TE 67/2018: From seniority regime to collective behavior in Po isotopes / SEREVIO

1. Project title: From seniority regime to collective behavior in Po isotopes

2. Project duration: 24 months, from 02.05.2018 until 30.04.2020

3. Project executive summary: The present project aims at investigating the transition from the seniority regime to the collective motion in the case of Po isotopes. The behavior of the transition probabilities in the two regions is completely opposite and therefore, represents a clear signature which allows one to distinguish between the two types of structure and to identify the microscopic structure of different excited states. In order to deduce the transition probabilities in atomic nuclei, one needs the lifetime of the excited states as a principal ingredient. These observables are very difficult to measure since usually the levels have lifetimes situated in the range below nanosecond. To perform such sensitive investigations, we plan to use the in-beam fast-timing method developed in our laboratory and a combination of HPGe and LaBr3:Ce detectors available in IFIN-HH. The method allows for lifetime measurements in a broad range and is perfectly suited for investigations in the region of Po isotopes. This ambitious task represents the goal of the present project and will allow revealing the nature of the structure in exotic nuclei. In addition, it will allow testing of different state-of-the-art theoretical models employed in the last years to interpret the structure of Po nuclei. These models are giving contradictory predictions and it is an open question which one, if any, truly describes the experimental situation in this region. All the new data determined from the experiment will be compiled and prepared to be included in the largest database of nuclear physics, the Evaluated Nuclear Structure Data File. Providing data in this format has the advantage to deliver the best values for different properties in nuclear structure.

4. Obtained results:

2018: The activities devoted to the present contract are related to experimental nuclear structure investigations. The project proposes the study of three Po isotopes populated in different nuclear reactions and the measurements of lifetimes for several excited states. In IFIN-HH, the procedure to perform an experiment at the Tandem laboratory requires that a written proposal is handed in and a presentation is given in front of a Program Advisory Committee (PAC) which decides about the quality and feasibility of the scientific case. Therefore, in a first step, our goal was to write a proposal presenting the main purposes and objectives of our investigations. We have shown that these measurements are very important for our understanding of the seniority scheme and of the collective behavior. Such conduct can be inferred from spectroscopic data like lifetime measurements and their corresponding transition probabilities. These data are lacking at the moment in many neutron-deficient Po isotopes. This study is very well suited for being performed at the Tandem laboratory of IFIN-HH which is equipped with an array which contains a combination of detectors that allow lifetime measurements in a broad range. Furthermore, the present theoretical predictions are in severe disagreement among themselves, and an experimental measurement will help clarifying the situation while pointing for further refinements of the models. This task was successfully achieved and the PAC acknowledged the importance of this study by offering the recommendation to perform the experiment. Therefore, during the year 2018 we concentrated our attention in studying the nucleus ^{206}Po, and the obtained results are detailed below.

The experiment has been performed at the 9 MV Tandem accelerator of IFIN-HH using the ROSPHERE spectrometer composed of 14 HPGe and 11 $LaBr_3$:Ce detectors. This mixed configuration allows for lifetime measurements using the fast timing method. The technique uses the $LaBr_3$:Ce detectors as electronic chronometers by making use of their very fast response in time. The nucleus ^{206}Po was produced in the beta-decay of ^{206}At ($T_{1/2}$~30 min), which in turn was created by using the ^{197}Au(^{13}C,4nγ)^{206}At reaction at an incident energy of E=62 MeV. When compared to the population through a usual fusion-evaporation reaction, our choice has the advantage of a cleaner spectrum which will facilitate the extraction of the lifetimes even without gating on the HPGe detectors and furthermore will enhance the population of different states which are not expected to be populated in the fusion-evaporation reaction. A 9.87 mg/cm^2 ^{197}Au target was used and a current of about 10 nA was impinged on the target for activation purposes. The activation and decay periods were chosen to be equal and each one was set to be about 1h long. The spectra collected in this experiment can be seen in Fig.1 for both types of detectors we have used. In addition, a gated spectrum on the first 2^+ transition is also presented in the last panel for the $LaBr_3$:Ce detectors.

