Magnetic rotation

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9. Magnetic rotation*

9.1. Introduction

The first experimental evidence for sequences of strongly enhanced magnetic dipole (M1) transitions in Pb isotopes that follow a rotational I(I+1) dependence was found about ten years ago [243-245]. The measurements were performed using the OSIRIS and TESSA3 spectrometers in Germany and the United Kingdom, respectively. These bands had surprising features: The M1 transitions were strong, and no, or only extremely weak, E2 crossover transitions were found. The resulting B(M1)/B(E2) ratios led to the conclusion that the deformation is very small. However, for near-spherical states the occurrence of regular band structures, similar to the bands of strongly enhanced E2 transitions in well-deformed nuclei, could not be understood.

Almost all the M1 bands that were discovered at that time were not connected to lower-lying states [243-251] and their excitation energy, spin and parity were not determined experimentally. From the decay pattern it was concluded that they are built on high-spin states, most likely on high-spin proton excitations coupled to the high-spin neutron states that were well known in the Pb isotopes [251]. It was noted, however, that the M1 bands are not built on these proton or neutron states directly.

The M1 bands are nowadays well understood in terms of a new mode of nuclear excitation which has been called "magnetic rotation" (MR) [252,253]. It is also established in other mass regions [254] of near-spherical nuclei where high-spin orbitals are close to the Fermi surface. Magnetic rotation occurs when the symmetry of the nuclear system is broken by the current distributions of a few high-spin particles and holes outside a spherical or near-spherical core. If these currents lead to a large component of the magnetic moment vector perpendicular to the total angular momentum, they generate the enhanced M1 radiation as illustrated schematically in Figure 9.1.

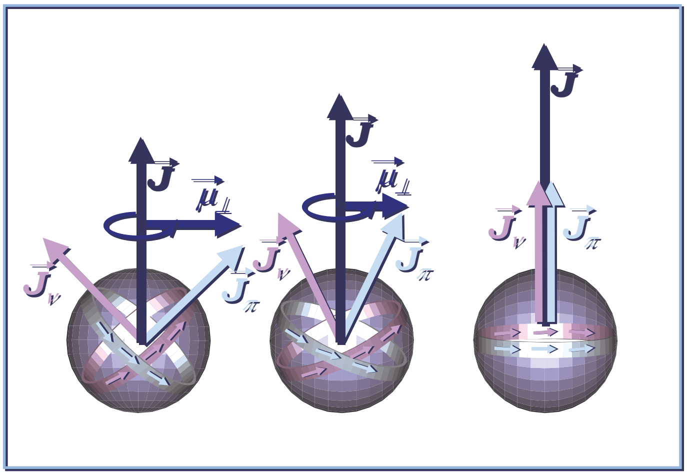

Figure 9.1: *Schematic illustration of the shears effect in magnetic rotation bands [256].*

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Asymmetric currents result from the coupling of particle- to hole-type of excitations. The particle-hole interaction is repulsive and favours a perpendicular orientation of the current distributions and, hence, of their angular momenta. The left-hand panel of Figure 9.1 shows the perpendicular coupling as it is realised near the band head of the MR bands. It has actually been verified experimentally by a measurement of the g factor of the band head of a MR band in ^{193}Pb [255]. The two other panels illustrate how angular momentum is generated within the bands by a step-by-step alignment of the particle and hole spins into the direction of the total spin. Since this resembles the closing of the blades of a pair of shears, the MR bands have also been called "shears bands" [256]. Consequences of the shears effect are that the total angular momentum J remains almost fixed in direction in the intrinsic system and that the perpendicular component of the magnetic dipole moment decreases with increasing J. As this component is responsible for the M1 radiation strength, the B(M1) values are expected to decrease in a characteristic way with increasing spin within the bands. This effect has been verified by lifetime measurements [257-266].

The right-hand panel of Figure 9.1 illustrates the full alignment of the particle and hole spins with the total angular momentum J. This is the maximum angular momentum that can be generated by the shears effect (a small contribution is added from the low-spin orbitals) and at this point the MR band terminates. A clear example of such a band termination is shown in Figure 9.2 where the angular momentum is plotted as a function of the transition energy for MR band 2 in ^{199}Pb [267]. Termination is reached for the configuration of this band at spin 57/2. At higher spins, an additional pair of $i_{13/2}$ neutrons is broken and this neutron-hole pair is coupled to the proton excitation causing the shears to open again. In that way a new band head is formed and a new shears band develops at higher spins.

