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ELECTROMAGNETIC PROPERTIES OF HIGH SPIN STATES

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Abstract: The development of suitable experimental methods, which exploit the heavy ion beam capabilities of the UNILAC accelerator at Darmstadt, opened up the possibility to measure electromagnetic properties of short-lived high spin states. The implications of recent results obtained for static magnetic dipole and E2-transition moments on our present understanding of the structure of the yrast states of deformed rare earth nuclei are discussed.

1. Introduction

In 1971 A. Johnson, H. Ryde and J. Sztarkier reported¹⁾ on an anomaly they observed around an angular momentum of $16\hbar$ in the yrast sequence of the well deformed nucleus ^{160}Dy . The occurrence of this discontinuity - usually referred to as backbending effect - showed for the first time in a rather dramatic way that deformed nuclei find energetically more favorable ways of generating high angular momenta than just by a collective rotational motion. It was in fact this experiment which prompted extensive experimental and theoretical investigations in order to study the question of how nuclei accommodate high angular momenta. Meanwhile the backbending effect has been observed in many deformed nuclei all over the periodic table. Similar anomalies were found to occur also in excited bands. Moreover, in some rare earth nuclei, which have been studied most thoroughly, an additional discontinuity was shown to occur in the yrast sequence around angular momenta of $26\hbar$.

It is now generally believed that the basic feature of the structure of the yrast line of deformed heavy nuclei can be described as an interplay between collective rotations and single particle excitations (see also fig.1): For deformed even nuclei, for example, the yrast states at low angular momenta are members of the $K=0$ ground state band, which is due to the collective rotation of the deformed, axially symmetric nucleus around an axis perpendicular to the symmetry axis, the moment of inertia being only approximately half the corresponding rigid rotor value because of the pairing correlations. With increasing rotational frequency, the increasing Coriolis force tends to successively break pairs of nucleons moving in high- j intruder orbits close to the Fermi surface (for rare earth nuclei, e.g., these are the $i_{13/2}$ neutron and $h_{11/2}$ proton pairs) and to align their individual angular momenta along the rotational axis. As such an aligned pair provides a considerable part of the total angular momentum of the nucleus (the maximum aligned angular momentum being e.g. $12\hbar$ and $10\hbar$ for an $i_{13/2}$ neutron or an $h_{11/2}$ proton pair, respectively), the core is rotating at a reduced speed, and in case the retrenchment of rotational energy outweighs the energy needed to break and align the pair, the rotational aligned configuration will be energetically favoured.

These considerations have led to the rotational alignment picture, where the anomalies occurring in the yrast sequence of deformed nuclei are interpreted as being due to the successive intersection of the paired ground state band (g-band) with a band (s-band) involving one aligned quasi-particle pair, the s-band with an s'-band involving two aligned quasi-particle pairs etc, while the abruptness of the discontinuity reflects the interaction strength between the two crossing bands. Calculations within the Cranked Shell Model (CSM) and in particular detailed microscopic calculations within the Cranked Hartree-Fock-Bogoliubov (CHFB) approach³⁾ indeed suggest that e.g. in deformed rare earth nuclei the first anomaly in the yrast sequence is mainly caused by the alignment of an $i_{13/2}$ neutron pair as originally proposed by Stephens and Simon (ref.4) while the second discontinuity is due to an additional alignment of an $h_{11/2}$ proton pair.

Fig. 1 Excitation energy of the yrast states of $^{152,156}\text{Dy}$ together with a schematic view of the main structure of these states.

It should be emphasized, that microscopically also the angular momentum attributed to a collective rotation has to be generated by breaking pairs of nucleons moving in orbitals close to the Fermi surface. Between two backbending points, however, the corresponding structural changes are small when going from one yrast state to the other, and the sequence of states can be approximately described as a rotational band, the rearrangement of the nucleons being reflected in small, more or less smooth dependences of the macroscopic parameters such as the deformation and the moment of inertia on the rotational frequency. The microscopic effects are expected to become more pronounced when going from well deformed nuclei with many active nucleons/pairs towards magic nuclei. For spherical nuclei with only a few active nucleons left, the single particle nature of the yrast states will be dominant; the yrast sequences of these nuclei will fluctuate and the transition matrix elements between consecutive states will adopt single particle values.

As an example for an yrast line which is dominated by single particle effects, the yrast sequence of ^{152}Dy is shown in fig.1; with $N=86$ this isotope of the $Z=66$ chain lies between the $N=82$ neutron shell and $N=88$, where a phase transition from spherical to deformed nuclei occurs. Indeed, and in contrast to ^{152}Dy , the experimentally known yrast sequence of the $N=90$ isotope ^{156}Dy , also given in fig.1, does show already a smooth dependence on the angular momentum; only one distinct discontinuity occurs at around $16\hbar$, which is interpreted as being due to the intersection of the g-band with the weakly interacting s-band built on a rotational aligned $i_{13/2}$ neutron pair. The second crossing point, known from neighbouring nuclei and model calculations to take place around $26-28\hbar$, is obviously smeared out in ^{156}Dy due to a strong interaction between the two and four quasi-particle band. Despite the fact, however, that ^{156}Dy possesses already - with the exceptions mentioned - a smooth yrast line similar to those of heavier, well-deformed rare earth nuclei, from the properties of the low lying states ^{156}Dy is known to be a transitional nucleus. One thus expects also the states belonging to the smooth parts of the yrast sequence to exhibit marked deviations from the properties expected for members of rotational bands of a well deformed, prolate nucleus. In particular, the consecutive rotational alignment of pairs of nucleons might lead to considerable triaxial deformations and finally even to an oblate nucleus "rotating" around its symmetry axis, i.e. to a configuration similar to

that expected for ^{152}Dy at high spins.

Although the rotational alignment picture emerging from calculations within the CSM and CHFB approaches does seem to provide an understanding of the dominant structural change occurring in the yrast sequence of deformed nuclei, it should be realized that the experimental verification of these model calculations is so far mainly based on level energies only. It is obvious that additional spectroscopic quantities, in particular static and dynamic electromagnetic multipole moments, are required to arrive at a more detailed understanding of the structure of high spin states and to allow for a more stringent test of the model calculations. So far our knowledge of electromagnetic moments of high spin states in deformed nuclei is rather scanty due to experimental difficulties caused by the short lifetime of these states; in ^{156}Dy , e.g., already the $I^\pi=12^+$ yrast state has a lifetime of less than 1 ps. The description of the methods developed during the last years to determine electromagnetic moments of such short lived high spin states as well as the discussion of the implication of these results will be the main topic of this talk. In order to demonstrate the information content of these moments, however, I shall first discuss some simple expressions for the static and dynamic M1 and E2 moments obtained within the particle-plus-rotor model.

