Measurements of competing structures in neutron-deficient Pb isotopes by employing Coulomb excitation
Resubmission of the proposal P-246

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Abstract

Coulomb excitation measurements to study the shape coexistence and quadrupole collectivity of the low-lying levels in neutron-deficient Pb nuclei are proposed. Even-mass $^{188-192}$Pb nuclei will be post-accelerated at REX-ISOLDE in order to measure transition probabilities and quadrupole moments for the first excited states. In combination with results obtained in lifetime measurements, this will allow the sign of the quadrupole deformation parameter to be extracted for the first time for 2^+ states in the even-mass $^{188-192}$Pb nuclei.

Introduction

The interplay between single-particle motion, collectivity, and pairing in light Pb nuclei is manifested as a rich gamut of coexisting nuclear shapes and exotic excitations [1, 2, 3, 4, 5]. One of the goals of modern nuclear physics research is to understand the origin of these structures and their relation to the fundamental interactions between the nuclear constituents. These subjects can be investigated particularly well in the Pb isotopes close to neutron mid-shell, where a relatively small proton shell gap, together with a large valence neutron space, provides fertile ground for studies of shape transitions within a small energy range. In α-decay studies, the first two excited states of the mid-shell nucleus ^{186}Pb were observed to be 0^+ states [6]. On the basis of α-decay hindrance factors, the 0_2^+ state was associated with mainly $\pi(2p-2h)$ configuration, whereas the 0_3^+ state was associated with a $\pi(4p-4h)$ configuration. Consequently, together with the spherical ground state [7], the three 0^+ states with largely different structures establish a unique shape-triplet in ^{186}Pb. Very recently, rotational bands built on these states were observed in in-beam γ-ray measurement [8] and their collectivity confirmed in lifetime measurements [9].

A complementary view of these 0^+ states is provided by mean-field methods in which each local minimum of the potential energy surface is associated with a different collective shape. The first calculations of quadrupole potential energy surfaces were performed within the Strutinsky approach [10, 11, 12]. The existence of a spherical ground state with low-lying oblate and prolate minima has been found in self-consistent mean-field approaches based on effective Skyrme [13, 14, 15] and Gogny [16] interactions. In a truncated shell-model approach, these oblate and prolate mean-field configurations can be associated with $\pi(2p-2h)$ and $\pi(4p-4h)$ excitations, respectively, forming a unique system of the three different shapes.

Although much experimental effort has been put into investigating light Pb nuclei, the information obtained is still rather scarce. It remains a challenge for both theoretical and experimental studies to obtain a consistent and detailed description of the observed phenomena.

We propose to carry out the investigations of nuclear collectivity and mixing of the low-lying states in the neutron-deficient Pb nuclei, namely even-mass isotopes $^{188-192}$Pb, employing the REX-ISOLDE facility. In Fig. 1, the level energy systematics of Pb isotopes is shown. The 0^+ states of the $\pi(2p-2h)$ configuration, associated with the oblate shape, intrudes down in energy close to the spherical ground state when approaching the neutron mid-shell at $N = 104$ and becomes the first excited state at $A = 194$. The onset of prolate deformation, mainly associated with the $\pi(4p-4h)$ configuration, can be seen around $A = 190$ for states with $I^\pi \leq 4^+$. The prolate states with $I^\pi \geq 4^+$ form the yrast band at $A = 188$. Thus, light Pb isotopes provide a unique laboratory to study the three competing structures of different shapes around 1 MeV.