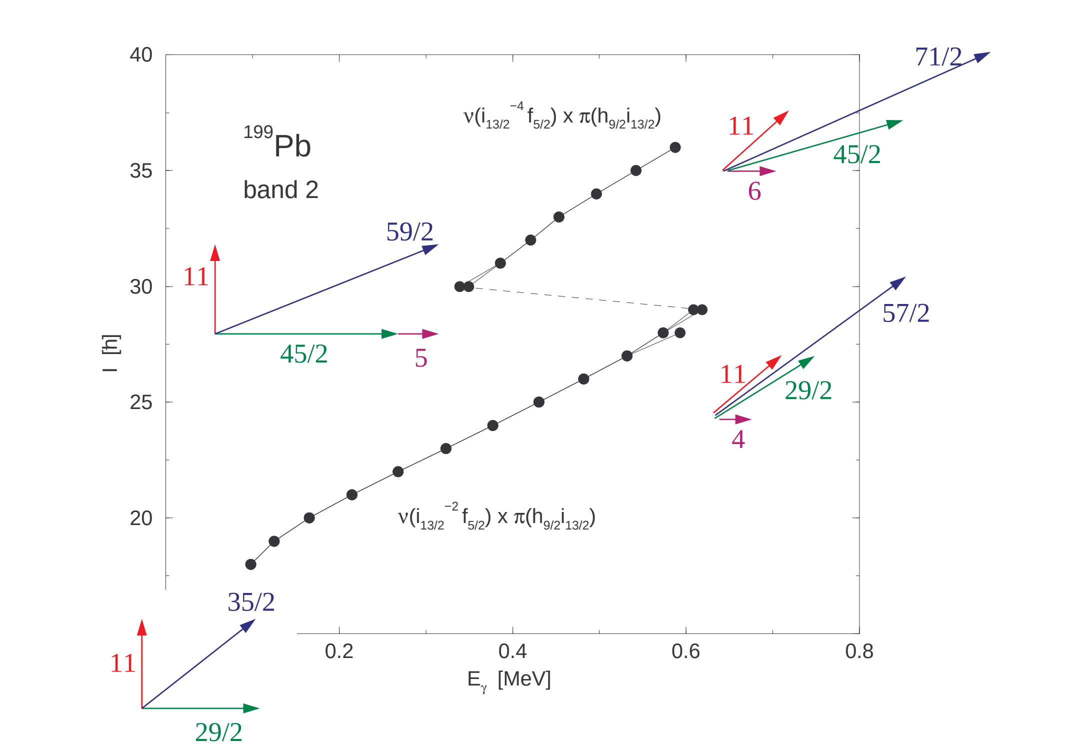

Figure 9.2: *Termination of a shears band in ^{199}Pb [267]. At higher spin a new band with an additional pair of decoupled $i_{13/2}$ neutrons develops.*

As mentioned above, before the multi-detector spectrometers EUROBALL (with its predecessors EUROGAM I and II) and GAMMASPHERE came into operation, most of the MR bands remained unconnected to lower-lying known levels. As band-head spins, parities and excitation energies were unknown, comparison to model calculations, like the tilted-axis cranking (TAC) [252,253,268] or the semi-classical calculations [269], remained largely speculative. With these powerful spectrometers existing bands could be linked to known states and extended to higher spins. In several cases E2 crossover transitions were discovered for the first time and the ordering of the M1 transitions was corrected. Furthermore, many new MR bands were found and new regions of magnetic rotation were established. For several bands precision lifetime measurements were performed which were needed to establish the shears effect. In the following sections the results on magnetic rotation obtained in recent EUROBALL experiments will be summarised.

9.2. Investigation of magnetic rotation with EUROBALL

Magnetic rotation in the A=130 mass region

In the A = 130 mass region sequences of M1 transitions have been observed in several nuclei [254]. However, in most of these cases the quadrupole deformation parameters are rather large, around 0.2. Therefore, it is not clear if these structures are MR bands or if they can be explained in terms of conventional high-K bands. The question may be answered by the behaviour of the B(M1) values as a function of spin.

