Collectivity and configuration mixing in ^{186,188}Pb and ^{194}Po

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Lifetimes of prolate intruder states in ^{186}Pb and oblate intruder states in ^{194}Po have been determined by employing, for the first time, the recoil-decay tagging technique in recoil distance Doppler-shift lifetime measurements. In addition, lifetime measurements of prolate states in ^{188}Pb up to the 8^+ state were carried out using the recoil gating method. The $B(E2)$ values have been deduced from which deformation parameters $|\beta_2| = 0.29(5)$ and $|\beta_2| = 0.17(3)$ for the prolate and the oblate bands, respectively, have been extracted. The results also shed light on the mixing between different shapes.

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The coexistence of energetically almost degenerate states of different shapes in mesoscopic systems such as atomic clusters and nuclei is a topic of current interest. The investigation of the origin of the shape coexistence [1] observed in the vicinity of $Z = 82$ nuclei close to the proton drip-line is one of the central current challenges, experimentally as well as theoretically. In the neutron mid-shell nucleus ^{186}Pb, the first two excited states above the spherical ground state are assigned as 0^+ states. In the shell model approach these states can be associated with intruder $\pi(2p-2h)$ and $\pi(4p-4h)$ excitations across the $Z = 82$ gap [2]. This picture is supported by hindrance factors derived from the α decays feeding these states [3]. These excitations of small numbers of particles over the shell gap lead to changes in the nuclear shape. In calculations based on the deformed mean field they appear as oblate and prolate minima intruding down close to the ground state when approaching the neutron mid-shell [4, 5]. Configuration mixing calculations of angular-momentum projected mean-field states using the Gogny [6] and Skyrme [7] interactions find prolate yrast rotational bands and excited oblate bands for $^{182-186}$Pb and a complex shape coexistence with mixed states for ^{188}Pb. Experimentally the yrast bands in $^{182-188}$Pb have been interpreted as being based on prolate shapes [8–11]. Recently, candidates for collective non-yrast bands built on the coexisting oblate minimum have been observed in ^{186}Pb and ^{188}Pb [12, 13].

The extension of spectroscopic studies to $Z = 84$ has revealed even further behavior of similar intruder structures in the neutron-deficient Po isotopes. When approaching the neutron mid-shell around $N = 104$, states associated with oblate deformed $\pi(4p-2h)$ configurations cross the yrast line of nearly spherical states and reach the ground state in ^{192}Po [14, 15]. Furthermore, a sudden change to an yrast band similar to the prolate bands in $^{182-188}$Pb is observed in ^{190}Po [16]. This picture is also supported by earlier Nilsson-Strutinsky calculations [5].

Calculations based on the mean-field predict that the deformation associated with the prolate shape of mid-shell Pb and Po nuclei is larger than that for the oblate one. Experimentally, the degree of deformation is in many cases deduced from moments of inertia, which is in general larger for prolate than oblate bands. However, when the level lifetimes are known, the absolute transtion probabilities provide a more direct measure of collectivity and allow fundamental questions such as the degree of mixing of shapes as a function of spin to be addressed. In addition to predictions of various theoretical calculations [6, 7, 17, 18], simple mixing calculations based on experimental data have been carried out for Pb and Po

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nuclei near the neutron mid-shell [12, 19, 20]. To verify these results measurements of level lifetimes are needed.

Nuclei around ^{186}Pb can be produced in heavy-ion induced fusion-evaporation reactions, thus rendering it possible to use the recoil distance Doppler-shift (RDDS) method in lifetime measurements. However, due to the very low production cross-section of these nuclei, in-beam detection of γ-rays of interest requires high selectivity. In the present work such a selectivity has been achieved by employing the recoil-decay tagging (RDT) technique [21], for the first time, in RDDS lifetime measurements. In this letter the results from the lifetime measurements of prolate yrast states up to $I^\pi = 8^+$ in ^{186}Pb and oblate yrast states up to $I^\pi = 4^+$ in ^{194}Po are presented Additionally, lifetime information in ^{188}Pb was obtained up to the 8^+ yrast state by using the recoil-gating method. This measurement essentially complements the results of an earlier RDDS measurement at Argonne National Laboratory [20], where lifetimes of the first 2^+ and 4+ states in ^{188}Pb were determined.

