COLLECTIVITY IN LIGHT Po ISOTOPES REVEALED IN RECOIL-DECAY-TAGGING EXPERIMENTS*

M. LEINO

and the Jurosphere Collaboration

University of Jyväskylä, Department of Physics
PB 35 (YFL) FIN-40351 Jyväskylä, Finland

(Received May 19, 2001)

It was predicted already more than 20 years ago that coexisting oblate- and prolate-shaped minima should come down in energy in neutron-deficient polonium isotopes around ^{192}Po. Progress in experimental techniques, and in particular in the use of the Recoil-Decay-Tagging method, has made it possible to verify these predictions. Recent RDT results obtained at the University of Jyväskylä on shape coexistence in very neutron-deficient Po isotopes will be discussed.

PACS numbers: 21.60.Ev, 23.20.Lv, 27.80.+w

1. Introduction

Polonium nuclei with two protons on top of the spherical-driving closed $Z = 82$ shell exhibit a variety of nuclear structure phenomena. Especially, the interplay between single particle and collective effects can be studied in the light Po nuclei. Neutron-deficient Po nuclei have been predicted to develop an oblate ground state at $N = 108$ (^{192}Po) and a prolate ground state at $N = 106$ (^{190}Po) [1]. They should thus provide us with a useful laboratory for studying nuclear shape coexistence.

During the last few years, there has been a significant increase in our knowledge about the structure of light polonium nuclei. Alpha decay fine structure studies of Rn and Po isotopes have revealed the existence of intruder states in the respective Po and Pb daughter nuclei [2]. This work has been beautifully complemented by in-beam gamma-ray experiments [3, 4]. It is very important to be able to combine decay and in-beam data for a consistent view on nuclear structure in this region. In the general case, spherical, oblate and prolate structures contribute to the observed spectra

---

* Invited talk presented at the *High Spin Physics 2001* NATO Advanced Research Workshop, dedicated to the memory of Zdzisław Szymański, Warsaw, Poland, February 6–10, 2001.

and transition rates. Three-level mixing calculations can then be performed on the basis of measured alpha decay hindrance factors and extrapolated unperturbed band head energies from in-beam data [5, 6] to give us the interaction strengths and level mixings.

In view of the intruder spin concept [7], the structure of Po nuclei should be closely related to that of Hg nuclei with two proton holes in the $Z = 82$ shell. A similar case to Po and Hg nuclei is provided by the Te and Cd nuclei [8]. In mid-shell Cd nuclei, it has been observed that intruder structures are important in generating low-lying quadrupole phonon states [9]. Experimentally, these two regions present very different challenges since in the tin region the neutron mid-shell is at the beta stability line while in the lead region it is situated close to the border of the known region of nuclei.

In-beam work is getting increasingly difficult as one approaches the proton drip line because the production rates of these exotic nuclei are very low and the gamma-ray background from the dominating fission channel is overwhelming. First steps to overcome the fission problem were taken with the aid of recoil catcher [10] and recoil filter [11] techniques. The most recent experimental development has been the introduction of the Recoil-Decay-Tagging, or RDT-technique [12]. The idea behind the method is that multi-detector Ge arrays are combined with highly efficient and very fast on-line recoil separators. Gamma-ray emitting nuclei emerging from a thin target are separated and identified using their characteristic decay at the focal plane of the separator. Only those prompt gamma-rays are then accepted for analysis which are in coincidence with the desired nuclei. The method can be complemented with isomer identification at the focal plane [13]. A very recent extension of the method is the measurement of RDT conversion electrons. This method has for the first time been employed at JYFL (University of Jyväskylä, Department of Physics) for the study of heavy nuclei [14, 15].

