EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

Probing the low-lying configurations in ^{191}Pb - transfer reaction programme in the neutron-deficient Pb region

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A. Illana[1,2], J. Pakarinen[1,2], R. Raabe[3], M. Labiche[4], A.D. Briscoe[1,2], P.A. Butler[5], D.M. Cox[6], S.J. Freeman[7], L.P. Gaffney[5], T. Grahn[1,2], B.P. Kay[8], Th. Kröll[9], I.H. Lazarus[4], A. Montes Plaza[1,2], J. Ojala[1,2], B. Olaizola[10], R.D. Page[5], P. Papadakis[4], D.K. Sharp[7], T.L. Tang[8], N. Timofeyuk[11] and P. Van Duppen[3]

[1] *Department of Physics, University of Jyväskylä, Jyväskylä, Finland*
[2] *Helsinki Institute of Physics, University of Helsinki, Helsinki, Finland*
[3] *Instituut voor Kern- en Stralingsfyica, KU Leuven, Leuven, Belgium*
[4] *STFC Daresbury Laboratory, Daresbury, Warrington, United Kingdom*
[5] *Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom*
[6] *Department of Physics, Lund University, Lund, Sweden*
[7] *Schuster Laboratory, The University of Manchester, Manchester, United Kingdom*
[8] *Physics Division, Argonne National Laboratory, Argonne, Illinois, USA*
[9] *Institut für Kernphysik, Technische Universität Darmstadt, Germany*
[10] *ISOLDE, CERN, Switzerland*
[11] *Department of Physics, University of Surrey, Guildford, Uk*

Spokesperson: Andres Illana [andres.illana@cern.ch],
Janne Pakarinen [janne.pakarinen@cern.ch]
Riccardo Raabe [riccardo.raabe@kuleuven.be]
Marc Labiche [marc.labiche@stfc.ac.uk]
Contact person: Bruno Olaizola [bruno.olaizola@cern.ch]

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Abstract: The aim of this proposal is to commence a programme of measurements to investigate the underlying structure of intruder states in the neutron-deficient Pb region. The advent of HIE-ISOLDE and commissioning of the ISOLDE Solenoidal Spectrometer allows for unprecedented exploration of these nuclei employing transfer reactions in inverse kinematics. Nucleon transfer reactions are the only technique that allow for the unambiguous determination of the configurations of intruder states and they provide

complementary information that cannot be extracted from Coulomb excitation or fusion-evaporation reactions. We propose a preliminary study of the single-neutron adding (d,p) reaction on ^{190}Pb in inverse kinematic at an energy of 7.5 Mev/u. This measurement provides an ideal starting point for the desired programme of measurements as the ^{191}Pb nucleus is located in the transitional region, where the generalized seniority regime changes to the region characterized by intruding configurations. It will allow for the determination of the occupancy of the neutron orbitals below the N = 126 shell closure and additionally provides information on the robustness of shell closures and location of subshell gaps far from stability. The outcome of the proposed experiment will guide the selection of other reaction studies within the research program.

Requested shifts: 17 shifts (split into 1 runs over 1 years)
Installation: ISOLDE Solenoidal Spectrometer

1 Physics case

In the atomic nucleus, the interplay between single-particle motion, collectivity and pairing is seen as a rich tapestry of coexisting shapes and exotic excitations, often associated with so called intruder states. One region where this phenomenon is especially prevalent is in very neutron-deficient nuclei close to $Z = 82$ with a neutron number close to the mid-shell of $N = 104$ [1, 2]. Shape coexistence was first established in this region by laser spectroscopy experiments in the early 1970s. The initial discovery noted a sudden change in the nuclear charge radius between ^{187}Hg and ^{185}Hg [3]. Since then, a plethora of spectroscopic techniques have 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].

To obtain a greater understanding of the shape coexistence phenomena, it is important to determine the mechanism that drives nuclei into deformation. What are the underlying structures of nuclear states with different shapes? What are the roles of pairing, the proton-neutron interaction and configuration mixing in this phenomenon. Numerous experimental techniques, employing germanium detector arrays, electron spectrometers and particle detectors have been instrumental in advancing our understanding, however these devices can only provide partial information on the nuclear de-excitation process and the underlying structure of states populated or which orbitals were involved.

