Eur. Phys. J. A 3, 17–20 (1998)

THE EUROPEAN
PHYSICAL JOURNAL A

First observation of excited states in ^{184}Pb: spectroscopy beyond the neutron mid-shell

J.F.C. Cocks[1], M. Muikku[1], W. Korten[2], R. Wadsworth[3], S. Chmel[4], J. Domscheit[4], P.T. Greenlees[5], K. Helariutta[1], I. Hibbert[3,a], M. Houry[2], D. Jenkins[3], P. Jones[1], R. Julin[1], S. Juutinen[1], H. Kankaanpää[1], H. Kettunen[1], P. Kuusiniemi[1], M. Leino[1], Y. Le Coz[2], R. Lucas[2], E. Mergel[4], R.D. Page[5], A. Savelius[1], W. Trzaska[1]

[1] Accelerator Laboratory, Department of Physics, University of Jyväskylä, 40351 Jyväskylä, Finland
[2] DAPNIA/SPhN CEA-Saclay, France
[3] Department of Physics, University of York, Heslington, York YO1 5DD, United Kingdom
[4] Institut für Strahlen- und Kernphysik, Universität Bonn, D-53115 Bonn, Germany
[5] Oliver Lodge Laboratory, Department of Physics, University of Liverpool, Liverpool L69 7ZE, United Kingdom

Received: 19 May 1998 / Revised version: 1 July 1998
Communicated by D. Schwalm

Abstract. Excited states have been identified for the first time in ^{184}Pb, the first even-even Pb isotope beyond the $82 < N < 126$ mid-shell, using the recoil-decay tagging (RDT) technique. A collective band built on the first-excited 2^+ state has been observed. This resembles those seen in ^{186,188}Pb and the Hg isotones, and can thus be associated with a prolate-deformed shape. Variable moment of inertia (VMI) fits of the prolate 0^+ level energies in ^{184,186,188}Pb indicate that the minimum appears at $N = 103$, the same neutron number at which the corresponding minimum in Hg isotopes is observed.

PACS. 21.60.Ev Collective models – 23.20.-g Electromagnetic transitions – 25.70.gh Compound nucleus – 23.60.+e α decay

1 Introduction

There now exists a large body of experimental information supporting the coexistence of different shapes at low excitation energies in isotopes of lead. Low-lying 0_2^+ levels associated with weakly-deformed oblate structures have been observed to coexist with spherical ground states in several Pb isotopes with $N \geq 106$ [1,2]. These states are thought to result from 2 particle-2 hole proton excitations across the $Z = 82$ shell gap to $1h_{9/2}$ orbitals [3]. A rotational structure built on such a state has been seen in ^{196}Pb [4] and $M1$ shears bands associated with weakly-deformed oblate shapes are known in several Pb isotopes near $A = 198$ [5–7]. In ^{186,188}Pb, low-lying deformed rotational structures have been observed at $I > 2\hbar$ by Heese *et al.* [8] and Baxter *et al.* [9]. The bands, which are similar to those in the corresponding isotones ^{184,186}Hg, are associated with predicted [10] prolate-deformed minima. In Hg isotopes the excitation energy of the prolate-deformed intruder band decreases with decreasing neutron number, reaching a minimum near the mid-shell at $N = 103$ [11]. This trend has been reproduced using Nilsson-Strutinsky calculations [10], which also predict a minimum close to $N = 103$ for Pb isotopes. In the present work γ rays have been studied for the first time in $^{184}\mathrm{Pb}_{102}$. This represents an extension of our knowledge of excited states in even-even Pb isotopes to beyond the $82 < N < 126$ mid-shell.

2 Experimental Details

The ^{148}Sm(^{40}Ca,4n)^{184}Pb reaction was employed with a target of thickness 500μg/cm^2 and 99.94% enrichment. The beam, consisting of 95% ^{40}Ca and 5% ^{40}Ar, was delivered by the K = 130 MeV cyclotron at the Accelerator Laboratory of the University of Jyväskylä (JYFL) at a bombarding energy of 195 MeV. Prompt γ rays from the target were detected by the JUROSPHERE array which consisted of 11 TESSA-type [12] and 14 EUROGAM Phase I [13] Compton-suppressed germanium detectors (absolute efficiency $\sim$ 1.6% at 1.3 MeV). Recoiling fusion-evaporation residues were magnetically separated in-flight from the background of primary beam and nuclei produced by fission using the RITU gas-filled recoil separator [14]. The recoils were then implanted into a 80mm (horizontal) × 35mm (vertical) Si detector covering approximately 70% of the image at the focal plane. The detector consisted of 16 strips of 5mm width, each position-sensitive in the vertical direction with a position

