JYVÄSKYLÄN YLIOPISTO
UNIVERSITY OF JYVÄSKYLÄ

This is a self-archived version of an original article. This version may differ from the original in pagination and typographic details.

Author(s): Julin, R.; Greenlees, P.T.; Helariutta, K.; Jones, P.; Juutinen, S.; Kankaanpää, H.; Ieenan, A.; Kettunen, H.; Kuusiniemi, P.; Leino, M.; Muikku, M.; Nlbminen, P.; Rahkila, P.; Uusitalo, J.; Joss, D.T.; Williams, S.J.; Kelsall, N.-S.; Wadsworth, R.; Hauschild, K.; Hünstel, A.; Korten, W.; Lecoz, Y.; Andreyev, A.N.; Van Vel, K.D.E.; Moore, C.J.; O'Leary, C.D.; Page, R.D.; Taylor, M.J.; Reviol, W.; Smith, M.B.

Title: Probing Structures of Exotic Heavy Nuclei

Year: 2001

Version: Published version

Copyright: © 2001 Jagellonian University

Rights: CC BY 4.0

Rights url: https://creativecommons.org/licenses/by/4.0/

Please cite the original version:

Julin, R., Greenlees, P.T., Helariutta, K., Jones, P., Juutinen, S., Kankaanpää, H., Ieenan, A., Kettunen, H., Kuusiniemi, P., Leino, M., Muikku, M., Nlbminen, P., Rahkila, P., Uusitalo, J., Joss, D.T., Williams, S.J., Kelsall, N.-S., Wadsworth, R., Hauschild, K., . . . Smith, M.B. (2001). Probing Structures of Exotic Heavy Nuclei. Acta Physica Polonica B, 32(3), 645-655.
https://www.actaphys.uj.edu.pl/R/32/3/645

Vol. 32 (2001) *ACTA PHYSICA POLONICA B* No 3

PROBING STRUCTURES OF EXOTIC HEAVY NUCLEI*

R. Julin[a], P.T. Greenlees[a], K. Helariutta[a], P. Jones[a]
S. Juutinen[a], H. Kankaanpää[a], A. Keenan[a], H. Kettunen[a]
P. Kuusiniemi[a], M. Leino[a], M. Muikku[a], P. Nieminen[a]
P. Rahkila[a], J. Uusitalo[a], D.T. Joss[b], S.J. Williams[b]
N-S. Kelsall[c], R. Wadsworth[c], K. Hauschild[d], A. Hürstel[d]
W. Korten[d], Y. LeCoz[d], A.N. Andreyev[e], K. Van de Vel[e]
C.J. Moore[f], C.D. O'Leary[f], R.D. Page[f], M.J. Taylor[f]
W. Reviol[g] and M.B. Smith[h]

[a]Department of Physics, University of Jyväskylä, 40351 Finland

[b]School of Sciences, Staffordshire University, Staffordshire, UK

[c]Department of Physics, University of York, York, UK

[d]CEA Saclay, DAPNIA/SPhN, France

[e]Instituut voor Kern- en Stralingsfysica, University of Leuven, Belgium

[f]Department of Physics, University of Liverpool, UK

[g]Department of Physics, University of Tennessee, Knoxville, Tennessee, USA

[h]Department of Physics and Astronomy, Rutgers University, New Jersey, USA

(Received November 20, 2000)

The JYFL gas-filled recoil separator RITU, combined with Ge detector arrays, has successfully been employed in Recoil-Decay-Tagging (RDT) experiments in order to probe, for the first time, structures of several very neutron deficient heavy nuclei. In this contribution new data for light even-mass Hg, Pb and Po nuclei are shown and discussed.

PACS numbers: 21.10.Re, 27.70.+q, 27.80.+w, 23.20.Lv

---

[*] Presented at the XXXV Zakopane School of Physics "Trends in Nuclear Physics", Zakopane, Poland, September 5–13, 2000.

