Eur. Phys. J. A 5, 257–262 (1999)

THE EUROPEAN
PHYSICAL JOURNAL A

Conversion electron spectroscopy of magnetic-rotational bands in ^{197}Pb and ^{199}Pb

W. Pohler[1], G. Baldsiefen[1], H. Hübel[1], W. Korten[1,a], E. Mergel[1], D. Roßbach[1], B. Aengenvoort[1], S. Chmel[1], A. Görgen[1], N. Nenoff[1], R. Julin[2], P. Jones[2], H. Kankaanpää[2], P.A. Butler[3], K.J. Cann[3], P.T. Greenlees[3], G.D. Jones[3], J.F. Smith[3,b]

[1] Institut für Strahlen- und Kernphysik, Universität Bonn, Nussallee 14-16, D-53115 Bonn, Germany
[2] Department of Physics, University of Jyväskylä, FIN-40351 Jyväskylä, Finland
[3] Oliver Lodge Laboratory, University of Liverpool, Liverpool L69 7ZE, UK

Received: 11 February 1999
Communicated by B. Herskind

Abstract. Magnetic–rotational bands in the nearly spherical nuclei ^{197}Pb and ^{199}Pb and their decay to the normal states have been investigated by in–beam conversion electron spectroscopy following (heavy ion,xn) reactions. The expected M1 multipolarity of the in–band transitions has been confirmed for the strongest bands and the multipolarity of several transitions in the decay of the bands has been determined.

PACS. 21.10.Hw Spin, parity and isobaric spin – 23.20.Nx Internal conversion – 27.80.tw 190≤A≤219

1 Introduction

Regular bands of strongly enhanced magnetic dipole transitions were first reported for ^{199}Pb [1] and were later found throughout the Pb region [2]. Their energy spacings are well described by a rotational dependence over wide spin ranges. The occurrence of regular sequences was unexpected, as rotational bands have previously been observed only in nuclei with well deformed mass distributions and not in near–spherical nuclei. Lifetime measurements [3,4], together with the weak or unobserved E2 crossover transitions, show that the quadrupole deformation is indeed very small in these excitations.

It has been suggested [5] that this new phenomenon can be explained by a quantal rotation of an anisotropic distribution of nucleonic currents. The name 'magnetic rotation' is appropriate because it indicates that magnetic moments which are connected with the currents are rotating around the angular momentum axis. This is in contrast to the familiar case of the deformed nuclei where the electric charge distribution rotates, which may then be called 'electric rotation'.

The anisotropic nucleonic currents are caused by a few excited high-spin protons and neutrons. For the protons, these are excitations across the closed Z = 82 shell gap into the $h_{9/2}$ and $i_{13/2}$ orbitals. These proton–particle excitations are coupled to $i_{13/2}^{-n}$ neutron–hole states. Since the particle–hole interaction is repulsive, their orbitals – and consequently also their angular momenta – will be oriented approximately perpendicular to each other at the bandhead. The total nuclear angular momentum J then points somewhere between the proton and neutron angular momenta. Higher angular momentum states are generated by a step–by–step alignment of the proton and neutron spins with the total angular momentum. Since this resembles the closing of a pair of shears, the M1 bands have been named 'shears bands' [6]. The proton particles and neutron holes effectively form an anisotropic arrangement of current loops which specify an orientation with respect to the angular momentum J and may rotate about this axis. The proton and neutron magnetic moments have opposite signs, but for the perpendicular coupling their transverse components add up. As the resulting large transverse component rotates around the angular momentum it generates the strong M1 radiation, the quanta of which form the magnetic–rotational bands [5].

In this work we report on measurements of internal conversion coefficients to confirm the expected magnetic character of the transitions in the bands (previous angular correlation results are compatible with stretched dipoles) and of several transitions in the decay of the bands to the normal states in ^{197}Pb and ^{199}Pb. Partial level schemes showing the strongest bands and their decay [6-9] are shown in Figs. 1 and 2. Our results show that the in-band ΔI=1 transitions have the expected M1 character. They confirm a previous conversion electron measurement for two bands in ^{199}Pb [10].