The one technique yet to be employed is transfer reactions. These can be used to determine a variety of nuclear properties, from basic level properties to structural characteristics such as single-particle, paring and cluster properties. Transfer reactions are an important spectroscopic tool because they exhibit an inherent selectivity connecting initial and final states in a single step accessing a particular degree of freedom. The reaction mechanism by which one or two nucleons are transferred is well understood, allowing a connection of experimental observables with the underlying physics. For example, single-nucleon transfer reactions have been invaluable in establishing and refining single-particle models in near-stable nuclei and with the advent of radioactive ion beams, the boundaries of feasible measurements has been widened by the use of measurements in inverse kinematics and state-the-art instruments.

The aim of this proposal is to initiate an experimental programme in which transfer reactions are employed to unambiguously determine the structure of intruder states in the neutron-deficient Pb region. The objectives of the research programme are:

1. Probe excited states in nuclei in the light Pb region using transfer reactions
2. Infer the properties of the intruder states in the neutron-deficient Pb region

The first point marks a new approach to studying the shape coexistence phenomenon in the region. It provides a direct measurement of the transferred angular momentum and enables the single-particle states involved in the transfer to be probed. Transfer measurements are the only method that can directly address the second objective, which currently remains unresolved. 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.

The occurrence of excited 0^+ states in this region is generally associated with multiproton excitations across the $Z = 82$ shell-closure [1, 8, 9, 10]. Figure 1 shows how the 0^+ states intrude downwards in energy towards the spherical ground state when approaching the neutron mid-shell at $N = 104$ [11]. Similar trends have be found for the $3/2^-$ and $13/2^+$ states in the odd-mass Pb isotopes. A partial level scheme of ^{191}Pb is shown on the right of Figure 1. Only one transition feeding the $3/2^-$ ground state [11] has been observed. Based on α-decay hindrance factors and a strong $E0$ component, it is assigned to the coupling of the $\nu 3\mathrm{p}_{3/2}$ orbital to the $\pi(2p\text{-}2h)$ intruder state in ^{190}Pb.

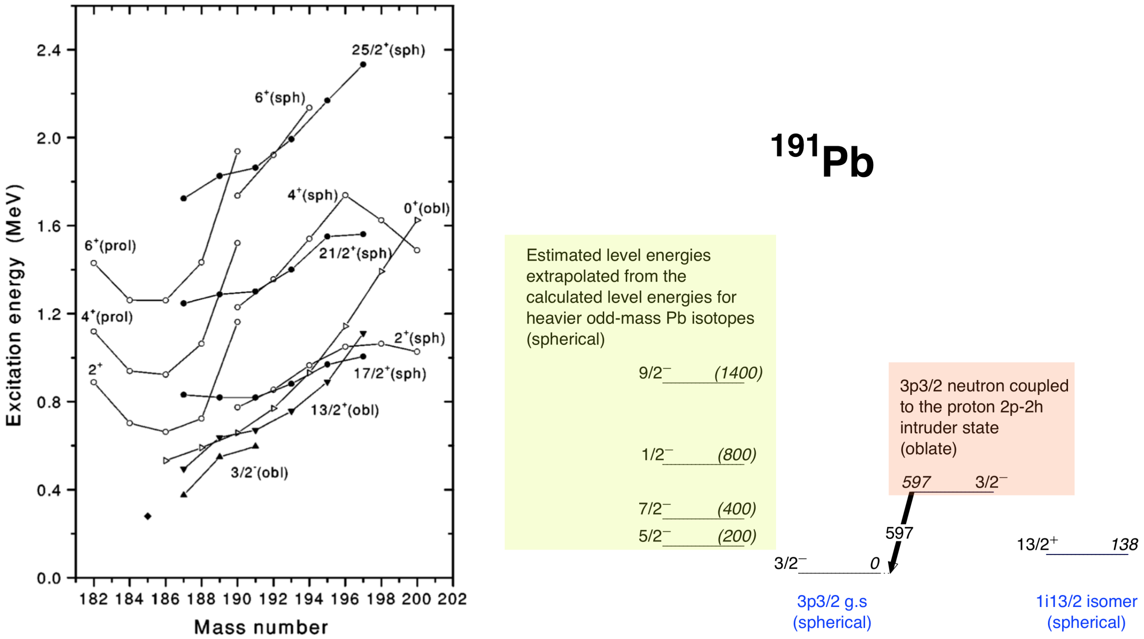

Figure 1: (Left) Level energy systematics of the neutron-deficient lead isotopes. Yrast states are indicated by circles, 0^+ states by empty right triangles, $13/2^+$ states by filled down triangles, and $3/2^-$ states by filled up triangles. Suggested deformation assignments to most of the states are indicated. The excitation energies are shown relative to the 0^+ ground state in the even-mass nuclei, and relative to the lowest $3/2^-$, $13/2^+$ states, for the negative- and positive-parity states, respectively, in the odd-mass nuclei [11]. (Right) Partial level scheme of ^{191}Pb. Estimated level energies are extrapolated from calculations by Ceneviva et al. [12].