The low-lying level structure of the nuclide ^{210}Po with nothing but two protons added to the doubly-magic ^{208}Pb nucleus is a good example of a two-particle $j = 9/2$ system with the characteristic group of 2^+, 4^+, 6^+, and 8^+ levels located at about 1.2–1.6 MeV above the 0^+ ground state [16]. As neutrons are removed from the system, the 2^+ energy drops down to about 700 keV already at ^{208}Po and stays approximately constant down to ^{200}Po. The pair of levels with $I^\pi = 6^+$ and 8^+ stay very close together in energy and rise steadily all the way to ^{200}Po. In the isotopes $^{200-206}$Po, the 4^+ level rises smoothly when the number of neutron holes increases and stays roughly equidistant from both the 2^+ level and the 6^+ level. (The level systematics of even–even Po nuclei is shown in Fig. 1.) At $N = 114$, corresponding to ^{198}Po, the above described smooth trends change. The

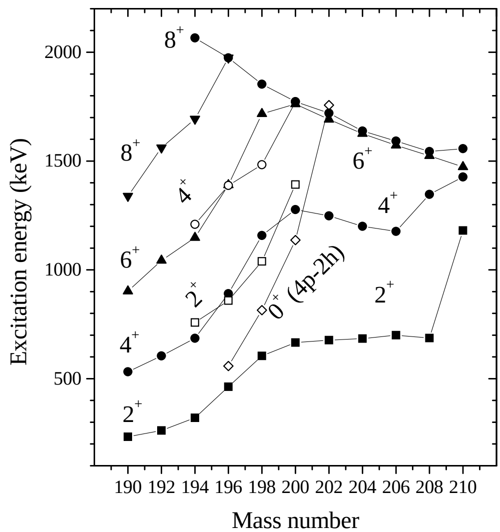

Fig. 1. Energies of selected low-lying levels of the even–even $^{190-210}$Po nuclei. Non-yrast states are marked by open symbols. The data are from Refs. [3, 17, 18] and references therein.

2^+_1, 4^+_1 and 6^+_1 levels drop down in energy so that they form an almost evenly spaced group of levels relative to the ground state. The down-sloping continues at ^{196}Po. In addition, second excited 2^+ and 4^+ states were observed in $^{194-200}$Po. In ^{194}Po, and in particular in ^{196}Po, they are very close in energy to the 4^+_1 and 6^+_1 states, respectively. This feature reminds us of two-and three-phonon multiplets and has led to the interpretation of the low-level structure of ^{196,198}Po in terms of a harmonic vibrator [17]. Branching ratio data support this conclusion provided the assumed E2 character of the observed transitions is correct. The measured data for ^{194}Po indicate increasing anharmonicity for this isotope [19].

Decay studies performed by the Leuven group have led to the identification of excited 0^+ states in $^{196-202}$Po [2]. These states have been interpreted in terms of $\pi(4p\text{–}2h)$ excitations across the closed shell at $Z = 82$. In accordance with theoretical studies [1, 20] these states are believed to have oblate deformation. These 0^+ levels are close in energy to the lowest 2^+ level in ^{196,198}Po and thus present a problem to the interpretation of these nuclei as vibrators. The structure of neutron-deficient Po nuclei has been discussed in terms of different models by Oros *et al.* [21]. They conclude that while Po nuclei down to ^{200}Po can be described in terms of particle–core coupling, this is not possible for ^{194,196}Po using physically meaningful parameter values. The particle-hole intruder interpretation is favoured by this study.

In the following, recent progress in the study of even–even and odd-mass Po nuclei at JYFL will be briefly reviewed.

2. Experimental apparatus

Heavy-ion induced fusion evaporation reactions were used to populate excited states in neutron-deficient Po nuclei. The JYFL 6.4 GHz ECR ion source ECRIS 1 and the $K = 130$ MeV cyclotron were used for producing the beam. The nuclei under study were separated from the primary beam and from unwanted reaction products using the gas-filled recoil separator RITU [22]. The efficiency of transporting fusion products through RITU to the focal plane detector was 25–30 % depending on the reaction. At the focal plane there was the standard RITU position-sensitive Si stop detector for observing the arrival of fusion products and their alpha decay. A gas counter [23] was installed in front of the stop detector to aid in discriminating against beam-related particle events.

