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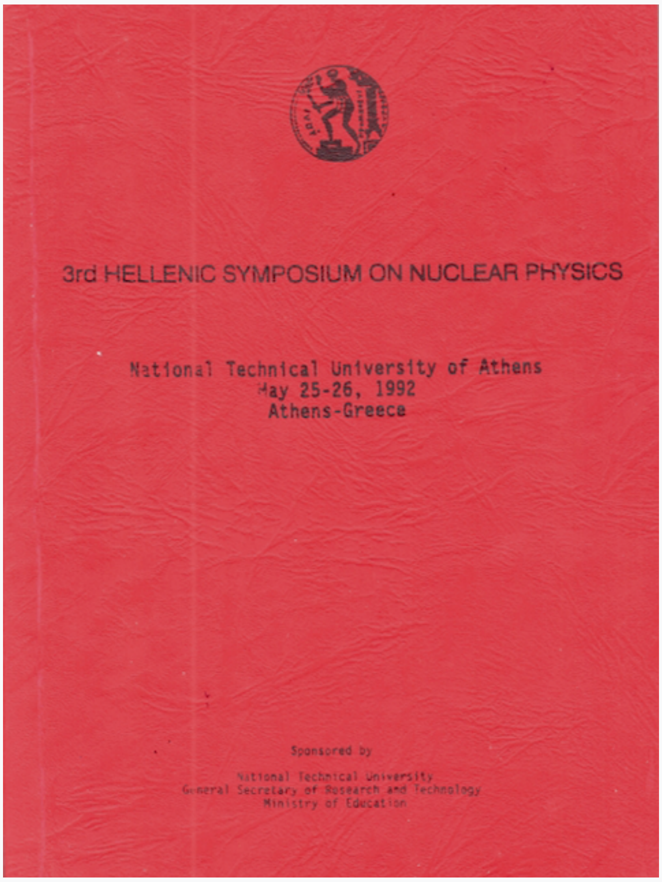

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HIGH SPIN STRUCTURE OF ^{155}Dy

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ABSTRACT

High spin states in ^{155}Dy have been studied by γ-γ coincidence measurements via the ^{124}Sn(^{36}S, 5n)^{155}Dy reaction at a beam energy of 155 MeV. Eight rotational bands have been populated and observed up to high spin (I<91/2).The band features have been analysed within the framework of the cranked shell model. The $i_{13/2}$ neutron alignments and the $h_{11/2}$ proton alignments are discussed. B(M1)/B(E2) ratios have also been extracted for the strongly coupled bands to deduce further information on the detailed structure of these bands.For the highest states (above spin 30) of the negative parity bands an irregularity in γ-ray energies appears which is discussed in terms of band termination.

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1. INTRODUCTION

One of the most interesting aspects of high spin spectroscopy is the evolution of nuclear shapes as a function of the rotational frequency. A shape change can be associated with the band termination concept, where a shape of an initial prolate deformation at low spin changes at high spin region until it reaches an oblate limit with rotation around the symmetry axis. This shape transition, due to the gradual alignment of all valence nucleons outside of a spherical closed shell, are expected to be favourable cases for band termination effects.

The region of N=88-90 nuclei is a good candidate for shape evolution, due to the small number of particles outside the ^{146}Gd shell. Nuclei in this region are expected to change from configurations corresponding to prolate ellipsoids rotating collectively about an axis perpendicular to the summetry axis ($\gamma=0^o$) to less collective configurations which eventually terminate to an oblate pattern structure with rotation around the symmetry axis ($\gamma=60^o$). Indeed, these band termination changing effects from collective rotation to single particle motion have been observed in ^{154}Dy [1], ^{156}Er [2], ^{158}Yb [3], ^{159}Yb [4], ^{158}Er [5], ^{160}Yb [4].