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 are still not fully understood. In some of these nuclei, deformed intruder states coexist with nearly spherical normal states [1], while, for example, in even-mass Cd nuclei the intruder structures clearly play a role in generating low-lying quadrupole phonon states [2]. These intruder structures are usually associated with 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 [3] and [4].

A review of experimental results on coexisting structures in even-mass mid-shell Cd, Sn and Te nuclei is presented in [2]. While these nuclei in the $Z = 50$ region lie in the valley of stability, the neutron mid-shell $Z \sim 82$ nuclei are very neutron deficient lying close to the proton drip line. They can be produced in fusion evaporation reactions, albeit, due to strong fission competition, 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 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 the products have emitted at the target. The method is especially powerful in in-beam studies of neutron deficient heavy nuclei, where the recoil-rate at the focal plane is low due to the low total fusion cross-section. During the last five years the RDT method has been used with great success at JYFL where the RITU gas-filled separator [8] of high transmission and various Ge detector arrays have been combined 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, 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.

Since 1997, about 50 recoil-tagging or RDT experiments have been carried out at RITU. In those experiments structures of neutron deficient nuclei close to $Z = 82$ have been probed. They also include unique experiments

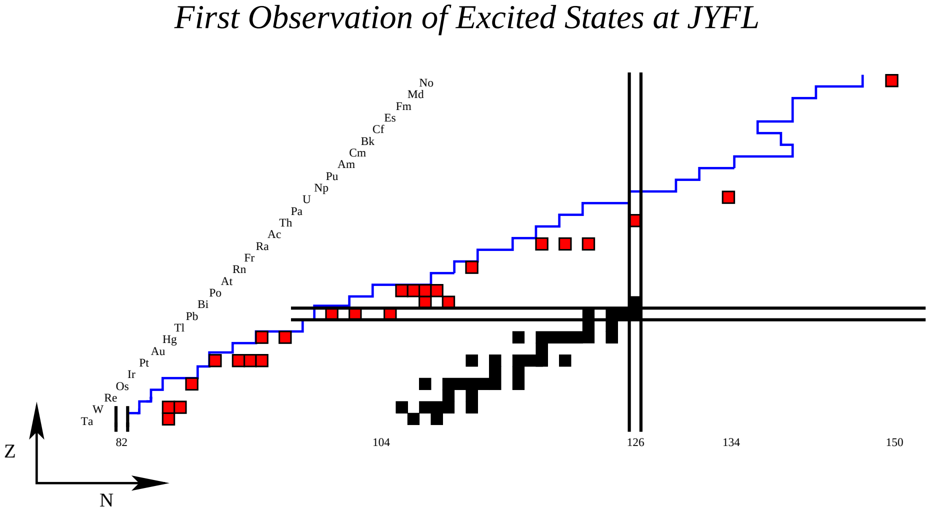

Fig. 1. A part of the chart of nuclei, where nuclei with excited states identified, for the first time, in our RDT measurements at RITU+Jurosphere have been marked with the grey squares.

where γ-rays from ^{254}No and ^{252}No have been observed [9]. In Fig. 1 those nuclides are marked, where excited states have been identified for the first time. In these experiments we have shown that the RDT method employed at RITU render in-beam γ-ray spectroscopic measurements possible at the level of 100 nb production cross-section for heavy nuclei.

In this contribution in-beam γ-ray 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

In an earlier RDT study we observed yrast states in ^{176}Hg up to $I^{\pi} = (10^{+})$ via the ^{144}Sm(^{36}Ar, $4n$) reaction with cross-section of about 5 μb [10]. To extend the systematics more beyond the $N = 104$ mid-shell we recently carried out an RDT study for ^{174}Hg, which was populated in the ^{112}Sn(^{64}Zn, $2n$) reaction with cross-section of only 230 nb. Due to target problems only about 900 full-energy ^{174}Hg α-decays ($t_{1/2} = 1.7(4)$ ms) were recorded. In Fig. 2 γ-ray energy spectrum obtained by gating with recoils and tagging with ^{174}Hg α-decays is shown. The most intense 647 keV peak is assigned as the $2^{+} \to 0^{+}$ transition in ^{174}Hg. On the basis of energy systematics the next most intense lines at 821 keV and 588 keV are tentatively associated with the $4^{+} \to 2^{+}$ and $6^{+} \to 4^{+}$ transitions in ^{174}Hg, respectively.