For ^{124}Xe, where an M1 band has been known from previous work [270], a recoil-distance method (RDM) lifetime measurement was performed with the EUROBALL spectrometer array [271]. The Köln plunger was used for a precise variation of the target-stopper distances. High-spin states in ^{124}Xe were populated in the reaction ^{110}Pd(^{18}O,4n) at a beam energy of 86 MeV. Lifetimes of states in the ground-state band as well as in the M1 band were determined from gamma-ray coincidence spectra. By gating above the levels of interest, uncertainties due to the feeding of the levels could be avoided.

The B(M1) values of transitions in the M1 band deduced from the lifetimes are displayed in Figure 9.3. As can be seen, they show a modest decrease with increasing spin. This is in

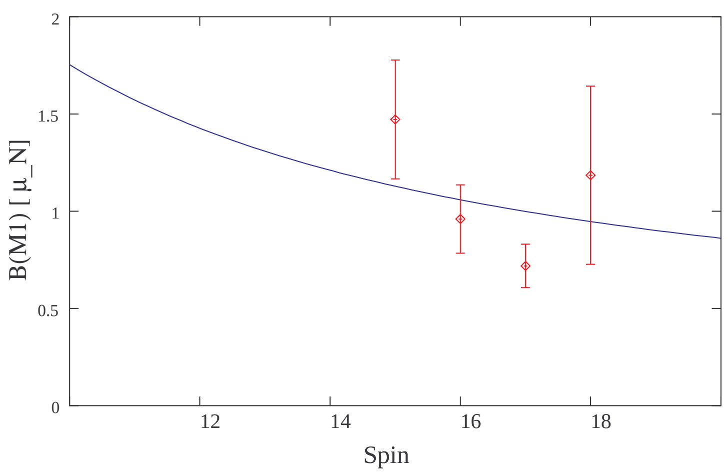

Figure 9.3: *Reduced M1 transition probabilities, B(M1), for states in the M1 band in ^{124}Xe [271]. In the calculation a high-K four quasi-particle configuration was assumed.*

contrast to the corresponding band in ^{128}Ba which shows increasing B(M1) values [272]. The calculated curve in Figure 9.3 was obtained assuming a four quasi-particle structure with high K. For the configuration of two $h_{11/2}$ protons coupled to a $h_{11/2}g_{7/2}$ neutron excitation the semi-classical approach of Dönau and Frauendorf [273] describes the observed behaviour rather well. Thus, the EUROBALL experiment shows that the M1 band in ^{124}Xe is probably not predominantly of magnetic rotation character.

Magnetic rotation around ^{142}Gd

In a search for magnetic-dipole bands around ^{142}Gd, high-spin states were populated in the reaction ^{99}Ru(^{48}Ti,xnyp) at a beam energy of 240 MeV at the Legnaro National Laboratory. The spectroscopic investigation with EUROBALL revealed four M1 bands in ^{142}Gd and ^{143}Gd. In ^{141}Eu three M1 bands and in ^{144}Gd two irregular dipole sequences were found. The level scheme of ^{142}Gd with the four M1 bands discovered in that nucleus is shown in Figure 9.4. From the intensity branching ratios the B(M1)/B(E2) ratios displayed in Figure 9.5 were obtained. They are exceptionally large and show the decrease expected for shears bands when compared to TAC calculations [274].

The M1 bands in ^{142}Gd can be associated with the minima seen in the calculated total routhian surfaces at small oblate deformation in the frequency range between 0.2 and 0.5 MeV. For this deformation the $h_{11/2}$ neutron-hole and $g_{7/2}$ proton-hole states with small K values and the $h_{11/2}$ proton states with large K values contribute to the configurations of the bands. A neutron $h_{11/2}$