However, there is another prolate to oblate shape change mechanism associated with a sequence of crossings of the collective prolate configuration with band structures having γ deformation closer to $\gamma=60^o$. In order to distinguish between this slightly irregular collective and the regular non-collective decay scheme arising from a terminating band, it is necessary to determine lifetimes which provide a direct measure of the collectivity. So, deviations from the smooth E(I)~I(I+1) pattern do not necessarily reflect a band termination process, unless lifetime measurements are available to testify the strong reduction in the E2 transition strength consistent with the band termination.

The present work focuses on the high spin study of ^{155}Dy which is a transitional nucleus lying in the region between spherical and deformed nuclei and can provide a fertile ground to test shape changes induced by fast rotation. Preliminary results of the present study have been published previously [6].

2. EXPERIMENTAL METHOD

Excited states of ^{155}Dy were populated through the compound nuclear reaction $^{124}Sn(^{36}S,5n)^{155}Dy$ at a beam energy of 155MeV. The beam was delivered by the Tandem Accelerator at the SERC Daresbury Laboratory. The self supporting target consisted of four stacked foils, each of an approximate thickness 350µg/cm^2 and isotopically enriched to 97.9% in ^{124}Sn. The γ-rays were recorded in the multi-detector system TESSA2[7]) consisted of 6 Ge escape suppressed detectors placed at angles 30^o,90^o and 150^o relative to the beam direction. The array also consisted of an inner BGO crystal ball with 50 elements. Events were recorded when two or more Ge detectors and at least one BGO detector were in coincidence. A total of 20 million γ-γ-BGO coincidence events were recorded on magnetic tapes and then sorted off-line into a 4K x 4K matrix. The low lying states of ^{155}Dy have previously been studied by Krien et al [8]), Torres et al and Borggreen et al[9]) up to spin 21/2$^-$. In the present work the decay scheme of ^{155}Dy has been extended up to spin 91/2$^-$ as it is shown in fig 1. The levels have been grouped into bands labeled from 1 to 8 to facilitate the discussion.

3. DISCUSSION

3.1 The Cranked Shell Model.

The behaviour of the rotational bands observed in ^{155}Dy at low spin can be understood within the framework of the Cranked Shell Model CSM [10]). Total Routhian Surfaces (TRS) have also been calculated to determine the minima of the total energy of the nucleus with respect to the deformation parameters ε_2, ε_4 and γ at different rotational frequencies and for different configurations. The results of the calculations indicate that none of the expected configurations (which will be discussed in the next section 3.2) undergoes any significant shape changes, with ε_2 varying from 0.21 to 0.22 and ε_4 and γ remaining constant at zero. These values of the deformation parameters were in fact used to carry out the calculations of quasi particle routhians. From these calculations it turns out that the neutron Fermi level is situated on the [660]1/2$^+$, [651]3/2$^+$, [541]1/2$^-$, [512]5/2$^-$ and [505]11/2$^-$ Nilsson states, while the proton Fermi level apparently lies near the [523]7/2$^-$, [411]1/2$^+$, [532]5/2$^-$ and [402]5/2$^+$ orbitals.