The isotopes of interest are of particular importance as they lie in so-called transitional region, where a transition from a weaker deformed oblate structure to a strongly deformed prolate structure is proposed for the yrast states. This is demonstrated by a recent theoretical study, in which the $B(E2)$ values and level

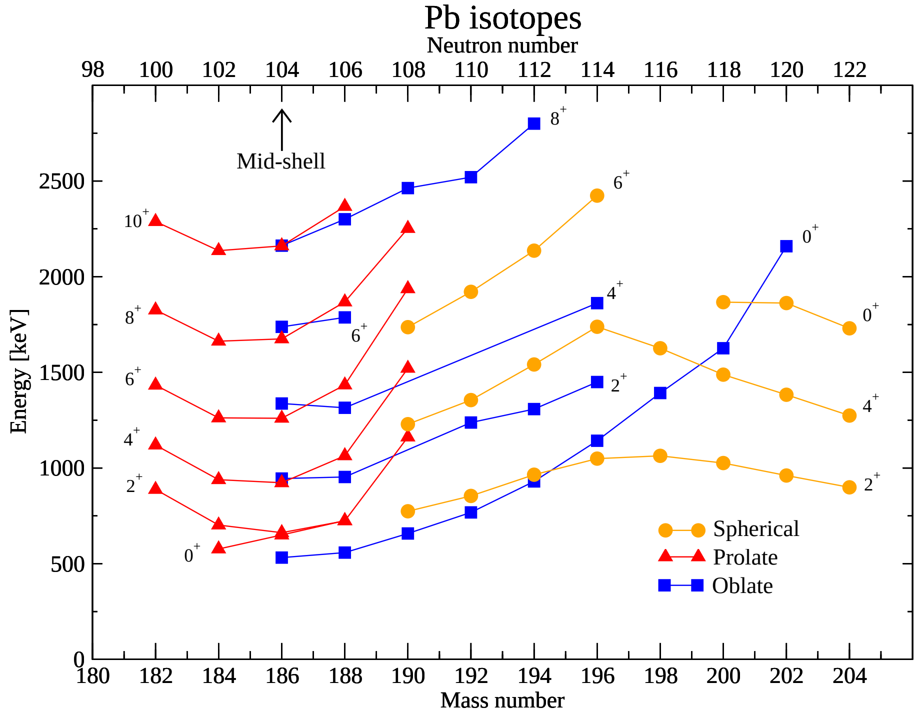

Figure 1: Level energy systematics for even-mass Pb isotopes adapted from Ref. [8].

energies were calculated within the Interacting Boson Model (IBM) for the even-mass $^{186-196}$Pb [17]. The calculated $B(E2)$ values for the $2^+ \rightarrow 0^+_{g.s.}$ transitions are illustrated in Fig. 2. Theoretical study in Ref. [17] suggests that yrast bands of the even-mass $^{190-196}$Pb are of $\pi(2p-2h)$ (oblate) character, whereas the 2^+ yrast state is seen as an admixture of regular (spherical) and $\pi(2p-2h)$ structures in its wave function. The oblate deformation of the yrast band is also proposed by the angular momentum projected mean-field calculations in Ref. [15]. The $B(E2)$ values calculated for the 2^+ states in ^{188}Pb by using Skyrme Sly6 [15] and Gogny D1S [16] interactions are also given in Fig. 2. Based on level energy systematics, the yrast bands of the even-mass $^{190-196}$Pb have been experimentally associated with spherical structure (see *e.g.* Ref. [5]).

In order to establish a complete picture of shape coexistence in this region, the knowledge of transition probabilities from nuclear states assigned with different shapes is essential. Transition probabilities are very sensitive to the details of a nuclear wave function and, consequently, information about nuclear shape and configuration mixing can be inferred. Furthermore, the knowledge of the nuclear wave functions renders it possible to extract an effective nucleon-nucleon interaction to produce a realistic nuclear potential. For example, different parameterisations have been used in mean-field nuclear models and recently, precision tests for those were carried out in the ^{74,76}Kr isotopes [18], where the Gogny D1S interaction succeeded to reproduce the experimental values. However, such tests have not yet been systematically carried out for the heavier, more complex systems. So far, collectivity of