[a] Present address: DAPNIA/SPhN, CEA Saclay, F-91191 Gif–sur–Yvette, France
[b] Present address: Schuster Laboratory, Univ. of Manchester, Manchester M13 9PL, UK

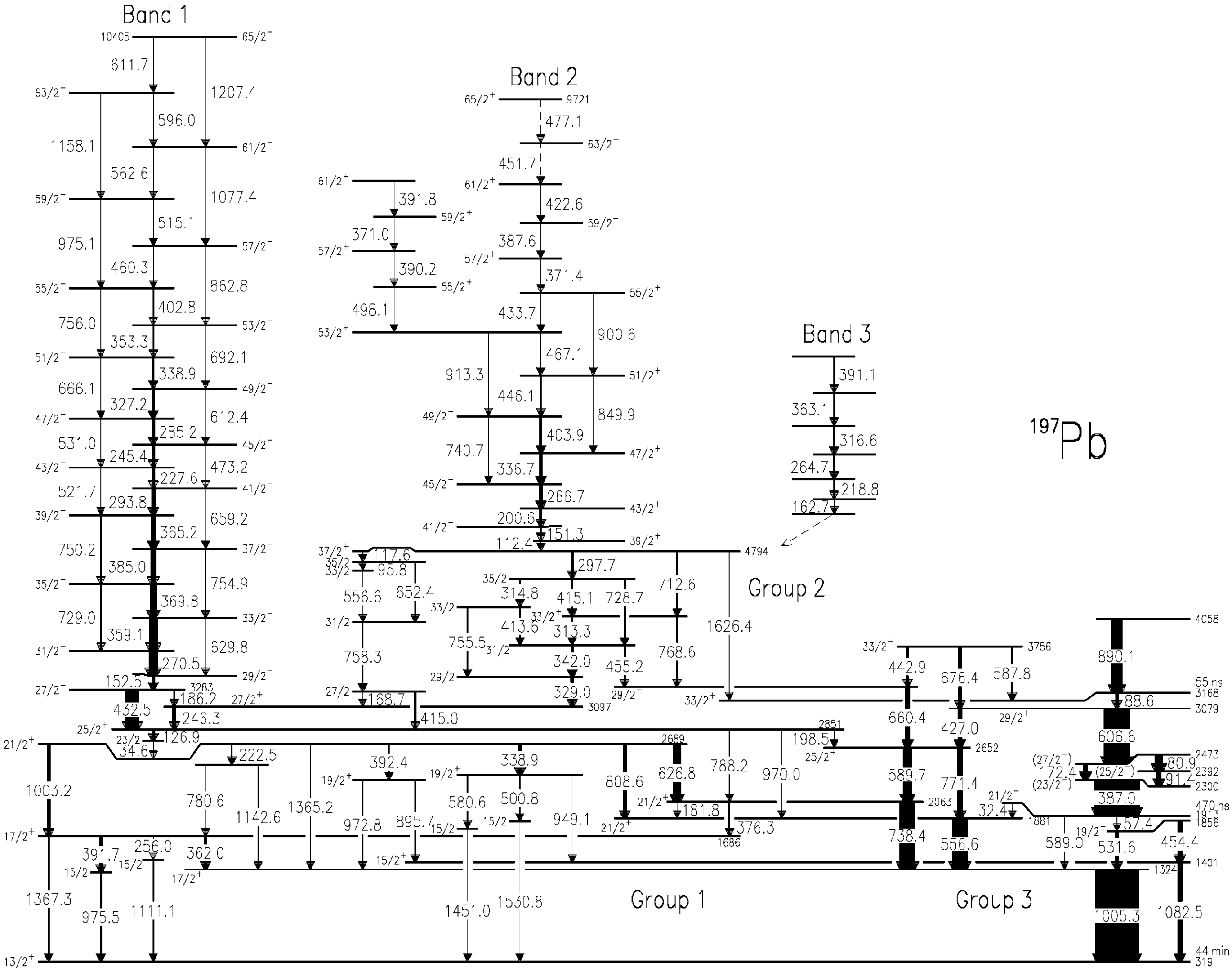

Fig. 1. Partial level scheme of ^{197}Pb, showing the shears bands and their decay to the normal states [7,9]