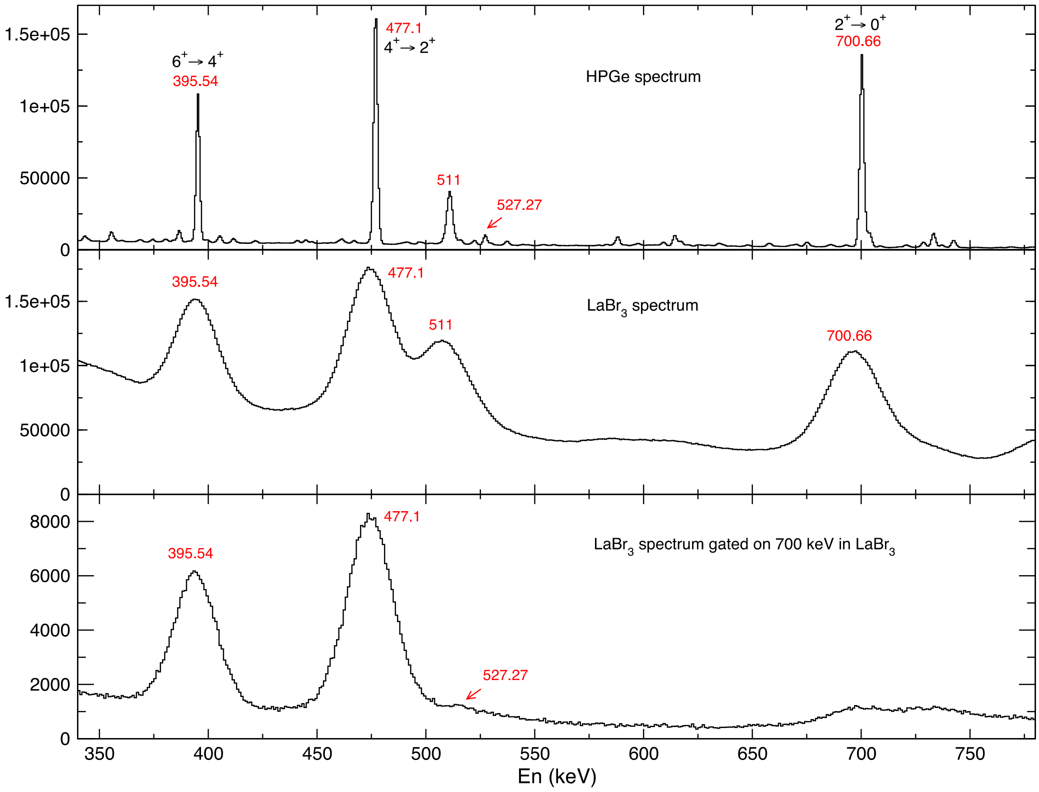

Fig.1: HPGe and $LaBr_3$:Ce spectra of ^{206}Po collected in the present experiment. The transitions corresponding to the levels of interest are indicated on the figure.

The method of obtaining the lifetimes requires a carefully analysis of data coming from pairs of $LaBr_3$:Ce detectors. In particular, the time spectra of the detectors are affected by the time walk and one must consider this effect when analyzing time difference spectra. In the present experiment, a careful analysis was performed using the ^{152}Eu source, which decays to ^{152}Sm and ^{152}Gd through beta decay and electron capture processes. These two nuclei contain well known lifetimes at several excitation energies and they can be used for a proper correction. The lifetimes obtained for the first three excited states in ^{206}Po and their corresponding transition probabilities are summarized in the following table:

Level	E_{gamma} (keV)	Lifetime (ps)	B(E2) (W.u.)
2^+	700	3.0 (19)	15.0(92)
4^+	477	54.7(11)	5.6 (1)
6^+	395	199(6)	3.8 (1)

The results obtained in the present experiment have to be compare to the theoretical models available. This comparison will be the subject of the last report of the project, together with the similar measurements in ^{202,204}Po.