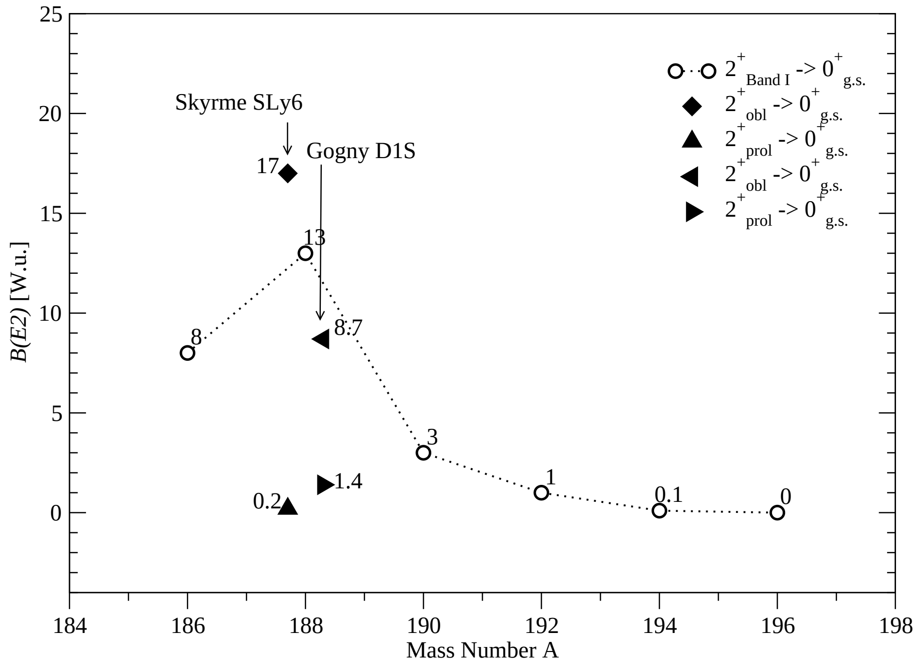

Figure 2: Theoretical $B(E2)$ values for the $2^+ \rightarrow 0^+_{g.s.}$ transitions in the even-mass $^{186-196}$Pb isotopes calculated within IBM [17] (open symbols). The $B(E2)$ values for the $2^+ \rightarrow 0^+_{g.s.}$ transitions in ^{188}Pb obtained with configuration mixing calculations of the angular momentum projected mean-field states using the Skyrme Sly6 [15] and Gogny D1S [16] interactions are given (filled symbols). Numerical values are given next to each data point in W.u..

γ-ray transitions originating from prolate states in ^{186,188}Pb has been established by in-beam lifetime measurements carried out at the University of Jyväskylä [9]. While in-beam lifetime experiments probe mainly yrast states, with Coulomb excitation the population of low-lying non-yrast states becomes feasible and, enables a comprehensive study of coexisting shapes and their mixing in these nuclei. In addition, heavier ^{190,192}Pb isotopes cannot be probed in in-beam lifetime measurements due to presence of relatively long-lived isomeric states. Hence, Coulomb excitation measurements would also enable the collectivity of weakly deformed states to be probed in these neutron-deficient Pb isotopes, for which the data are conspicuously lacking.

Proposed experiment and data analysis

Radioactive beams of neutron-deficient Pb isotopes will be produced using the UC_X primary target and RILIS laser ion source [19]. The use of RILIS will allow Pb beams to be purified from isobaric contaminants. The required charge state to accelerate Pb beams up to 2.95 MeV/u will be obtained with REX-EBIS charge breeder. Accelerated Pb beams will be delivered to MINIBALL target position where Pb nuclei will be Coulomb excited in inverse kinematics using the secondary ^{112}Cd target (E_{2^+} = 617.4 keV). MINIBALL Ge-detector array, with a photopeak