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 [13, 14, 15, 16].

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 [17, 18] and Gogny [19] 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. However, contrary to that, it has also been shown that the low-lying prolate and oblate minima in the neutron-deficient Pb isotopes can be characterized by neutron correlations whereas the protons behave as spectators rather than playing an active role [20]. Regardless of the large amount of theoretical work conducted in the this region, limited efforts have focused on the odd-mass isotopes. The closest theoretical predictions were carried out by Ceneviva *et al.* [12], however they have only produced calculations down to ^{193}Pb with a note that they can not address mixing that is present in A<196 nuclei [12].

Different types of reactions will be used to address the objectives of the physics programme. A good starting point are single-neutron transfer reactions, specifically the (d,p) reaction which has been performed in inverse kinematics numerous times before. Besides the selectivity related to the single-particle structure of the populated states, phase-space considerations dictate that this reaction will preferentially populate low spin-states because of the limited amount of transferred angular momentum. Hence, on odd-mass Pb isotopes we expect states that are connected to the low-spin $3/2^-$ ground state to be populated much more effectively than the isomeric $13/2^+$ state.

Recent theoretical efforts have been made to link the phenomenon of shape coexistence to changes in the single-particle orbits (called "shell evolution") due to nuclear forces. Changes in shell structure across isotopic chains have long been attributed to effects of the tensor interaction and how spherical single-particle energies are shifted as protons or neutrons occupy certain orbits [21]. In the lead region, neutron particle-hole excitations from the $1h_{9/2}$ orbit to the $1i_{13/2}$ orbit cause a reduction in the proton spin-orbit splitting, implying a reduction of the $1h_{11/2}$ - $1h_{9/2}$ splitting [22]. This is known as "type II shell evolution". Due to type II shell evolution, the single-particle energies can be re-arranged with reduced spin-orbit interaction. This implies weaker resistance against deformation, and a strongly deformed local minimum may occur. Key to aiding the understanding of this phenomenon is accurate knowledge of the occupancies of valence orbitals. Transfer reactions have been used numerous times to ascertain this information and with the high beam energies available at HIE-ISOLDE, we are now able to probe this information in the neutron-deficient Pb region. This has been best demonstrated in the very successful study of ^{207}Hg employing ISS at HIE-ISOLDE [23].

2 Experimental details

We propose to measure single-neutron transfer in inverse kinematics to probe the single-particle structure in neutron-deficient ^{191}Pb, in the vicinity of the $N = 104$ mid-shell. The proposed measurement will make use of the ISOLDE Solenoidal Spectrometer to momentum analyze the outgoing protons from the ^{190}Pb(d,p) reaction at 7.5 MeV/u.

The $3/2^-$ ground state of ^{191}Pb is found to be spherical in charge-radii measurements [24]. It is connected to the excited $3/2^-$ state at 597 keV, which is considered as the coupling of the $3p_{3/2}$ odd-neutron to the excited proton $2p$-$2h$ intruder 0^+ state at 658 keV in ^{190}Pb [11] (see Figure 1). These intruder states have been associated with an oblate shape. **The aim of the proposed experiment is to investigate the low-lying negative parity states and the population of the oblate $3/2^-$ intruder state at 597 keV in ^{191}Pb via one-neutron transfer.**

There are several advantages of utilising ISS over Miniball+T-REX (or similar) for the proposed case. The detector efficiency is larger, requiring only known geometrical-efficiency. As a result, thin targets can be employed leading to good Q-value resolution without the negative effects of kinematic compression. Consequently, γ-ray detection is not needed to identify populated states. More importantly, the T-REX type charged-particle array does not have sufficient angular resolution for spectroscopy of such heavy nuclei in inverse kinematics. In addition, the large δ-electron flux which strongly depends on projectile Z hampers the performance.

The post-accelerated beam energies at HIE-ISOLDE allow a measurement well-suited for transfer reactions, both in terms of cross sections and characteristic angular distributions. At a beam energy of 7.5 MeV/u, the (d,p) reaction is well matched for low-ℓ transfers owing to the reaction Q-value and momentum matching conditions. These are demonstrated in Figure 2, where the proton angular distributions as a function of centre of mass angle for $\ell = 1$, 3, 5 and 6 for the (d,p) reaction at 7.5 MeV/u are shown. The calculations were carried out using the distorted wave Born approximation with the Ptolemy code [27]. Typical bound-state form factors were used along with the global-optical model parameters of An & Cai for deuterons [28] and Koning & Delaroche for protons [29] to describe the distorting potentials. A simulated proton energy spectrum for calculated ℓ transfers is also shown in Figure 2 for completeness. The extracted energy resolution is approximately 120 keV.