[a] *Present address:* Oliver Lodge Laboratory, Department of Physics, University of Liverpool, Liverpool L69 7ZE, United Kingdom
Correspondence to: James.Cocks@phys.jyu.fi

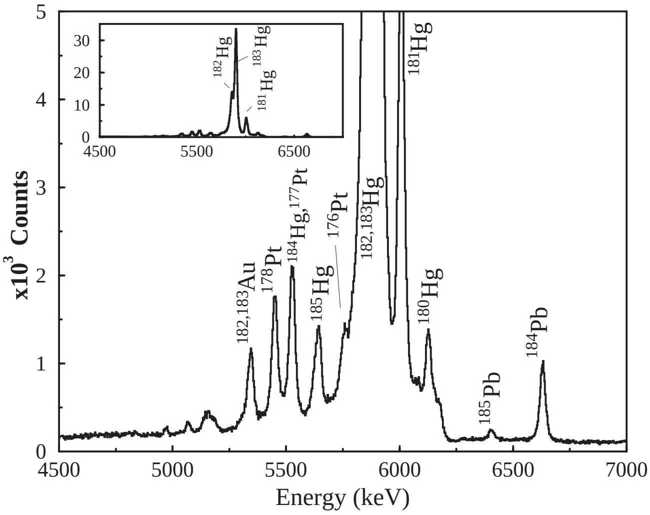

Fig. 1. Singles α-particle energy spectrum for the ^{40}Ca + ^{148}Sm reaction. The prominent peaks are assigned to known activities. An α-particle energy of 6626(6) keV was measured for ^{184}Pb using 9000(100) decays

resolution of 400μm. For the recoils and their α decays, the position, energy and time of detection was recorded. Figure 1 shows the energy spectrum for single α-decay events. The spectrum was calibrated internally using the following α-particle energies from literature [15]: ^{178}Pt $E_\alpha = 5446(3)$ keV, ^{177}Pt $E_\alpha = 5517(4)$ keV, ^{183}Hg $E_\alpha = 5904(4)$ keV, ^{181}Hg $E_\alpha = 6005(4)$ keV and ^{180}Hg $E_\alpha = 6119(5)$ keV. An α-particle energy of 6626(6) keV was obtained for ^{184}Pb from 9000(100) decays. This is consistent with the previously-measured value of 6632(10) keV [16].

3 Results

Figure 2(a) is a spectrum showing prompt γ rays in coincidence with all recoils detected at the RITU focal plane. It is dominated by those from Hg isotopes produced in (^{40}Ca, αxn) and (^{40}Ar,xn) channels. Prompt γ rays emitted by ^{184}Pb residues were selected from those produced via other exit channels using the recoil-decay tagging (RDT) technique [17,18]. The events of interest corresponded to the detection of a recoil and a ^{184}Pb α decay at the same position in the Si detector within a time interval of 1.5 seconds (approximately three ^{184}Pb α-decay half-lives). Using these events and the method prescribed in [19], a half-life value of 0.60(9)s for ^{184}Pb was deduced which is consistent with the value of 0.55(6)s obtained in the previous measurement [16]. Figure 2(b) is a spectrum showing RDT-gated γ rays in ^{184}Pb. Four γ-ray transitions are clearly identified along with Pb X-rays. The dashed lines marked on the spectra illustrate that the transitions observed in Fig. 2(b) are not observed in Fig. 2(a) because of the large background of γ rays from other nuclei. The inset to Fig. 2(b) is a tentative level scheme deduced using this spectrum. The $I^\pi = (2^+)$ state is assigned an energy of 701.5 keV on the basis of 2^+ energy-