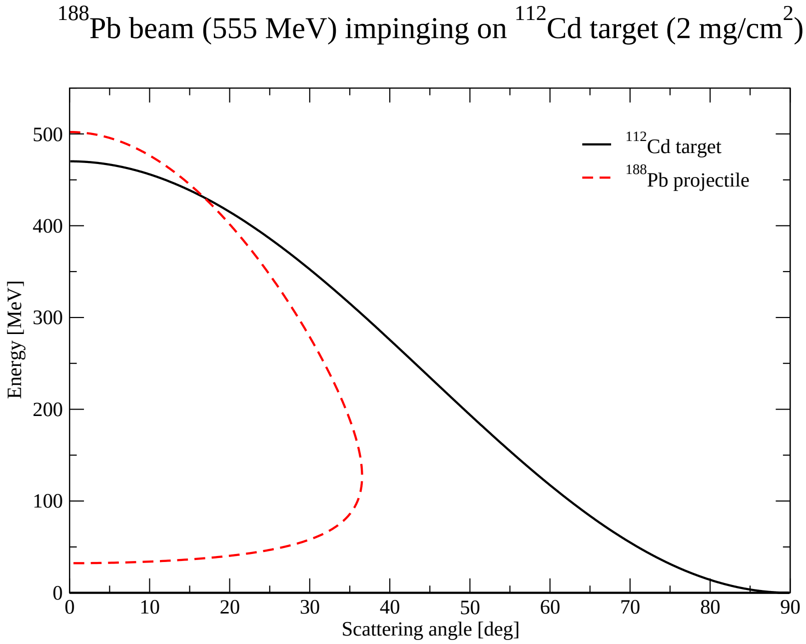

Figure 3: Kinematics plot for the ^{188}Pb projectile impinging on the ^{112}Cd target at 2.95 MeV/u.

efficiency of $\approx 7\%$ for 1.3 MeV γ rays, will detect γ rays de-exciting levels under investigation. Both scattered projectiles and target recoils will be detected using an annular double sided silicon strip detector (CD) positioned on the beam axis after the secondary target. In Fig. 3, the scattering of a ^{188}Pb projectile impinging on the ^{112}Cd target is shown, for other proposed isotopes the plot is very similar. The maximum projectile scattering angle is around 36.5° and the target nuclei detected in CD covering angles $> 32°$ can be distinguished from the projectile nuclei.

The selectivity of RILIS laser ion source will provide purified Pb beams, although in Ref. [19], it was observed that surface ionised Tl and Fr contaminants remain. Fr contaminants will only present a problem at $A > 206$ [19], whereas a test run was recently carried out to investigate the amount of isobaric Tl impurities. It has been reported, that pure beams of ^{190,192}Pb of at least 80% are to be expected, but the isobaric contamination originating from Tl and the ^{188}Pb yield were found to be of the same order of magnitude [20]. However, the presence of ^{188}Tl would not pose a problem since low-energy γ-ray transitions ($E_\gamma \sim 300$ keV) can be easily distinguished from the ones associated with ^{188}Pb ($E_\gamma = 724$ keV). The level of target excitation originating from the Tl impurities can be ascertained by measuring the γ-ray yield with the RILIS laser off in addition to the usual laser on measurement.

A sample γ-ray energy spectrum of ^{182}Hg and first results from the ongoing analysis of the Coulomb excitation of ^{186}Hg are shown in Figs. 4 and 5, respectively. These data are taken from the experiment IS452 investigating shape coexistence in

