Measurements of competing structures in neutron-deficient Pb isotopes by employing Coulomb excitation

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Abstract

A Coulomb excitation measurement to study the shape coexistence and quadrupole collectivity of the low-lying levels in neutron-deficient Pb nuclei is proposed. Even-mass $^{188-192}$Pb nuclei will be post-accelerated at REX-ISOLDE in order to measure matrix elements for the lowest lying transitions. In combination with results obtained in previous lifetime measurements, this will allow the sign of the quadrupole deformation parameter to be extracted for the first time for ^{188}Pb. In addition, collectivity of low-lying 2^+ states will be probed for ^{190,192}Pb.

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, collective rotational bands built on these states were observed in in-beam γ-ray measurement [8].

A complementary view of these 0^+ states is provided by mean-field methods in which each intruder 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 [9, 10, 11]. 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 [12, 13, 14] and Gogny [15] 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 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 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 $\pi(2p-2h)$ configuration, associated with an oblate shape, intrudes down in energies 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 $A = 190$. The prolate states form the yrast band at $A = 188$. Thus, light Pb isotopes provide a unique laboratory to study competing structures of different shapes around 1 MeV.

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. So far, collectivity of γ-ray transitions orig-

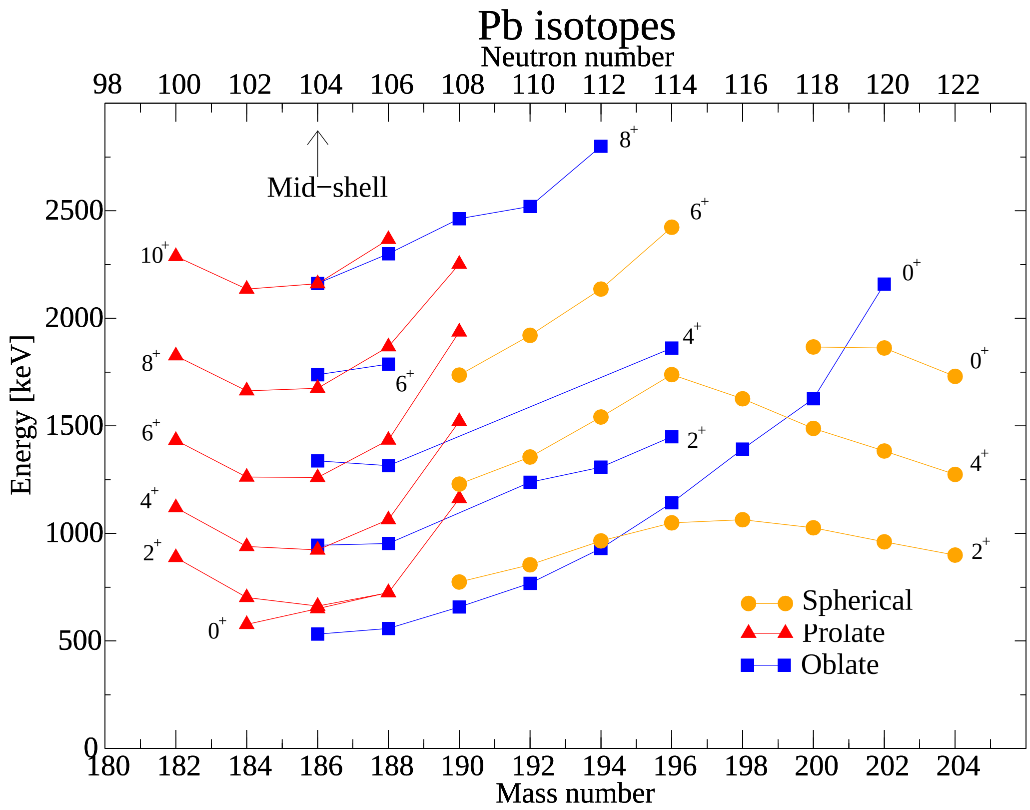

Figure 1: Level energy systematics for even-even Pb isotopes adapted from Ref. [8].

inating from prolate states in ^{186,188}Pb has been established by in-beam lifetime measurements carried out at the University of Jyväskylä [16]. While in-beam lifetime experiments probe mainly yrast states, with Coulomb excitation the population of 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 measurement due to presence of relatively long-lived isomeric states. Hence, Coulomb excitation measurements would also enable the collectivity of spherical states to be probed in these neutron-deficient Pb isotopes, for which the data are conspicuously lacking.

Proposed experiment

Radioactive beams of neutron-deficient Pb isotopes will be produced using the UC_X primary target and RILIS laser ion source [17]. 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 using the secondary ^{112}Cd target (E_{2+} = 617.4 keV). MINIBALL Ge-detector array, with a photopeak 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 the annular double sided silicon strip detector positioned on the beam axis after the secondary target.

