EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

IS572: Study of shell evolution around the doubly magic ^{208}Pb via a multinucleon transfer reaction with an unstable beam

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J.J. Valiente-Dobón[1], S. Szilner[2], A. Illana[1], P. Čolović[2], G. de Angelis[1], G. Benzoni[3], M.J.G. Borge[4], A. Boso[5,6], S. Ceruti[3,7], L. Corradi[1], J.G. Cubiss[8], E. Fioretto[1], L.P. Gaffney[9], F. Galtarossa[1], M.L. Jurado-Gomez[10], Th. Kröll[11], T. Marchi[1,7], R. Menegazzo[5,6], D. Mengoni[5,6], T. Mijatović[2], D.R. Napoli[1], Zs. Podolyak[12], F. Recchia[5,6], D. Testov[5,6], N. Vukman[2]

[1] *INFN, Laboratori Nazionali di Legnaro, Legnaro, Italy.* [2] *Ruđer Bošković Institute, Zagreb, Croatia.* [3] *INFN, Sezione di Milano, Milano, Italy.* [4] *Instituto de Estructura de la Materia CSIC, Madrid, Spain.* [5] *Dipartimento di Fisica e Astronomia, Università degli Studi di Padova, Padova, Italy.* [6] *INFN, Sezione di Padova, Padova, Italy.* [7] *KU Leuven, Instituut voor Kern-en Stralingsfysica, Leuven, Belgium.* [8] *Department of Physics, University of York, York, United Kingdom.* [9] *ISOLDE, CERN, Switzerland.* [10] *Instituto de Física Corpuscular CSIC, Valencia, Spain.* [11] *Institut für Kernphysik, Technische Universität Darmstadt, Darmstadt, Germany.* [12] *Department of Physics, University of Surrey, Guildford, United Kingdom.*

Spokesperson: J.J. Valiente Dobón [Javier.Valiente@lnl.infn.it]
Co-Spokesperson: S. Szilner [Suzana.Szilner@irb.hr]
Contact person: J. Konki [Joonas.Konki@cern.ch]

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Abstract: Using the multinucleon transfer reactions with the heavy unstable beam for the first time we succesfully populated the nuclei of neutron-rich region in vicinity of doubly-magic nucleus ^{208}Pb. The ^{94}Rb beam was delivered by HIE-ISOLDE at 6.2 MeV·A onto a ^{208}Pb (1 and 13 mg/cm^2) targets. The γ-rays were recorded by the MINIBALL γ-ray spectrometer, and particles with a compact CD particle detector. The experiment was granted a 9 days beam-time, with expected current of $1.5{\cdot}10^7$ pps onto a target. It was carried out during the September 2017, and was not given 15 remaining shifts in 2018. The beam time in 2017 was partly successful due to the safety limits of the radiation in the experimental hall. When the experiment started the production of the primary beam and subsequent beam losses throughout the experimental hall caused a radiological risk to

personnel working in the hall during the beam-time. Consequently, the experiment had to be carried out lowering the current by the order of magnitude, thus reducing our allocated beam time for 120 hours. Despite the poor statistics, ongoing data analysis reveals the proof of principle that multinucleon transfer reaction with neutron-rich unstable beam is efficient mechanism to populate neutron-rich heavy binary partner. The preliminary results in terms of particle angular distribution and Pb nuclei excitation level schemes are presented.

Remaining shifts: 15 shifts
Installation: [MINIBALL + CD-only]

1 Physics case

The main aim of the experiment IS572 was to study the neutron-rich region around the doubly-magic nucleus ^{208}Pb populated via a multinucleon transfer reaction. We used ^{94}Rb beam delivered by HIE-ISOLDE at 6.2 MeV per nucleon and the ^{208}Pb (1 mg/cm^2 and 13 mg/cm^2) targets. The γ rays were recorded by the MINIBALL spectrometer, while the reaction fragments were detected in the CD silicon detector.
The aim of the experiment was twofold:

- to demonstrate that the multinucleon transfer (MNT) reactions with neutron-rich unstable beams is an efficient reaction mechanism for the production of the neutron-rich heavy binary partners and that this mechanism represents a competitive method to cold fragmentation

- to populate medium- and 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^- in ^{210}Hg not described by any nuclear model.