2 Experimental procedure and results

High–spin states in ^{197}Pb and ^{199}Pb were populated in ^{12}C and ^{16,18}O induced reactions on ^{192}Os and ^{186}W targets, respectively. The experiments were carried out at the Bonn and Jyväskylä cyclotrons. In both laboratories a superconducting solenoid spectrometer [11] was available for the conversion electron spectroscopy. Gamma rays were detected in a single large–volume Ge detector. Coincidences between conversion electrons as well as between electrons and γ rays were measured. At Bonn two Si(Li) detectors of 3 mm thickness with an active area of 300 mm^2 each were used for the e$^-$ – e$^-$ coincidence measurements. At Jyväskylä a segmented Si detector, SACRED [12], was available for conversion electron coincidence measurements. In the experiments at Bonn the recoil–shadow method [11] was used to search for delayed electrons in the decay of the bands in ^{199}Pb, populated in the ^{192}Os(^{12}C,5n) reaction at 82 MeV. A 300 μg/cm^2 thick self–supporting metallic Os foil, enriched in ^{192}Os to 99 %, was used as a target. Electrons from states with lifetimes above about 0.1 ns could be detected. Delayed coincidences were measured between the fast γ rays within the bands and the electrons in their decay.

The reactions ^{186}W(^{16}O,5n) and ^{186}W(^{18}O,5n) at 97 and 94 MeV, respectively, were used at Jyväskylä to populate the dipole bands in ^{197}Pb and ^{199}Pb. A self–supporting metallic ^{186}W foil of 400 μg/cm^2 thickness, enriched to 97 %, was used as a target. Prompt as well as delayed e$^-$–e$^-$ and e$^-$–γ coincidences were measured. For the delayed electron measurements again the recoil–shadow technique was applied. In the prompt measurements the background of low-energy δ electrons was suppressed by an electrostatic barrier of -35 kV. As examples of the prompt coincidence spectra, Fig. 3 shows the conversion electrons of bands 1 and 2 in ^{197}Pb and band 2 in ^{199}Pb obtained with coincidence gates on γ–ray transitions in those bands. The K– and L–conversion lines of the strongest transitions are clearly visible. Transitions