2019: The activity for this year is a continuation of the one started in 2018 which aims at finding an experimental signature that will allow a clear distinction between the seniority regime and the collective behavior. This year we continue the effort by studying two additional nuclei of the Po isotopic chain, ^{202}Po and ^{204}Po. In order to perform this experimental investigation, one has first to write a proposal presenting the scientific case of the problem addressed. The proposal is presented and defended in front of an international Program Advisory Committee that decides about the scientific quality of the experiment. The main idea of the proposal we have presented was that the difference between the two regimes we plan to characterize can be performed efficiently if the appropriate transition probabilities in the yrast band are known. Therefore, we would need to measure the lifetimes of these excited states which are laying in the tens of picoseconds to nanoseconds range, according to the theoretical predictions. However, it worth mentioning that these calculations are giving contradictory predictions of the lifetimes in this region, and therefore, only the experimental data can help establish which model is accurately describing the reality. The proposal was submitted by our group to be considered by the PAC, and the committee recognized the importance of our scientific effort and allocated 14 days to perform this experiment.

Lifetimes of the yrast states in ^{202}Po and ^{204}Po have been measured in an experiment performed at the “Horia Hulubei” National Institute for Physics and Nuclear Engineering in Bucharest using the 9 MV Tandem accelerator. In order to populate the excited states in these two nuclei, we have used two fusion-evaporation nuclear reactions: ^{196}Pt(^{12}C,4nγ)^{204}Po and ^{194}Pt(^{12}C,4nγ)^{202}Po, both using an incoming ^{12}C beam accelerated at 62 MeV. We used a 9.8 mg/cm^2 ^{196}Pt foil and a 9.4 mg/cm^2 target for ^{194}Pt. The gamma rays were detected with the Romanian Array for Spectroscopy in Heavy Ion Reactions (ROSPHERE) composed of 14 HPGe detectors and 11 $LaBr_3$(Ce) detectors. This combination of detectors with very good energy resolution and fast time response is crucial for the fast-timing method that uses the electronic timing measurement between two gamma rays that have to be first selected from a spectrum of densely packed gamma rays. The spectra we have collected in the present experiment can be seen in Fig. 2 in the case of ^{204}Po. One can see that the most intense peaks belong to ^{204}Po, but there are clear contaminants in the spectrum located in the vicinity of the yrast transitions. Therefore, the spectrum showed in the second panel corresponding to the same excitation range taken with the $LaBr_3$(Ce) detectors contains all the peaks convoluted together. Therefore, two independent methods have been used in the present analysis, the isomer tagging and the fold method. The last two panels in Fig. 2 present examples of the $LaBr_3$(Ce) spectra analyzed with the isomer tagging method.