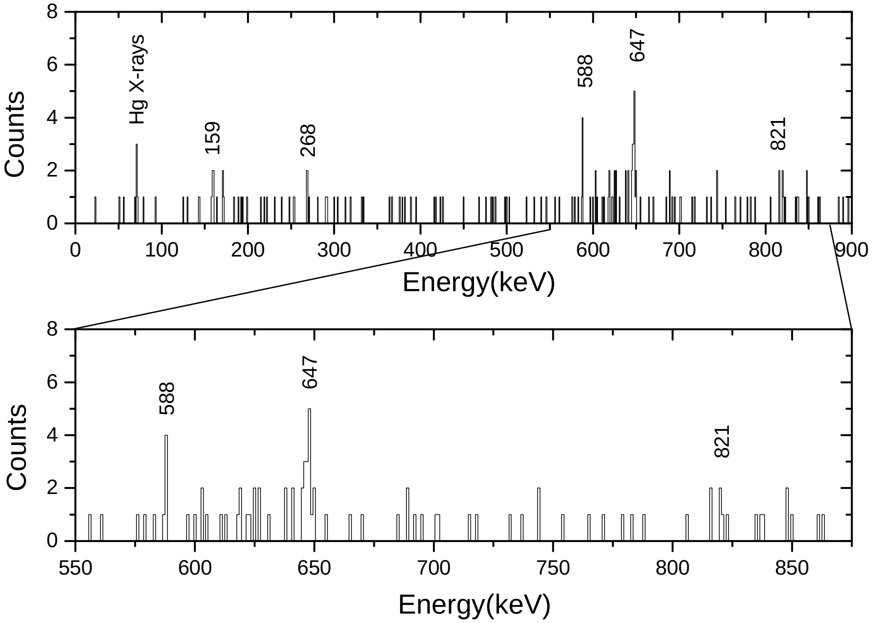

Fig. 2. An energy spectrum of prompt γ-rays obtained by gating with fusion evaporation residues from the ^{64}Zn + ^{112}Sn reaction and by tagging with ^{174}Hg α-decays.

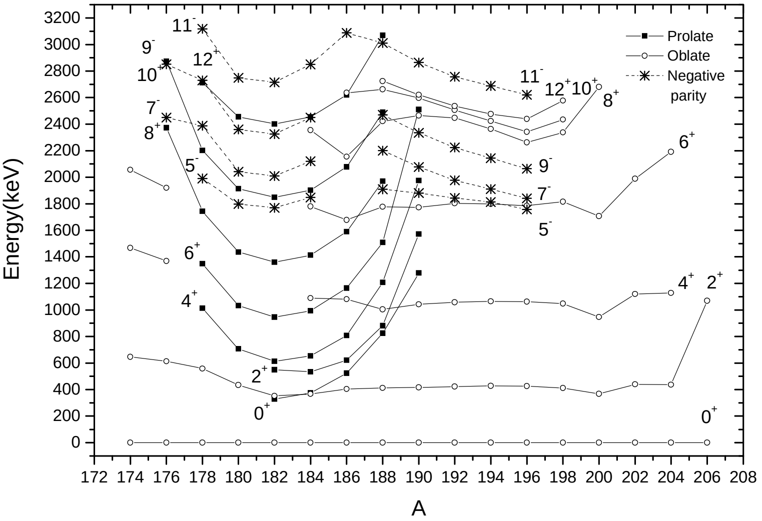

Fig. 3. Level systematics for even-mass Hg isotopes. The data for ^{174}Hg and ^{176}Hg are from the RITU+Jurosphere experiments.

The level-energy systematics for even-A Hg isotopes from $N = 126$ to $N = 94$ is shown in Fig. 3. 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 [11], but still lie above the ground state. In accordance with theoretical predictions [12], a further increase in the excitation energy of the prolate band was observed in ^{178}Hg [13]. Our data for ^{176}Hg [10] 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. [12].