Prompt gamma-rays from the target were detected using the JUROSPHERE array of Compton-suppressed Ge detectors. JUROSPHERE consists of 15 Eurogam Phase 1 detectors and 10 NORDBALL or TESSA detectors. Total efficiency at 1.3 MeV varied between 1.5 and 1.8 %. Typical beam intensities were of the order of 10 pnA. This value was set by the counting rate limit in the Ge detectors (~ 10 kHz).

3. Experimental results

Yrast structures in ^{192}Po [3], ^{191}Po [24] and in ^{190}Po [18] were observed for the first time in the RDT studies at JYFL. In addition, significantly different data from those published for ^{193}Po [4] were collected in these experiments [3]. Finally, improved or slightly changed level schemes compared with those published in [4, 19] were extracted for ^{194,195}Po [3].

The nucleus ^{194}Po was studied using the reactions ^{170}Yb(^{28}Si,4n) and ^{171}Yb(^{28}Si,5n). Altogether about 2 million decays of ^{194}Po were collected. This was sufficient for obtaining gamma–gamma coincidence and gamma-ray angular distribution information. The yrast band was extended to $I^{\pi} = (16^{+})$ and a side band of low-lying second excited 2^{+} and 4^{+} states was extended to the 6_2^{+} state.

The nucleus ^{192}Po was produced in the reaction ^{160}Dy(^{36}Ar,4n). A total of 35000 ^{192}Po alpha decays were observed. Also in this case, support for the extracted level scheme came from gamma–gamma coincidence measurements. The yrast band was observed up to the (10^{+}) level.

The most neutron-deficient Po nucleus studied was ^{190}Po which is only two neutrons heavier than the lightest known Po isotope with $A = 188$ [25]. Due to target problems, only about 1000 correlated alpha decays were observed from the reaction ^{142}Nd(^{52}Cr,4n). This corresponds to a production cross section of about 200 nb which is at the limit of present-day RDT techniques. Four clear gamma-rays observed in the tagged spectrum were associated with an yrast cascade on the basis of their intensities.

Several reactions including ^{36}Ar + ^{160}Dy and ^{28}Si + ^{170}Yb were used to study the excited states of ^{195}Po. In neutron-deficient odd-mass Po isotopes, two alpha-decaying states with $I^{\pi} = 3/2^{-}$ and $I^{\pi} = 13/2^{+}$ have been observed. It was not possible to build a level scheme on top of the $3/2^{-}$ ground state in ^{195}Po. (The same turned out to be true for ^{191,193}Po.) The level scheme built on top of the $13/2^{+}$ isomer confirms the one by Fotiades *et al.* [4] and adds a tentative side band and one new level to the yrast cascade.