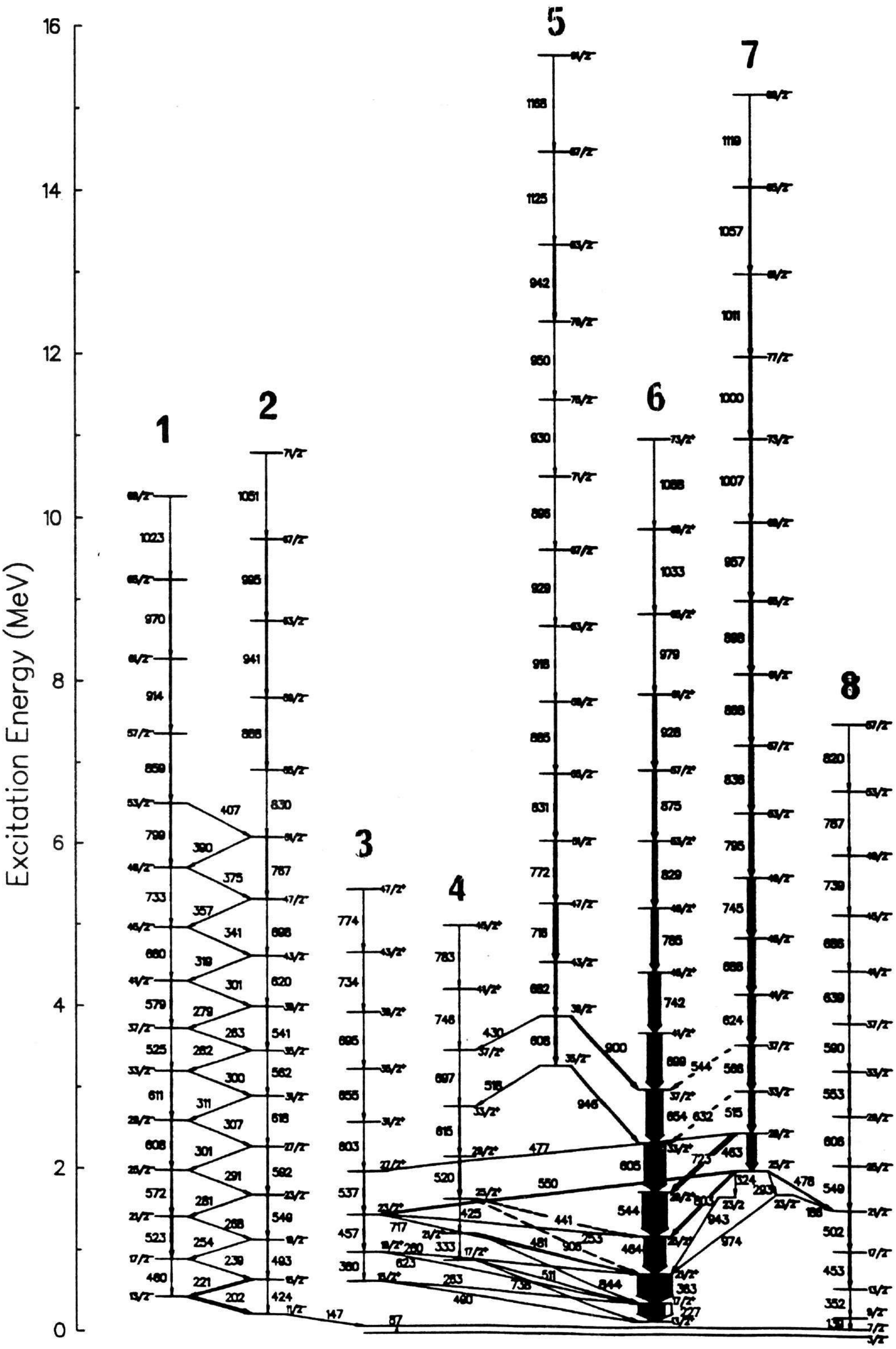

Fig. 1. The level scheme of ^{155}Dy. Energies are in keV. Dashed

To identify the configuration which characterizes each particular rotational band, experimental values of the routhians and alignments as a function of the rotational frequency were extracted from the data. A reference configuration based on a parametrized moment of inertia $J=J_0+J_1\omega^2$ with $J_0=32.1 MeV^{-1}\hbar^2$ and $J_1=34.0 MeV^{-3}\hbar^4$ has been subtracted from the experimental quantities. These values of the Harris parameters J_0 and J_1 have been adopted from ref.11 from ^{156}Dy as they produce a nearly constant value of the alignment at low rotational frequencies. The experimental routhians e' and alignments i_x are plotted as a function of rotational frequency $\hbar\omega$ for the 8 bands observed in ^{155}Dy in figs. 2 and 3 respectively.