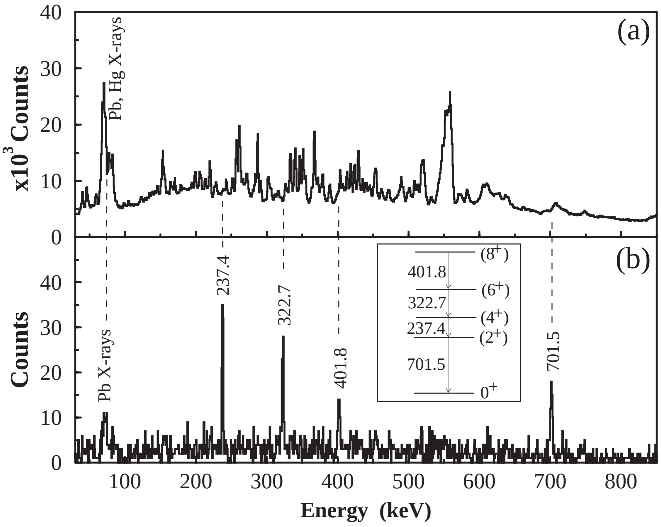

Fig. 2. a Singles energy spectrum of γ rays in coincidence with all fusion-evaporation residues detected in the RITU focal-plane Si detector, **b** singles energy spectrum showing γ-ray transitions in ^{184}Pb and Pb X-rays. The spectrum was generated using the RDT technique (see text). Inset: tentative decay scheme for ^{184}Pb

level systematics in Pb isotopes; the only intense peak in the region of the spectrum where the 2^+ to 0^+ transition is expected has an energy of 701.5 keV. The transitions of energies 237.4, 322.7 and 401.8 keV appear to form a rotational band similar to those built on 2^+ states in ^{186,188}Pb. They are therefore tentatively assigned as the following transitions: (4^+) to (2^+), (6^+) to (4^+) and (8^+) to (6^+) respectively. The relative intensities of the 701.5, 237.4, 322.7 and 401.8 keV transitions are 100(11), 98(12), 94(13) and 38(13) respectively.

4 Interpretation

Aligned angular momentum, i_x, as a function of rotational frequency is shown for ^{184,186,188}Pb in Fig. 3. The transition energies of ^{186,188}Pb were taken from [8,9]. The same variable moment of inertia reference parameters, $J_0 = 27$ $\hbar^2$MeV^{-1} and $J_1 = 199$ $\hbar^4$MeV^{-3}, have been used for the three nuclei. It should be noted that there is evidence for quasi-particle alignment in ^{188}Pb at $\hbar\omega = 0.3$ MeV. Above $I = 2\hbar$ the alignment properties of the rotational bands in the three isotopes are similar, but not identical. The alignment of the intruder bands decreases with increasing neutron number, indicating a gradual decrease in collectivity. This is in contrast with the behaviour of the Hg isotones where no significant change in collectivity with neutron number is observed for ^{182,184,186}Hg [21]. The behaviour of the three Hg isotopes above 0.2 MeV is almost identical to that of ^{186}Pb in Fig. 3. The similarities between the Pb and Hg isotopes indicate that the low-lying bands in the Pb isotopes are built on the same prolate-deformed structures assigned to the Hg bands.

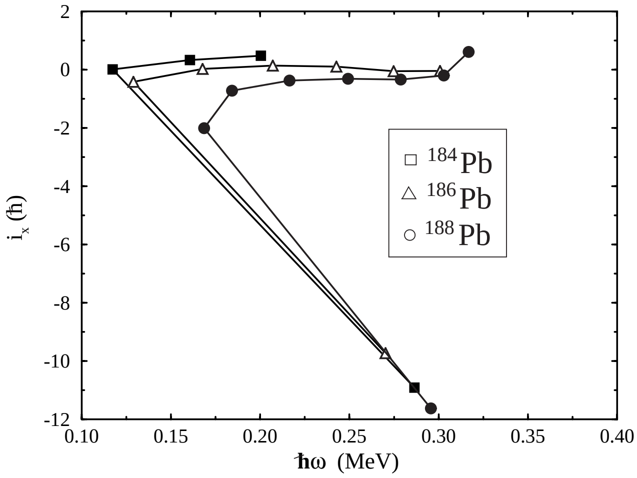

Fig. 3. Plots of aligned angular momentum, i_x, as a function of rotational frequency, $\hbar\omega$, for the ^{184}Pb (this work) and ^{186,188}Pb [8,9]. Rotational references with Harris parameters of $J_0 = 27\ \hbar^2\text{MeV}^{-1}$ and $J_1 = 199\ \hbar^4\text{MeV}^{-3}$ have been subtracted