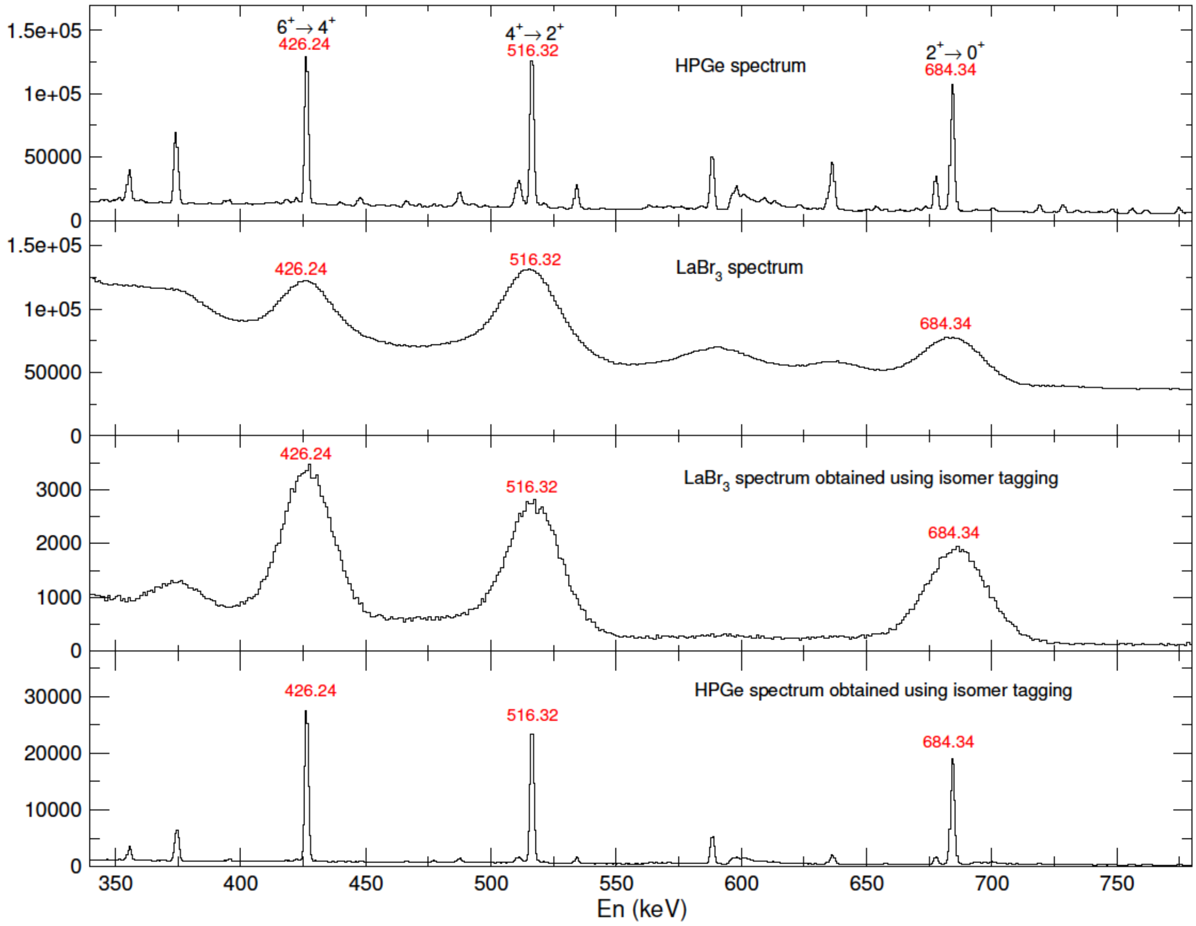

Fig. 2: HPGe and $LaBr_3$(Ce) gamma-ray spectra collected in the present experiment for ^{204}Po. Top panel: HPGe single spectrum showing the most intense transitions from the yrast band of ^{204}Po; Second panel: Corresponding spectrum taken with $LaBr_3$(Ce) detectors; Third panel: $LaBr_3$(Ce) spectrum obtained using the isomer tagging method; Last panel: Corresponding spectrum obtained in the case of HPGe detectors.

One of the main corrections that has to be done in the case of fast-timing technique is the so-called "walk correction". This is an electronic effect and arises from the fact that signals with different amplitudes will have a different time behavior. This non-linear behavior was corrected using a ^{152}Eu calibration source. In addition, we have used the data for ^{204}Pb and ^{202}Pb, obtained as by-products following beta-decay of ^{204}Po and ^{202}Po, respectively, to ensure that the correction is reliable.

The experimental lifetimes have been obtained from the spectra analyzed with the fast-timing method. The data are collected in the following table for ^{204}Po and ^{202}Po:

	Level	E_{gamma} (keV)	$T_{1/2}$ (ps)	B(E2) (W.u.)
^{204}Po	2^+	684	4.2(24)	12.5 (70)
	4^+	516	12.4(18)	16.9 (25)
^{202}Po	2^+	677	<5	>11
	4^+	571	<5	>26

2020: The last part of the project was dedicated to the interpretation of the experimental results obtained using the available nuclear structure theoretical models and compilation of the obtained experimental results in the ENSDF format. In the first two years of this project we have shown the details of the experiments aiming at lifetime measurements of yrast states of three Po isotopes: ^{202}Po, ^{204}Po, and ^{206}Po.