2. Electromagnetic moments of yrast states in deformed nuclei

Within the rotational alignment picture the dominant structural changes in the yrast sequence of well deformed nuclei are attributed to the consecutive intersection of rotational bands involving zero, one, two etc. rotation-aligned quasi-particle pairs in high-j intruder orbits. Between crossing points the yrast states are thus being interpreted as members of rotational bands involving aligned quasi-particle pairs. In the following the properties of these band will be discussed in the high spin limits using the particle-plus-rotor model (see e.g. ref.5); more precisely, the limiting condition is $I^2 \gg R^2$, where R denotes the maximum K-value which has to be considered in an expansion of the wavefunction of the state with angular momentum I in terms of eigenfunction of the symmetric top. In even, strongly deformed nuclei this condition is expected to be well fulfilled for all bands contributing to the yrast sequence: At low spins these nuclei exhibit axially symmetric, prolate deformations and the yrast states can be described as being members of the ground state rotational band with $K=0$. For rotational band involving aligned quasi-particles, K is no longer a constant of motion. However, at least at a spin regime where these bands become yrast, the condition $I^2 \gg R^2$ will be still valid if the quasi-particles are well aligned and the deviations from axial symmetry are not too large.

For a rotational band with $I^2 \ll R^2$ the expectation value I_x of the total angular momentum I in the direction of the rotational (x -) axis is given by (see also ref.2)

$$I_x(I) = \sqrt{I(I+1)} \approx I + 0.5 \quad (1)$$

and can be expressed as a sum of two contributions

$$I_x(I) = R(\omega(I)) + i, \quad (2)$$

where $R(\omega)$ denotes the collective angular momentum produced by the rotation, which is connected to the moment of inertia θ and the rotational frequency ω by $R(\omega) = \theta \cdot \omega$, and i is given by $i = \sum i_\mu$, where i_μ is the single-particle angular momentum produced by the aligned pair μ along the rotational axis. As the rotational frequency can be deduced²⁾ from the transition energy $\Delta E(I \rightarrow I-2)$ via

$$\hbar\omega(I_x(I-1)) = \frac{\Delta E(I \rightarrow I-2)}{I_x(I) - I_x(I-2)} \approx \frac{1}{2} \Delta E(I \rightarrow I-2) \quad (3)$$

from a plot of I_x vs. $\hbar\omega$ the moment of inertia θ as well as the aligned angular momentum i of the band can be determined.

Fig. 2 Left: Collective and single-particle contributions to the g-factor of the yrast states in rare earth nuclei.
Right: γ -dependence of the two intrinsic quadrupole moments Q_t and Q_d .

The static magnetic dipole moment $\mu(I)$ of a state belonging to a rotation-aligned band, or rather the gyromagnetic ratio, $g(I)$, is given by⁶⁾

$$g(I) = \frac{\mu(I)}{\mu_N \cdot I} = g_R + \sum_{\mu} (g_{\mu} - g_R) \frac{i_{\mu}}{I}, \quad (4)$$

where μ_N denotes the Bohr magneton. The gyromagnetic ratio $g_R = \theta_{\pi}/(\theta_{\pi} + \theta_{\nu})$, which is due to the collective rotation, is expected to be slightly smaller than Z/A : Because the pairing correlations between the protons (π) are larger than those between the neutrons (ν), the moment of inertia due to the protons is smaller than that due to the neutrons; for rare earth nuclei one finds $g_R \approx 0.35$. The second term in eq.(4) is due to the magnetic moments produced by the aligned nucleons. It depends on the aligned angular momentum i_{μ} of the pair μ and in particular - via the gyromagnetic ratio g_{μ} of the nucleons - on whether protons or neutrons are being aligned. For neutrons in the $i_{13/2}$ -orbit or protons in the $h_{11/2}$ -orbit - the two high-j intruder orbits important in rare earth nuclei - g_{μ} is expected to be $g_{\mu} \approx -0.15$ and $g_{\mu} \approx +1.2$, respectively, assuming the spin gyromagnetic ratios of the free nucleons to be attenuated by a factor of 0.6. The resulting single-particle contributions $\delta g_{\mu} = (g_{\mu} - g_R) i_{\mu} / I$ as well as the collective contribution g_R to the total g-factor $g(I)$ are shown in fig.2 assuming $g_R \approx 0.35$ and $i_{\mu} = 10$.

The reduced E2-transition moments between and the static quadrupole moments of states belonging to a rotation-aligned band can be expressed via

$$B(E2, I \rightarrow I-2) = \frac{5}{16\pi} \frac{3I(I-1)}{2(4I^2-1)} Q_t^2 \quad (5)$$

and

$$Q(I) = - \frac{I}{2I+3} Q_d \quad (6)$$

in terms of two intrinsic moments Q_t and Q_d , respectively. For very high spins these moments are connected with the usual quadrupole deformation parameters β , γ ($\beta > 0$) by

$$Q_t = Q_0 \frac{2}{\sqrt{3}} \cos(30^\circ - \gamma) \quad (7a)$$

and

$$Q_d = Q_0 2 \sin(30^\circ - \gamma) \quad (7b)$$

with

$$Q_0 = \frac{3}{\sqrt{5}\pi} e Z \beta R_0^2, \quad (7c)$$

Z being the nuclear charge and R_0 the average nuclear radius; they are plotted in fig. 2 as a function of γ for $-60^\circ \leq \gamma \leq +60^\circ$. The convention used for γ is that of ref.5, where $\gamma = +60^\circ$ (-60°) corresponds to a rotation of an oblate nucleus around an axis perpendicular (parallel) to the symmetry axis, while $\gamma=0^\circ$ corresponds to a prolate nucleus rotating around an axis perpendicular to the symmetry axis. Eqs.(5),(6) together with eqs.(7) are valid for yrast states at very high spins without any restriction on β and γ (see e.g. ref.7). For lower spin values they are valid if again $I^2 \gg R^2$, i.e. if γ is restricted to values not too far from those describing axial symmetry: In ref.8 they have been shown to approximately describe e.g. the E2-properties of the 18^+ yrast states of rare earth nuclei if $|\gamma| \leq 20^\circ$. Moreover, for $\gamma=0^\circ$ eqs.(5)-(7) reduce to the usual formulae for an axially symmetric prolate rotor with $K=0$ expected to describe the low spin yrast states of deformed even nuclei rather well.