3. Two shapes of ^{182}Pb$_{100}$

In a recent RDT experiment dedicated to the study of ^{182}Pb we used the ^{144}Sm(^{42}Ca,4n) fusion evaporation channel and recorded 3500 ^{182}Pb α-decays [14]. The extracted cross-section was about 300 nb and the ^{182}Pb half-life $t_{1/2} = 64(7)$ ms is in accordance with the earlier value of 55 ms [15]. The RDT analysis resulted in a very clean energy spectrum of prompt γ-rays shown in Fig. 4.

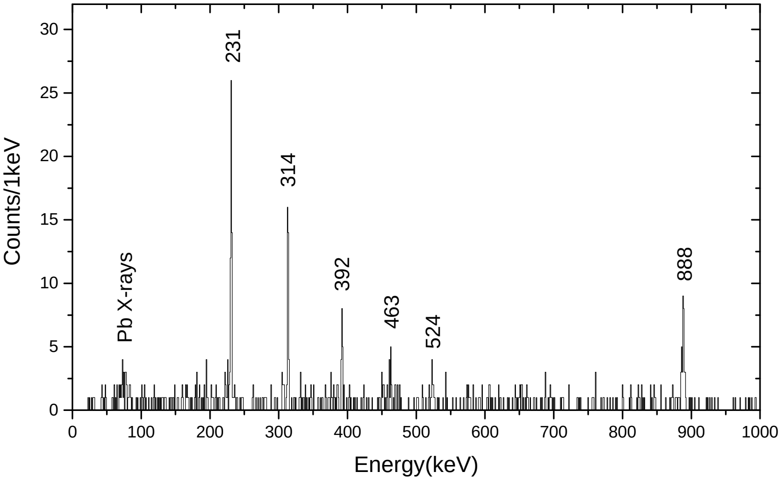

Fig. 4. A prompt γ-ray energy spectrum generated by gating with fusion evaporation residues from the ^{42}Ca + ^{144}Sm reaction and tagging with ^{182}Pb α-decays.

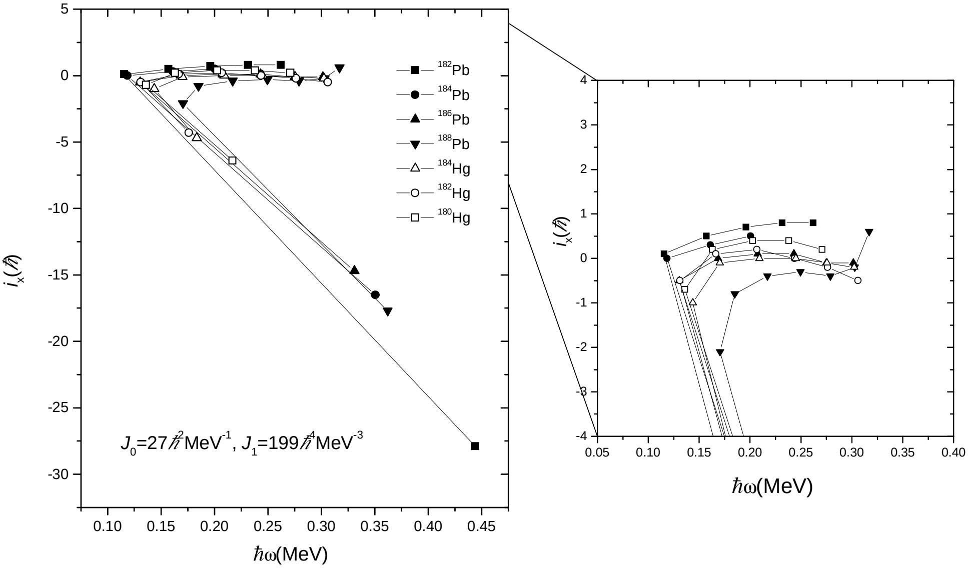

Fig. 5. Plots of aligned angular momentum, $\boldsymbol{i}_x$, as a function of rotational frequency, for the even-A $^{182-188}$Pb and $^{180-184}$Hg. Rotational references with Harris parameters of $J_0 = 27\ \hbar^2\mathrm{MeV}^{-1}$ and $J_1 = 199\hbar^4\mathrm{MeV}^{-3}$ have been subtracted.