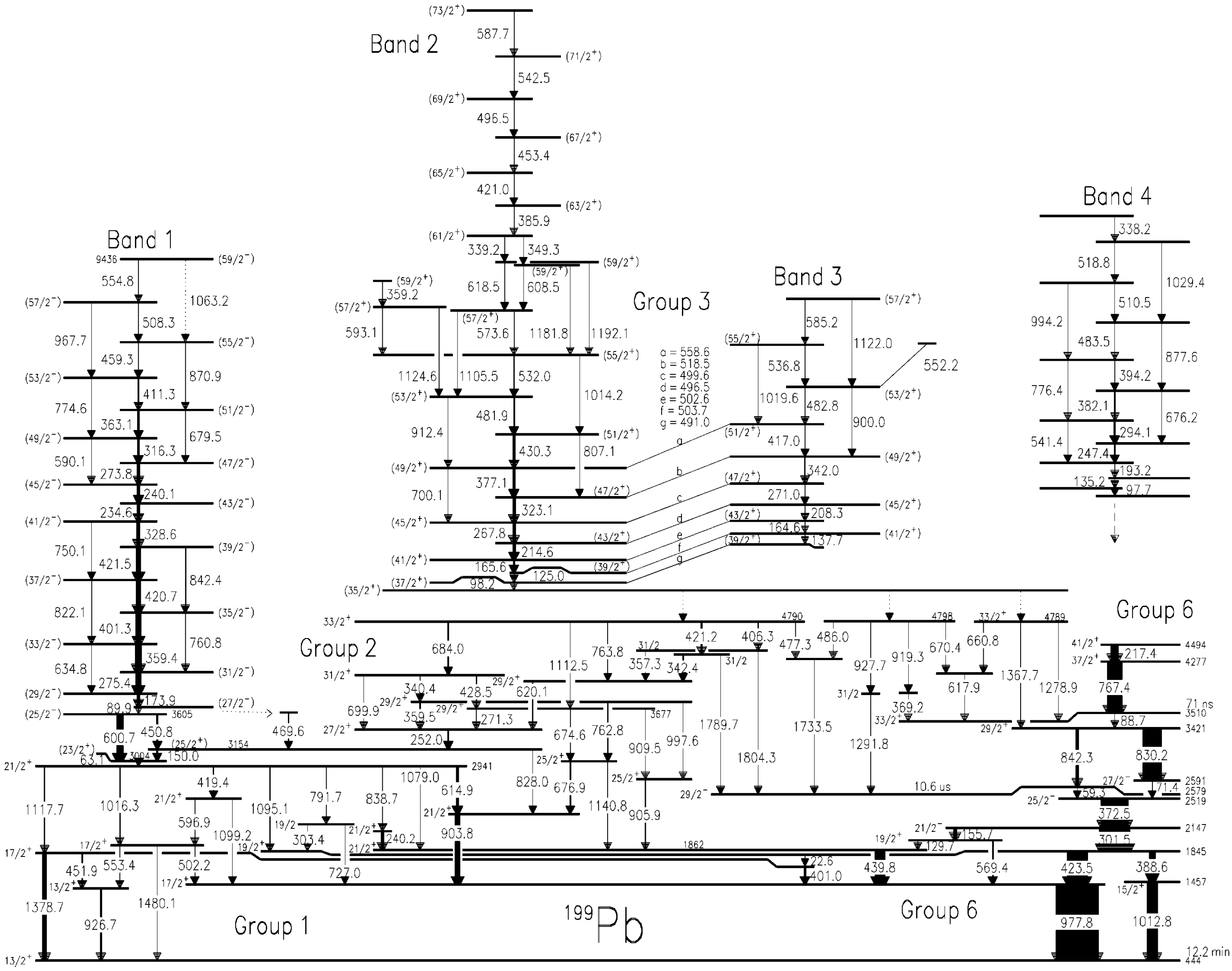

Fig. 2. Partial level scheme of ^{199}Pb, showing the shears bands and their decay to the normal states [6,8,9]

belonging to the normal decay schemes with known multipolarities served as normalizations for the determination of the conversion coefficients. Table 1 summarizes the conversion coefficients for the strongly populated bands in ^{197}Pb and ^{199}Pb and for some of the connecting transitions. Although the experimental uncertainties are large in most cases, the expected M1 multipolarity is confirmed for the in–band transitions.

In addition, conversion coefficients have been determined for several transitions in the decay of the bands. Of particular interest is the 432.5 keV transition in ^{197}Pb which connects band 1 to the normal states. Our conversion coefficient is compatible with E1 multipolarity for that transition. This result is in agreement with recent linear polarization measurements [9,14,15]. It establishes negative parity for the band. The transition of similar energy, 450.8 keV, in the decay of band 1 in ^{199}Pb has less intensity. We are unable to find it in the conversion electron spectra, which is an indication that it is also an E1 transition. The 600.7 keV transition in parallel to the 450.8 keV transition is too high in energy for the SACRED detector. Therefore, the parity assignment to band 1 in ^{199}Pb remains somewhat uncertain.