The transition probabilities that were derived from these measurements represent key ingredients that can reveal important information about the structure of a nucleus. Therefore, a close inspection of these significant data was performed in connection with the relevant theoretical models.

The first model uses the concept of seniority. Seniority represents the number of unpaired particles in a state of angular momentum J and reflects the tendency of particles to couple in pairs with J=0$^+$. An immediate consequence is the fact that the transition probabilities of the yrast transitions have a different behavior and can be used to easily distinguish between the two regimes (seniority and collectivity) by measuring the appropriate lifetimes of excited states.

The nucleon pair approximation (NPA) is a version of the shell model that provides a possibility to truncate the available space by introducing collective S and D nucleon pairs constructed from valence nucleons. In this way, the shell-model Hamiltonian is diagonalized in a coupled nucleon pair subspace.

The interacting boson model (IBM) is a phenomenological model that couples the valence fermions into pairs and uses an algebraic mathematical framework to treat these pairs as bosons. One of the most successful extensions is the one with configuration mixing, namely the incorporation of another system of s and d bosons with a two-particle – two-hole structure that is able to describe the shape coexistence phenomenon.

One of the most successful nuclear models ever developed is the shell model. This theoretical model is analogue with the atomic shell model and was triggered by the existence of certain magic numbers of protons and neutrons. The Large-Scale Shell Model (LSSM) version was applied in the case of Po isotopes.

The comparison between the experimental data and the theoretical calculations has revealed that in general the best agreement is provided by the calculations in the LSSM framework, which are intermediate between the NPA and the IBM predictions. The NPA model severely underestimates the experimental data for these spin values, while the IBM it overestimates the data. This means that the IBM indicates an increased collectivity in the structure of Po isotopes, while the NPA underestimates the collective degree of freedom.

In Fig. 3 we present the complete B(E2) experimental values in the case of Po isotopes ranging from A=198 to A=214. The values are presented for each transition of the yrast band as a function of mass number.

It is clear that the most complete set of states belongs to the $8^+ \to 6^+$ transition (panel (a)), for which we have added the last point in ^{202}Po by determining for the first time the energy of the gamma ray linking the two states. Besides some small variations, the transition probability of this transition has an almost constant behavior. Of course, the detailed fluctuations might still reveal important information about the structure of these isomers. The $6^+ \to 4^+$ (panel (b)) and $4^+ \to 2^+$ (panel (c)) transitions have only a few experimental points, but a rather constant level of collectivity could be observed from Fig. 3, maybe with a slight increase of the values with lighter mass isotopes in the case of $4^+ \to 2^+$ transitions. Finally, the $2^+ \to 0^+$ (panel (d)) transition reveal an increasing trend with lowering the mass number, indicating an increased collectivity as we move away from the shell closure at N=126.