We plan to compare the experimental results with the reaction theories as well as with large-scale shell-model calculations using the realistic Kuo-Herling interaction that involves a large valence space. These comparisons will help

- to extract the cross section of the neutron-rich heavy binary partners and to identify the important degrees of freedom that influence the evolution of the reaction

- to elucidate the role of effective three-body forces in this region.

A detailed discussion of the motivation, the method and experimental set-up with all the references can be found in the original proposal [1].

2 Status Report

Nuclear reactions where few quanta - energy, angular momentum, and number of nucleons - are exchanged between projectile and target, provide an important tool to study the properties of nuclei close to their ground states. From the reaction mechanism point of view, the study of multinucleon transfer reactions provides an insight about which degrees of freedom have to be included in any model to describe the evolution of the heavy-ion reaction from the quasielastic to the deep inelastic regimes and to fusion. With the correct selection of mass asymmetry of the system and collision energy this exchange leads to the population of the moderately neutron-rich nuclei region of the nuclear chart which is difficult to reach and where challenging aspects in the behavior of the nuclear structure have been foreseen.
The experiment was carried out during the 9 days of beam-time at the XT01 line of HIE-ISOLDE, where the MINIBALL γ-ray detector was set-up. When the experiment started the production of the primary beam and subsequent beam losses throughout the experimental hall caused a radiological risk to personnel working in the hall during the beam-time. Due to the radiation protection rules, the expected current of $1.5{\cdot}10^7$ pps on target was reduced to 10-100 times lower intensity. Consequently, this shortened the effective beam-time for 120 hours and the expected statistics of experiment dramatically. Those remaining 15 shifts (120 hrs) were not allocated in 2018. Although it will be very difficult to get new spectroscopic data for the more neutron-rich Pb/Hg isotopes, we will be able to get the first measurements on cross sections for the ^{94}Rb+^{208}Pb reaction. The ongoing data analysis will provide better understanding of the excitation energy and angular momentum populated in reaction, as well as the underlying character of the strongly excited states.

2.1 Differential cross sections

The high-resolution MINIBALL spectrometer, coupled to a position sensitive silicon detector, allowed the identification of reaction products via their associated γ rays. By constructing the matrix of energy vs. scattering angle measured in the range of $\theta = 24^\circ$ - 63° a clear separation between the beam-like and target-like fragments was achieved. The selection of the beam-like and target-like fragments improves Doppler correction for the γ-rays emitted in flight, resulting in E_γ resolution of 1.2% at 1.5 MeV. The $E - \theta$ matrix of the CD fragment detector is displayed in Fig. 1. The calibration of the energy was performed by comparing the most energetic events with the Rutherford scattering (see lines in Fig. 1), while the position information was tuned by taking into account the Doppler correction.
From the same, $E - \theta$ matrix, we extracted angular distributions for quasi-elastic scattering of the detected Rb-like and Pb-like fragments, and combined them in a single distribution. We remind that we do not have charge and mass identification in the CD detector, thus the experimental distribution, especially around the grazing angle, is a sum of the elastic, inelastic and transfer differential cross sections. We know that at the most forward measured angles, this distribution is a pure Rutherford scattering. This fact was used to obtain the normalization factor. The distribution has been compared