3 Discussion

The results of the measurements presented above give further support to the previously suggested configurations of the magnetic–rotational bands 1 and 2 in ^{197}Pb and ^{199}Pb. Bands 1 in both isotopes are built on a pair of protons coupled to an $i_{13/2}$ neutron hole. The proton pair is excited from the $s_{1/2}$ orbital across the Z = 82 shell gap into the $h_{9/2}$ and $i_{13/2}$ states. These proton particles couple their angular momenta to the maximum possible value of 11 $\hbar$, as is known from neighbouring even–even Pb isotopes [2]. The particle–hole interaction is repulsive and therefore the neutron $i_{13/2}$ holes couple with their angular momenta approximately perpendicular to the proton–particle spins,

Table 1. Conversion coefficients of transitions in the strongly populated bands in ^{197}Pb and ^{199}Pb and in their decay

Nucl./ Band	E_γ (keV)	Conversion α_K^{exp}	Coefficients α_L^{exp}	$\alpha_{KorL}^{theor.}$	Mult.
^{197}Pb	126.9	–	0.64(0.24)	0.73^b	M1
	186.2	0.24(0.19)	–	0.07	E1
	432.5	0.03(0.02)	–	0.01	E1
band 1	152.6	2.02(0.75)	–	2.42	M1
	152.6	–	0.56(0.21)	0.48	M1
	227.6	0.75(0.32)	–	0.79	M1
	245.4	0.54(0.27)	–	0.64	M1
	270.5	0.42(0.10)	–	0.52	M1
	285.2	0.37(0.13)	–	0.45	M1
	293.8	0.31(0.18)	–	0.40	M1
	327.2	0.38(0.29)	–	0.30	M1
	338.9	0.19(0.09)	–	0.28	M1
	353.3	0.26(0.15)	–	0.25	M1
	359.1	0.14(0.11)	–	0.24	M1
	365.2	0.22(0.15)	–	0.23	M1
	369.8	0.11(0.11)	–	0.22	M1
	385.0	0.17(0.06)	–	0.19	M1
band 2	151.3	1.70(0.95)	–	2.42	M1
	200.6	1.41(0.38)	–	1.13	M1
	266.7	0.45(0.11)	–	0.54	M1
	336.7	0.30(0.19)	–	0.28	M1
	403.9	0.10(0.07)	–	0.17	M1
	446.1	0.12(0.07)	–	0.13	M1
^{199}Pb	63.1	–	6.92(1.78)	5.67	M1
	71.4	–	2.99(2.37)	3.85	M1
	150.0	2.47(1.32)	–	2.55	M1
	252.0	0.69(0.13)	–	0.61	M1
band 1	89.9	–	1.98(0.92)	1.63	M1
	173.9	1.59(0.23)	–	1.66	M1
	234.6	0.60(0.11)	–	0.72	M1
	240.1	0.60(0.13)	–	0.67	M1
	273.8	0.29(0.09) [a]	–	0.49	M1
	275.4	0.29(0.09) [a]	–	0.49	M1
	316.4	0.32(0.06)	–	0.33	M1
	328.6	0.20(0.05)	–	0.30	M1
	359.4	0.17(0.09)	–	0.24	M1
	363.1	0.27(0.07)	–	0.23	M1
	401.3	0.13(0.04)	–	0.17	M1
	420.7	0.13(0.07) [a]	–	0.15	M1
	421.0	0.13(0.07) [a]	–	0.15	M1
band 2	125.0	3.53(0.84)	–	4.00	M1
	125.0	–	1.09(0.28)	0.74	M1
	165.6	1.82(0.37)	–	1.93	M1
	214.6	0.93(0.15)	–	0.93	M1
	267.8	0.69(0.18)	–	0.54	M1
	323.1	0.20(0.09)	–	0.31	M1
	430.3	0.24(0.15)	–	0.15	M1
	481.9	0.16(0.11)	–	0.11	M1
band 4	135.2	3.49(0.91)	–	3.42	M1
	193.2	0.95(0.20)	–	1.24	M1
	247.4	1.03(0.17)	–	0.64	M1
	294.1	0.40(0.05)	–	0.40	M1

[a]Unresolved doublet
[b]Theoretical K or L conversion coefficients [13] are given for comparison with experimental K and L coefficients, respectively