Although the assumption that the yrast states in between the crossing points are members of pure rotational bands is certainly only a first order approximation, the expressions derived within the particle-plus-rotor approach do show rather clearly what one can expect to learn from a measurement of electromagnetic moments of high spin yrast states in deformed nuclei. While the transition energies $\Delta E(I \rightarrow I-2)$ can be used to determine the moment of inertia θ and the total amount of alignment i , the static magnetic moments are in particular sensitive to the single particle properties of the yrast states; e.g. they allow to distinguish between i_γ and i_π , that is between the amount of single particle angular momentum produced by aligning a neutron or a proton pair, respectively. On the other hand, the E2-moments are in particular sensitive to the collective properties of the yrast states, that is to the deformation β and γ of the nucleus. As discussed in sect.1, more or less smooth changes of the macroscopic quantities describing the rotation-aligned bands are expected due to changes in the underlying microscopic structure. Thus the observed ω dependence of the moment of inertia - usually parameterized by $\theta = \theta_0 + \omega^2 \theta_1 + \dots$ - can be attributed to the weakening of the pairing correlations (Coriolis-Anti-Pairing effect) and/or to spatial rearrangements (e.g. Centrifugal Stretching). Again both effects will have different impacts on the electromagnetic moments of the band. An ω dependence of the deformation parameters will be reflected in the static and dynamic E2-moments, while the Coriolis-Anti-Pairing effect might lead to an ω dependence of g_R in case the protons are effected differently than the neutrons.

Around the intersection points of the rotation aligned bands the properties of the yrast states will depend on the amount of mixing between the two crossing bands. While a strong interaction will lead to a large mixing and thus to a rather smooth, continuous transition from one band to the other, the yrast state properties, in particular those involving different states such as the transition energies and the $B(E2)$ values, will show pronounced discontinuities if the interaction is small. Note, moreover, that in the region where bandmixing occurs, $M1$ -transitions between the two bands become possible. The corresponding reduced $M1$ -transition probability, which connects the higher lying (yrare) state to the lower lying (yrast) state, are given in first order by⁶⁾

$$B(M1, I \rightarrow I) = \frac{3}{4\pi} \mu_N^2 (g_\mu - g_R)^2 i_\mu^2 a^2(I) (1 - a^2(I)), \quad (8)$$

where μ denotes the additional aligned pair which distinguishes to two crossing bands, and $a(I)$ is the mixing amplitude. As the static $M1$ -moments the $B(M1)$ values are sensitive to the single-particle properties of the yrast states.

3. Experimental methods

The possibility to measure electromagnetic moments of short lived, high spin states has been opened up by the availability of very heavy ion beams such as those supplied by the UNILAC-accelerator operated by GSI at Darmstadt. In the following I would like to briefly discuss the main features of the experimental methods we have developed at GSI to measure $B(E2)$ values as well as static magnetic moments of high spin states in deformed nuclei.

For the time being, static quadrupole moments of short lived, high spin states are not yet experimentally accessible. Although the multiple Coulomb excitation process is in principle sensitive to the static quadrupole moments of the states excited, the measurements are still not accurate enough to allow for an extraction of $Q(I)$ (see subsection 3.1 below). Another conceivable technique would be a precession measurement of the angular correlation of the de-excitation γ -rays, exploiting the hyperfine interaction of $Q(I)$ with a large electric field gradient. This technique has been successfully used for long lived high spin isomers. So far, however, no methods are known for producing field gradients which are large enough to result in a measurable precession for states with lifetimes of the order of 1 ps. As far as the measurement of $B(M1, I \rightarrow I)$ -values between the yrare and yrast band around the crossing point are concerned, they can be deduced from the lifetimes of the initial yrare states if the corresponding branching ratios and multipole mixing ratios are known. Unfortunately, these $\Delta I=0$ transitions are difficult to observe because they are strongly suppressed by the transition energy factor. Note, however, that in a contribution to this conference, Nagai et al.⁹⁾ report on a recent measurement performed in rare earth nuclei, where they succeeded to determine two such $B(M1, I \rightarrow I)$ values.

3.1 MULTIPLE COULOMB EXCITATION WITH ^{208}Pb PROJECTILES

For the population of high spin states via the multiple Coulomb excitation process, ^{208}Pb constitutes the almost ideal projectile not only because of its large nuclear charge ($Z=82$) but also because of its double-magic structure. The first excited state of ^{208}Pb , the $I^\pi=3^-$ state at 2.6 MeV, as well as the higher states are only weakly excited. This is important not only from an experimental point of view, it also leads to a considerable simplification in the theoretical description of the excitation process as the ^{208}Pb nucleus can be viewed as a monopole charge not possessing any internal structure.

The excitation of high spin states in Coulomb excitation studies with very heavy ions is the result of a multistep process, which is induced by the Coulomb interaction between the projectile and the target nucleus; magnetic excitations as well as relativistic contributions to the electric transitions are usually negligible small. Moreover, the electric excitation amplitudes decrease drastically with increasing multipolarity. Thus e.g. the members of the yrast sequence of a well deformed nucleus are mainly excited via consecutive E2-transitions, E1-excitations via levels of opposite parity are usually very small as the $B(E1)$ values between states not involving the giant dipole resonance are in most cases strongly hindered compared to the E1 single-particle units. Despite the limitation to E2-transitions, the excitation probability of a particular level, which can be deduced from the intensities Y of its de-excitation γ -rays, is determined by all the E2-moments connecting this state via several intermediate states to the ground state of the nucleus. Nevertheless it is possible to deduce individual $B(E2)$ values at least for states belonging to the most strongly excited sequence, which is usually the yrast line: For c.m. scattering angles θ_{cm} of the projectile smaller than a certain maximum angle $\theta_{\text{cm}}(I)$, e.g. the γ -intensity ratios $Y_{I \rightarrow I-2}(\theta_{\text{cm}})/Y_{I-2 \rightarrow I-4}(\theta_{\text{cm}})$ for two consecutive γ -transitions within the yrast sequence of an even deformed nucleus is only determined by the $B(E2; I-2 \rightarrow I)$ value. As $\theta_{\text{cm}}(I)$ increases with increasing spin I , reaching $\sim 150^\circ$ for the highest spin states observed, the $B(E2; I-2 \rightarrow I)$ values within the yrast sequence can be determined in a model independent way if the γ -intensities $Y_{I \rightarrow I-2}(\theta_{\text{cm}})$ are measured over a large range of scattering angles including $\theta_{\text{cm}} \sim 150^\circ$ (for more details see e.g. ref.10).

Fig. 3 Schematic view of the experimental set-up used in multiple Coulomb excitation experiments of rare earth nuclei with ^{208}Pb ions (from ref.10).