3.2. The region of low rotational frequency

Two strongly coupled bands, labeled 1 and 2 have been established up to spin $69/2^-$ and $71/2^-$ respectively. These two bands are characterized by the absence of signature splitting as indicated in the routhians (fig. 2). Similar behaviour is also observed in ^{156}Dy [11]) and ^{157}Dy [12]). Based on the features of this band and the systematics of the neighbouring nuclei the configuration based on the [505]11/2$^-$ Nilsson orbital has been assigned to the two signature parteners of this band. This configuration is expected theoretically to appear in the region of N=90 Fermi energy at a ground state deformation ε_2=0.20-0.25 and exhibits no signature splitting due to the large Ω-value which is in agreement with the experimental data. Furthermore, this asignment is in agreement with the one proposed by Krien et al[8]) for the low lying states of this band.

Two sequences labeled band 3 and 6 have been assigned as the two signature parteners of a configuration characterized by a large signature splitting indicative of an $i_{13/2}$ neutron lying on the [660]1/2$^+$ orbital. This signature splitting shows up in the experimental routhians plotted in fig. 2. Band 6 is the yrast band at low rotational frequencies and has also been observed in the neighbouring isotones ^{153}Gd [13]), ^{157}Er [14]), and ^{159}Yb [4]) up to spin $33/2^+$, $65/2^+$ and $65/2^+$ respectively. On the contrary, from the the signature partener of the yrast band (band 3), only a few trnsitions have been identified in the above mentioned isotones, whereas, in the present work band 3 has been clearly observed up to spin $51/2^+$. The yrast band at low rotational frequency carries an alignment of about 5$\hbar$ which is in agreement with the value predicted by the CSM calculation for the $i_{13/2}$[660]1/2$^+$ configuration. The alignment of ~4$\hbar$ carried by band 3 at low rotational frequencies is also consistent with the alignment expected from the constructed routhians of the CSM calculations.

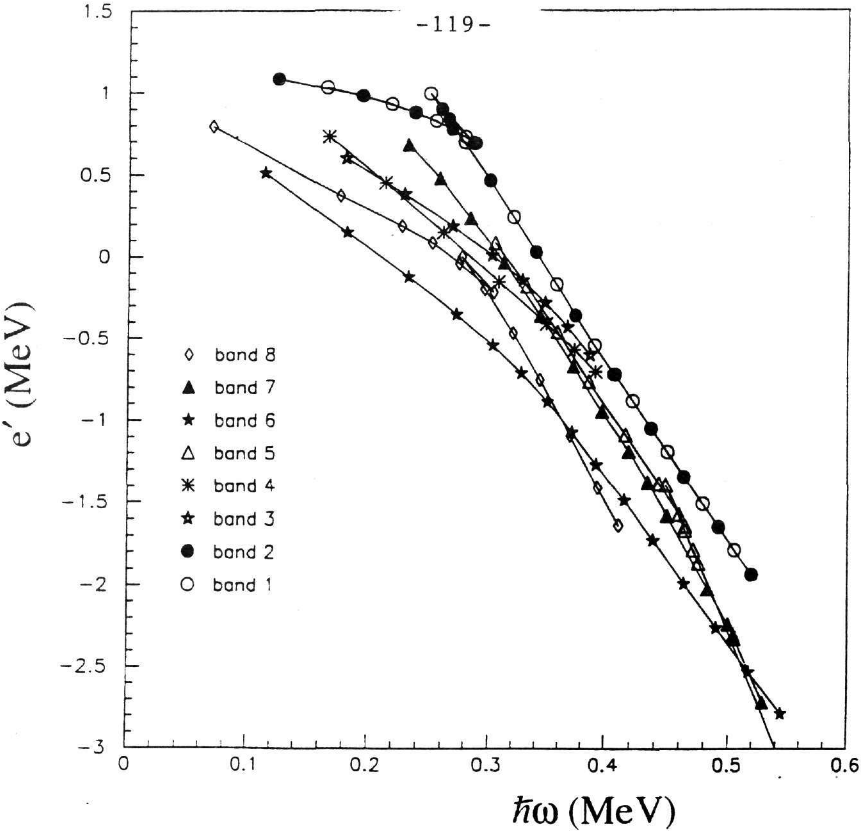

Fig. 2. Experimental routhians as a function of $\hbar\omega$ for bands in ^{155}Dy. A reference based on the moment of inertia parameters J_0=32.1MeV$^{-1}\hbar^2$ and J_1=34.0MeV$^{-3}\hbar^4$ has been extracted.

