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In-beam studies of very neutron-deficient heavy nuclei

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Abstract. The JYFL gas-filled recoil separator RITU, combined with Ge detector arrays and a SACRED magnetic solenoid spectrometer, has been successfully employed in recoil-decay-tagging (RDT) experiments in order to probe structures of very neutron-deficient heavy nuclei. The present contribution focuses on the light Pb region where the new data extend the systematics of shape-coexisting yrast states towards the proton dripline. Similarities between band structures and their relation to possible multi-particle multi-hole intruder excitations will be discussed.

PACS. 21.10.Re Collective levels – 27.70.+q $150 \leq A \leq 189$ – 27.80.+w $190 \leq A \leq 219$ – 23.20.Lv Gamma transitions and level energies

1 Introduction

The evolution and microscopic origin of quadrupole collectivity and shape coexistence at low excitation energies in neutron mid-shell nuclei near the $Z = 50$ and $Z = 82$ shell closures is an intriguing question. The shape coexistence is usually associated with intruder states involving multi-proton excitations across the main shell gap. However, the importance of deformation driving high-j neutron orbitals in these states has also been pointed out in [1] and [2].

A review of experimental results on coexisting structures in even-mass mid-shell Cd, Sn and Te nuclei is presented in [3]. A review of new results on intruder states in neutron-deficient Hg, Pb and Po nuclei has been published very recently [4]. While the $Z = 50$ neutron mid-shell nuclei lie in the valley of stability, the mid-shell $Z \sim 82$ nuclei are very neutron deficient lying close to the proton dripline. They can be produced in fusion evaporation reactions with very low cross-sections. Fusion products can be separated from other reaction products by employing recoil separators and collected at the separator focal plane. Very important information about the shape-coexisting states in this region has been extracted in α-decay studies of fusion products, especially when detecting γ-rays or electrons in coincidence with α-particles [5,6].

The short lifetimes of α-decaying neutron-deficient $Z \sim 82$ nuclei render it possible to employ the recoil-decay-tagging (RDT) method [7] in γ-ray or electron spectroscopic studies of these nuclei. In the RDT experiments characteristic decay products from the fusion products observed at the focal plane are used to resolve prompt γ-rays or electrons emitted at the target. The method is especially powerful for in-beam studies of neutron-deficient heavy nuclei, where the recoil rate in the focal plane is low due to the low total fusion survival cross-section.

Since 1996, the RDT method has been used with great success at JYFL where the RITU gas-filled separator [8] of high transmission has been combined with various Ge detector arrays and very recently with the SACRED electron spectrometer [9,10] for in-beam studies of exotic heavy nuclei. In most of the experiments the Jurosphere array was used to detect prompt γ-rays. This array consisted of 25 Compton-suppressed Ge detectors (15 Eurogam Phase 1,

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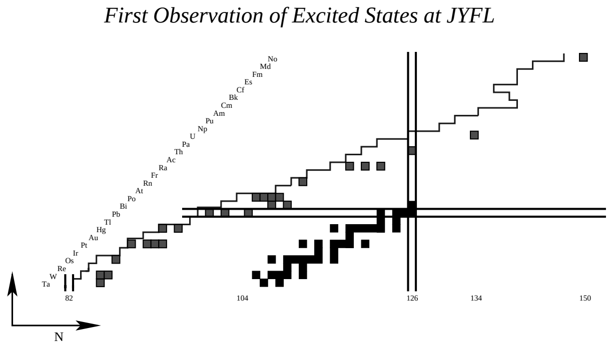

Fig. 1. A part of the chart of nuclei, where nuclei with excited states identified, for the first time, in our RDT measurements at RITU + Jurosphere have been marked with the grey squares.

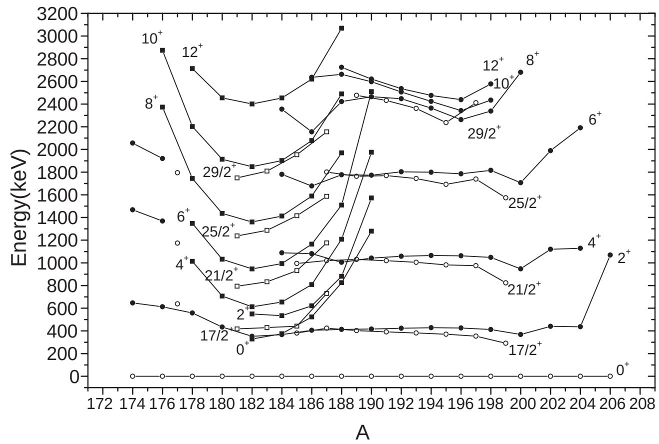

Fig. 2. Level systematics for even-mass Hg isotopes. The data for ^{174}Hg and ^{176}Hg are from the RITU + Jurosphere experiments.