A schematic view of the experimental set-up used in most Coulomb excitation studies performed at GSI with ^{208}Pb -projectiles is shown in fig.3. A thin ($\leq 1\text{mg}/\text{cm}^2$), self-supporting target is bombarded by ^{208}Pb -projectiles with energies close to the "safe" energy, which is the maximum bombarding energy satisfying the condition that the two colliding nuclei stay outside the range of the nuclear forces. De-excitation γ -rays are recorded by two Ge detectors in coincidence with the recoiling target nuclei, which are observed in a large-area avalanche detector (L) positioned at a distance of 15 cm from the target. The detector measures the angle ϑ_2 of the recoiling target nuclei in an angular range of $150^\circ \leq \vartheta_2 \leq 60^\circ$, which corresponds to projectile c.m. scattering angles of $150^\circ \leq \theta_{\text{cm}} \leq 60^\circ$. In order to be able to decide whether the recoiling target nucleus (and not the scattered projectile) has been observed in the recoil detector, the corresponding projectile is detected in a second position-sensitive detector (R). By measuring the time-of-flight difference and/or the ϑ -correlation between the two coincident particles, events with recoil nuclei in detector (L) can be uniquely identified. For ^{208}Pb ions impinging on rare earth nuclei a detector identical to the recoil detector can be used to detect the scattered projectiles without restricting the efficiency of the set-up by the coincidence requirement. For more details concerning the particle detectors used and in particular of the continuous delay-line read-out of the ϑ_2 -information, which allows for an on-line correction of the observed γ -ray for its rather large Doppler shift, see ref.10.

A Doppler-corrected γ -ray spectrum observed e.g. for ^{164}Dy by bombarding a $800\text{ }\mu\text{g}/\text{cm}^2$ thick ^{164}Dy target with $4.7\text{ MeV}/\text{amu}$ ^{208}Pb -projectiles is shown in fig.4. All observed γ -lines can be attributed to the decay of states belonging to the ground state band and the γ -band of ^{164}Dy and to the ground state band of ^{162}Dy contained as a $\approx 3\%$ impurity in the target used. The spin assignments are primarily based on energy systematics and on the θ_{cm} -dependence of the γ -ray intensities.

While the $B(E2)$ values between the high spin states of the ground state band can be extracted from the γ -ray intensities observed in the triple-coincidence measurement between $60^\circ \leq \theta_{\text{cm}} \leq 150^\circ$, for the determination of $B(E2)$ value between low spin members it is usually necessary to enlarge the angular range to lower θ_{cm} -values. This is achieved by requiring only double coincidence between the γ -ray and the recoil detector (L) and by analyzing also those events, which correspond to the detection of the scattered Pb-projectiles in (L), using the observed Doppler shift to distinguish these events from those corresponding to the detection of the recoiling nuclei in (L). Thus it is possible to determine γ -yields between low spin states also for c.m. scattering angles as small as 30° ; the actual lower limit depends, of course, on the target mass.

Fig. 4 Total Doppler-corrected γ -spectrum following multiple Coulomb excitation of ^{164}Dy with ^{208}Pb ions ($64^\circ \leq \theta_{\text{cm}} \leq 146^\circ$). The unmarked lines are due to the excitation of the target impurity ^{162}Dy (from ref.11).

Using the technique described above, $B(E2)$ values between the yrast states of many rare earth and actinide nuclei have been determined. The highest states that could be observed in these experiments are the $\Pi=22^+(30^+)$ yrast levels in well deformed rare earth (actinide) nuclei. Some of these results will be discussed in section 4. It should be pointed out that the excitation probabilities are in principle also sensitive to the diagonal $E2$ -matrix elements, i.e. to the static quadrupole moments of the states belonging to the excitation paths. However, for scattering angles where the γ -intensity ratios are most sensitive to $Q(I)$, other $E2$ -transition matrix elements contribute as well and it is normally not possible to disentangle these different contributions. So far we succeeded only in one case to exploit the $Q(I)$ -dependence to determine quadrupole moments of higher lying states; in a Coulomb excitation experiment of ^{104}Ru with ^{208}Pb ions we were able to determine the quadrupole moments of the ground state band of ^{104}Ru up to the $\Pi=8^+$ state¹²).

3.2 LIFETIME MEASUREMENTS USING THE RECOIL-DISTANCE METHOD

The recoil-distance method is a well established technique to measure nuclear lifetimes as short as a few picoseconds. However, in order to be able to apply this method in the sub-picosecond region, i.e. in a lifetime region expected to be relevant for high spin states in deformed nuclei, one has to introduce some modifications which I would like to discuss below, taking our experiment performed on ^{156}Dy as an example.

A schematic view of the recoil-distance set-up used in this experiment is shown in fig.5. The ^{156}Dy nuclei were produced via the inverse reaction $^{25}\text{Mg}(^{136}\text{Xe}, 5n)$ by bombarding a stretched, self-supporting ^{25}Mg foil with ^{136}Xe -ions of 640 MeV. The residual nuclei recoiled with well defined initial velocities v_i out of the target, transversed a stretched gold foil mounted at an adjustable distance d behind the target, and were finally stopped in a thick ^{208}Pb foil several cm further downstream. As the velocity of the ^{156}Dy ions after the gold foil was smaller than that in front of the foil, the γ -rays from the decay of a certain state in ^{156}Dy - observed at 0° (180°) with respect to the beam axis - exhibited two components which could be clearly distinguished by their different Doppler shifts: A fully Doppler shifted component due to the decay of the Dy nuclei before the Au foil and a less shifted component (retarded component) due to the decays

Fig. 5 Schematic view of the recoil-distance set-up used in the ^{156}Dy lifetime measurement.

occurring behind the foil. By performing the measurement for several distances d between the target and the gold foil, i.e. for different flight times d/v_i , the decay curves (and thus the lifetimes) the states in ^{156}Dy could be deduced from the intensities of both components of the corresponding de-excitation γ -ray lines.

The main features of the set-up used are the following: By inverting the reaction (light target, heavy beam) the residual nuclei recoil out of the target with extremely large, well defined velocities. In fact, the reaction $^{25}\text{Mg} (^{136}\text{Xe}, 5n)^{156}\text{Dy}$ at $E(^{136}\text{Xe})=646$ MeV leads to initial recoil velocities of 8.2% of the velocity of light (corresponding to $v_i=24$ $\mu\text{m}/\text{ps}$) and recoil directions $\leq 2^\circ$ with respect to the beam. As minimum plunger distances of $d \approx 10 \mu\text{m}$ can be realized with an accuracy of $\pm 1 \mu\text{m}$, the time scale accessible in these experiments extends down to a few tenth of a picosecond. The high recoil velocity also allows to replace the solid stopper, used in standard recoil-distance set-ups, by a thin foil, the "retardation foil". In the ^{156}Dy experiment a gold foil was used; its thickness was adjusted such that the velocity change amounted to 20%, which led to an energy splitting of the two components of 1.6% sufficient to resolve the two γ -lines. On the other hand, the transient time through the Au foil was only 0.13 ps, which is smaller than the expected lifetimes of even the highest spin states observed. Thus the number of nuclei which decay during the passage through the foil and thus do not contribute to either one of the two components, was small enough to be treated as a correction in the analysis of the decay curves. In comparison, the slowing down time of the Dy ions in a thick Au stopper would amount to about 1.5ps; in this case the retarded component from the decays of a short lived high spin state would not exhibit a sharp but rather a broad, Doppler-smeared γ -ray line-shape whose intensity cannot be determined reliably. Note, moreover, that by evaporating the ^{25}Mg target directly onto the Au foil, the retarded components could be measured also for effective flight times of ≈ 0.13 psec, which constituted an important extension of the time scale as far as the extraction of the lifetimes of the highest observed spin states was concerned. In fact, the highest spin state that could be analyzed in the ^{156}Dy measurement was the $I^\pi=30^+$ yrast state, which has a lifetime of only $\tau(30^+) = 0.17 \pm 0.08$ ps.

