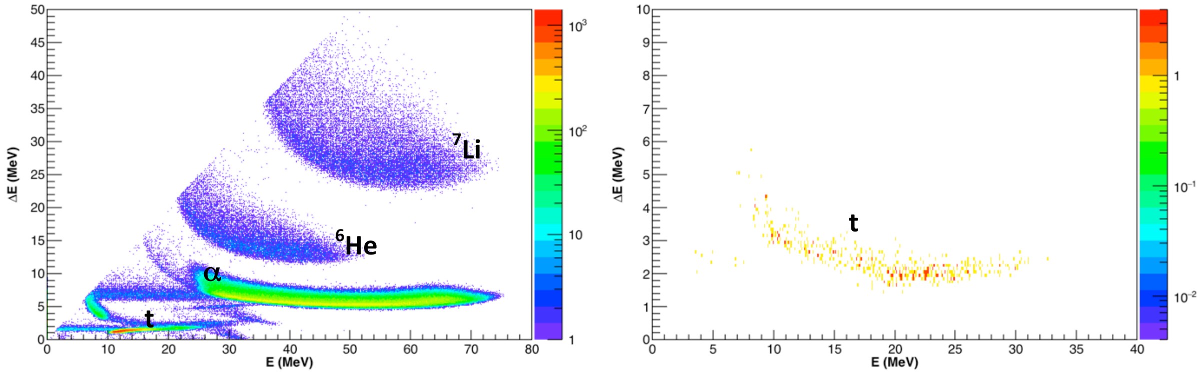

Figure 3: Left: Simulated ΔE-E spectrum measured with T-REX following the ^{7}Li(^{186}Hg,t)^{190}Pb reaction at beam energy of 3.5MeV/u and with yields listed in Table 2. Flat centre of mass angular distribution was used. Different reaction channels are labeled. Right: Same as left but zoomed in ^{3}H range and demanding coincidence with the 774keV γ-ray.

The α-particle transfer reaction was chosen as the first approach as no beam, target or instrumentation development is needed. One-nucleon transfer is not ideally suited if the intruder states are based on *np-mh* excitations. Concerning the two-proton or two-neutron transfers, beam and target development is needed. Based on the results obtained from the proposed experiment, we will submit an addendum to perform the same reaction with the ISS when the forward angle Si-detector array is available. The high resolution of ISS is needed to distinguish between the excited 0_2^+ (658keV) and the ground state. For completeness, other example reactions to access the structure of ^{190}Pb nucleus are listed in Table 3 together with possible challenges. The outcome of the proposed experiment will pave the way and guide the selection of reaction for further studies in this region.

Table 3: Different approaches to study ^{190}Pb via nucleon transfer.

Beam	Reaction	Set-up	Study	Challenge
^{188}Hg	(^{16}O,2p)	MB+T-REX	Proton occupancy	Target material
^{188}Tl	(^{7}Li,^{3}He2n)	ISS	Proton occupancy	Isomerically pure beam
^{191}Bi	(d,^{3}He)	MB+T-REX and ISS	Proton (non)-occupancy	Effective target thickness
^{188}Pb	(t,p)	ISS	Neutron occupancy	Target material

The quantitative interpretation of the results from the transfer reactions will require a substantial theoretical effort. The extracted cross sections and angular distributions will be compared to calculations using the finite-range DWBA code Fresco [23] to obtain information on the angular momentum of the final states and spectroscopic factors.

The proposed experiment will complement the data obtained in a recent Coulomb excitation experiment at REX-ISOLDE addressing shapes, collectivity and mixing in the even mass $^{188\text{-}198}$Pb nuclei.

Summary of requested shifts:

15 shifts of beam time are required for the proposed ^{190}Pb experiment.

Reference

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[1] K. Heyde and J. L. Wood, Rev. Mod. Phys. 83 1467–521 (2011).
[2] R. Julin, K Helariutta and M. Muikku, J. Phys. G **27,** R109 (2001).
[3] J. Bonn, G. Huber, H.-J. Kluge and E. W. Otten, Physics Letters B **38**, 308 (1972).
[4] J. Pakarinen *et al.*, Phys. Rev. C **75**, 014302 (2007).
[5] R. Julin, T. Grahn, J. Pakarinen and P. Rahkila, J. Phys. G: Nucl. Part. Phys. **43,** 024004 (2016).
[6] A. Andreyev *et al.*, Nature **405**, 430 (2000).
[7] T. Grahn *et al.*, Phys. Rev. Lett. **97**, 062501 (2006).
[8] P. Van Duppen, E. Coenen, K. Deneffe, M. Huyse, K. Heyde and P. Van Isacker, Phys. Rev. Lett. **52**, 1974 (1984).
[9] P. Van Duppen, M. Huyse, K. Heyde and J. L. Wood, J. Phys. G: Nucl. Part. Phys. **16**, 441 (1990).
[10] K. Heyde, J. Schietse and C. De Coster, Phys. Rev. C **44**, 2216 (1991).
[11] P. Van Duppen, E. Coenen, K. Deneffe, M. Huyse and J. L. Wood, Phys. Lett. **B154**, 354 (1985).
[12] N. Bijnens *et al.*, Z. Phys. A **356**, 3 (1996).
[13] A. N. Andreyev *et al.*, Eur. Phys. J. A **6**, 381 (1999).
[14] F. R. May, V. V. Pashkewich and S. Frauendorf, Phys. Lett. **B68**, 113 (1977).
[15] R. Bengtsson and W. Nazarewicz, Z. Phys. A **334**, 269 (1989).
[16] W. Nazarewicz, Phys. Lett. **B305**, 195 (1993).
[17] N. Tajima, P. Bonche, H. Flocard, P.-H. Heenen and M. S. Weiss, Nucl. Phys. **A551**, 409 (1993).
[18] T. Duguet, M. Bender, P. Bonche and P.-H. Heenen, Phys. Lett. **B559**, 201 (2003).
[19] M. Bender, P. Bonche, T. Duguet and P.-H. Heenen, Phys. Rev. C **69**, 064303 (2004).
[20] R. R. Rodriguez-Guzman, J. L. Egido and L. M. Robledo, Phys. Rev. C **69**, 054319 (2004).
[21] S. Bottoni *et al.*, Phys. Rev. C **92**, 024322 (2015).
[22] G. D. Dracoulis *et al.*, Phys. Lett. **B** 432, 37–44 (1998).
[23] I. J. Thompson, Comput. Phys. Rep. 7, 167 (1988).

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 + T-REX (or C-REX)	☒ Existing	☒ To be used without any modification

HAZARDS GENERATED BY THE EXPERIMENT

(if using fixed installation) Hazards named in the document relevant for the fixed MINIBALL + T-REX 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)	^{186}Hg		
Beam intensity	5×10^7		
Beam energy	3.5MeV/u		
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)*

… kW