The six lines marked in the spectrum are firmly assigned to originate from ^{182}Pb. The most intense 888 keV line obviously represents the $2^+ \to 0^+$ 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, $\boldsymbol{i}_x$, show that, indeed, the intruder bands seen in $^{182-188}$Pb are similar to those in $^{180-184}$Hg and are therefore associated with 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. 6 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.

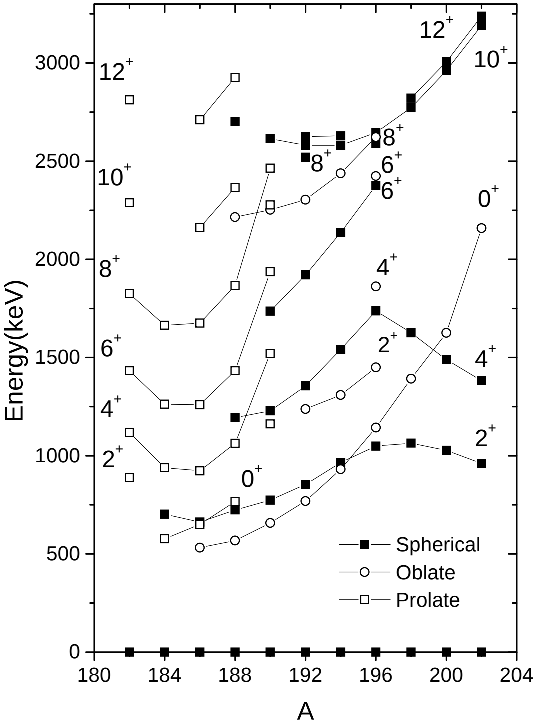

Fig. 6. Level systematics for even-mass Pb isotopes. The data for ^{182}Pb and ^{184}Pb (except the 0_2^+ state) are from the RITU+Jurosphere experiments.

4. Towards prolate Po isotopes

The first highlight in the series of successful RDT measurements at JYFL was the first observation of yrast transitions in ^{192}Po with the DORIS Ge detector array at RITU [17]. The data revealed that the deformed intruder structures, associated with oblate deformation, have become yrast and dominate in the ground-state configuration of ^{192}Po.

In a very recent Jurosphere+RITU campaign we carried out an RDT experiment to observe yrast transitions in ^{190}Po [18]. A ^{142}Nd target was bombarded with a ^{52}Cr beam and excited states in ^{190}Po were produced via the $4n$-fusion-evaporation channel with cross-section of about 200 nb. The ^{190}Po α-decays were used to tag prompt γ-rays resulting in a preliminary spectrum shown in Fig. 7.

In this spectrum clear peaks are observed at 233, 299, 370, and 437 keV and possibly also at 485 keV. Based on the intensity behaviour and regularity of the γ-ray lines we preliminarily associate this pattern with an yrast E2 cascade in ^{190}Po. By combining this information with available data for