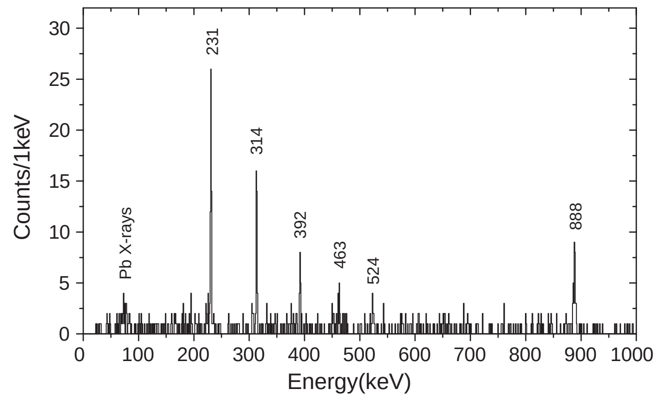

Fig. 3. A prompt γ-ray energy spectrum generated by gating with fusion evaporation residues from the ^{42}Ca + ^{144}Sm reaction and tagging with ^{182}Pb α-decays.

10 Nordball and TESSA detectors) and had a photo-peak efficiency of 1.5–1.8% for 1.3 MeV γ-rays. In addition, in most of the measurements 1-5 Ge detectors were used at the focal plane for detecting γ-ray transitions following isomeric or α-decays.

In fig. 1 those nuclides are marked, where excited states have been identified for the first time. We have shown that the RDT method employed at RITU renders in-beam γ-ray spectroscopic measurements possible at the level of a 100 nb production cross-section for heavy nuclei.

In this contribution in-beam γ-ray and electron spectroscopic data for neutron-deficient even-A Hg, Pb and Po nuclei from the latest RDT measurements at JYFL are presented and discussed with other available data for low-lying yrast levels in this region.

2 Towards spherical Hg isotopes

The RDT studies of ^{176}Hg and ^{174}Hg were carried out by using the ^{144}Sm(^{36}Ar, 4n) and ^{112}Sn(^{64}Zn, 2n) reactions, respectively. Yrast states in ^{176}Hg up to $I^\pi = (10^+)$ were indentified [11]. In ^{174}Hg three γ-rays were identified and tentatively assigned to depopulate the yrast 2^+, 4^+ and 6^+ levels [4].

The level energy systematics for even-A Hg isotopes from $N = 126$ to $N = 94$ is shown in fig. 2. In the neutron-deficient even-mass Hg isotopes the properties of the weakly oblate ground-state band remain rather constant with decreasing neutron number until in ^{188}Hg, where the band is crossed by an intruding deformed band associated with a prolate-deformed energy minimum. The prolate states, assumed to result from the excitation of four protons across the $Z = 82$ shell gap, minimise their energies in ^{182}Hg [12], but still lie above the ground state. In accordance with theoretical predictions [13], a further increase in the excitation energy of the prolate band was observed in ^{178}Hg [14]. Our data for ^{176}Hg [11] revealed that this increase between $N = 98$ and 96 is already 500 keV. Therefore, in the new data for ^{174}Hg no trace of a prolate band can be seen. The energies of the first-excited 2^+ and 4^+ states in ^{176}Hg and ^{174}Hg lie higher than in any other Hg isotope with $N < 126$ indicating a transition towards a spherical ground state as predicted in ref. [13].

3 Even-mass Pb isotopes beyond the neutron mid-shell

A very clean energy spectrum of prompt γ-rays shown in fig. 3 was obtained for ^{182}Pb from the ^{144}Sm(^{42}Ca, 4n) reaction by employing the RDT technique [15].

The most intense 888 keV line in the spectrum obviously represents the $2^+ \rightarrow 0^+$ transition. The other five transitions clearly form a rotational band similar to those built on the 2^+ states in ^{184,186,188}Pb and therefore they are tentatively assigned as $E2$ transitions. The regular spacing of the transitions indicate that the band is not much disturbed by possible mixtures of other shape-coexisting states.