The Ge detectors were operated in coincidence with a multiplicity filter consisting out of four large NaI detectors positioned at $\approx 90^\circ$ with respect to the beam. By requiring at least two of the four detectors to fire, events connected with low γ -multiplicities could be strongly suppressed; in particular, events due to the Coulomb excitation of ^{197}Au were quantitatively removed from the resulting Ge spectra. An additional NaI detector was operated in coincidence with the multi-

plicity filter and either one of the two Ge detectors. These spectra were used to estimate some average properties - such as the number of γ -transitions - of the unresolved sidefeeding cascades (see also ref.13).

The analysis of the decay curve observed in this type of experiments for a given level is complicated by the fact that it depends not only on the lifetime of the level the decay of which is studied, but also on the lifetimes of all the states in the feeding cascades. However, the feeding of the yrast states is usually dominated by the decay from the next higher yrast level; thus in these cases the time structure of the main feeding component to the state under investigation can be extracted from the decay curve observed for the preceding yrast transition. Of the remaining feeding components - collectively denoted by "sidefeeding" - usually only the intensity carried by these unresolved cascades are known. Thus the time structure of the sidefeeding cascades has to be parameterized using simplifying models, adjusting the corresponding parameters together with the lifetime to the measured decay curve. Two extreme assumptions for the sidefeeding cascades were used in the analysis of our measurements: (i) A single cascade with an adjustable number of states, and (ii) several cascades involving only one transition each. For both assumptions the extracted lifetimes of the yrast (and yrare) states were found to be consistent within their statistical errors. For a more detailed description of the analysis and the various corrections which have to be taken into account, including those due to the deorientation effect, see ref.14.

So far the recoil distance technique was applied by us to determine the lifetimes of high spin states in ^{158}Dy (ref.13), $^{157,156}\text{Dy}$ (ref.14) and in ^{154}Dy , the latter being still in the state of analysis. The B(E2) values resulting from these measurements will be discussed in section 4.

3.3 DETERMINATION OF MAGNETIC DIPOLE MOMENTS

The experiments performed so far to determine magnetic dipole moments of short-lived states are based on measuring the precession of the angular correlation of the de-excitation γ -rays which is caused by the transient magnetic field that acts on swift ions traversing polarized ferromagnetic foils¹⁵⁾. This technique is the only one known to be suited for the purpose of measuring the size and the sign of g-factors of levels with lifetimes in the ps range, as is the case for levels in the first backbending region of rare earth nuclei. Most previous attempts to determine magnetic moments of these levels, however, were hampered by experimental difficulties: In (HI,xn) reactions the complex feeding pattern makes the extraction of g-factors of the yrast states extremely difficult (see e.g. ref.16). In Coulomb excitation experiments, on the other hand, the feeding can be controlled, but with projectiles lighter than Pb high spin states at and above backbending are not accessible because of their weak population. For example, a recent Coulomb excitation experiment with 4.1 MeV/amu ^{86}Kr ions¹⁷⁾ could probe the yrast levels of $^{170,174}\text{Yb}$ and ^{160}Dy around spins 8^+ , 10^+ and 12^+ only, with very little sensitivity to the g-factors of the 14^+ and 16^+ levels; nevertheless, the precession data indicate a decrease of the magnetic moments with spin, suggestive of an increasing role of aligned neutron configurations in the yrast state structure of these nuclei.

The experiment¹⁸⁾ I would like to discuss below was performed at GSI and designed to be most sensitive to the 14^+ and 16^+ yrast states of ^{158}Dy , thus probing directly the backbending region in this nucleus. In these measurements the transient field acting in magnetized iron foils was exploited. Although the atomic origin of the field is well established¹⁹⁾ quantitative estimates of its size cannot be made yet. Thus cumbersome calibration experiments are necessary to determine the field strength for the relevant recoil velocities and atomic numbers Z; for light rare earth nuclei recoiling in iron this has been done in a series of experiments performed by the Chalk River group²⁰⁾. Note that the action of the transient field on the nuclear magnetic moment can be described by that of a classical magnetic field pointing in the same direction as the external field used to magnetize the ferromagnetic foil, and that its strength amounts to about 4000 Tesla for Dy nuclei recoiling in Fe at velocities of 5% of the velocity of light.

Fig. 6 (a) Schematic view of the set-up used in the g-factor measurement on ^{158}Dy . The dashed curve represents the γ -angular correlation for an $I \rightarrow I-2$ transition, measured in coincidence with Dy ions recoiling at an angle ϑ_p .
(b) Details of the target composition.

A schematic view of the experimental set-up used is shown in fig.6. The yrast levels of ^{158}Dy were populated by Coulomb excitation with 4.7 MeV/amu ^{208}Pb projectiles. The target (fig.6b) consisted of a layer of $1\text{mg}/\text{cm}^2$ ^{158}Dy deposited on a $4.4\text{ mg}/\text{cm}^2$ thick iron foil, which was backed by $50\text{ }\mu\text{g}/\text{cm}^2$ of Al to prevent the possibility of polarized electron pick-up of the recoiling Dy ions on emergence from the ferromagnetic foil. The foil was magnetized by an external field of 0.03 Tesla which was proved to be sufficient for saturation by a magnetometer measurement. Recoiling target nuclei and/or scattered particles traversing the iron backing were detected in two position-sensitive parallel-plate detectors (P_R and P_L in fig.6a, see also subsection 3.1) positioned in the forward hemisphere symmetrically to the beam axis, each subtending an angular range of $20^\circ \leq \vartheta \leq 40^\circ$ and $\Delta\varphi = 56^\circ$. The Dy ions were distinguished from recoiling Fe and scattered Pb ions by means of the kinematical correlation between their scattering angles and their flight-times measured relative to the beam burst. Gamma rays in coincidence with Dy ions were detected by six Ge detectors placed symmetrically around the beam direction (fig.6a) such that for the right and left particle detectors, respectively, four out of the six detectors were at angles of large logarithmic slope of the corresponding γ -ray angular correlations. The positions of the particle- and γ -detectors have been chosen symmetrically about the beam axis in order to minimize systematic errors. The symmetry implies that the detection of a γ -ray in detector (i) in coincidence with a particle at angle ϑ_p in P_L and external field "up" ("down") corresponds to detecting a γ -ray in the detector (7-i) in coincidence with a particle at ϑ_p in P_R and field "down" ("up"). From the γ -intensities observed for a certain transition in ^{158}Dy we can hence define double ratios by

$$R_i = \left[\frac{Y(\text{up}, L, i)}{Y(\text{do}, L, i)} \cdot \frac{Y(\text{do}, R, 7-i)}{Y(\text{up}, R, 7-i)} \right]^{1/2}, \quad (9)$$

which are sensitive to the precession of the angular correlation but insensitive to the different γ -detector efficiencies as well as "up" - "down" particle counting rate differences.