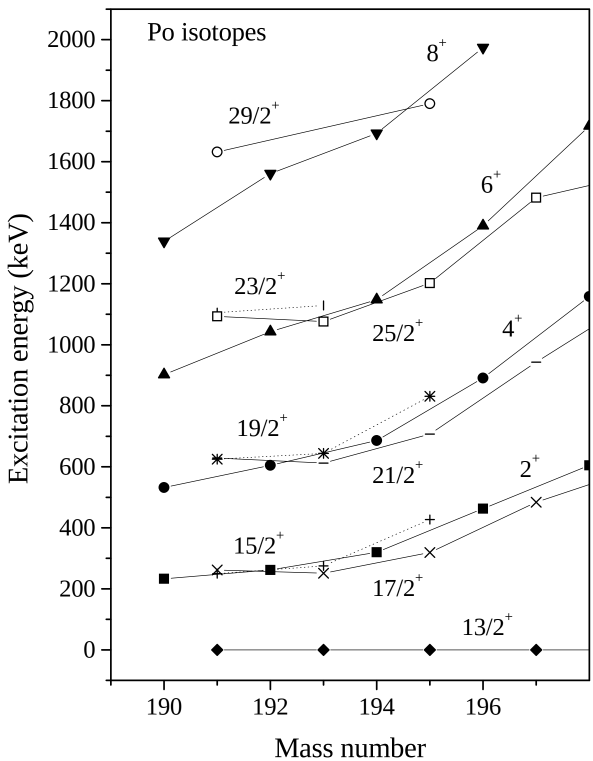

Fig. 2. Level energies of selected low-lying states in the odd-mass nuclei $^{191-197}$Po relative to the $13/2^{+}$ states. Lowest 2^{+}, 4^{+}, 6^{+} and 8^{+} states in the even–even nuclei are shown for comparison. For the odd-mass nuclei, solid lines connect favoured states and dotted lines unfavoured states. The data are from Refs. [3,4,24] and references therein.

The ^{160}Dy(^{36}Ar,$3n$) reaction was used to populate excited states on top of the $13/2^{+}$ state in ^{193}Po. The constructed level scheme differs significantly from the one proposed in Ref. [4].

In a very recent RDT experiment at RITU an attempt was made to observe gamma-rays on top of the ^{191}Po isomers [24]. The reaction used was ^{142}Nd(^{52}Cr,3n)^{191}Po. Again, levels on top of the $13/2^+$ isomer were established.

In all cases studied, the constructed level schemes were based on results of gamma–gamma coincidence and gamma-ray angular distribution measurements, if available, and on systematics of Po level structure. Our experimental findings, together with earlier data, are shown in the partial excitation energy systematics of states of Po nuclei in Figs. 1 and 2.

4. Discussion

We will first discuss the even–even isotopes. In ^{192,194,196}Po the yrast line forms a clear collective band. The band can be associated with the oblate structure. Our new in-beam data on ^{190,192}Po show that the down-sloping trend of the 2^+, 4^+, 6^+ and 8^+ states continues. However, the energy drop for the 2^+ state is already quite small between ^{192}Po and ^{190}Po. A plausible starting point for analysing the situation is that while the low-spin states are expected to be mixed, the higher members of the collective bands should be quite pure. One can then extrapolate unperturbed 0^+ energies for the bands. This will provide input for two-level (spherical and oblate) mixing calculations. Because the first excited 0^+ states have never been observed in ^{192,194}Po, the (perturbed) level energies were taken from the calculations of Oros *et al.* [21].

The results from the mixing calculation for ^{192,194}Po are the following [3,9]: In ^{194}Po the unperturbed oblate 0^+ state is barely above the spherical 0^+ state while in ^{192}Po the oblate state has become the ground state. The contribution of the oblate intruder component in the ground state is 45 % in ^{194}Po and 73 % in ^{192}Po. The value for ^{192}Po is in good agreement with that extracted from alpha decay fine structure data [5]. Our calculations show that the lowest 2^+ state is already a very pure oblate intruder state both in ^{194}Po and in ^{192}Po. The unperturbed 2^+–0^+ energy difference can be used to extract the value $|\beta_2| \sim 0.17$ for the quadrupole deformation parameter using the Grodzins formula [26]. There is a significant change in the level scheme of ^{190}Po as compared with ^{192,194}Po. The 6^+ and 8^+ level energies are dropping considerably. The resulting kinematic moments of inertia for ^{190}Po are shown in Fig. 3 and compared with several neighbouring even–even isotopes, including ^{186}Hg and ^{188}Pb which are known to exhibit prolate deformation [11]. The close similarity in the moments of inertia is a strong indication of prolate structures becoming yrast for the first time in ^{190}Po in agreement with the early predictions of May *et al.* [1]. These structures are associated with $\pi(6p$–$4h)$ excitations across the $Z = 82$ shell [20]. Fine