The plot of aligned angular momenta, i_x in fig. 4, shows that, indeed, the intruder bands seen in $^{182-188}$Pb are similar to those in $^{180-184}$Hg and are therefore associated with

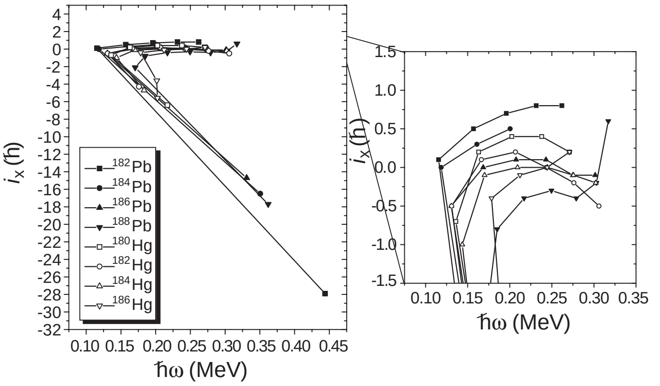

Fig. 4. Plots of aligned angular momentum, i_x, as a function of rotational frequency, for the even-A $^{182\text{-}188}$Pb and $^{180\text{-}184}$Hg. Rotational references with Harris parameters of $J_0 = 27\hbar^2\,\mathrm{MeV}^{-1}$ and $J_1 = 199\hbar^4\,\mathrm{MeV}^{-3}$ have been subtracted.

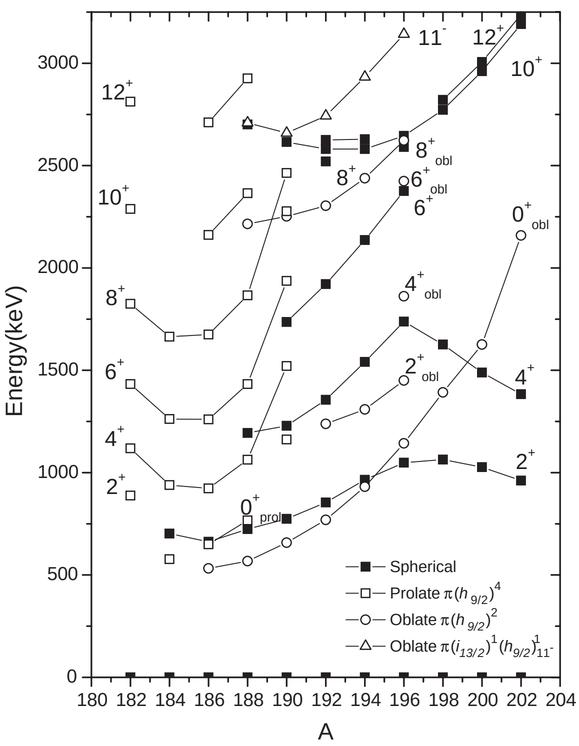

Fig. 5. Level systematics for even-mass Pb isotopes. The data for ^{182}Pb and ^{184}Pb (except the 0_2^+ state) are from the RITU + Jurosphere experiments.

a prolate shape. The alignment slightly increases with decreasing neutron number, indicating an increase of collectivity. This increase is more pronounced in Pb nuclei.

In the level systematics of fig. 5 the new ^{182}Pb JYFL data along with the data from an earlier JYFL RDT experiment for ^{184}Pb [16] are shown together with the available data for heavier even-A Pb isotopes. Our data reveal that the minimum excitation energy of the prolate band is reached at $N = 103$, exactly as for the prolate structures in the even-A Hg nuclei.

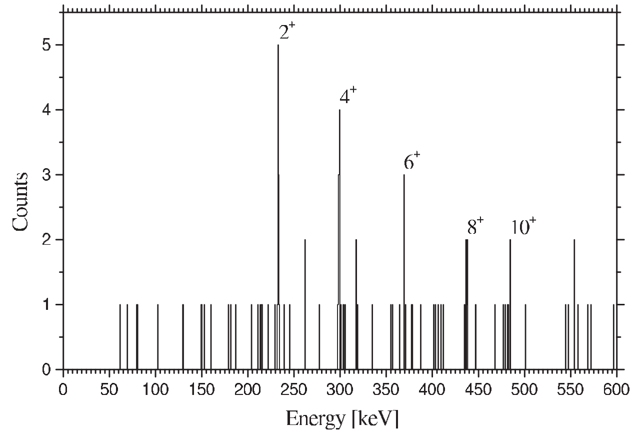

Fig. 6. A preliminary energy spectrum of prompt γ-rays obtained by gating with fusion evaporation residues from the ^{52}Cr + ^{142}Nd reaction and by tagging with ^{190}Po α-decays.