The main features of the set-up used are the following:

(i) By monitoring the "up-down" count-rate differences for the scattered Pb ions detected at $\vartheta_p \approx 20^\circ$ in the two particle detectors, the influence of the external field onto the direction of the beam and scattered particles was found to be negligibly small, in agreement with theoretical estimates using average charge states and the measured stray field profile. Similar estimates for the recoiling

Dy nuclei resulted in correspondingly small changes.

(ii) Pb events. For Pb-detection angles $20^\circ \leq \theta_p \leq 27^\circ$ the corresponding Dy recoils are stopped in the iron foil. These events correspond to small c.m. scattering angles ($43^\circ \leq \theta_{cm} \leq 64^\circ$) and hence to a predominant excitation of low spin levels. Moreover, the Dy ions are not only subjected to the transient field but also - after being stopped within about 1.3 ps - to the static field, which is opposite in sign to the transient field; its strength was determined by us to be $B(\text{Dy Fe}) = -245 \pm 25$ Tesla in an auxiliary measurement performed on ^{164}Dy in the same set-up. Using this value, from the measured precession of the $4^+ \rightarrow 2^+$ transition in ^{158}Dy , which is dominated by the static field because of the long lifetime of the 4^+ state of $\tau(4^+) = 103$ ps (ref.13), a g-factor of $g(4^+) = +0.36 \pm 0.06$ is deduced, in agreement with the result of an earlier recoil-in-Gd measurement²¹). This proves that under the kinematical conditions required for the Pb events all Dy nuclei came to rest in the Fe foil and that the magnetization of the iron foil did not deteriorate throughout the measurement. For the 6^+ state in ^{158}Dy ($\tau(6^+) = 13$ ps (ref.13)), the contribution of the static field to the precession is expected - using the parametrization of ref.20 - to be compensated by that of the transient field being of opposite sign, in excellent agreement with what is observed experimentally. This proves that the transient field was acting and that its average strength within the relevant velocity region of $\leq 5\%$ of the velocity of light is consistent with what was measured in ref.20. For the 8^+ state in ^{158}Dy ($\tau(8^+) = 4.2$ ps (ref.13)), the precession of which is dominated by the transient field effect, a g-factor of $g(8^+) = +0.41 \pm 0.13$ is obtained.

(iii) Dy events. Dy-detection angles of $20^\circ \leq \theta_2 \leq 40^\circ$ correspond to cm. scattering angles of the Pb projectile of $140^\circ \geq \theta_{cm} \geq 100^\circ$. Thus in these events the high spin yrast states of ^{158}Dy are excited, the main excitation probability being concentrated around the 14^+ and 16^+ state. Depending on the recoil angle, the Dy ions recoil with average velocities between 5% and 8% of the velocity of light through the iron foil. The corresponding transient times of 0.3 ps to 0.4 ps are short compared to even the shortest lifetimes involved (e.g. $\tau(18^+) = 0.79$ ps (ref.13)); the precession therefore occurs only in the state directly populated in the Coulomb excitation process. As the excited Dy nuclei recoil into vacuum, the γ -angular correlations might be attenuated due to the hyperfine interaction between the nuclear moments and the highly excited atomic shell. The attenuation was investigated by comparing the measured γ -angular correlations to those calculated using a multiple Coulomb excitation code. For the high spin yrast state transitions $I \rightarrow I-2$ with $I^\pi \geq 12^+$ the experimental correlation functions turn out to be essentially unperturbed; for the decays with $I^\pi \leq 10^+$, however, the attenuation is increasing, the $4^+ \rightarrow 2^+$ transition being consistent with an isotropic angular correlation. The size of the attenuation was found to be of the same order of what is known from other experiments involving heavy nuclei recoiling at such high velocities²²). The average precession angles ϕ of the high spin angular correlations with $I^\pi \geq 10^+$ derived from the various double ratios (see eq.(9)) are all consistent with $\phi = 0$; only for the $8^+ \rightarrow 6^+$ transition a finite value of $\phi = -16 \pm 5$ mrad was found. In view of the various checks and tests built into the experiment and discussed in detail above, this result shows that the g-factors of the yrast states in ^{158}Dy around the first backbending point have values close to $g \approx 0$.

A detailed analysis of the experiment just described can be found in ref.18. The resultant g-factors are shown in fig.9 (left panel) and are further discussed in the next section.

4. Electromagnetic properties of Dy nuclei

As discussed already in the introduction, the irregularity observed in the yrast sequence of ^{160}Dy about 10 years ago has been the main starting point of high-spin state spectroscopy. Although many rare earth nuclei have been studied meanwhile and found to exhibit similar effects, the interest in the Dy isotopes has never been ceased. Also since we started at GSI several years ago with our measurements of electromagnetic properties of high spin states in deformed nuclei,

Fig. 7 Plot of the projection I_x vs. the rotational frequency for the yrast and yrare levels known in $^{156,158,164}\text{Dy}$ (left panel) and the yrast states $^{23-25}$ of the $N=90$ isotopes ^{156}Dy , ^{158}Er and ^{160}Yb (right panel). The closed circles indicate states populated in the Coulomb excitation experiments with ^{208}Pb ions.

the Dy chain has been one of our central points of interest. I would therefore like to discuss in the following some of our results obtained for these nuclei to exemplify the role of the static and dynamic electromagnetic moments for our understanding of the structure of fast rotating nuclei.

In fig.7 (left panel) an alignment plot is shown for the yrast and yrare states of the three Dy isotopes $^{156,158,164}\text{Dy}$, which was derived from the measured spins and transition energies using eqs.(1)(3). The two light isotopes clearly show the meanwhile familiar backbending behaviour; using eq.(2) together with the expansion $R(\omega) = \omega(\theta_0 + \omega^2\theta_1)$ to describe the collective angular momentum, the aligned single particle angular momentum i of the crossing band is found to be $\approx 8\hbar$ in ^{156}Dy and $\approx 6\hbar$ in ^{158}Dy . Moreover, judging from the abruptness of the transition from the g-band to the s-band, occurring around a critical frequency of $\hbar\omega_{c1} \approx 0.28$ MeV, the interaction strength between the two crossing bands is weak in the case of ^{156}Dy and strong for ^{158}Dy , in agreement with results obtained from cranked shell model calculations of the type carried out by Bengtsson and Frauendorf²). These calculations also predict a very strong interaction between the g- and s-band in ^{164}Dy ; indeed, only a very gradual "upbending" is observed in this nucleus.