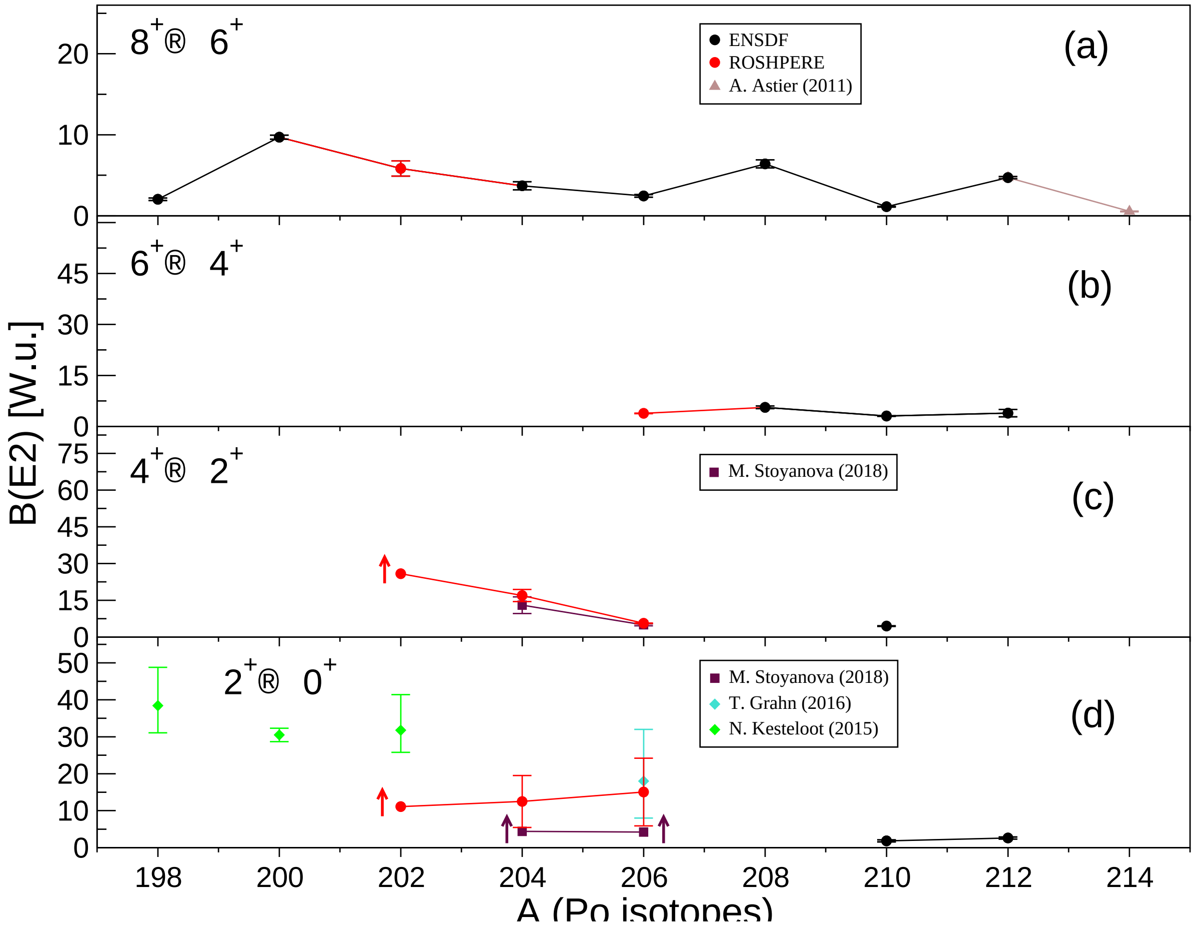

Fig.3: Experimental transition probabilities in the Po isotopes as a function of mass number, given for the $8^+ \rightarrow 6^+$ (a), $6^+ \rightarrow 4^+$ (b), $4^+ \rightarrow 2^+$ (c), and $2^+ \rightarrow 0^+$ transitions (d).

As a conclusion, we emphasize the need for more reliable information concerning the transition probabilities in this region, as they are key observables that can help disentangle the complex structure of the nuclei in this mass region. In addition, new theoretical calculations are required, especially extending the LSSM calculations which were proved to be the most reliable by the present analysis. Furthermore, the IBM predictions are obtained from a fit of known experimental observables, so it is possible that including the new results in the fit could improve the results of the transition probability calculations.

As a final task, the data were compiled in the format required by the ENSDF. This is one of the most intensive used tools in the field, and the task of maintaining the database up to date is tremendous. Therefore, we have performed also the part of implementing these results in the format required by the network of evaluators. This project and the presented experiments represented a very good opportunity to familiarize the young scientists with the ENSDF format and to train them to use the dedicated codes. The compilation of these results will help the entire scientific community to have easy access to all the relevant and up to date nuclear experimental information.