Protons emitted in forward centre-of-mass angles are emitted in backwards angles in the laboratory frame relative to the incident beam direction. The new silicon array will be placed upstream of the target inside the solenoid at a distance of 12 cm from the target, covering a range in z of -62 cm to -12 cm. Figure 3 shows the proposed experimental setup within the solenoidal spectrometer. With the solenoid field set at 2.5 T, proton yields will be measured over an angular range of $10^\circ \lesssim \theta_{cm} \lesssim 40^\circ$ for states below 4 MeV. The angular range of the silicon array covers the first maxima of the angular distributions for $\ell = 1$ and 3 transfers. Spectroscopic factors are best extracted from the peaks of the angular distributions where the assumptions implicit in DWBA are most valid. In this regime, the calculated distributions are shown to be distinct.

The targets used in the measurement will be deuterated polyethylene of nominal thickness 100 μg/cm^2. These targets have been used extensively in past HELIOS experiments

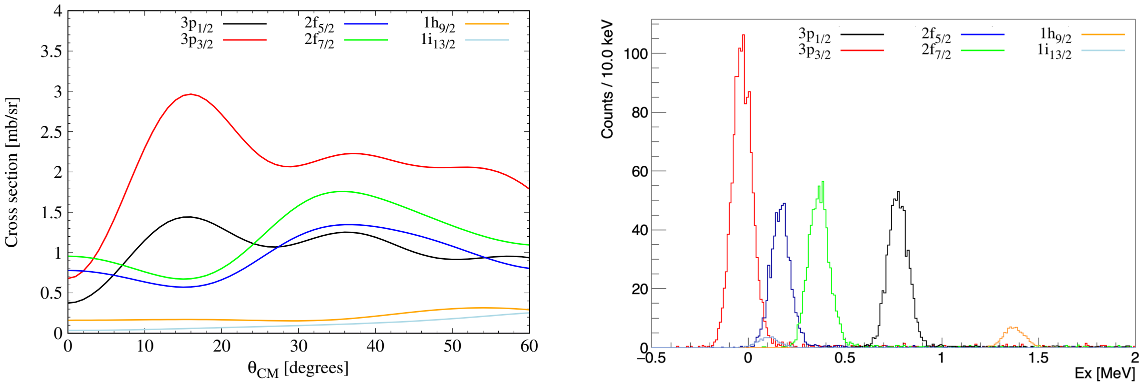

Figure 2: (Left) Proton angular distributions for the ^{190}Pb(d,p)^{191}Pb reaction at 7.5 MeV/u obtained using the Ptolemy code. (Right) Simulated proton energy spectrum for the proposed reaction. In this case, a conservative beam emittance, beam energy spread, and DSSD intrinsic resolution have been considered.

and are known to degrade under bombardment with medium mass beams [30], as it was observed during the IS631 experiment with a high intensity ^{206}Hg beam [23]. Potential target degradation can be evaluated by measuring elastically scattered deuterons on an annular silicon detector positioned at z = 20 cm.

3 Beam time request

Neutron-deficient lead beams have previously been produced at ISOLDE using a UC$_x$ target. The ^{190}Pb beam has been previously produced and post-accelerated at ISOLDE in the past. The most recent case was during the IS494 experiment at Miniball. During this experiment, the beam intensity was up to 2×10^6 pps with 3% of beam transmission and 86% of the beam purity [31, 32]. The only contaminant was the isobaric contamination of ^{190}Tl. For the current proposal, a beam intensity of ∼1×10^6 ions per second impinging on the CD$_2$ target and a ∼5% transmission efficiency through HIE-ISOLDE are assumed. Higher beam purity can be achieved if VADLIS is used [33]. Owing to the isobaric Tl contamination of Pb beams, we require 3 extra shifts for laser on/off data to evaluate the influence of the isobaric Tl isotopic contamination. In addition, a smooth background of protons from fusion evaporation reactions on the carbon in the target will be present on the array. Calculations using the PACE code suggest that the number of protons, which increases linearly along the length of the array, from fusion evaporation events is similar to previous measurements at ISS with a ^{206}Hg beam [23]. As a result, we propose an additional measurement of the beam on a ^{12}C foil to aid in ascertaining the levels of fusion evaporation protons and subsequent removal of this background from the (d,p) reaction spectra.