Figure 4 shows plots of excitation energy as a function of $I(I+1)$ for the levels in ^{184}Pb from this work and ^{186,188}Pb from refs. [8,9]. The values of E^* at $0\hbar$ for these three nuclei were estimated using variable moment of inertia (VMI) [22] fits using levels in the intruder bands. Dashed lines connect these points to the experimental data points. The energies of the following levels were used in the fits: levels with $I^\pi = 4^+$ to 8^+ for ^{184}Pb, 8^+ to 14^+ for ^{186}Pb and 6^+ to 14^+ for ^{188}Pb. The 16^+ state in ^{188}Pb was not included in the fit because here there is evidence for quasi-particle alignment (see Fig. 3). Omission of either the 6^+ or 14^+ states, which may be displaced by mixing and quasi-particle alignment respectively, did not alter the estimated bandhead energy for ^{188}Pb. The estimated bandhead energies are given in Table 1, along with the fitted VMI parameters J_0 and C.

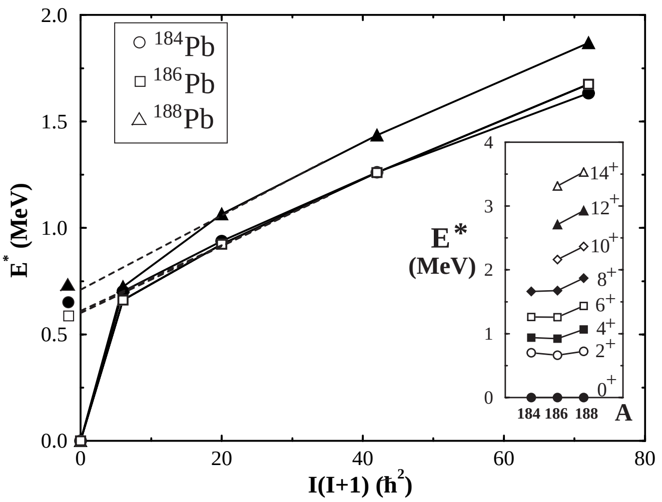

Fig. 4. Plots of excitation energy, E^*, as a function of spin, I, for ^{184,186,188}Pb. The dashed lines are extrapolations to zero spin, where the values of E^* have been determined using VMI fits. Inset: yrast states in ^{184,186,188}Pb

Table 1. Fitted VMI parameters and bandhead energies

Nucleus	J_0 (keV^{-1})	C (10^6 keV^3)	Bandhead energy (keV)
^{184}Pb	0.0281	2.19	610
^{186}Pb	0.0284	2.80	600
^{188}Pb	0.0244	2.24	710

In order to compare the prolate bandhead energies for the three Pb isotopes it is necessary to ascertain the extent to which the low-spin (0^+, 2^+) states are perturbed by mixing with other configurations. The mixing of states of different deformation in ^{188}Pb is discussed in [20]. The mixing of the 0^+ states in this nucleus serves to *increase* the prolate 0^+ level energy by ∼50 keV. This perturbation does not effect the following arguments so the unmixed prolate bandhead energy obtained from the VMI fit is used. The high-lying, high-spin members of the prolate band in ^{188}Pb are unmixed and unperturbed so the estimated bandhead energy of 710 keV is reliable. The oblate-deformed 0^+ states have not been observed in ^{184,186}Pb. The excitation energy of the oblate-deformed minimum is predicted [10] to increase suddenly as N decreases from 106 to 104, so the mixing between the oblate and prolate configurations is assumed to be weak for ^{184,186}Pb.

In the present work the effect of mixing between the prolate-deformed and spherical configurations has been calculated. In ^{186}Pb a perturbation of the prolate bandhead of 2.7 keV is expected if the experimentally-observed 2^+ state is assumed to be prolate, while a 3.7 keV displacement is predicted if the 2^+ state is spherical. Both scenarios lead to the conclusion that the energy of the prolate-deformed 0^+ state is close to 600 keV.