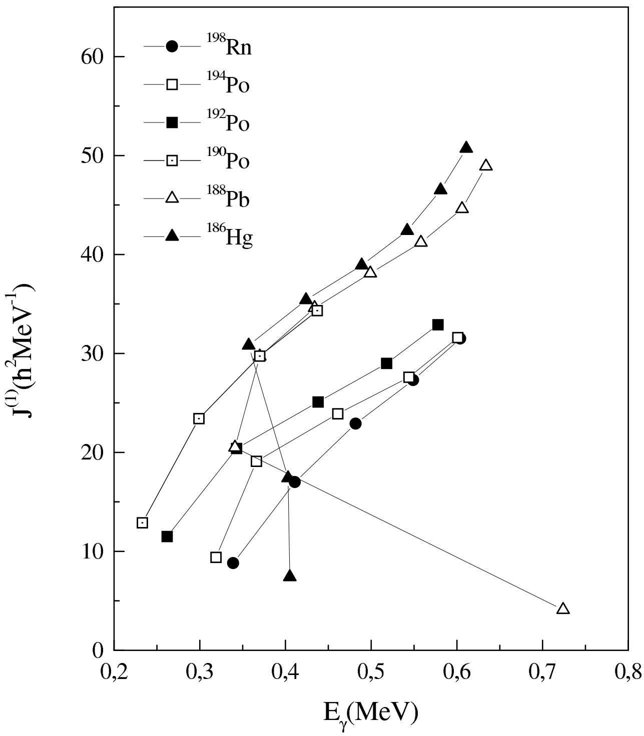

Fig. 3. Kinematic moments of inertia for yrast states of the even–even nuclei ^{190,192,194}Po compared with ^{186}Hg, ^{188}Pb and ^{198}Rn.

structure in the alpha decay of ^{190}Po was observed recently using the velocity filter SHIP at GSI [27]. These data indicate that there is a significant mixture of the prolate configuration in the ground state of ^{190}Po [6].

We continue the discussion with the odd-mass Po isotopes. In Fig. 2 are shown the level systematics deduced in the present work and built on top of the $13/2^+$ states in odd-mass isotopes ^{191,193,195}Po. The close similarity between the level patterns of the odd-mass and even–even isotopes indicates a weak coupling of the $i_{13/2}$ neutron to the even core. This may be regarded as coupling of the odd neutron to a vibrating spherical core [4] or as a decoupling of an $i_{13/2}$ neutron hole from the oblate core.

Candidates for the unfavoured $15/2^+$, $19/2^+$ and $23/2^+$ states of the $i_{13/2}$ band were found in ^{191}Po, ^{193}Po and ^{195}Po. These states approach the favoured ones in ^{193}Po and even fall below them in ^{191}Po. This is an indication of a possible change towards the strong-coupling scheme when neutron mid-shell is being approached. This may reflect the oblate–prolate shape change taking place in the ^{190}Po core.

It is of interest to compare these findings with the results of a recent alpha decay study performed at RITU [28]. In this work, a sudden change in the alpha decay hindrance factor for the $13/2^+$ state was observed at ^{191}Po. The interpretation is that there is a change from a mixed $(4p\text{–}2h) + (2p\text{–}0h)$ structure in ^{193,195}Po to a pure proton $4p\text{–}2h$ structure in ^{191}Po. Since no corresponding change was observed for the $3/2^-$ state, the phenomenon was called shape staggering (such as takes place in Hg nuclei [29]).

In view of the shape staggering it is of interest that no clear change in the spacings of the lowest members of the $i_{13/2}$ band is observed between ^{193}Po and ^{191}Po. On the other hand, as shown by the mixing calculations for ^{192}Po and ^{194}Po, the yrast line does not necessarily reflect very well the structure of the ground state. The ground states of both ^{192}Po and ^{194}Po are strongly mixed while the 2^+ state is already a quite pure oblate intruder state.

5. Conclusion

The study of coexisting structures in the vicinity of the $Z = 82$ closed shell has provided us with a large amount of data on Hg, Pb and Po nuclei. In this work, alpha decay and in-beam studies provide crucial and complementary information. As often is the case, life time measurements would be very helpful in further illuminating the situation. Low production rates make the conduction of such experiments quite difficult. Nevertheless, tests have shown that timing experiments can be performed with Ge/BaF arrays in conjunction with RITU and have been scheduled to further study neutron-deficient Po nuclei [30]. Another way of proceeding is to make use of the unique capability of the RITU+SACRED conversion electron setup [14,15]. First data from such an experiment to observe E0 conversion electrons from the lowest excited 0^+ state in ^{194}Po are being analysed.