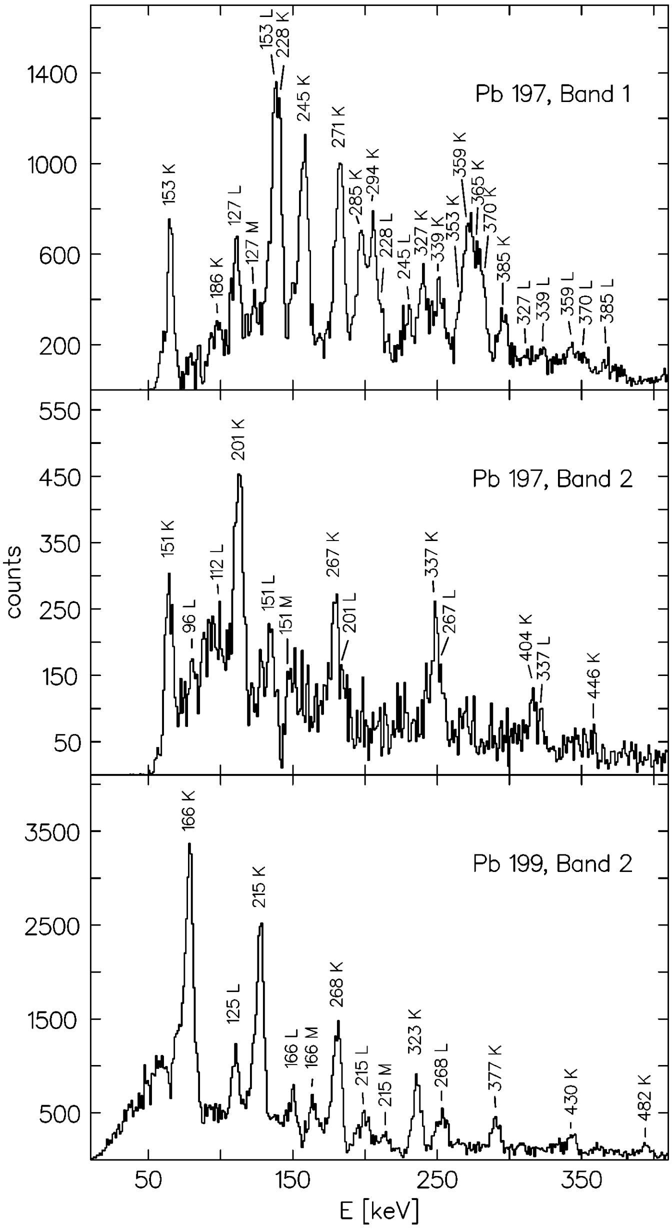

Fig. 3. Conversion electrons in coincidence with γ-ray transitions of band 1 and band 2 in ^{197}Pb and band 2 in ^{199}Pb

resulting in band–head spins in the range of 25/2 to 27/2 $\hbar$. Thus, in the lower–spin part of these bands the configuration is $\pi(h_{9/2}i_{13/2})_{11^-} \otimes \nu i_{13/2}^{-1}$.

In the neutron system pairing plays an important role because the Fermi level is located well below the N = 126 shell gap, whereas for the protons pairing may be neglected [6]. Therefore, we use the cranking–model classification for the neutron quasiparticles: A,B,C,D for the unnatural–parity neutrons (of $i_{13/2}$ origin) and E, F, ... for the natural–parity neutrons (predominantly of $f_{5/2}$ and $p_{3/2}$ origin). The configuration of bands 1 in ^{197}Pb and ^{199}Pb at low spins may then be written as A11, where '11' denotes the spin of the proton configuration.