Only 4 excited levels were observed in ^{184}Pb, therefore the 4^+ level was included in the VMI fit to estimate the energy of the prolate 0^+ state. In practice the 4^+ state will be mixed and therefore displaced, resulting in a perturbation of the VMI-fitted 0^+ state. Displacement of the 4^+ level in ^{186}Pb was calculated to be small (7 keV) so the displacement of the 4^+ state, and therefore the fitted 0^+ state, in ^{184}Pb is also expected to be small. Measurement of ^{185}Bi proton decay [23] has provided additional evidence that the mixing strength is small in ^{184}Pb. If the 4^+ state in ^{184}Pb is assumed to be prolate as in ^{186}Pb, the unmixed prolate 4^+ level will be higher in energy than the observed (mixed) 4^+ state and therefore the bandhead energy will be raised above the fitted value. The prolate-deformed 0^+ state may therefore be slightly higher than the VMI-fitted value of 610 keV. However, within the uncertainties of the fitting, the energies of the prolate 0^+ states in ^{184}Pb and ^{186}Pb are the same, regardless of which configurations are assumed for the 2^+ and 4^+ states. This indicates that the excitation energy of the prolate-deformed configuration has a minimum close to $N = 103$. The corresponding minimum in Hg isotopes can be found at the same neutron number [11].

It would be of considerable interest to study the α-decay fine structure of ^{190}Po in order to measure directly the excitation energy of the prolate 0^+ state in ^{186}Pb and extract the mixing strength from the hindrance factor relative to decay to the ground state. Unfortunately a corresponding measurement for ^{188}Po appears to be beyond the reach of current experimental techniques.

5 Summary

Transitions have been identified for the first time in ^{184}Pb using the RDT technique. This represents γ-ray spectroscopy beyond the $82 < N < 126$ mid-shell in Pb isotopes. A low-lying rotational structure has been observed. The band behaves in a similar way to those observed in ^{186,188}Pb and the Hg isotones and is thus assigned a prolate-deformed configuration. VMI calculations of the bandhead energies for the rotational structures in ^{184,186,188}Pb reveal that the prolate-deformed minimum occurs at $N = 103$, as seen in the Hg isotopes.

We are grateful to Hannu Koivisto and the K = 130 MeV cyclotron group for providing the ^{40}Ca beam. Support for this work was provided by the Academy of Finland and the Access to Large Scale Facility program under the Training and Mobility of Researchers program of the European Union. Additional support was given by the UK Engineering and Physical Sciences Research Council. DJ and PTG acknowledge receipt of EPSRC postgraduate studentships. RDP is an EPSRC Advanced Fellow.

References

1. J.L. Wood *et al.*, Phys. Rep. **215**, 101 (1992)
2. N. Bijnens *et al.*, Z. Phys. A **356**, 3 (1996)
3. P. Van Duppen *et al.*, Phys. Rev. Lett. **52**, 1974 (1984)
4. J. Penninga *et al.*, Nucl. Phys. **A471**, 535 (1987)
5. R.M. Clark *et al.*, Phys. Lett. **B 275**, 247 (1992)
6. G. Baldsiefen *et al.*, Phys. Lett. **B 275**, 252 (1992); Z. Phys. A **343**, 245 (1992)
7. T.F. Wang *et al.*, Phys. Rev. Lett. **69**, 1737 (1992)
8. J. Heese *et al.*, Phys. Lett. **B 302**, 390 (1993)
9. A.M. Baxter *et al.*, Phys. Rev. C **48**, 2140 (1993)
10. W. Nazarewicz, Phys. Lett. **B 305**, 195 (1993)
11. G.D. Dracoulis *et al.*, Phys. Lett. **B 208**, 365 (1988)
12. P.J. Nolan, D.W. Gifford and P.J. Twin, Nucl. Instrum. Methods Phys. Res. A **236**, 95 (1985)
13. P.J. Nolan, Nucl. Phys. **A520**, 657c (1990)
14. M. Leino *et al.*, Nucl. Instrum. Methods Phys. Res. B **99**, 653 (1995)
15. A. Rytz, At. Data Nucl. Data Tables **47**, 205 (1991)
16. U.J. Schrewe *et al.*, Phys. Lett. **B 91**, 46 (1980)
17. R.S. Simon *et al.*, Z. Phys. A **325**, 197 (1986)
18. E.S. Paul *et al.*, Phys. Rev. C **51**, 78 (1995)
19. M. Leino, S. Yashita and A. Ghiorso, Phys. Rev. C **24**, 2370 (1981)
20. R.G. Allatt *et al.*, submitted to Phys. Lett. B.
21. G.D. Dracoulis, Phys. Rev. C **49**, 3324 (1994)
22. M.A. Mariscotti, G. Scharff-Goldhaber and B. Buck, Phys. Rev. **178**, 1864 (1969)
23. C.N. Davids *et al.*, Phys. Rev. Lett. **76**, 592 (1996)