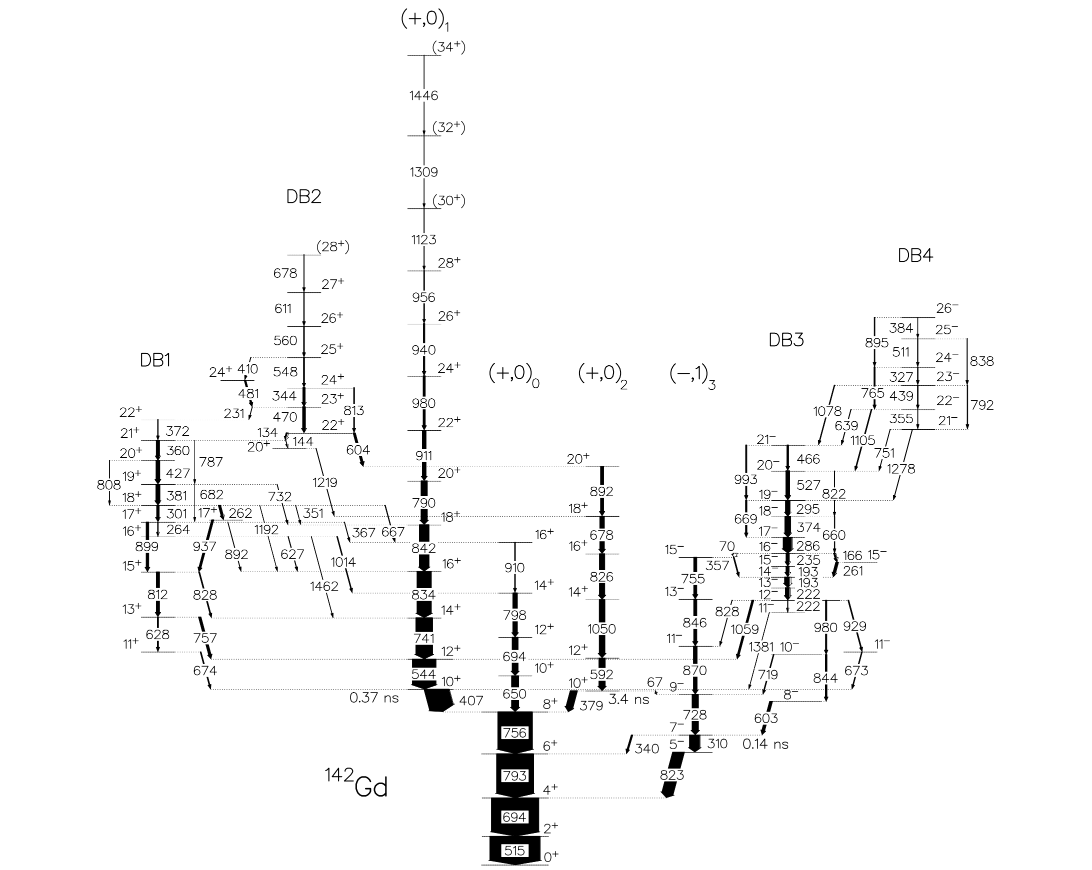

Figure 9.4: *Partial level scheme of ^{142}Gd [274].*

two-hole excitation coupled to a proton $h_{11/2}$ two-particle configuration may be assigned to dipole band 1. The same neutron $h_{11/2}$ two-hole excitation coupled to a proton $h_{11/2}g_{7/2}$ particle configuration may be responsible for band 3. Bands 2 and 4 most likely result from the breakup of an additional $h_{11/2}$ neutron-hole pair. Considering an alignment of the spins of the hole states along the rotation axis and those of the particle states along the symmetry axis, these configurations could give rise to MR bands. However, for a final confirmation, we have to wait for the results of a lifetime measurement performed recently with EUROBALL.

The angular momenta of two of the dipole bands in ^{141}Eu and ^{143}Gd, respectively, have similar frequency dependencies as bands 1 and 2 in ^{142}Gd, but the angular momenta are smaller. This indicates that their configurations result from those of ^{142}Gd by subtraction of a proton and a neutron hole, respectively. In this case the band crossings may result from the breakup of a second $h_{11/2}$ neutron-hole pair [275].