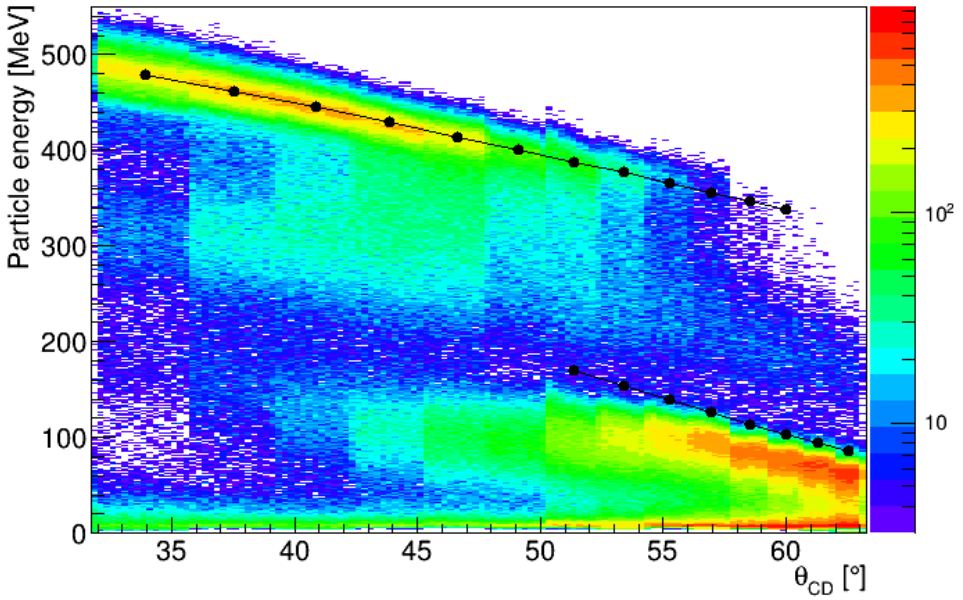

Figure 1: The $E - \Theta$ matrix of the CD detector for 1 mg/cm^2 target. Black curves correspond to the Rutherford cross sections for ^{94}Rb (top) and ^{208}Pb (bottom).

with the GRAZING calculated for the entrance channel mass partition, i.e. ^{94}Rb+^{208}Pb. The experimental and calculated distributions agree well at the forward angle, and at the quarter point, indicating that the geometry and sizes of the potential are quite good and well defined.
In a similar way we also extracted the angular distribution of the 3^- state in the ^{208}Pb, by taking into account Rb-like or Pb-like fragment in coincidence with the $3^- \rightarrow 0^+$ transition. This distribution will be compared with the distorted-wave Born approximation (DWBA) calculation, which treats more accurately octupole excitation, in the collaboration with the theoretical group at University of Torino.
Comparison of these distributions with the reaction models will provide, besides the normalization factor, also the interaction potential and will better define the degrees of freedom which are important in the reaction, like deformations, single particle levels, surface modes et alia.

2.2 Electromagnetic transitions

To better understand the character of the strongly populated states we compared the observed electromagnetic transitions of Pb isotopes in the ^{94}Rb+^{208}Pb measurement (1 mg/cm^2 target) with the transitions observed in the ^{40}Ar+^{208}Pb and ^{90}Zr+^{208}Pb reactions. These comparisons for ^{207}Pb, ^{208}Pb, and ^{209}Pb are displayed in Figs. 2, 3, and 4, respectively. The ^{40}Ar+^{208}Pb and ^{90}Zr+^{208}Pb reactions have been measured in LNL accelerator center by using the PRISMA spectrometer for the fragment identification coupled to the CLARA gamma-array, at energies close to the Coulomb barrier. Presented