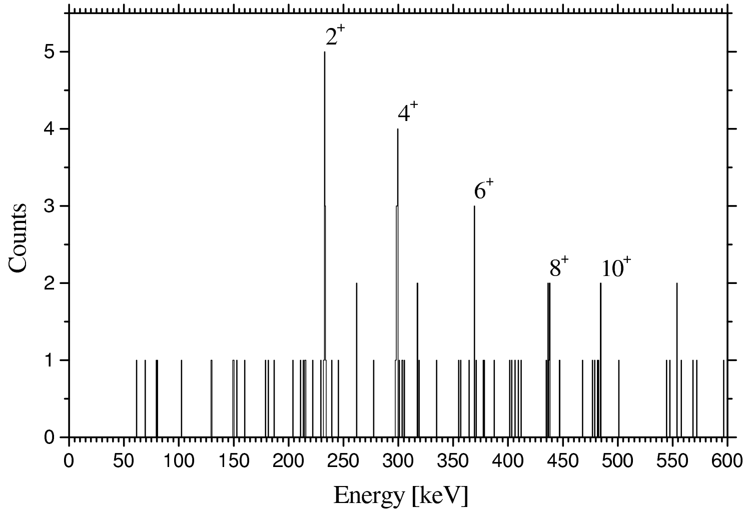

Fig. 7. A preliminary energy spectrum of prompt γ-rays obtained by gating with fusion evaporation residues from the ^{52}Cr + ^{142}Nd reaction and by tagging with ^{190}Po α-decays.

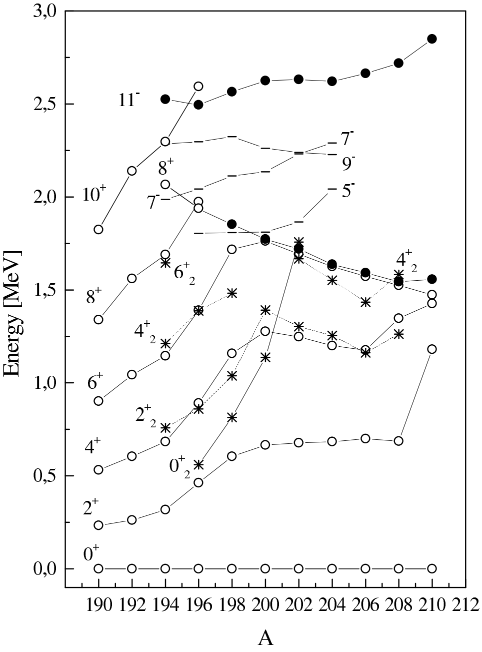

Fig. 8. Level systematics for even-mass Po isotopes. The data for ^{190}Po, ^{192}Po and partially ^{194}Po are from the RITU+Jurosphere experiments. The open circles denote the positive parity yrast levels, the asterisks the non-yrast ones and the bars the negative parity levels. The isomeric states are denoted by the filled circles.

heavier even-A Po isotopes, the level systematics of the even-A Po nuclei shown in Fig. 8 is obtained. The expected levelling off of the level energies when moving to ^{190}Po is observed only for the 2^+ states. For other higher-spin yrast levels a drop of energies is seen. In fact the transitions from the 10^+, 8^+ and 6^+ states are close in energy to those for the prolate band in the isotone, ^{188}Pb . Consequently, our new data for ^{190}Po reveal, for the first time, prolate structures becoming yrast in ^{190}Po.

5. Discussion

In Fig. 9, 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 $^{190-194}$Po nuclei are plotted with those for ^{186}Hg, ^{188}Pb and ^{198}Rn.

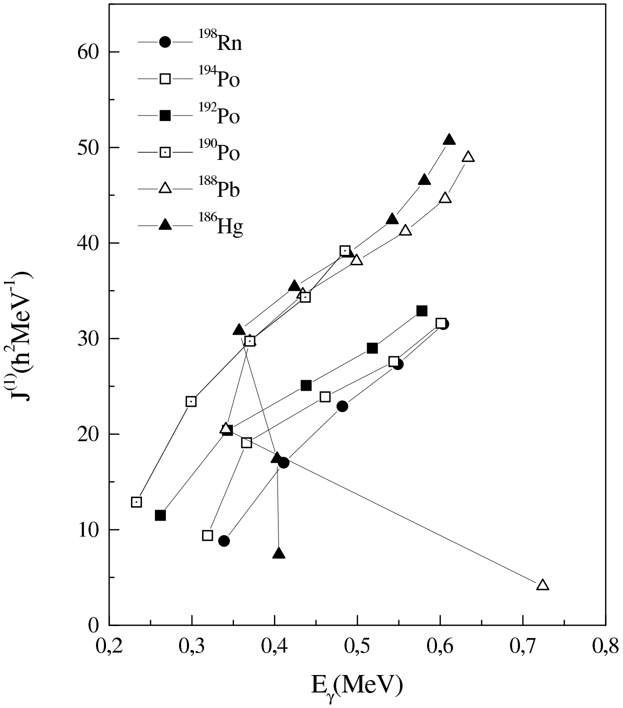

Fig. 9. Kinematic moments of inertia for the yrast line of the even-A $^{190-194}$Po nuclides compared to the ones for ^{186}Hg, ^{188}Pb and ^{198}Rn.