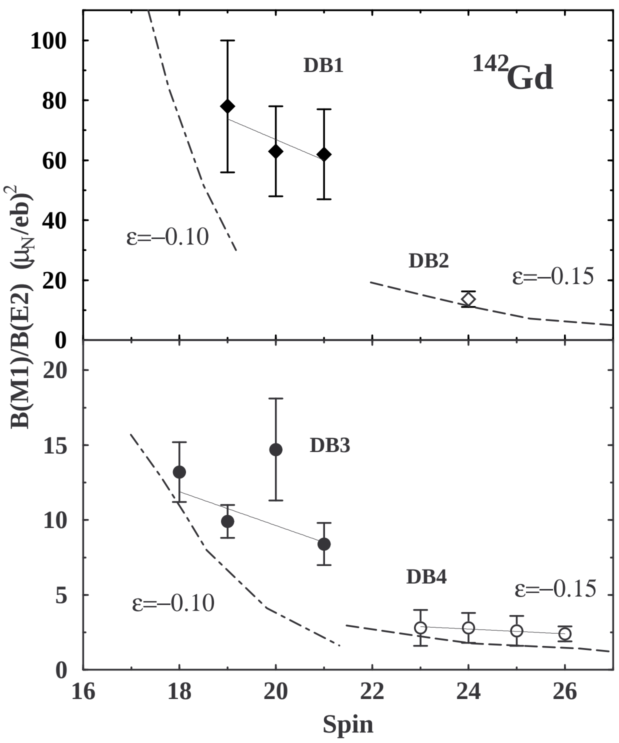

Figure 9.5: *Ratios of reduced transition probabilities B(M1)/B(E2) for the M1 bands in ^{142}Gd [274]. The dashed lines were obtained by TAC model calculations.*

Detailed study of magnetic rotation in ^{196}Pb

An experiment to study magnetic rotation in ^{197}Pb and ^{198}Pb using the EUROGAM II spectrometer [276] showed a significant improvement in the quality of the data compared to previous studies. In both nuclei, new MR bands were found and the known ones were partly reordered and extended to higher spins. In most cases, transitions connecting the MR bands to lower-lying states were identified.