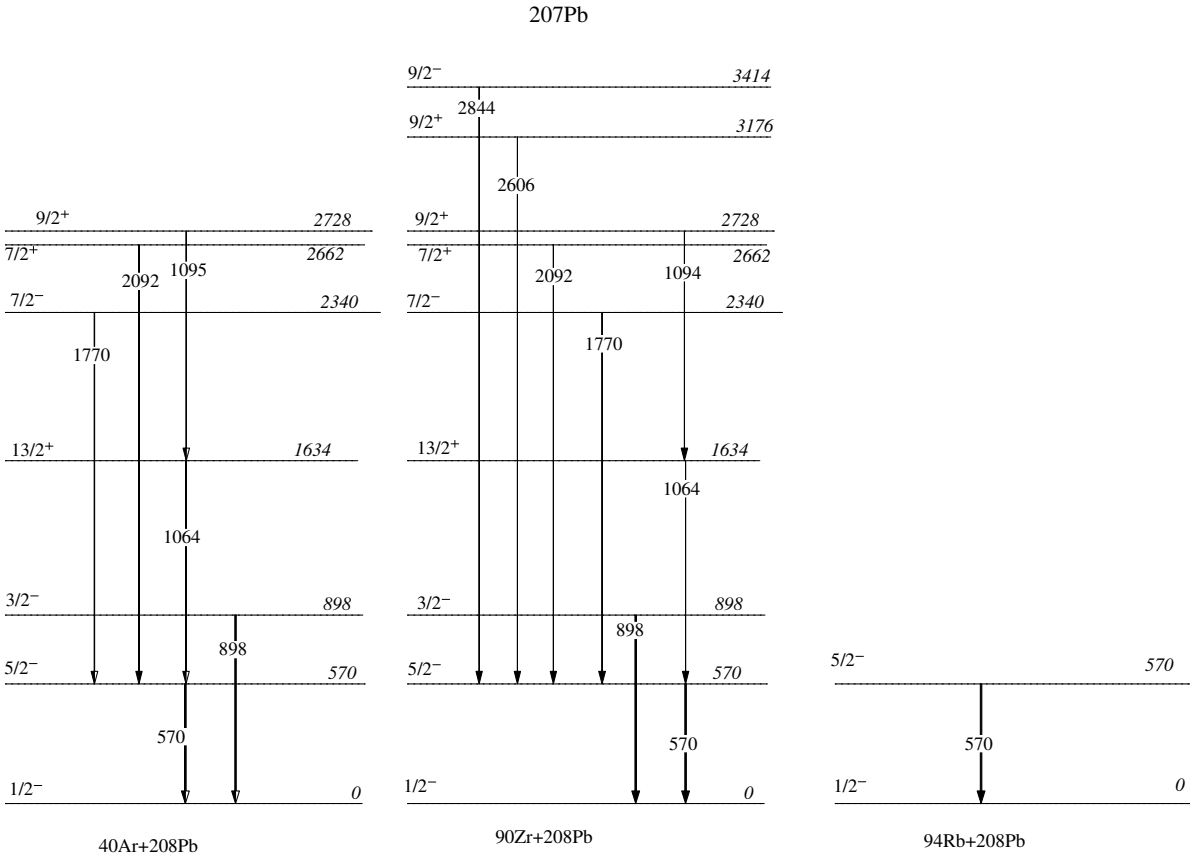

Figure 2: Level scheme of ^{207}Pb populated in the ^{40}Ar+^{208}Pb, ^{90}Zr+^{208}Pb, and ^{94}Rb+^{208}Pb ("thin target") reactions. Relative γ-ray intensities are indicated by the width of the arrows. Only γ transitions observed in our measurements are plotted.

level schemes are partial and were constructed from fragment-γ coincidences measured with the "thin" target (1 mg/cm^2).

As the same reaction mechanism is used to produce different Pb isotopes, we expect that the states of similar character will be populated. From the reaction model we know that the excitation and transfer processes are mediated by the well known single-particle form factors for the fermion degrees of freedom and by the collective form factors, for the vibrational modes. The same degrees of freedom should play a significant role in the distribution of the transfer strength over different states. In fact, in Figs. 2, 3, and 4 one observes a selective population of the specific states.

In ^{208}Pb, the strongest observed transition is the $3^- \rightarrow 0^+$, in all measured reactions. One has to keep in mind that the total statistics in these three reactions is quite different. In even-odd Pb isotopes we observed a strong excitation of the states of single-particle character. In ^{209}Pb, reached via neutron transfer, we observed a significant population of the $15/2^-$ state. The structure of this $15/2^-$ state matches, in a simple phenomenological description, a stretched configuration of the valence neutron coupled to the octupole excitation of the ^{208}Pb core.