The selectivity of RILIS laser ion source will provide rather pure Pb beams, although in Ref. [17], it was observed that surface ionised Tl and Fr contaminants remain. Fr contaminants will only present a problem at $A > 206$ [17], but the level of Tl contaminants remains unknown for the proposed Pb beams. Thus, a separate test run is required to ascertain the isobaric purity of neutron-deficient Pb beams.

Count rate estimate and beam time request

The experiment IS452 carried out in 2007 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 that experiment, the transmission efficiency of REX was reduced (0.19% instead of 1%). The reported primary yield for ^{184}Hg is $1.3 \times 10^8 \mu C^{-1}$.

The yield of the radioactive Pb beams for the proposed experiment would be similar to that in experiment IS452. In Table 1 number of counts for the transitions from the first 2^+ state to the ground state in even-mass $^{188-192}$Pb nuclei have been estimated based on the measured ISOLDE primary yields. The reduced matrix element for ^{188}Pb has been extracted from the experimental lifetimes reported in Ref. [16]. For ^{190,192}Pb the matrix element has been assumed to be similar to that in ^{188}Pb. The MINIBALL γ-ray detection efficiency and REX transmission efficiency have been assumed to be 10% and 1%, respectively. The low-lying level structure of the even-mass $^{188-192}$Pb is illustrated in Fig. 2 showing also the known level lifetimes.

Table 1: Counts obtained in one day (3 shifts) of beam time for the $2^+_1 \rightarrow 0^+_{g.s.}$ transition for each nucleus. Reduced matrix elements have been extracted from lifetimes measured in Ref. [16]. For ^{190,192}Pb, matrix elements have been assumed to be similar to that in ^{188}Pb. Primary yields have been taken from the ISOLDE database.

Nucleus	ISOLDE yield (μC^{-1})	Beam intensity on MINIBALL target (pps)	$\langle 0 \| \hat{E2} \| 2 \rangle$ (eb)	γ-ray yield
^{188}Pb	1.7×10^6	1.7×10^4	0.475	550
^{190}Pb	2.3×10^7	2.3×10^5	0.475	7400
^{192}Pb	4.0×10^7	4.0×10^5	0.475	10700

The principal goal of the proposed experiment is to determine the diagonal matrix element for the lowest 2^+ state in ^{188}Pb as the level lifetimes of the low-lying yrast states have recently been measured [16]. This will allow the sign of the quadrupole deformation parameter to be extracted from the proposed Coulomb excitation measurements. For ^{190,192}Pb, lifetimes of the lowest 2^+ states remain unknown. However, despite the lack of level lifetime information, $B(E2)$ values for the

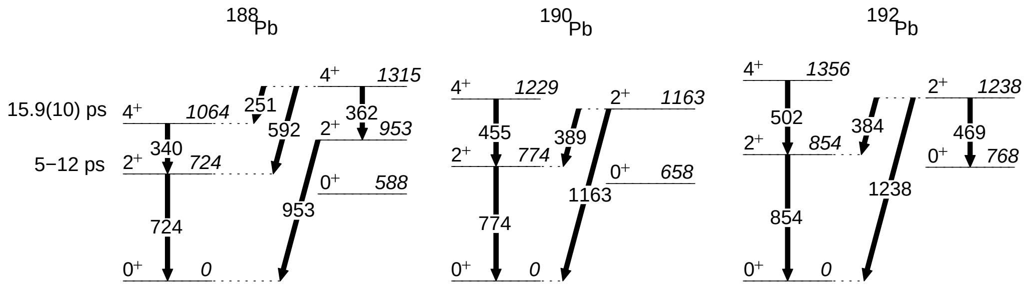

Figure 2: Partial level scheme showing observed γ-ray transitions below 1.4 MeV for the even-mass $^{188-192}$Pb. Transitions feeding the excited 0^+ states in ^{188,190}Pb have not been observed. This figure is reproduced from Refs. [8, 18] and level lifetimes are taken from Ref. [16].

$2_1^+ \rightarrow 0_{\rm g.s.}^+$ transitions can be obtained and, thus, level of collectivity of these transitions can be deduced. In ^{190,192}Pb, intruder structures are expected to lie higher in energy, hence the proposed measurement will elucidate the collectivity of assumed spherical 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 [18]. 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.

For the proposed programme, the following experimental procedure is suggested:

1. Pb beam purity measurement (3 shifts) to test the feasibility of the proposed experiment.

2. Provided that the purity of required Pb beams is sufficient, 11 shifts of beam time are required for the γ-ray yield measurement of ^{188}Pb. For the measurements of ^{190,192}Pb, 2 shifts for each nucleus are required. A further 3 shifts are required for setting up the REX facility.

The beam time request is summarised in Table 2.

Table 2: A summary of the beam time request.

Beam	Target	Ion source	Shifts
Beam purity test	UC_X	RILIS	3
REX set-up	UC_X	RILIS	3
^{188}Pb	UC_X	RILIS	11
^{190}Pb	UC_X	RILIS	2
^{192}Pb	UC_X	RILIS	2
Total			21

It should be noted that the proposed programme would be a forerunner for 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, namely ^{186}Pb.

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