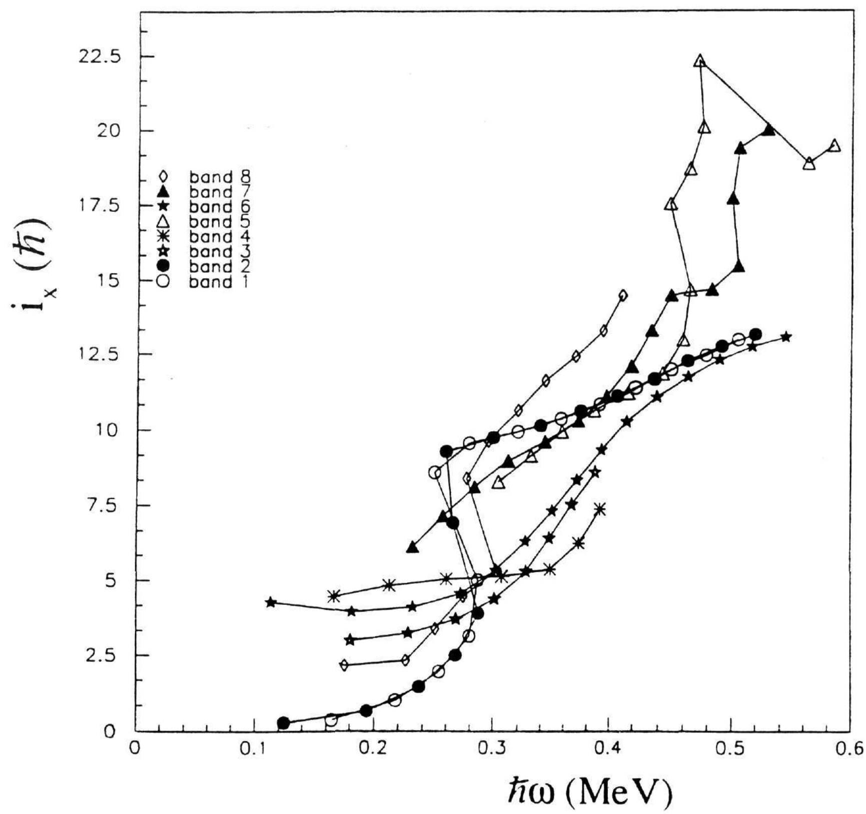

Fig. 3. Experimental quasiparticle alignments for bands in ^{155}Dy. Reference subtructed as in fig.2.

In the level scheme of ^{155}Dy presented in fig. 1, band 8 is assigned as the favoured signature component of the [541]1/2$^-$ configuration and it corresponds to the lowest negative parity orbital predicted by the CSM calculations. The absence of the unfavoured signature partner implies large signature splitting and low-K value, consistent with the [541]1/2$^-$ configuration. The tendency of the experimental routhian in this band, shown in fig. 2, further supports this assignment. On the other hand the theoretical routhians reveal a quite significant slope which would correspond to an initial alignment contradictory to the lack of initial experimental alignment presented in fig. 3.

Another two $\Delta I=2$ bands , labeled 5 and 7 were strongly populated and observed up to high spin. They have been associated with the next negative parity orbital predicted by the CSM calculations the neutron [512]5/2$^-$ orbital. These two bands, however, do not appear at low rotational frequencies. They have been observed above 0.23 MeV, so they will be discussed in more detail in the next section.