Similarities between the prolate bands in the mid-shell Hg and Pb nuclei were already shown by Fig. 5. 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 in light even-A Rn isotopes [19].

The experimentally observed shape coexistence in the neutron mid-shell $Z = 82$ region is well predicted by the calculations using a deformed mean-field approach: The light Hg and Pb nuclei in Refs. [12] and [20] and the light Po nuclei including the onset of prolate deformation in Refs. [21] and [22].

An application of the simple intruder-spin concept, related to the multi-proton excitations across the $Z = 82$ shell gap, has not been straightforward [23]. 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. 8) 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 [24] 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. [12] and [23], 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 are needed [12] and [23].

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. [4] for ^{196}Po and further discussed in Ref. [19], where the level properties of ^{194}Po provided evidence in support of the phonon picture.

This work has been supported by the Academy of Finland under the Finnish Centre of Excellence Programme 2000–2005 (Project No. 44875, Nuclear and Condensed Matter Programme at JYFL) and by the European Union Fifth Framework Programme "Improving Human Potential — Access to Research Infrastructure".

REFERENCES

[1] J.L. Wood *et al.*, *Phys. Rep.* **215**, 101 (1992).

[2] R. Julin, *Phys. Scr.* **T56**, 151 (1995).

[3] S. Juutinen *et al.*, *Nucl. Phys.* **A573**, 306 (1994).

[4] L.A. Bernstein *et al.*, *Phys. Rev.* **C52**, 621 (1995).

[5] N. Bijnens *et al.*, *Phys. Rev. Lett.* **75**, 4571 (1995).

[6] A.N. Andreyev *et al.*, *Phys. Rev. Lett.* **82**, 1819 (1999).

[7] E.S. Paul *et al.*, *Phys. Rev.* **C51**, 78 (1995).

[8] M.E. Leino *et al.*, *Nucl. Instrum. Methods Phys. Res.* **B99**, 653 (1995).

[9] M.E. Leino *et al.*, *Eur. Phys. J.* **A6**, 289 (1999); R.-D. Herzberg *et al.*, to be published.

[10] M. Muikku *et al.*, *Phys. Rev.* **C58**, R3033 (1998).

[11] G.D. Dracoulis *et al.*, *Phys. Lett.* **B208**, 365 (1988).

[12] W. Nazarewicz, *Phys. Lett.* **B305**, 195 (1993).

[13] M. Carpenter *et al.*, *Phys. Rev. Lett.* **78**, 3650 (1997).

[14] D. Jenkins *et al.*, *Phys. Rev.* **C62**, 021302(R) (2000).

[15] K.S. Toth *et al.*, *Phys. Rev.* **C60**, 011302(R) (1999).

[16] J. Cocks *et al.*, *Eur. Phys. J.* **A3**, 17 (1998).

[17] K. Helariutta *et al.*, *Phys. Rev.* **C54**, R2799 (1996).

[18] K. Van de Vel *et al.*, to be published.

[19] K. Helariutta *et al.*, *Eur. Phys. J.* **A6**, 289 (1999).

[20] R. Bengtsson, W. Nazarewicz, *Z. Phys.* **A334**, 269 (1989).

[21] F.R. May *et al.*, *Phys. Lett.* **B68**, 113 (1977).

[22] A.M. Oros *et al.*, *Nucl. Phys.* **A465**, 107 (1999).

[23] C. De Coster *et al.*, *Phys. Rev.* **C61**, 067306 (2000).

[24] N. Bijnens *et al.*, *Z. Phys.* **A356**, 3 (1996).