In the present RDDS experiments the Köln plunger device has been combined with the JUROGAM Ge-detector array and the RITU gas-filled separator [22] of the Accelerator Laboratory at the University of Jyväskylä. In the plunger device the usual stopper foil was replaced by a degrader foil allowing fusion evaporation residues to recoil into RITU and thus to be separated from other reaction products. Experimental details are listed in Table I. Due to small angle scattering in the degrader foils the transmission of RITU for the Pb and Po recoils was somewhat reduced. Fifteen JUROGAM Ge detectors were used for γ-ray detection. Separation between the fully-shifted and degraded components of the peaks in the final γ-ray spectra ranged from 1.6 keV (320 keV $2^+ \rightarrow 0^+$ transition in ^{194}Po, measured at 134°) to 6.8 keV (724 keV $2^+ \rightarrow 0^+$ transition in ^{188}Pb, measured at 158°). The beam intensity was limited to 1 - 3 pnA by the Ge detector counting rates.

The separated recoils were detected at the RITU focal plane by the GREAT spectrometer [23]. Temporal and spatial correlations of a recoil and its subsequent radioactive decay in double sided silicon strip detectors of GREAT were performed and singles RDT and recoil-gated γ-ray spectra were constructed.

In the RDDS measurement of ^{186}Pb, singles in-beam RDT γ-ray spectra tagged with the ^{186}Pb α decay ($t_{1/2}$ = 4.8 s, E_α = 6.38 MeV) were collected at 11 different target-to-degrader distances ranging from 10 μm to 1600 μm. In the corresponding measurement for the α emitter ^{194}Po ($t_{1/2}$ = 390 ms, E_α = 6.99 MeV), 13 distances ranging from 5 μm to 3000 μm were used. For ^{188}Pb, recoil-gated singles γ-ray spectra were collected at 10 target-to-degrader distances from 10 μm to 600 μm. Samples of γ-ray spectra are shown in Fig. 1. It is essential to note that in spite of the low number of events in the ^{186}Pb and ^{194}Po spectra compared to those for ^{188}Pb, the much lower background still enables resolution of the peaks of interest.

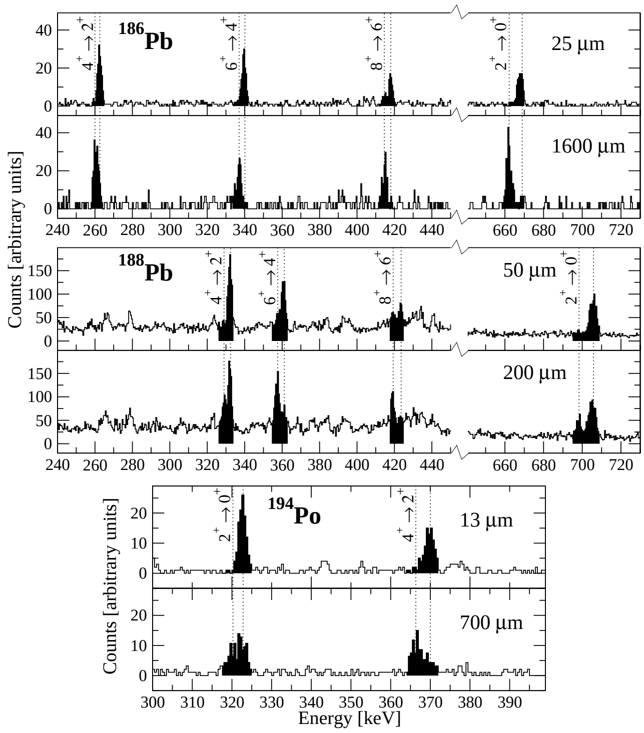

FIG. 1: Singles RDT γ-ray spectra of ^{186}Pb (two upper panels) and ^{194}Po (two lower panels) as well as recoil-gated singles γ-ray spectra of ^{188}Pb (two panels in the middle) measured at two target-to-degrader distances with five JUROGAM detectors at 158°. Dotted lines indicate the positions of the fully Doppler-shifted and degraded components of the yrast transitions presented in Table II.