The more rich level schemes are expected from the analysis of the "thick" 13 mg/cm^2 target where more statistics have been collected. This part of the measurement is still

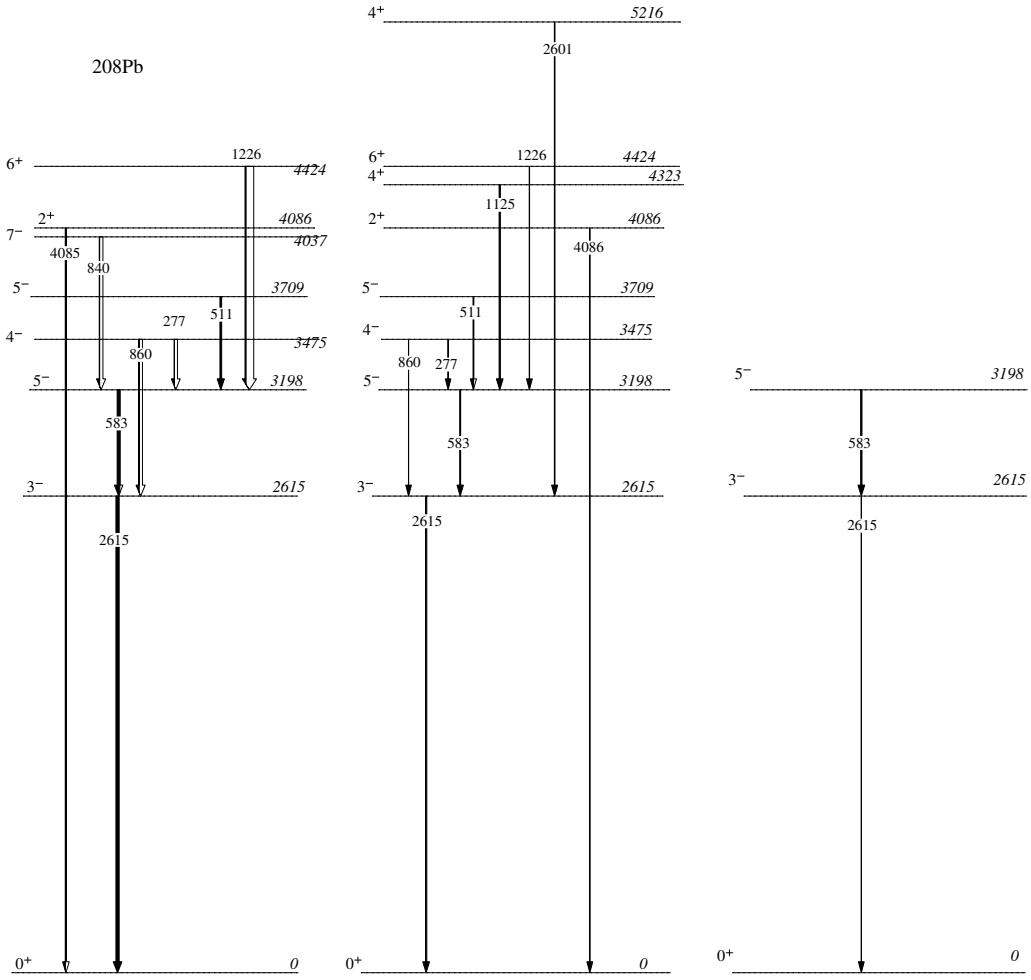

Figure 3: Level scheme of ^{208}Pb populated in the ^{40}Ar+^{208}Pb, ^{90}Zr+^{208}Pb, and ^{94}Rb+^{208}Pb ("thin target") reactions. Relative γ-ray intensities are indicated by the width of the arrows. Only γ transitions observed in our measurements are plotted.

under analysis. As an example, we observed in two-neutron transfer channel, ^{210}Pb, excitation up to 3.5 MeV with the strong selection of the yrast states, in particular we observed the $10^+ \rightarrow 8^+ \rightarrow 6^+ \rightarrow 4^+ \rightarrow 2^+ \rightarrow 0^+$ cascade.