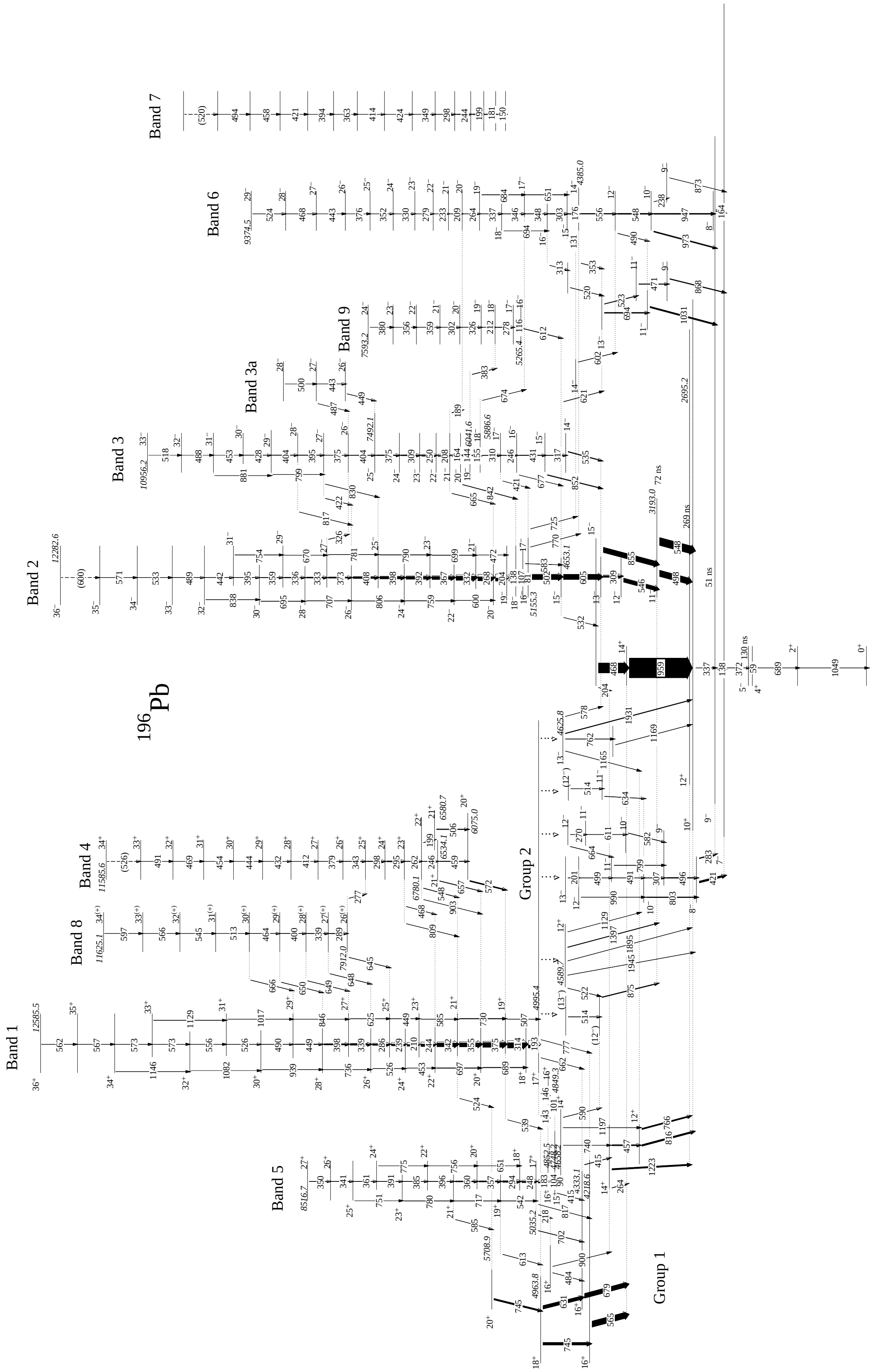

***Figure 9.6:** Partial level scheme of ^{196}Pb [277].*

Three experiments were performed for a detailed investigation of magnetic rotation in ^{196}Pb using the EUROBALL spectrometer. One was performed with a thin target [277] aimed at extending the bands to very high spins and one with a gold-backed target optimized for a study of the decay of the bands and to determine lifetimes [278] using the Doppler-shift attenuation method (DSAM). In a third experiment, lifetimes were measured in the low-spin region of band 1 [261] using the RDM. In the first experiment, high-spin states in ^{196}Pb were populated in the ^{186}W(^{16}O,6n) reaction at a beam energy of 110 MeV at the tandem accelerator of the Legnaro National Laboratory. The second experiment was performed at the Vivitron accelerator of the Institut de Recherches Subatomiques, Strasbourg. The reaction ^{170}Er(^{30}Si,4n)^{196}Pb was used at a beam energy of 144 MeV. In the RDM experiment, the reaction ^{164}Dy(^{36}S,4n)^{196}Pb was used at a beam energy of 168 MeV and was performed at the Legnaro National Laboratory. These reactions gave the higher recoil velocities needed for the lifetime measurements. The Köln plunger device was used to measure coincidence spectra at 15 target-stopper distances [261].

The analysis of the spectroscopic data resulted in the level scheme presented in Figure 9.6; only the part that is relevant to the MR bands and their decay is shown. In addition to the previously known four bands [249], five new bands were discovered. Many new E2 crossover transitions have also been observed for the first time, which fix the ordering of the M1 transitions. All the bands, except band 7, are now connected to lower-lying states. The measurement of the DCO ratios and the linear polarisation of the transition allowed the spin assignments shown in Figure 9.6 to be made.

Lifetimes for four of the MR bands in ^{196}Pb were determined in the high-spin regions by the DSAM [278] and for band 1, lifetimes were measured at low spins by the RDM [261]. Previously, precision lifetime results were only available for band 1 at high spins [259]. The B(M1) values derived from the lifetimes are displayed in Figure 9.7. The experimental results

