EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

Study of shell evolution around the doubly magic ^{208}Pb via a multinucleon transfer reaction with an unstable beam

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Abstract:

This proposal aims at the study of the neutron-rich region around the doubly-magic nucleus ^{208}Pb populated via a multinucleon transfer reaction. An unstable ^{94}Rb beam will be delivered by HIE-ISOLDE at 5.5 MeV·u onto a ^{208}Pb 13.0 mg/cm^2 target. The γ rays will be recorded by the MINIBALL γ-ray spectrometer. The aim of the experiment is twofold: i) firstly it will represent the proof of principle that multinucleon transfer reactions with neutron-rich unstable beams is efficient to populate neutron-rich heavy binary partners and represents a competitive method to cold fragmentation ii) secondly we aim at populating medium- to high-spin states in ^{212,214}Pb and ^{208,210}Hg to elucidate the existence of the 16^+ isomer in the lead isotopes and at the same time to disentangle the puzzling case of a very low energy 3^- state in ^{210}Hg not described by any nuclear model. The experimental results will be compared with large-scale shell-model calculations using the realistic Kuo-Herling interaction that involves a large valence space. This comparison will help to elucidate the role of effective three-body forces in this region and the possible structure change in ^{210}Hg.

Requested shifts: 27 shifts, (split into 1 run over 1 year)
Installation: [MINIBALL]

1 Scientific motivation

The shell model is nowadays able to provide a comprehensive view of the atomic nucleus. It is a many-body theoretical framework, successful in explaining various features of the structure of nuclei, based on the definition of a restricted valence space where a suitable Hamiltonian can be diagonalized. For example the shell model has been capable to explain the magic numbers, as a key feature in finite fermionic systems, as well as its evolution when going away from the stability line. In the last years, theoretical predictions and experimental results have indicated that magic numbers can change depending on the N/Z ratio, thus implying a more local applicability [1, 2, 3]. For instance, the tensor component of the residual interaction is expected to strongly depend on the specific orbits being filled and acts in all nuclear regions, not necessarily close to the drip-lines [4, 5].
The regions around double-shell closures are a benchmark for the study of nuclear structure since they are a direct source of information on the nucleon-nucleon effective interaction in nuclei. These regions have been mostly studied for light and medium-mass nuclei, using fission, deep-inelastic and transfer reactions. However, the region around the heaviest doubly-magic nucleus known in the whole Segré chart, i.e. the ^{208}Pb, is particularly difficult to reach experimentally and has not been thoroughly explored so far, due to its high mass and neutron richness.
As a consequence, spectroscopic information on neutron-rich lead and nearby isotopes are rather scarce. Pioneering work in this area by using multinucleon transfer reaction with stable beams has been done by Broda and collaborators [6, 7], where using state-of-the-art Compton suppressed large γ-ray arrays they managed to measure high-spin yrast states in many different isotopes. However, the most neutron-rich isotope that they

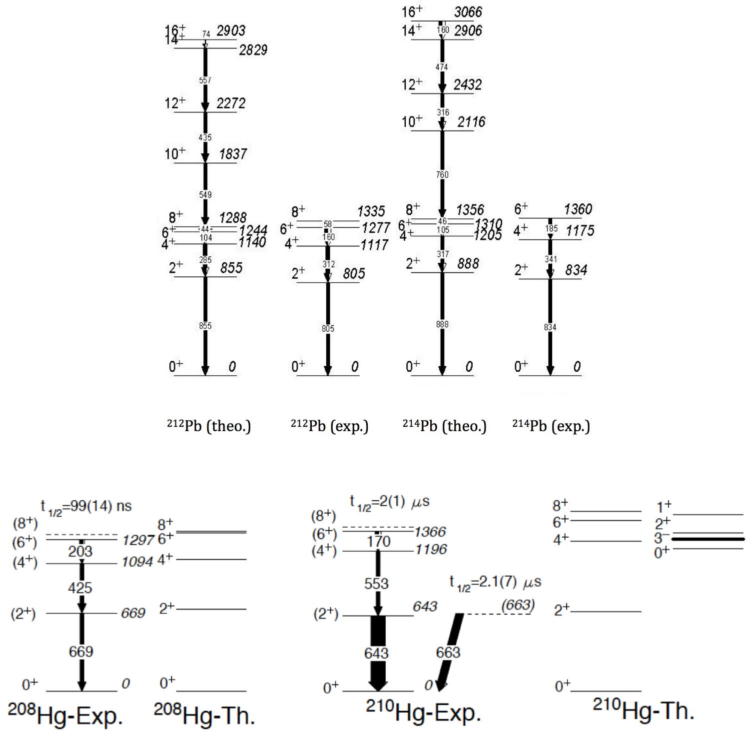

Figure 1: Experimental and theoretical level schemes of ^{212,214}Pb, taken from Ref. [13] (top), and ^{208,210}Hg, taken from Refs. [12, 14] (bottom). In the theoretical lead level schemes one can appreciate the 16^{+} isomer predicted by state-of-the-art shell-model calculations, not observed experimentally, on the other hand the ^{210}Hg shows a level at 663 keV that has been tentatively interpreted as a 3^{-} .