The different interaction strength in ^{156}Dy and ^{158}Dy is manifested at least qualitatively in the path the multiple Coulomb excitation proceeds through at the intersection point: As indicated in fig.7, in ^{156}Dy the Coulomb excitation follows the ground state band while it follows the aligned band in ^{158}Dy . To demonstrate this behaviour in a more quantitative way, in fig.8 the $B(E2, I \rightarrow I-2)$ values connecting the yrast states of ^{156}Dy and ^{158}Dy , respectively, are shown, which were normalized to the rigid rotor prediction using eq.(5) and adjusting the transition quadrupole moment to reproduce the $B(E2, 2^+ \rightarrow 0^+)$ value. In ^{156}Dy the $B(E2)$ value between the 16^+ and 14^+ yrast states is strongly retarded as compared to the neighbouring E2-transition moments, in contrast to the transition between the 16^+ yrare and the 14^+ yrast state, which carries the full collective strength. The $B(E2)$ -values clearly show that the structure of the yrast states in ^{156}Dy changes abruptly between the 14^+ and 16^+ state as expected from a simple two-band mixing calculation if the s-band crosses the q-band between spin $14\hbar$ and $16\hbar$ and the interaction between both bands is assumed to be very weak. In ^{158}Dy , on the other hand, the $B(E2)$ values around the crossing point are very similar, supporting the inference from the alignment plot that the interaction between the s- and g-band

Fig. 8 Normalized $B(E2)$ values for transitions between the yrast states (closed circles) in ^{156}Dy and ^{158}Dy . The data shown are average values obtained from Coulomb excitation experiments with ^{208}Pb (ref.26) and recoil distance measurements (ref.13,14); for the low spin states in ^{156}Dy , also the results of ref.23 were included. The open circle represents the $B(E2)$ value observed for the 16^+ yrare to the 14^+ yrast state of ^{156}Dy .

Fig. 9 Left: g-factors obtained for yrast states in ^{158}Dy and ^{164}Dy (ref.18) together with the predictions of Diebel et al.²⁸ (dashed line: ^{158}Dy ; dotted line: ^{164}Dy).

Right: Average g-factors for states in ^{156}Dy (ref.16); yrast as well as pre-yrast states are sampled in this experiment (see text).

is strong. Note, however, that the $B(E2)$ values observed between states below and above the first backbending point do deviate considerably from those expected for pure rotational bands. These deviations, which will be discussed in more detail further below, show that the assumption of a constant deformation of the rotating nucleus, common to many of the current theoretical approaches to the backbending behaviour of deformed nuclei and in particular to the type of cranked shell model calculations based on the ideas of ref.2, is not well fulfilled in this mass region.

Despite of this deficiency, however, the main structural changes occurring around the first backbending point are accounted for by these models; cranked shell model calculations predict - as do the more sophisticated self-consistent cranked Hartree-Fock-Bogoliubov calculations - that the spin gain i is due to the alignment of an $i_{13/2}$ neutron pair. The observed reduction of the g -factors in the backbending region of ^{158}Dy (see fig.9, left panel) constitutes a stringent test of this prediction: The measured average g -factor of $g = +0.04 \pm 0.11$ directly demonstrates that indeed the alignment of an $i_{13/2}$ neutron pair rather than that of an $h_{11/2}$ proton pair is the dominant cause of the first discontinuity in these nuclei. The amount of reduction observed, however, is slightly larger than expected from Cranked Hartree-Fock-Bogoliubov calculations²⁸). Note that eqs.(2)(4) also describe $I_x(I)$ and $g(I)$ of the yrast states in the crossing region between the paired g -band and the s -band involving one aligned pair μ if i , respectively i_μ , is replaced by $i(I) = i_\mu a^2(I)$, $a(I)$ being the amplitude of the aligned band in the yrast state⁶). Using these relations, the average g -factor measured in the backbending region of ^{158}Dy results in $i(14) \approx 9 \pm 3 \hbar$ as compared to $\approx 5 \hbar$ expected from Cranked Shell model calculations and $\approx 3 \hbar$ deduced from the alignment plot. In view of the accuracy of the g -factor measurement and the approximations made in both procedures to extract $i(I)$, the significance of these deviations is not yet clear; obviously more precise and complete g -factor measurements are required.

In the light rare earth nuclei a further discontinuity in the yrast sequence is known to occur around critical frequencies of $\hbar\omega_{c2} \approx 0.42$ MeV, corresponding to critical spin values of $\approx 28 \hbar$. In fig.7 (right panel) the alignment graphs are displayed e.g. for the three $N=90$ isotopes ^{156}Dy , ^{158}Er and ^{160}Yb ; both, the ^{158}Er and the ^{160}Yb nucleus, show a pronounced second upbending indicating a strong interaction between the s -band and the crossing s' -band, the alignment gain i being of the order of $6 \hbar$. The qualitative properties of the second discontinuity in these nuclei are again in agreement with cranked Hartree-Fock-Bogoliubov (see e.g. ref.27) as well as cranked shell model results. In both calculations the spin gain is found to be due to the additional alignment of an $h_{11/2}$ proton pair. Moreover, these calculations predict that in ^{156}Dy the second discontinuity should be smeared out due to a very strong interaction between the crossing two and four quasi-particle band. There exists a direct experimental hint supporting the role of aligned $h_{11/2}$ proton pairs in this spin region, which stems from a g -factor measurement performed in ^{156}Dy by the Chalk River group¹⁶). To interpret their results (fig.9, right panel), which were obtained by exploiting the transient field acting in a thin magnetized iron foil, one has to take into account that a (HI, xn) -reaction was employed to populate the high spin states in ^{156}Dy . Because of the sidefeeding inherent in these reactions, the precessions deduced from the γ -angular correlation of the low spin ($\leq 8 \hbar$) ground band transitions were probing the g -factors of states on and above the yrast line; only the spin region sampled could be varied by using different bombarding energies. Some reduction of the average g -factor - as compared to the collective value of $g_R \approx 0.35$ - should thus be observed when probing the low spin region because of the predominance of aligned $i_{13/2}$ neutron components in the states sampled, while in the high spin measurements the average g -factors are expected to be larger than g_R (see also fig.2 and eq.(4)) due to the increasing role of aligned $h_{11/2}$ proton pairs in the structure of the states in the probed angular momentum region. These expectations are obviously in qualitative agreement with what has been actually observed in the experiment.