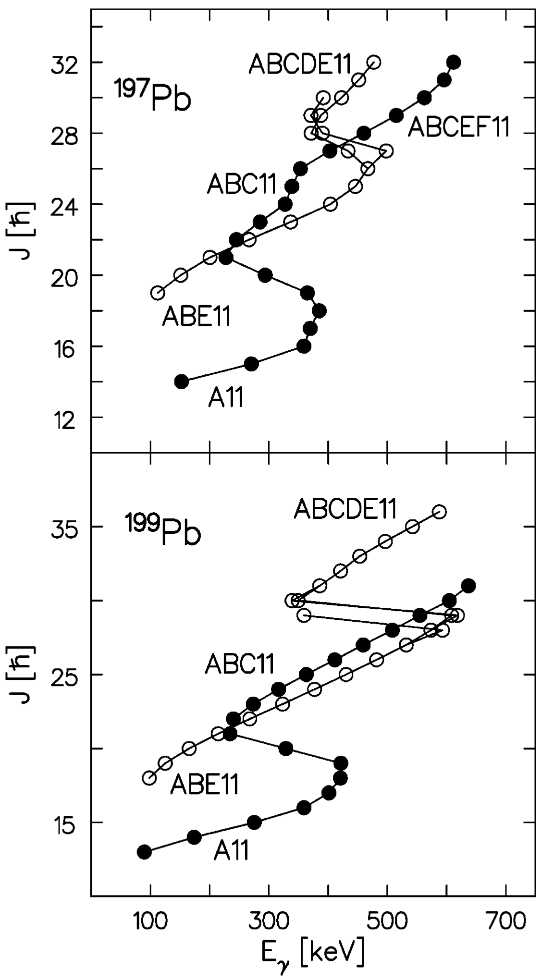

Fig. 4. Experimental angular momentum as a function to transition energy for band 1 (full circles) and band 2 (open circles) in ^{197}Pb and ^{199}Pb

Along the bands the angular momentum is increased by the shears effect [6], i.e. the protons and neutrons align their spins step–by–step into the direction of the total angular momentum. The spin of this configuration is exhausted when the proton and neutron angular momenta are fully aligned – plus a small 'collective' contribution from the other nucleons near the Fermi surface. At that point an additional $i_{13/2}$ neutron–hole pair must be excited to produce the higher–spin states, resulting in the configuration $\pi(h_{9/2}i_{13/2})_{11^-}\otimes\nu i_{13/2}^{-3}$, or ABC11. This is the configuration of bands 1 in ^{197}Pb and ^{199}Pb at higher spins.

The change from the configuration A11 with one quasineutron A coupled to the proton pair with spin 11 to the configuration ABC11 with three quasineutrons ABC coupled to the same proton pair is seen as a 'backbending' in the plot of spin as a function of transition energy in Fig. 4. The gain in alignment of about 8 $\hbar$ is in agreement with tilted–axis cranking calculations [6]. These configurations have negative parity, in agreement with the E1 multipolarity of transitions connecting the bands to low–lying positive–parity levels. Band 1 in ^{197}Pb shows a second irregularity around spin 51/2 with a small alignment gain, see Fig. 4. This may be explained by a decoupling of a natural–parity neutron pair, EF. The configuration of this band at the highest spins would then be ABCEF11. In ^{199}Pb, with two additional neutrons, this alignment is not seen in band 1 in the observed frequency range, possibly due to the difference in the position of the Fermi surface.

For bands 2 in both isotopes the configuration ABE11 was suggested at the bottom of the bands [6–9]. At high spins, again, an additional $i_{13/2}$ neutron–hole pair is excited resulting in the configuration ABCDE11. This configuration change is connected with a more sudden gain in alignment than observed for bands 1 where the crossings of the configurations occur at lower spins, see Fig. 4. Apparently there is a larger interaction between the configurations resulting in more mixing of the wave functions in bands 1 than in bands 2 where the configurations cross at higher spins. Furthermore, in the spin range where the configuration changes, several states with the same spin are observed until a new regular band with the configuration ABCDE11 is formed at higher spins.

In summary, internal conversion coefficients have been measured for the in–band transitions of five dipole bands in ^{197}Pb and ^{199}Pb and of several transitions in the decay of the bands. The results are compatible with M1 multipolarity for the in–band transitions, as expected for magnetic rotation. The present results also confirm the proposed nucleon configurations which give rise to these bands.

This work was supported by DFG, Germany, and by EPSRC, UK.