4 Shape changes in light Po nuclei

In earlier RDT measurements at JYFL ^{192,193,194,195}Po nuclei were studied with various Ge detector arrays at RITU [17]. The data revealed that the deformed intruder structures, associated with oblate deformation and 2p-2h configurations, become yrast and dominate in the ground-state configuration of ^{192}Po.

On the basis of level systematics and mixing calculations [17] a 0_2^+ state should be the first-excited state in ^{194}Po. This state could be missed in the γ-ray experiments. Therefore, in a very recent experiment we employed the collinear SACRED magnetic solenoid spectrometer combined with RITU to detect prompt conversion electrons [18] from the possible $E0(0_2^+ \to 0_1^+)$ transition. In a recoil-gated and α-tagged electron spectrum from the $^{171}\mathrm{Yb}(^{28}\mathrm{Si}, 5\mathrm{n})^{194}$Po reaction a candidate electron line is seen which could represent such an $E0$ transition from a 0_2^+ at about 220 keV in ^{194}Po. More experiments are needed for confirming this result.

In a recent Jurosphere + RITU campaign we carried out an RDT experiment to observe yrast transitions in ^{190}Po [19] via the $^{142}\mathrm{Nd}(^{52}\mathrm{Cr}, 4\mathrm{n})$ reaction. The ^{190}Po α-decays were used to tag prompt γ-rays resulting in a preliminary spectrum shown in fig. 6.

The peak pattern of this spectrum can be assigned to an yrast $E2$ cascade in ^{190}Po. It is intriguing that the γ-rays from the 10^+, 8^+ and 6^+ states are close in energy to those for the prolate band in the isotone, ^{188}Pb. Consequently, the new data for ^{190}Po reveal, for the first time, prolate structures becoming yrast in ^{190}Po.

In fig. 7, energies of yrast levels of even-mass neutron-deficient Po nuclei are shown together with the observed level structure built on top of the $13/2^+$ state in odd-mass Po nuclei. The data for ^{191}Po, ^{193}Po and ^{195}Po are from Jurosphere + RITU measurements [17,20].

Especially in the lightest isotopes the level patterns of the odd-mass nuclei are close to the ones of the adjacent even-mass isotopes. This indicates a weak coupling of the $i_{13/2}$ neutron to the even-mass core which could

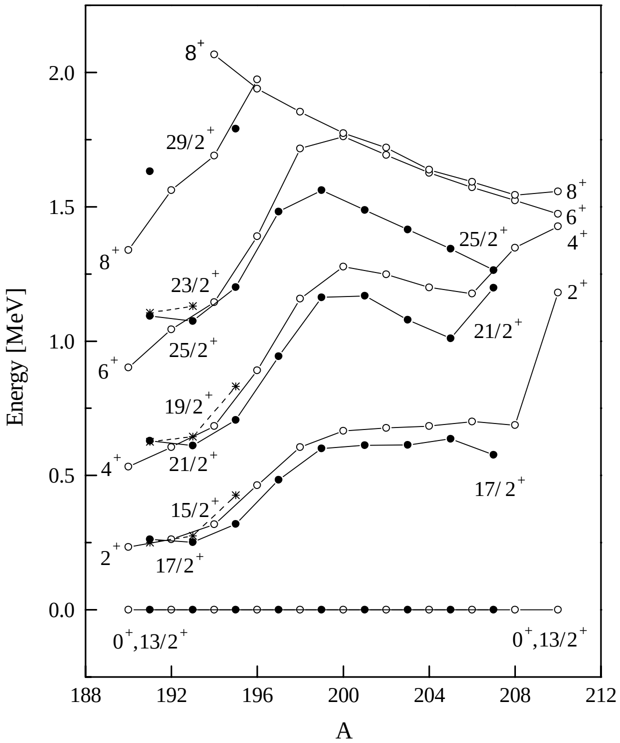

Fig. 7. Energies of the yrast levels of the even-mass $^{190\text{-}210}$Po nuclei (open circles) together with the levels on top of the $13/2^+$ states in the odd-mass $^{191\text{-}207}$Po nuclei; filled circles denote the favoured states and the asterisks the unfavoured ones.