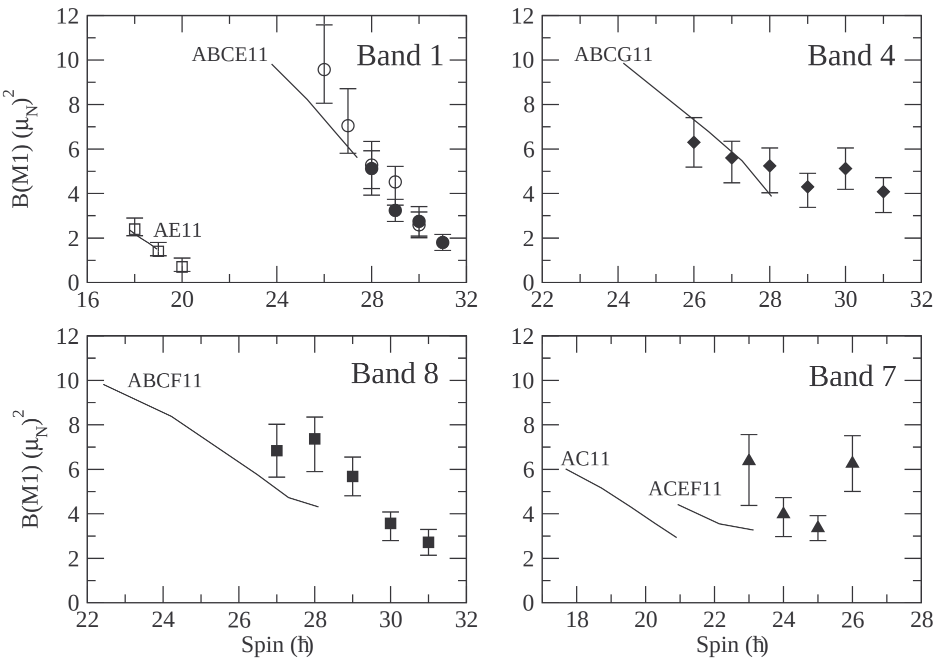

Figure 9.7: *Reduced M1 transition probabilities, B(M1), for states in MR bands 1, 4, 7 and 8 in ^{196}Pb [261,278]. The calculations were performed within the framework of the TAC model.*

are compared with calculations performed within the framework of the TAC model. The B(M1) values are large and show the characteristic decrease that is expected for shears bands.

The new detailed information on the MR bands in ^{196}Pb, in particular the spins, parities and excitation energies, enabled us to make configuration assignments for all bands, except for band 7. These assignments were also guided by the systematic behaviour of the bands [276,277] and by comparisons with results of TAC calculations. The MR bands may be explained by a coupling of either the two-proton $(h_{9/2}i_{13/2})_{11}^{-}$ or two-proton $(h_{9/2}^{2})_{8}^{+}$ particle states to the high-spin neutron-hole excitations with one or more $i_{13/2}$ quasi-neutrons involved.

9.3. Summary and outlook

The highly efficient spectrometer arrays EUROBALL and EUROGAM have allowed the detailed spectroscopy of magnetic rotational bands to be carried out in different mass regions. In the case of the M1 band in ^{124}Xe, the lifetime results revealed a smaller decrease of the B(M1) values than would be expected for a shears band. On the other hand, the bands found in ^{142}Gd show the characteristic features of magnetic rotation. However, for a final proof the knowledge of lifetimes is necessary. In the Pb isotopes reliable configuration assignments could be made to a large number of MR bands.

While a large body of information on magnetic rotation exists in the Pb region [254,276,277], it would be highly desirable to study other regions of nuclei near closed shells in similar detail. Such investigations can give information on core-polarisability effects and the influence of prolate and oblate deformation on magnetic rotation. Here, systematic investigations are lacking.

Furthermore, there are several interesting questions connected to magnetic rotation and the shears effect that need to be addressed. One of them is the possibility of antimagnetic rotation [253]. This type of excitation may occur when the current distributions of a few high-spin orbitals break the symmetry of an otherwise near-spherical nucleus, but the magnetic moments couple approximately antiparallel. In that case a band of E2 transitions with very small B(E2) values is expected. Up to now, little evidence exists for this type of excitation [253,279,280]. Another interesting question is the possibility of the opening of the shears to angles larger than 90^0. This would lead to bands with decreasing spin with increasing energy. Such bands might be populated in direct reactions rather than in heavy-ion induced compound reactions. They will probably be only populated with low intensity and new efficient spectrometers will be necessary to find them.

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