The spectra of the two JUROGAM Ge detector rings were both separately analyzed by means of the differential decay curve method (DDCM) [24]. Intensities of the fully-shifted components of the transitions under investigation, recorded at different target-to-degrader distances, were normalized to the sum of the areas of the fully-shifted and degraded components. The resulting lifetime of each level is an average of the lifetimes extracted from the decay curves measured by the detector rings at 158° and 134°. Sample decay curves are illustrated in Fig. 2.

Lifetimes of the four lowest yrast states in ^{186}Pb and ^{188}Pb, and the two lowest yrast states in ^{194}Po were extracted (Table II). The time behavior of the unobserved feeding was assumed to be similar to that of the observed feeding. For most of the levels, uncertainties due to the unobserved feeding fall within the statistical error bars of the derived lifetimes. In ^{188}Pb ambiguities arise due to the relatively slow feeding of the 2^+ state from the yrast 4^+ state. The resulting value for the lifetime of the 2^+ state varies between 5 ps and 12 ps corresponding to lifetimes of unobserved feeding of 0.1 ps and 16 ps, respectively. The measured lifetime of 15.9(10) ps for

TABLE I: Experimental details. In order to maximize the transmission of RITU, several types of degrader foils were used in the ^{186}Pb measurement.

Reaction	E_{beam} [MeV]	σ	v/c	Target thickness [mg/cm^2]	Degrader(s) [mg/cm^2]	Tagging mode
^{106}Pd(^{83}Kr,3n)^{186}Pb	357	$\approx$ 280 μb	3.8%	1.0	Au: 2.6, 2.2 Al: 1.0, Mg: 1.0	RDT
^{108}Pd(^{83}Kr,3n)^{188}Pb	340	$\approx$ 1.1 mb	3.8%	0.95	Au: 2.5	Recoil gating
^{114}Cd(^{83}Kr,3n)^{194}Po	375	$\approx$ 120 μb	3.6%	1.0 + 1.0 Ta support	Mg: 1.0	RDT

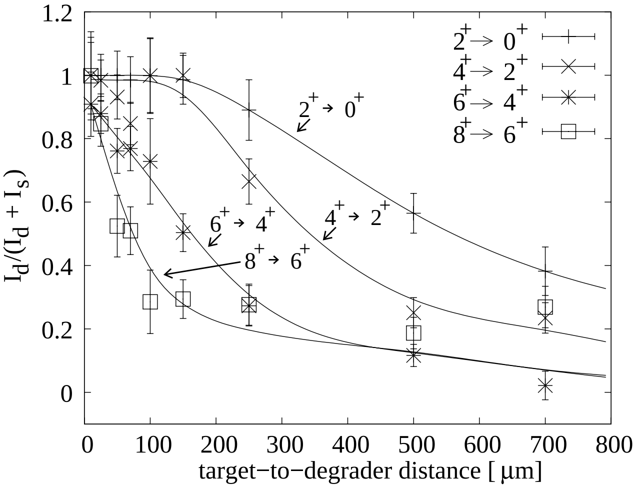

FIG. 2: Decay curves of yrast transitions in ^{186}Pb measured with ten JUROGAM detectors at 134°. The smooth lines are drawn to guide the eye.