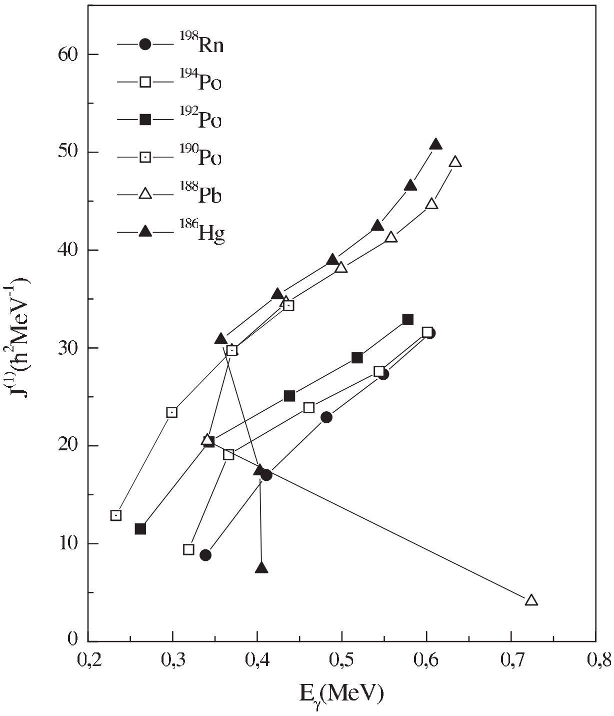

Fig. 8. Kinematic moments of inertia for the yrast line of the even-A $^{190\text{-}194}$Po nuclides compared to the ones for ^{186}Hg, ^{188}Pb and ^{198}Rn.

be regarded as a coupling of the odd $i_{13/2}$ neutron to a vibrating spherical core or, in accordance with the rotational and intruder picture, as a decoupling of an $i_{13/2}$ neutron hole (low Ω) from the oblate core.

In ^{191}Po, ^{193}Po and ^{195}Po candidates were found for the unfavoured $15/2^+$, $19/2^+$ and $23/2^+$ states of the $i_{13/2}$ band. In ^{193}Po the unfavoured states come down closer to and in ^{191}Po even below the favoured states indicating a change towards a strong-coupling scheme when the number of neutron holes increases. This behaviour is as expected for oblate deformation and in agreement with the picture of the onset of oblate deformation at low spin in light Po nuclei with $N \approx 108$. Increase of the energies of the favoured states (fig. 7) when going to ^{191}Po evidences a change in the coupling of the $i_{13/2}$ neutron, possibly reflecting the oblate-prolate shape change observed in the ^{190}Po core.

5 Discussion

In fig. 8, values $J^{(1)}$ of the kinematic moment of inertia as a function of γ-ray transition energy derived from the yrast level energies of the even-A $^{190\text{-}194}$Po nuclei are plotted with those for ^{186}Hg, ^{188}Pb and ^{198}Rn.

Similarities between the prolate bands in the mid-shell Hg and Pb nuclei were already shown by fig. 4. The $J^{(1)}$ values for ^{190}Po are very close to the values for isotones ^{186}Hg and ^{188}Pb showing that indeed the yrast line of ^{190}Po represents a prolate structure very similar to the ones seen in Hg and Pb nuclei. The $J^{(1)}$ values for the oblate intruder yrast band of ^{192}Po and ^{194}Po are smaller and similar to the yrast band in ^{198}Rn indicating that similar oblate deformation as in Po nuclei sets in light even-A Rn isotopes [17].

An application of the simple intruder-spin concept, related to the multi-proton excitations across the $Z = 82$ shell gap, has not been straightforward [21]. The intruder 0^+ states observed in decay studies [5] down to ^{196}Po are associated with the oblate proton 4p-2h intruder configuration. On the basis of systematics (fig. 7) it is obvious that the observed band structures in ^{194}Po and ^{192}Po can be assigned to be based on this structure. However, it is not clear whether there are any corresponding 2p-4h oblate states in the even-A Hg isotones. There are well-known oblate intruder 0^+ states observed in Pb isotopes [22] which are of the proton 2p-2h origin, but no clear band structure is observed on these states.

As proposed earlier and discussed in refs. [13] and [21], the prolate shapes in the mid-shell $Z = 82$ region can be assigned to proton np-nh excitations. In accordance with the intruder-spin picture, the observed prolate structure in ^{190}Po resembles the one in ^{186}Hg and could represent the 6p-4h and 4p-6h excitations, respectively. However, to explain the similarity between these bands and the prolate bands in even-A Pb nuclei, mixing of different np-nh configurations is needed [13] and [21].

Finally, it is interesting that some of the observed properties of even-A nuclei near the neutron mid-shell can also be associated with features of quadrupole vibrational nuclei. This was pointed out in ref. [2] for ^{196}Po and further discussed in ref. [17], where the level properties of ^{194}Po provided evidence in support of the phonon picture.

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