were able to populate was not so far from the stability (A = 211 [7]). An alternative approach to populate this region is offered by cold fragmentation of lead or uranium, where one takes advantage of the long-lived high-spin isomers populated in the reaction. Using this technique pioneering work was done by Pfützner and collaborators [8], where with just two clover detectors at the focal plane of the Fragment Separator (FRS) [9] they succeeded to measured the isomeric decay of ^{212}Pb. Very recently, progress has been made in this direction by using a more efficient γ-ray array such as RISING [10]. In Ref. [11] a large number of heavy neutron-rich nuclei in the Ta-Hg region was measured by using the fragmentation of ^{208}Pb. Meanwhile with the cold fragmentation of ^{238}U it was possible to go further away from the stability and populate nuclei in the Bi-Hg region as for example up to ^{216}Pb and ^{208,210}Hg [12, 13, 14].
Figure 1 shows the level schemes for ^{212,214}Pb and ^{208,210}Hg deduced from isomeric decay data and populated via cold fragmentation of ^{238}U. These neutron-rich lead isotopes have taught us how the description of the 8^{+} seniority $\nu g_{9/2}$ isomer in a shell-model framework requires the introduction of effective three-body interactions and two-body transition operators, questioning the common paradigm of one-body transition operators with constant effective charges to account for the truncated model space. This work was thus a first hint of the importance of properly treating the effective many-body

terms and it is a benchmark for future shell-model calculations. However one can see that the 16^+ isomer predicted by state-of-the-art shell-model calculations was not observed experimentally. The existence or not of this isomer, that could be elucidated in this experiment, is directly related to the appearance of higher order 16^+ seniority isomers close in energy. More experimental data is needed in order to improve realistic nucleon-nucleon interactions such as the Kuo-Herling interaction [15]. Furthermore, the cases of ^{208,210}Hg isotopes makes the region even more attractive. The scheme of ^{210}Hg presents two isomeric states: the 8^+ isomer expected from the seniority scheme in the $\nu g_{9/2}$ shell and a second one at low spin and low excitation energy. The decay strength of the 8^+ isomer confirms the need of effective three-body forces as in the case of neutron-rich lead isotopes. However, the other unexpected low-lying isomer has been tentatively assigned as a 3^- state, although this is in contrast with theoretical expectations. If this was the case, this state at 663 keV will correspond to the lowest known 3^- state in the whole Segré chart up to mass A=200. In addition, what is even more puzzling is that none theoretical calculation is able to predict for this nucleus a 3^- state at the measured energy. This experiment will yield light about this unexpected transition and its possible 3^- character.

Multi-nucleon transfer reactions by using neutron-rich unstable beams may be a suitable mechanism to reach the region below ^{208}Pb. To understand how one can try to approach this neutron-rich heavy region, we have to keep in mind that transfer processes are governed by form factors and optimum Q-value considerations. With neutron deficient projectiles on heavy targets only proton-stripping and neutron pick-up channels, for the projectiles, are available, while with neutron-rich projectiles also proton pick-up and neutron-stripping channels, for the projectiles, open up [16]. This corresponds, for the heavy partner, to the population in the south-east direction, leading to the neutron-rich heavy region. Due to the characteristic behaviour of the binding energy, the process is essentially governed by the lighter partner of the reaction. In Fig. 2 is shown an example of GRAZING calculations [16] for the collision of different Rb beams on ^{208}Pb target. The figure indicates the change of population pattern from ^{76}Rb (neutron deficient) to ^{94}Rb (neutron rich) isotopes. The calculated cross section is already corrected by neutron evaporation, by taking into account the average excitation energies of the binary products. This limits the final yield of neutron-rich nuclei very far from stability. Nevertheless, the secondary processes may strongly affect the heavy partner, i.e. the competitive processes of evaporation and/or (transfer induced) fission might shift the final yield to lower mass values. Presently ongoing studies try to get quantitative information on the final yield distributions and compare them with theoretical predictions. The available data about the survival of the heavy neutron-rich fragments are rather scarce. One of the few examples is the ^{58}Ni+^{208}Pb measurement [17] where it has been shown how the experimental values of the cross sections for the heavy partner can be quite well described by the same theory used to compare with the distributions of the light partner. Even if ones takes into account the possible effect of the secondary process, the large primary cross sections with radioactive beams, make this mechanism a competitive tool for the production of heavy-neutron rich nuclei around ^{208}Pb.
We therefore propose to perform a multinucleon transfer reaction with a neutron-rich