3 Conclusion

We emphasize that the completion of this experiment will have a high impact on scientific community. Under the given experimental circumstances we demonstrated that the dominant flux of the multinucleon transfer reactions with unstable beam is indeed in the direction of neutron-rich heavy target nuclei, as predicted by the GRAZING code but never measured before. The experimental set-up, highly modular MINIBALL spectrometer coupled to position sensitive particle detector, allowed to successfully select

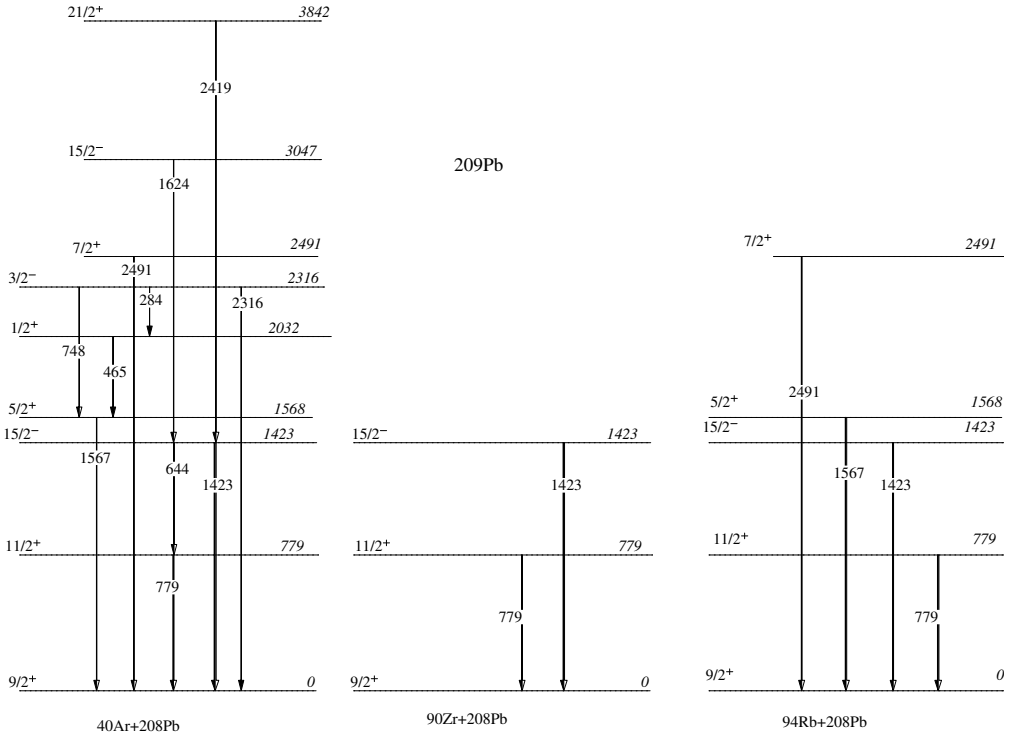

Figure 4: Level scheme of ^{209}Pb populated in the ^{40}Ar+^{208}Pb, ^{90}Zr+^{208}Pb, and ^{94}Rb+^{208}Pb ("thin target") reactions. Relative γ-ray intensities are indicated by the width of the arrows. Only γ transitions observed in our measurements are plotted.

multinucleon transfer channels and their associated gamma-rays. Our preliminary results constitute a proof of principle of new technique, involving various and new scientific groups working at ISOLDE facility.

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Appendix

DESCRIPTION OF THE PROPOSED EXPERIMENT

The experimental setup comprises:

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

HAZARDS GENERATED BY THE EXPERIMENT

Hazards named in the document relevant for the fixed MINIBALL + only CD installation.