3.3. Three and five quasiparticle configurations

In the previous section 3.2, bands 1 and 2 were identified as being the two components of [505]11/2$^-$ $h_{11/2}$ configuration. An $i_{13/2}$ (AB) neutron crossing is thus expected to take place in these bands at 0.24 MeV. Indeed, in the alignment plots of fig. 3, a strong backbending is observed for bands 1 and 2 to occur at 0.27 MeV, producing a gain of alignment of $7\hbar$ units, which can be associated with the AB $i_{13/2}$ neutron crossing suggested also by the calculated routhians. This interpretation can be further corroborated by using the experimental B(M1)/B(E2) ratios. As described in detail in section 3.4, B(M1)/B(E2) ratios reveal a pronounced decrease with increasing spin, consistent with neutron origin of the experimentally observed alignment.

At higher frequencies the alignment of bands 1 and 2 is observed to increase gradually with increasing angular frequency and this can be the sign of a second band crossing . Since three neutrons from the $i_{13/2}$ orbital are already decoupled, this crossing is more likely to be attributed to the protons. The calculated quasiproton diagrams show that the lowest negative parity proton orbital is the $h_{11/2}$[523]7/2$^-$ which is predicted to align at $\hbar\omega$=0.34 MeV. The observed gradual gain of alignment implies that the A_pB_p alignment has a large interaction strength and the interaction region is spread over a wide frequency range. Thus the experimental crossing frequency cannot be well defined. This interpretation is further supported by the theoretical calculations which predict rather large interaction strength associated with this π $h_{11/2}$ band crossing.

Bands 3 and 6, which have been interpreted as the two members of the $i_{13/2}$ [660]1/2^{+} configuration, carry an initial alignment of about 3ħ and 4ħ, respectively, consistent with the CSM calculations up to 0.25 MeV. Then the quasiparticle alignment of fig.3 is observed to increase gradually through a wide frequency range (0.28-0.50 MeV) and gains about 9ħ units in band 6, while in band 3 is not seen to have reached its maximum value. Due to the blocking of the AB crossing, the neutron BC and AD crossings are candidates for bands 6 and 3, respectively.The gain in alignment at this crossing, however, is greater than expected for a single BC crossing. This indicates that a second crossing occurs at this frequency region. It is proposed that an A_pB_p proton alignment occurs which, as discussed for bands 1 and 2, takes place gradually and the frequency range of the crossing is smeared out due to the large strength of the interaction. This interpretation is in accordance with the theoretical predictions . Therefore, based on both the experimental evidence and the theoretical calculations it is concluded that the neutron BC and the proton A_pB_p alignments in band 6 occur very close together with the proton crossing being spread over a wide frequency range.

In band 3 the crossing is perhaps not yet completed at the last data points, but obviously the AD crossing takes place around the same frequency with the BC crossing, which is in agreement with the theoretical predictions. As for the protons, similar situation with band 6 could occur, however, more experimental points are needed in order to draw definite conclusions.

Additional support for the above proposed band crossing picture can be extracted from the behaviour of the neighbouring isotopes ^{157}Er and ^{159}Yb. The yrast band in these isotopes experiences at 0.4 MeV a neutron BC crossing together with a proton A_pB_p crossing. The gain in alignment of 8-9ħ units in the yrast bands of the two isotopes at 0.4 MeV is much greater than expected for just one of these alignments indicating that both neutron BC and proton A_pB_p crossings occur at the same rotational frequency.

Bands 5 and 7 start with an initial alignment of 7 and 9ħ, respectively and undergo an alignment gain above 0.4 MeV. The large initial value of the alignment indicates that bands 5 and 7 start out as three-quasiparticle configurations. An alignment of a pair of AB quasineutrons is expected to couple to the odd-neutron [512]5/2^{-} structure around 0.24 MeV, while at higher frequencies an A_pB_p crossing could be responsible for the observed gradual gain in alignment. This $h_{11/2}$ proton crossing should be spread over a wide frequency range due to the strong interaction associated with this proton crossing.

Band 8 is seen to undergo a band crossing at 0.27 MeV which could be associated to an AB neutron crossing. This interpretation is consistent with the theoretical predictions as far as the alignment gain of $7\hbar$ units is concerned, but the crossing frequency is predicted to occur at the slightly lower frequency of 0.24 MeV. The onset of an upbend at 0.38 MeV in this band has been interpreted as the alignment of an A_pB_p pair of quasiprotons arising from the $h_{11/2}[523]7/2^-$ orbital.