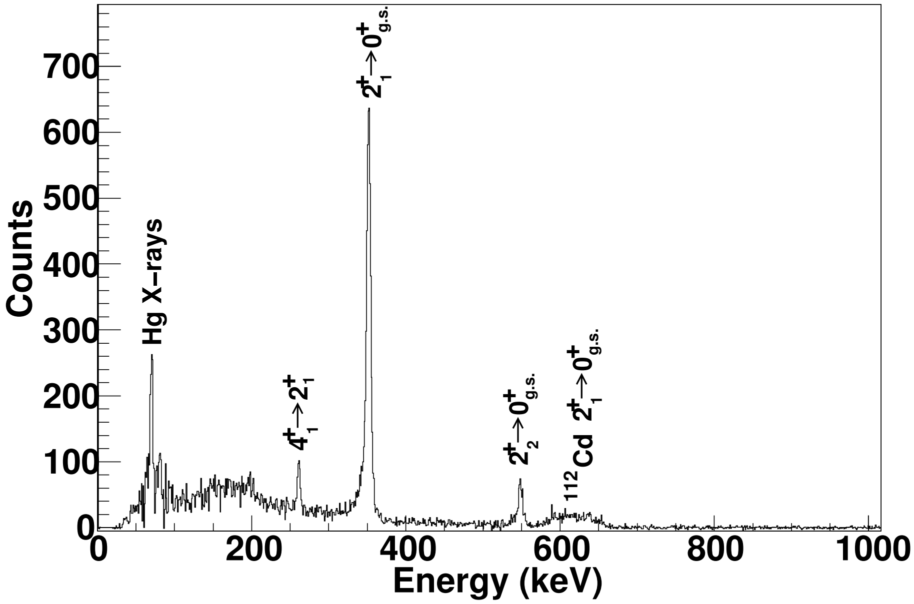

Figure 4: Doppler-corrected γ-ray spectrum of ^{182}Hg following Coulomb excitation. The data are taken from the experiment IS452.

the even-mass $^{182-188}$Hg. Thereby, we use the nuclear reorientation effect [21] which connects the experimentally observed Coulomb excitation cross section $\sigma_{CE}(J_i \to J_f)$, the transition matrix element (TME) $\langle J_f|O(\hat{E}2)|J_i\rangle$ and the diagonal matrix element (DME) $\langle J_f|O(\hat{E}2)|J_f\rangle$:

$$\sigma_{CE}(J_i \to J_f) \propto |\langle J_f|O(\hat{E}2)|J_i\rangle|^2 \cdot [1 - \langle J_f|O(\hat{E}2)|J_f\rangle \cdot f(\zeta)]. \quad (1)$$

The DME can be associated with the corresponding spectroscopic quadrupole moment of the state J_f. Using the angular dependency of the Coulomb excitation cross section by splitting up the observed angular regions, different curvatures of the hyperbolas determined by Eq. 1 can be extracted (see Fig. 5). The overlapping region determines the DME. Thus, even without knowing the lifetime of the investigated level we will be able to determine (at minimum) the sign of the spectroscopic quadrupole moment. The additional knowledge of the lifetime (shown in Fig. 5 as horizontal band) leads to a further constrain of the overlapping region and to a more precise measurement of the DME.

Count rate estimate and beam time request

The experiment IS452 carried out in 2007 and 2008 successfully demonstrated that heavy radioactive beams, such as ^{184}Hg can be exploited for Coulomb excitation studies at REX-ISOLDE. In that experiment, ^{184}Hg beam intensity on a target was observed to be 3000 pps. However, due to technical problems in the first part of the experiment, the transmission efficiency of REX was reduced (0.19% instead of 1%).