I am much indebted to Rauno Julin for illuminating discussions. This work is supported by the Academy of Finland under the Finnish Centre of Excellence Programme 2000–2005 (Project No. 44875, Nuclear and Condensed Matter Physics Programme at JYFL) and by the European Union Fifth Framework Programme 'Improving Human Potential — Access to Research Infrastructure' (Contract no HPRI-CT-1999-00044).

REFERENCES

[1] F.R. May, V.V. Pashkevich, S. Frauendorf, *Phys. Lett.* **68B**, 113 (1977).
[2] N. Bijnens *et al.*, *Phys. Rev. Lett.* **75**, 4571 (1995).
[3] K. Helariutta *et al.*, *Eur. Phys. J.* **A6**, 289 (1999).
[4] N. Fotiades *et al.*, *Phys. Rev.* **C56**, 723 (1997).
[5] R.G. Allatt *et al.*, *Phys. Lett.* **B437**, 29 (1998).
[6] R.D. Page, private communication (2001).
[7] K. Heyde, C. De Coster, J. Jolie, J.L. Wood, *Phys. Rev.* **C46**, 541 (1992).
[8] J. Kumpulainen, R. Julin, J. Kantele, A. Passoja, W.H. Trzaska, E. Verho, J. Väärämäki, D. Cutoiu, M. Ivascu, *Phys. Rev.* **C45**, 640 (1992).
[9] R. Julin, K. Helariutta, M. Muikku, *J. Phys. G: Nucl. Phys.*, in press.
[10] D. Alber *et al.*, *Z. Phys.* **A339**, 225 (1991).
[11] J. Heese *et al.*, *Phys. Lett.* **B302**, 390 (1993).
[12] E.S. Paul *et al.*, *Phys. Rev.* **C51**, 78 (1995).
[13] D.M. Cullen *et al.*, *Phys. Rev.* **C58**, 846 (1998).
[14] H. Kankaanpää *et al.*, to be submitted to *Nucl. Instrum. Methods Phys. Res.*
[15] P.A. Butler, *Acta Phys. Pol.* **B32**, 2519 (2001).
[16] R.F. Casten, *Nuclear Structure from a Simple Perspective*, 2nd. ed., Oxford University Press, Oxford UK (2000).
[17] L.A. Bernstein *et al.*, *Phys. Rev.* **C52**, 621 (1995).
[18] K. Van de Vel *et al.*, to be published.
[19] W. Younes *et al.*, *Phys. Rev.* **C52**, R1723 (1995).
[20] W. Nazarewicz, *Phys. Lett.* **B305**, 195 (1993).
[21] A. M. Oros *et al.*, *Nucl. Phys.* **A645**, 107 (1999).
[22] M. Leino *et al.*, *Nucl. Instrum. Methodds Phys. Res.* **B99**, 653 (1995).
[23] H. Kettunen *et al.*, *Acta Phys. Pol.* **B32**, 989 (2001).
[24] A.N. Andreyev *et al.*, to be published.
[25] A.N. Andreyev *et al.*, *Eur. Phys. J.* **A6**, 381 (1999).
[26] L. Grodzins, *Phys. Lett.* **2**, 88 (1962).
[27] A.N. Andreyev *et al.*, *Nature* **405**, 430 (2000).
[28] A.N. Andreyev *et al.*, *Phys. Rev. Lett.* **82**, 1819 (1999).
[29] J. Bonn, G. Huber, H.-J. Kluge, L. Kugler, E.W. Otten, *Phys. Lett.* **38B**, 308 (1972).
[30] H. Mach *et al.*, proposal for the JYFL Accelerator Laboratory (2001).