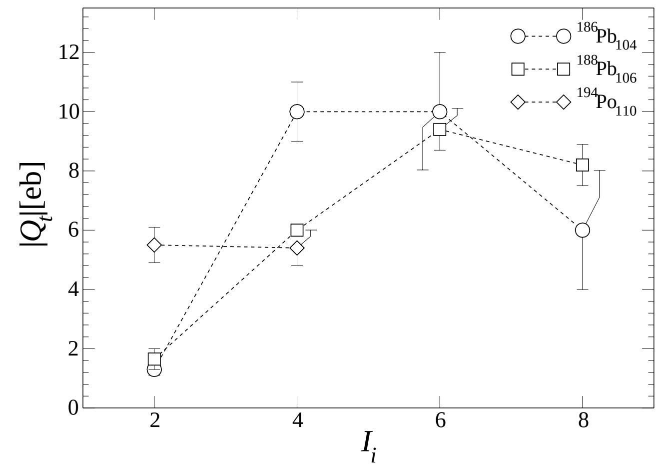

FIG. 3: Transition quadrupole moments $|Q_t|$ extracted from the present work for yrast levels in ^{186}Pb, ^{188}Pb and ^{194}Po.

TABLE II: Electromagnetic properties of the low-lying yrast states in ^{186,188}Pb and ^{194}Po.

	E_γ [keV]^a	I_i^π	τ [ps]	$B(E2)$ [W.u.]	$\lvert Q_t\rvert$ [eb]
^{186}Pb	662	2^+	18(5)	6(2)	1.3(2)
	261	4^+	18(4)	510(120)	10.3(10)
	337	6^+	6(2)	460(160)	10(2)
	415	8^+	5(2)	200(140)	6(2)
^{188}Pb	724	2^+	5 - 12	12 - 5	2.0 - 1.3
	340	4^+	15.9(10)	160(10)	6.0(2)
	370	6^+	4.0(6)	440(70)	9.4(7)
	434	8^+	2.4(4)	350(60)	8.2(7)
^{194}Po	320	2^+	37(7)	90(20)	5.5(6)
	367	4^+	14(4)	120(40)	5.4(8)

^{a}Taken from references [12, 13, 19]

the 4^+ state in ^{188}Pb is in agreement with the value of 16(8) ps obtained in Ref. [20]. In the same reference the value of 13(7) ps for the 2^+ state in ^{188}Pb obtained from the coincidence measurement would slightly favor the upper limit of 12 ps determined in the present work.

In addition to the $B(E2)$ values, Table II also gives values for the transition quadrupole moment $|Q_t|$ extracted from the experimental $B(E2)$ values defined for a rotating quadrupole-deformed nucleus. The $|Q_t|$ values of Table II are plotted in Fig. 3.

In the framework of coexistence of spherical, oblate and prolate shapes, interesting conclusions from the present results can be drawn. The weak transition strength reflects the low collectivity of the $2^+ \rightarrow 0^+$ transition supporting the concept of the unmixed spherical ground state of ^{186}Pb and ^{188}Pb. If the picture of the prolate yrast band in ^{186}Pb and ^{188}Pb is accepted, the observed high collectivity of the $4^+ \rightarrow 2^+$ yrast transition indicates a large prolate component in the 2^+ states. In ^{186}Pb this transition has a $B(E2)$ value approximately three times larger than that in ^{188}Pb, resulting in a $|Q_t|$ value as high as those for the transitions between the yrast 4^+, 6^+ and 8^+ states, assumed to be pure prolate states in both of these nuclei. This shows that the 2^+ state in ^{186}Pb is a pure member of the prolate band, whilst for the yrast 2^+ state in ^{188}Pb, a prolate contribution of 40% can be derived from the present results in a simple two-band mixing calculation as formulated in Ref. [12]. This result supports the calculations in references [6, 7, 17] where a strong admixture of the prolate and oblate structures for the 2^+ state in ^{188}Pb is deduced.