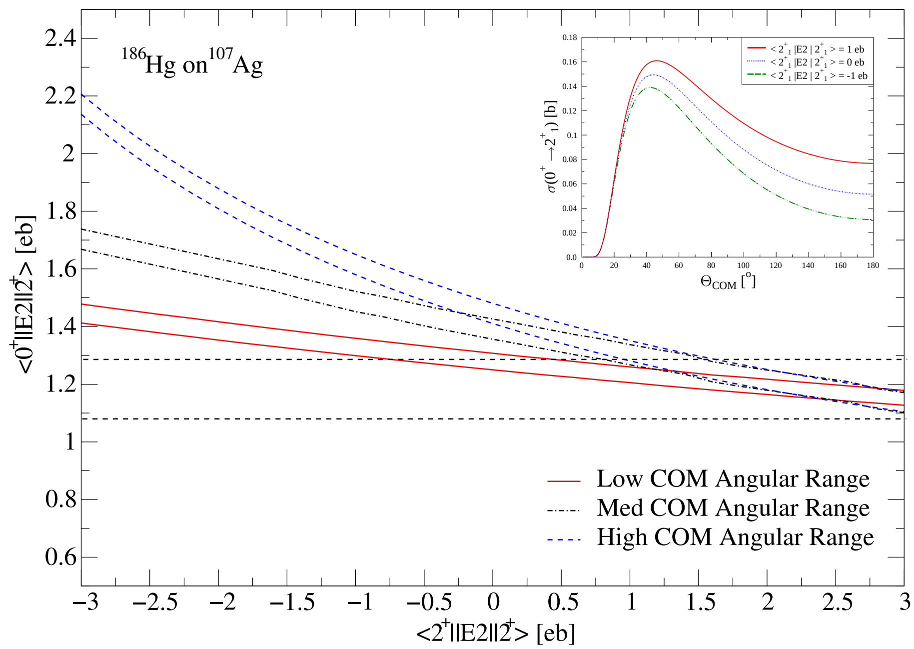

Figure 5: Illustration of matrix elements extracted for the 2_1^+ state in ^{186}Hg. The data are taken from the experiment IS452. The curves represent the values of the matrix elements extracted by gating with different centre-of-mass (COM) angular ranges in the MINIBALL CD detector. The dashed horizontal lines represent the value for the respective transition quadrupole moment extracted from the lifetime measurement. The inset shows the Coulomb excitation cross section σ_{CE} dependence of the COM angle Θ_{COM}. Different spectroscopic quadrupole moments are assumed to demonstrate the change in σ_{CE}.

The measured primary yield for ^{184}Hg was $2.7\times10^6\mu\text{C}^{-1}$, although the corresponding value in ISOLDE database is $1.3\times10^8\mu\text{C}^{-1}$.

The yield of the radioactive Pb beams for the proposed experiment would be similar to those in experiment IS452. In Table 1 the number of counts for the transitions from the first 2^+ state to the ground state in the even-mass $^{188-192}$Pb nuclei have been calculated using GOSIA code [22]. The reduced matrix element for ^{188}Pb has been extracted from the experimental lifetime reported in Ref. [9]. For ^{190,192}Pb the TME has been assumed to be similar to that extracted from the lifetime in ^{188}Pb. The MINIBALL γ-ray detection efficiency and REX transmission efficiency have been assumed to be 10% and 1%, respectively. Despite the rather low TME assumed in the Table 1, we will collect sufficient statistics to be able to carry out similar analysis as for the experiment IS452 (*c.f.* the level of statistics in Fig. 4). The low-lying level structure of the even-mass $^{188-192}$Pb is illustrated in Fig. 6 showing also the known level lifetimes.

The principal goal of the proposed experiment is to determine the sign of the diagonal matrix elements for the lowest 2^+ states in the even-mass $^{188-192}$Pb nuclei. As demonstrated by the similar measurements with Hg beams, $B(E2)$ values and