I would like to come back now to a more detailed discussion of the $B(E2)$ values, which signal that considerable deformation changes occur in the lighter

Fig. 10 Left: The static intrinsic quadrupole moments of the ground states of odd Dy nuclei²⁹). Middle: Transition quadrupole moments in the ground state bands of even Dy nuclei (additional data: ^{152,154}Dy (ref.30), ¹⁶²Dy (ref.31)). Right: Transition quadrupole moments in rotational aligned bands of Dy nuclei; the star denotes the yrare band of ¹⁵⁶Dy. Insert: Possible development of the shape of the ¹⁵⁶Dy nucleus as a function of spin (see also text).

Dy isotopes. For this purpose the transition quadrupole moments $Q_t(I \rightarrow I-2)$ were calculated from the measured $B(E2)$ values using eq.(5); they are plotted in fig.10 separately for the ground state band (middle panel) and bands involving rotational aligned quasi-particle pairs (right panel). Also shown in fig.10 (left panel) are the intrinsic quadrupole moments ($Q_d \equiv Q_0$) of the ground states of odd Dy isotopes, which were calculated from the measured static quadrupole moments²⁹) using the expression corresponding to eq.(6) but for $K \neq 0$.

The ground state quadrupole moments Q_0 of the odd Dy nuclei nicely display the long-known transition from spherical to well deformed nuclei occurring around $N=88$; this transition also occurs in the even Dy nuclei around this neutron number as can be seen from the collectivity of the $2^+ \rightarrow 0^+$ decays reflected by the $Q_t(2^+ \rightarrow 0^+)$ values. Note, however, that for $N > 88$ the collectivity in the ground state sequence is increasing with spin and approaches a common Q_t value around spins $\geq 10 \hbar$ of close to 7.5 eb, which is as large as the $Q_t(2^+ \rightarrow 0^+)$ value of the well deformed nucleus ¹⁶⁴Dy. Obviously at higher angular momenta the transition region between spherical and well deformed prolate nuclei is shifted to lower neutron numbers. This behaviour can also be seen in the excitation energies using a gauge space plot as recently promoted by Bengtsson et al³²): In close analogy to the alignment plot, where one displays the angular momentum vs. the rotational frequency, i.e. vs. the derivative of the (total) energy $E(N, Z, I)$ with respect to the angular momentum, in the gauge space plot the neutron (proton) number is displayed as a function of the neutron (proton) fermi energy λ_N (λ_Z), i.e. of the derivative of the total energy $E(N, Z, I)$ with respect to the neutron (proton) number; in these plots transitions due to shape changes will result in an up- or backbending type of behaviour, in a very similar way as changes in the pairing correlations are emphasized in alignment plots. In fig.11 a gauge space plot is shown for the even Dy isotopes, which does indeed nicely display the shift of the transition region from spherical to well deformed prolate nuclei as a function of the angular momentum; while the ground states are obviously fully deformed for $N > 91$, the 12^+ states seem to approach the maximum deformation already for neutron numbers $N > 87$ in agreement with what can be read off the Q_t values shown in fig.10. Note, moreover, that the same behaviour - although experimentally less well investigated - is also observed e.g. in the Gd and Sm nuclei.

Fig. 11 Plot of the neutron number N vs. the Fermi energy λ_N for the even Dy nuclei. The Fermi energy was calculated as indicated from the total energies of the $I^\pi = 0^+, 4^+$ and 12^+ yrast states, respectively.

A more closer inspection of the spin dependence of the Q_t values in the ground state sequence of the Dy isotopes reveals that this dependence is by no means smooth. Even the Q_t values of the well deformed nucleus ^{164}Dy display statistically significant deviations from the rigid rotor behaviour which presumably cannot be explained by macroscopic models such as e.g. the rotation-vibration model. The fluctuations, which seem to increase for decreasing neutron number, are likely due to the increasing importance of the single-particle effects alluded to in the introduction and can therefore probably only be explained by detailed microscopic calculations.

Compared to the maximum Q_t value of ≈ 7.5 eb reached by $^{156,158}\text{Dy}$ just below the first backbending point, the Q_t values in the rotation-aligned bands of these two nuclei are clearly retarded. For $I^\pi \leq 20^+$ they average to about 6.5 eb, and a further reduction is observed at higher spins resulting in an average Q_t value of ≈ 5 eb for $I^\pi \geq 24^+$. Even smaller Q_t values have been recently reported³³⁾ for ^{154}Dy in this spin region. In $^{156,158}\text{Dy}$ the reductions observed seem to be connected with the number of aligned particles: For $I^\pi \leq 20^+$ the states are members of the s-band built on an aligned $i_{13/2}$ neutron pair, while the highest spin states observed should be dominated by the s'-band involving an aligned $i_{13/2}$ neutron as well as an aligned $h_{11/2}$ proton pair. A similar decrease of Q_t when the number of aligned particles is increasing is also observed in the yrare sequence of ^{156}Dy above the first backbending point as well as in the yrast sequence of ^{157}Dy ; in both cases the reduction occurs around a critical spin of $\approx 20 \hbar$ where - as indicated in the corresponding alignment plots - the alignment of a less favoured $i_{13/2}$ neutron pair (as compared to that involved in the s-band) takes place. It is thus intriguing to attribute the observed reductions of the transition quadrupole moments to an increasing γ -deformation of the nucleus towards $\gamma = -60^\circ$ (see fig.2). Triaxial shapes with $\gamma < 0^\circ$ can be expected for configurations involving rotational aligned quasi-particles because of core polarization effects (see also fig.1); in fact, self-consistent cranked Hartree-Fock-Bogoliubov calculations do show that the alignment processes lead to triaxial configurations with $\gamma < 0^\circ$. A possible path of the ^{156}Dy nucleus in the β - γ plane, deduced from the measured Q_t values by using eqs.(7a,c), is depicted in the insert of fig.10. Note, however, that other β - γ combinations are possible to explain the observed Q_t values; a unique determination of both β and γ would in addition require a measurement of the static quadrupole moments which is outside the scope of present experimental techniques. Despite of these ambiguities, the general trend of the Q_t moments indicates that shape changes occur in these nuclei; what we might have seen in $^{156,158}\text{Dy}$ at high

spins is the beginning of a transition from a prolate nucleus rotating around an axis perpendicular to the symmetry axis to an oblate nucleus "rotating" around the symmetry axis.

The present talk was not intended to give a review about high spin state spectroscopy. I have restricted my discussion to the Dy nuclei and have not mentioned all the nice results obtained also by other groups working in different mass regions. It was my aim to discuss examples for the experimental techniques available to measure electromagnetic properties of short-lived high spin states and to point out the significance of these properties in our effort to understand the structure of nuclei at high angular momenta.

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