The estimated proton rates are based on the assumption that the angular coverage

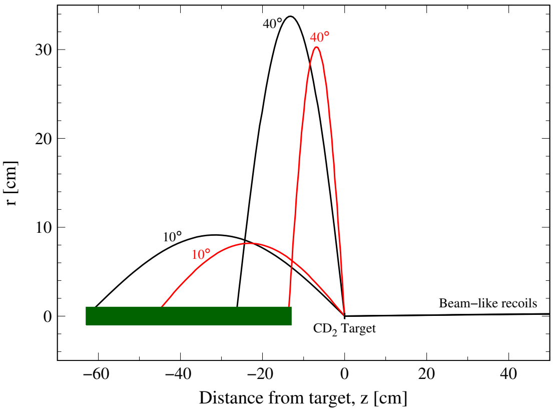

Figure 3: Proposed experimental setup within the ISS at 2.5 T. Indicated distances are relative to the target position. The black line represents protons from the population of the ground state in the (d,p) reaction, whilst the red lines correspond to protons from population of a theoretical state at an excitation of 4 MeV in the residual nucleus. All angles shown are given in the centre of mass frame.

is $10^\circ \lesssim \theta_{cm} \lesssim 40^\circ$. Further assumptions made are a beam intensity of $\sim 1\times10^6$ pps impinging on CD$_2$ targets with a thickness of $\sim$100 μg/cm^2. Cross sections were calculated using the DWBA code Ptolemy as discussed above. Assuming a conservative estimate of spectroscopic factor of 0.3 [34], and four days (12 shifts) of beam on target, the expected yields of protons for transfer to states of $1/2^-$, $3/2^-$, $5/2^-$, $7/2^-$, $9/2^-$ and $13/2^+$ will be $\sim$803, 1539, 689, 883, 111 and 60 counts, respectively. These statistics will allow for determining angular distributions for outgoing protons for ℓ <5 transfers. In particular, as the level energies of the so-far unobserved states are crude estimates, enough statistics will be needed to distinguish between potentially overlapping level energies within the given ISS energy resolution. It is clear that yields for ℓ >5 transfers are negligibly small and will not interfere the measurement of the low-ℓ transfers. Proton yields resulting from the population of the excited $3/2^-$ state are difficult to assess and have not been addressed here. It should be however noted that the non-observation of this state would be an important finding as it could confirm whether the state is coupled to the proton $2p$-$2h$ excitation.

4 Summary of requested shifts

In total 17 shifts of beam time are requested to perform the (d,p) reaction on ^{190}Pb at 7.5 MeV/u. 12 shifts of these are for obtaining data about outgoing protons, 3 shifts will be dedicated to study the influence of the isobaric contamination employing the laser On/Off technique, 1 shift will be used for optimisation and calibration of the setup, and 1 shift to record background from fusion-evaporation events of the beam on a carbon foil.

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Appendix

DESCRIPTION OF THE PROPOSED EXPERIMENT

The experimental setup comprises: The ISOLDE Solenoidal Spectrometer (ISS).

Part of the	Availability	Design and manufacturing
(if relevant, name fixed ISOLDE installation: Miniball + only CD, Miniball + T-REX)	☐ Existing	☐ To be used without any modification
ISOLDESolenoidal Spectrometer	☒ 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			
Thermodynamic and fluidic			
Pressure			
Vacuum			
Temperature	4 K		
Heat transfer			
Thermal properties of materials			
Cryogenic fluid	LHe, ~1650 l, LN_2, ~200 l, 1.0 Bar		
Electrical and electromagnetic			
Electricity	0V, 300A		
Static electricity			
Magnetic field	2.5T		
Batteries			
Capacitors			
Ionizing radiation			
Target material	Deuterated Polyethylene [CD_2]		
Beam particle type	^{190}Pb		
Beam intensity	1×10^6 pps at ISS		
Beam energy	7.5 MeV/u		
Cooling liquids			

Gases			
Calibration sources:	☒		
• Open source	☒ (α calibration sources)		
• Sealed source			
• Isotope			
• Activity			
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			
Harmful			
CMR (carcinogens, mutagens and substances toxic to reproduction)			
Corrosive			
Irritant			
Flammable			
Oxidizing			
Explosiveness			
Asphyxiant	Helium		
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			

Hazard identification:

Average electrical power requirements (excluding fixed ISOLDE-installation mentioned above): 5 kW