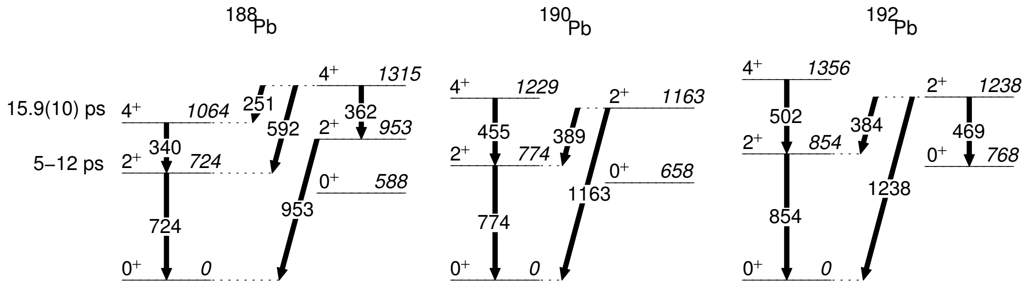

Figure 6: Partial level schemes below 1.4 MeV showing observed γ-ray transitions for the even-mass $^{188-192}$Pb. Transitions feeding the excited 0^+ states in ^{188,190}Pb have not been observed. This figure is reproduced from Refs. [8, 23] and level lifetimes are taken from Ref. [9].

quadrupole moments for the $2^+_1 \rightarrow 0^+_{\text{g.s.}}$ transitions can be obtained and, thus, level of collectivity and deformation of these transitions can be deduced. In addition, the level lifetime of the 2^+ state in ^{188}Pb is known, which increases the accuracy of the extracted matrix elements (see Fig. 5). Furthermore, the proposed programme includes a re-measurement of this lifetime in a separate experiment at the University of Jyväskylä in order to improve its accuracy.

In ^{190,192}Pb, prolate intruder structures are expected to lie higher in energy, hence the proposed measurement will elucidate the collectivity of assumed oblate/spherical 2^+ states in these nuclei. It is anticipated that the cross section to populate low-lying non-yrast states is an order of magnitude lower than that for the yrast states. However, in ^{192}Pb a low $B(E2; 2^+_2 \rightarrow 0^+_2)/B(E2; 2^+_2 \rightarrow 0^+_1) = 5(4)$ ratio with rather large error bars has been observed [23]. This has been explained by strong mixing of the 2^+_1 and 2^+_2 states. Together with relatively large ISOLDE primary yield this fact may allow the population of the 2^+_2 state in ^{192}Pb.

Based on the yield estimates given in Table 1, **9** shifts of beam time are required for the γ-ray yield measurement of ^{188}Pb. For the similar measurement of ^{190,192}Pb, **3** shifts for each nucleus are required. To verify the level of γ-ray yield of target excitation induced by Tl contaminant in ^{188}Pb beam, separate runs to measure the

Table 1: Counts obtained in one day (3 shifts) of beam time for the $2^+_1 \rightarrow 0^+_{\text{g.s.}}$ transition for each nucleus. Reduced matrix elements have been extracted from lifetimes measured in Ref. [9]. For ^{190,192}Pb, transition matrix elements have been assumed to be similar to that in ^{188}Pb, *i.e.* $\langle 0^+_{g.s.} || O(\hat{E}2) || 2^+_1 \rangle = 0.475$ eb. Primary yields have been taken from the ISOLDE database.

Nucleus	ISOLDE yield (μC^{-1})	Beam intensity on MINIBALL target (pps)	γ-ray yield	Expected beam purity [20]
^{188}Pb	1.7×10^6	1.7×10^4	550	n/a, see text
^{190}Pb	2.3×10^7	2.3×10^5	7400	>80%
^{192}Pb	4.0×10^7	4.0×10^5	10700	>80%

γ-ray yields with RILIS laser off are required. Additional **3** shifts of beam time should be sufficient for the laser off measurement. A further **3** shifts are required for setting up REX. The beam time request is summarised in Table 2.

It should be noted that the proposed programme will be a necessary step towards a campaign at HIE-ISOLDE where the higher energy will allow going a step further in the multi-step Coulomb excitation. In addition, the proposed experiment will shed more light on capability of the REX-ISOLDE + MINIBALL facility to probe even lighter Pb isotopes, such as ^{186}Pb.

Table 2: A summary of the beam time request.

Beam	Target	Ion source	Shifts
REX set-up	UC_X	RILIS	3
^{188}Pb	UC_X	RILIS	12
^{190}Pb	UC_X	RILIS	3
^{192}Pb	UC_X	RILIS	3
Total			**21**

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