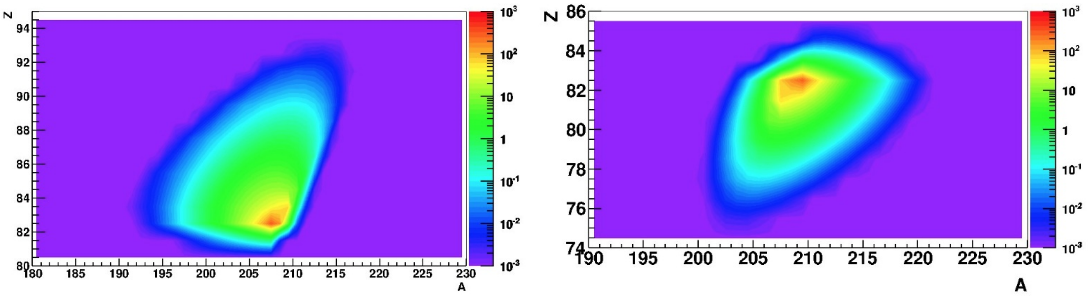

Figure 2: GRAZING code calculations for the production cross sections of multinucleon transfer reactions as a function of transferred protons and neutrons. The results refer to the collision of Rb isotopes on ^{208}Pb at energies about 20% above the nominal Coulomb barrier. The frames correspond to the heavy binary partner in the reactions: ^{76}Rb+^{208}Pb (left) and ^{94}Rb+^{208}Pb (right).

unstable beam of ^{94}Rb produced and accelerated by HIE-ISOLDE at 5.5 MeV·u and a stable ^{208}Pb target to populate medium- to high-spin states in ^{212,214}Pb and ^{208,210}Hg. The γ-γ- time coincidence data will help to build up more complete level schemes beyond the known isomers and measure the lifetimes of possible new isomeric states. In addition, we expect to populate many other nuclei such as Bi (one proton with respect to lead) and Tl (one proton hole with respect to lead). These additional information will improve the effective single particle energies knowledge in the lead region.

2 Experimental method

In the proposed experiment, excited states in ^{212,214}Pb and ^{208,210}Hg will be populated via a multinucleon transfer reaction, where a beam of ^{94}Rb at 5.5 MeV·u will impinge on a 13.0 mg/cm^2 ^{208}Pb target. The thickness of the target has been calculated in order to allow the beam pass throughout the target, that it will be subsequently stopped in a properly shielded beam dump far from MINIBALL. The reactions will happen up to a thickness of around 4 mg/cm^2, after this the beam energy will be below the nominal Coulomb barrier. Thus, for the subsequent rate calculations we will consider 4 mg/cm^2. A production yield of ^{94}Rb as high as 2×10^8 at/μC with a 10% contamination from the isobaric Sr isotope has been measured in ISOLDE using an UC$_\chi$ target [18]. The ^{94}Rb isotope will be surface ionized, and post-accelerated to 5.5 MeV·u using HIE-ISOLDE and delivered to the MINIBALL target position. Assuming a transmission efficiency for post-acceleration of 5%, and an average proton current of 1.5 μA, a ^{94}Rb beam intensity of the order of 1.5·10^7 pps is expected at MINIBALL. The beam will be pulsed in 1.2 s cycles and slow extraction will be requested in order to reduce instantaneous deadtime. With the new 9-gap amplifier a 1.5 ms pulse length should be achieved.
The experimental setup will consists just on the MINIBALL [19] γ-ray spectrometer. Since typical stopping times are around 2 ps most of the γ rays will be emitted at rest and therefore no Doppler correction will be performed. The selection of the reaction channel will rely on the previously known γ rays that will be used to gate and select the

Table 1: γ-γ coincidence events for each of the isotopes of interest after 9 days of experiment. We have considered a target thickness of 4.0 mg/cm^2 and a γ efficiency of 6.0%, for 0.8 MeV γ rays.

Isotope	$\sigma_{GRAZING}$ (mb)	γ-γ events
^{212}Pb	8.6	$4.3{\cdot}10^3$
^{214}Pb	1.1	$5.4{\cdot}10^2$
^{208}Hg	3.1	$1.4{\cdot}10^3$
^{210}Hg	0.9	$5.4{\cdot}10^2$

nucleus of interest. The possible background coming from radioactivity in the reaction chamber, due to scattering of the beam in the target will be subtracted using a procedure that relies on the timing relative to the pulsed beam. This method has be shown to properly work in Ref. [20]. The 10% contamination of the ^{94}Rb by the isobaric Sr isotope does not represent a problem for this experiment and it will contribute to the final yield of the isotopes of interest.
The γ-γ-time coincidence data will be collected with a trigger, requiring two or more γ rays to be in coincidence in MINIBALL for the in-beam as well as for the out-of-beam events. Considering a primary beam intensity of 1.5 μA resulting in $1.5{\times}10^7$ pps, a target thickness of 4.0 mg/cm^2 and a γ efficiency of 6.0%, for 0.8 MeV γ rays [21] (the γ rays of interest are expected to be below 800 keV) we assume the following counting rates, see Table 1. These yields, might be reduced up to a factor 5, according to our estimates, due to the secondary processes.

Based on the previous calculated rates we request 9 days of beam time

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Appendix

DESCRIPTION OF THE PROPOSED EXPERIMENT

The experimental setup comprises:

Part of the	Availability	Design and manufacturing
MINIBALL	☒ Existing	☒ To be used without any modification

HAZARDS GENERATED BY THE EXPERIMENT

Hazards named in the document relevant for the fixed MINIBALL installation.