3.4. B(M1)/B(E2) ratios

Further information about the structure of the bands can be obtained from the competition between M1 and E2 transitions within the $\Delta I=1$ bands. The ratio of the reduced magnetic dipole and stretched electric quadrupole transition probabilities have been extracted from the $[505]11/2^-$ band, using the formula:

$$\frac{B(\mathrm{M1}: I \to I-1)}{B(\mathrm{E2}; I \to I-2)} = 0.693 \frac{I_\gamma(I \to I-1)}{I_\gamma(I \to I-2)} \times \frac{E_\gamma^5(I \to I-2)}{E_\gamma^3(I \to I-1)},$$

where the transition energies are in MeV and the E2/M1 mixing ratio δ has been approximately been set equel to zero. Experimental γ-ray intensities have been obtained whenever possible from coincidence gates in order to reduce effects of contaminants. The experimentally deduced B(M1)/B(E2) ratios for bands 1 and 2 of ^{155}Dy are presented in fig.4 together with the theoretical predictions obtained from the semiclassical formula of Donau and Frauendorf[15])

$$\frac{B(\mathrm{M1}; I \to I-1)}{B(\mathrm{E2}; I \to I-2)} = \frac{12}{5Q_0^2 \cos^2(\gamma+30°)} \left[1 - \frac{K^2}{(I-\frac{1}{2})^2}\right]^{-2} \frac{K^2}{I^2}$$
$$\times \{(g_1 - g_R)[(I^2-K^2)^{1/2} - i_1] - (g_2 - g_R) i_2\}^2$$

The subscripts 1 and 2 refer to strongly coupled quasiparticle and decoupled quasiparticles, respectively. The rotational gyromagnetic factor g_R is taken as Z/A=0.426 and the Schmidt values were used for the g factors. The alignment values were taken from the experimentally extracted i_x of fig. 4. For the quadrupole moment the value of Q_0=5.5eb was used. The deformation parameter γ was set to zero since no significant variation of γ from zero was found in the TRS calculations. This model of Donau and Frauendorf predicts a decrease inthe B(M1)/B(E2) ratio for the strongly coupled band in odd-N nuclei when an alignment of a pair of neutrons takes place. The theoretical predictions are illustrated by solid lines in fig. 4 in comparison with the experimental data. The data do show a pronounced decrease by a factor of 2 at spin $19/2^-$. This is the place where a strong backbend appears in the alignment plot of fig. 3. The observed trend is quite satisfactorily reproduced by the theory, suggesting that indeed the alignment gain of bands 1 and 2 at 0.27 MeV is attributed to a pair of $i_{13/2}$ neutrons.

4. BAND TERMINATION

When approching termination, the spin is expected to be gained by consuming small amount of energy. Therefore, if one plots the excitation energy E(I) as a function of spin, relative to a rigid rotor reference, the levels associated with a terminating band sequence should be down sloping.

A plot of excitation energies for the observed for the observed bands in ^{155}Dy with rigid rotor term subtracted, is presented in fig. 5. For the highest states of bands 5 and 7 an irregularity in γ-ray energies appear in the figure, while the rest of the bands are characterized by a smooth increase of the transition energies with respect to spin. This behaviour can be understood in terms of band termination or a change in shape from well deformed prolate to weakly deformed oblate[16]).

In lifetime measurements of Emling et al[17]) evidence was found for long-lived states (t>1.5ps) at high spin (J=71/2 and 75/2) in band 5, implying that the band termination scenario could be applied in this band. In band 7, however, the lifetimes at high spin were estimated to lie from 0.17 to 0.64 ps, so no definite conclusions could be drawn.