References

1. G. Baldsiefen et al., Proc. X. Internat. School on Nucl. Phys., Neutron Phys. and Nucl. Energy, eds. W. Andreitscheff and D. Elenkov, Varna (1991)
2. R.B. Firestone, V.S. Shirley, C.M. Baglin, S.Y.F. Chu and J. Zipkin, eds., Table of Isotopes, J. Wiley & Sons (1996)
3. M. Neffgen,G. Baldsiefen, S. Frauendorf, H. Grawe, J.Heese, H. Hübel, H. Kluge, A. Korichi, W. Korten, K.H. Maier, D. Mehta, J. Meng, N. Nenoff, M. Piiparinen, M. Schönhofer, R. Schubart, U.J. van Severen, N. Singh, G. Sletten, B.V. Thirumala Rao and P. Willsau, Nucl. Phys. A 595, 499 (1995)
4. R.M. Clark, S.J. Asztalos, G.Baldsiefen, J.A. Becker L. Bernstein, M.A. Deleplanque, R.M. Diamond, P. Fallon, I.M. Hibbert, H. Hübel, R. Krücken, I.Y. Lee, A.O. Macchiavelli, R.W. MacLeod, G. Schmid, F.S. Stephens, K. Vetter and R. Wadsworth, Phys. Rev. Lett. 78, 1868 (1997)
5. S. Frauendorf, Z. Phys. A358, 163 (1997)
6. G. Baldsiefen, H. Hübel, W. Korten, D. Mehta, N. Nenoff, B.V. Thirumala Rao, P. Willsau, H. Grawe, J. Heese, H. Kluge, K.H. Maier, R. Schubart, S. Frauendorf and H.J. Maier, Nucl. Phys. A574, 521 (1994)

7. G. Baldsiefen, S. Chmel, H. Hübel, W. Korten, M. Neffgen, W. Pohler, U.J. van Severen, J. Heese, H. Kluge, K.H. Maier and K. Spohr, Nucl. Phys. A587, 562 (1995)
8. H. Hübel, G. Baldsiefen, R.M. Clark, S.J. Asztalos, J.A. Becker, L. Bernstein, M.A. Deleplanque, R.M. Diamond, P.Fallon, I.M. Hibbert, R. Krücken, I.J. Lee, A.O. Macchiavelli, R.W. MacLeod, G. Schmid, F.S. Stephens, K. Vetter and R.Wadsworth, Z. Phys. A358, 237 (1997)
9. H. Hübel, Prog. Part. Nucl. Phys. 38, 89 (1997)
10. J. Duprat, C. Vieu, F. Azaiez, G. Baldsiefen, C. Bourgeois, R.M. Clark, I. Deloncle, J.S. Dionisio, B. Gall, F. Hannachi, H. Hübel, M. Kaci, A. Korichi, Y. Le Coz, M. Meyer, N. Perrin, M.G. Porquet, N. Redon, C. Schück, H. Sergolle and R. Wadsworth, Z. Phys. A347, 289 (1994)
11. M. Guttormsen, H. Hübel, A. von Grumbkow, Y.K. Agarwal, J. Recht, K.H. Maier, H. Kluge, A. Maj, M. Menningen and N. Roy, Nucl. Instr. Meth. 227, 489 (1984)
12. P.A. Butler, P.M. Jones, K.J. Cann, J.F.C. Cocks, G.D. Jones, R. Julin, W.H. Trzaska, Nucl. Instr. Meth. Phys. Res. A 381, 433 (1996)
13. R.S. Hager and E.C. Seltzer, Nucl. Data Tables A4, 1 (1968)
14. A. Görgen, Diploma Thesis, Univ. Bonn (1996)
15. G.J. Schmid, A.O. Macchiavelli, S.J. Asztalos, R.M. Clark, M.A. Deleplanque, R.M. Diamond, P. Fallon, R. Krücken, I.Y. Lee, R.W. MacLeod, F.S. Stephens, K. Vetter, Nucl. Instr. Meth. Phys. Res. A 417, 95 (1998)