The $|Q_t|$ values extracted for the $8^+ \rightarrow 6^+$ transitions in ^{186}Pb and ^{188}Pb seem to indicate a drop of collectivity. However, taking into account the error bars collectivity may well stay on the level of that for the $6^+ \rightarrow 4^+$ transitions as expected on the basis of the smooth behavior of the moments of inertia. By using the average $|Q_t|$ value in the transitions between the pure prolate 2^+, 4^+, 6^+ and 8^+ states in ^{186}Pb and 4^+, 6^+ and 8^+ states in ^{188}Pb, a quadrupole deformation parameter $|\beta_2| = 0.29(5)$ for both of these nuclei can be extracted. This value is in agreement with the theoretical values obtained from different approaches [4, 7, 25, 26].

For ^{194}Po the present results reveal that the collectivity of the $2^+ \rightarrow 0^+$ and $4^+ \rightarrow 2^+$ transitions is much lower than in the transitions between the prolate states in ^{186}Pb and ^{188}Pb. In earlier mixing calculations based on the measured level energies [19] and α-decay hindrance factors [15], the yrast 2^+ and 4^+ states in ^{194}Po are interpreted as pure $\pi(4p-2h)$ oblate states, while the oblate component in the ground state is predicted to be around 50%. The similar $|Q_t|$ values for the $2^+ \rightarrow 0^+$ and $4^+ \rightarrow 2^+$ transitions from the present results indicate that the oblate component in the ground state could be much larger, although the near-spherical shape mixed with the oblate one in the even-mass Po isotopes is not expected to represent such a well-defined energy minimum as the ground states of the even-mass Pb isotopes. From the average of the $|Q_t|$ values for the $2^+ \rightarrow 0^+$ and $4^+ \rightarrow 2^+$ transitions, a deformation parameter $|\beta_2| = 0.17(3)$ for ^{194}Po is obtained. This is consistent with the value of $|\beta_2| \approx 0.2$ in the theoretical predictions [5, 18].

Prolate yrast bands with moments of inertia very similar to the prolate bands of ^{186}Pb and ^{188}Pb have been observed in even-mass Hg and Pt nuclei near the $N = 104$ midshell. Lifetime mesurements of yrast levels have been carried out for ^{184}Hg [27], ^{186}Hg [28] and ^{184}Pt [29]. The $|\beta_2|$ values extracted from the lifetimes of the assumed prolate states in ^{184}Hg and ^{186}Hg lie within the error bars of those in ^{186}Pb and ^{188}Pb, while the $|\beta_2|$ value for the prolate band in ^{184}Pt is remarkably smaller. In ^{184}Hg and ^{186}Hg the ground state and the lowest 2^+ and 4^+ states are assumed to represent a weakly deformed oblate shape. The lifetime measurements reveal that collectivity associated with these states is lower than that for the oblate states in ^{194}Po studied in the present work. This is obvious as in ^{184,186}Hg the low-lying oblate states are associated with a $\pi(0p-2h)$ configuration while in ^{194}Po with the $\pi(4p-2h)$ configuration.

In summary, the lifetimes of low-lying yrast states in ^{186,188}Pb and ^{194}Po have been measured in order to establish the collectivity of the bands and to extract the value of $|\beta_2|$ for both prolate and oblate shapes in the neutron deficient Pb region. As these pioneering RDDS experiments have demonstrated, the RDT technique provides essentially background-free γ-ray spectra for lifetime studies and enables the extension of the RDDS measurements to exotic nuclei near the proton-drip line with relatively low production cross section. For the 2^+ state in ^{188}Pb the $|Q_t|$ value indicates that mixing of two shapes plays a crucial role while in ^{186}Pb the present measurements reveal that the 2^+ state is a pure member of the prolate band. In ^{194}Po, the oblate component could dominate the ground state. In the heavier Po isotopes, the deformed intruder states lie higher in energy and in order to elucidate the degree of collectivity in their low-lying yrast states, further lifetime measurements would be required.

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