It is interesting to note that both bands 5 and 7 of ^{155}Dy in fig. 5 reveal a smooth behaviour to their termination. Thisis not the case in neighbouring isotopes which experience band termination. Plots of excitation energy relative to spin may show strong staggering as in ^{152}Dy and ^{154}Er or weaker irregularities from the smooth downsloping behaviour as in ^{154}Dy [1]), ^{156}Dy [11]), ^{156}Er[2]), ^{158}Er [5]).

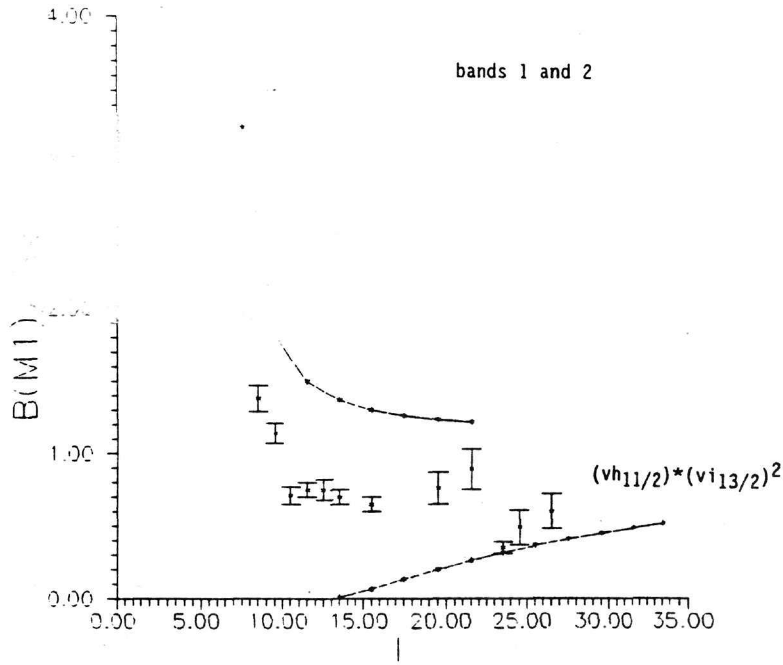

Fig. 4. Experimental and theoretical B(M1)/B(E2) ratios for the [505]11/2$^-$ band. Theoretical predictions for the given configurations are obtained from the semmiclassical model of Donau and Frauendorf[15]).

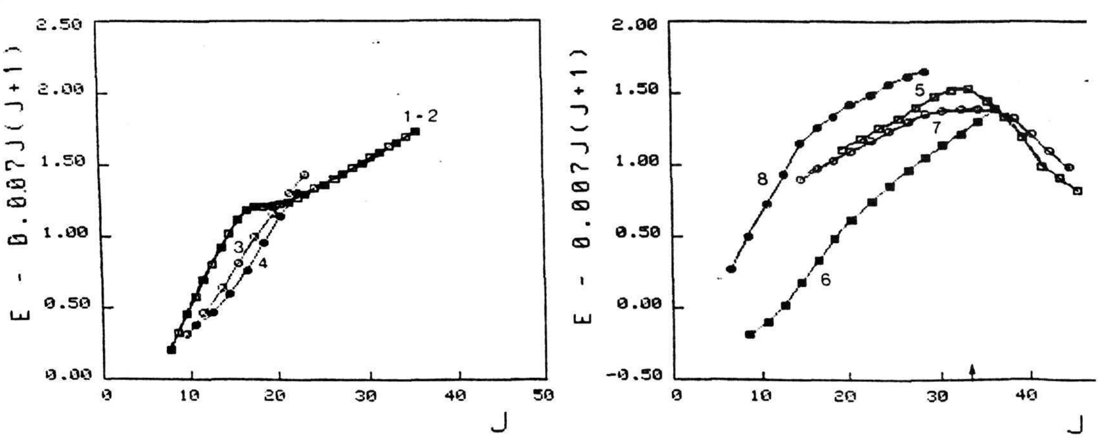

Fig. 5. Excitation energies of observed levels in ^{155}Dy, with an arbritrary rigid rotor term subtructed, as a function of angular momentum.

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