Low spin S-band members in ^{160,162}Dy

E. Andersen, H. Helstrup, G. Løvhøiden, T. F. Thorsteinsen
Department of Physics, University of Bergen, Bergen, Norway

M. Guttormsen, S. Messelt, T. S. Tveter
Department of Physics, University of Oslo, Oslo, Norway

M. A. Hofstee, J. M. Schippers, S. Y. van der Werf
KVI, Groningen, The Netherlands

Abstract

Low spin S-band members are established in ^{160,162}Dy. The coupling between the S-band and the ground state band is significant in ^{160}Dy, but unnoticed in the ^{162}Dy isotope. This observation appears contrary to theoretical expectations.

1. Introduction

The $i_{13/2}$ intruder orbital plays an important role in the structure of the deformed nuclei in the rare-earth region. In particular, the phenomenon of backbending may be explained as a band crossing between the ground state band and a 'super-band' (S-band) based mainly on a pair of aligned $i_{13/2}$ neutrons. Whether this leads to a "backbending" in the yrast line or not depends on the magnitude of the interaction between the bands. The nuclei with small interactions are "sharp" backbenders, whereas the ones with strong interactions between the ground state band and S-band show only a smooth upbending of the moment of inertia parameter J (see fig. 1).

Very little information is available on the S-band members below the crossing point, however. One of the interesting questions is, e.g., whether the low spin S-band members constitute a regular rotational band as predicted by cranking models, or are structured in a more irregular manner. In the Dy region ($N \approx 96$) of deformed rare-earth nuclei, the lowest two-quasiparticle configuration is constructed [1] by occupying the two neutron levels $\frac{5}{2}[642]$ $\alpha = 1/2$ and $\frac{5}{2}[642]$ $\alpha = -1/2$. This results in a band with spin values I=0, 2, 4, $\cdots$ and signature $\alpha = 0$, which constitute the above-mentioned S-band.

The nucleus ^{161}Dy is one of the three stable nuclei that have an $i_{13/2}$ neutron configuration in its ground state and is therefore a suitable target for a study of the $i_{13/2}$ neutron strength distribution in ^{160}Dy and ^{162}Dy by transfer reactions, see fig. 2. As these reactions favour transfer of high *l*-

Low spin S-band members in ^{160,162}Dy

E. Andersen, H. Helstrup, G. Løvhøiden, T. F. Thorsteinsen
Department of Physics, University of Bergen, Bergen, Norway

M. Guttormsen, S. Messelt, T. S. Tveter
Department of Physics, University of Oslo, Oslo, Norway

M. A. Hofstee, J. M. Schippers, S. Y. van der Werf
KVI, Groningen, The Netherlands

Abstract

Low spin S-band members are established in ^{160,162}Dy. The coupling between the S-band and the ground state band is significant in ^{160}Dy, but unnoticed in the ^{162}Dy isotope. This observation appears contrary to theoretical expectations.

1. Introduction

The $i_{13/2}$ intruder orbital plays an important role in the structure of the deformed nuclei in the rare-earth region. In particular, the phenomenon of backbending may be explained as a band crossing between the ground state band and a 'super-band' (S-band) based mainly on a pair of aligned $i_{13/2}$ neutrons. Whether this leads to a "backbending" in the yrast line or not depends on the magnitude of the interaction between the bands. The nuclei with small interactions are "sharp" backbenders, whereas the ones with strong interactions between the ground state band and S-band show only a smooth upbending of the moment of inertia parameter J (see fig. 1).

Very little information is available on the S-band members below the crossing point, however. One of the interesting questions is, e.g., whether the low spin S-band members constitute a regular rotational band as predicted by cranking models, or are structured in a more irregular manner. In the Dy region ($N \approx 96$) of deformed rare-earth nuclei, the lowest two-quasiparticle configuration is constructed [1] by occupying the two neutron levels $\frac{5}{2}[642]$ $\alpha = 1/2$ and $\frac{5}{2}[642]$ $\alpha = -1/2$. This results in a band with spin values I=0, 2, 4, $\cdots$ and signature $\alpha = 0$, which constitute the above-mentioned S-band.

The nucleus ^{161}Dy is one of the three stable nuclei that have an $i_{13/2}$ neutron configuration in its ground state and is therefore a suitable target for a study of the $i_{13/2}$ neutron strength distribution in ^{160}Dy and ^{162}Dy by transfer reactions, see fig. 2. As these reactions favour transfer of high l-

values, it is expected that the low-lying $i_{13/2}$ strength may be identified in the spectra. The stripping reaction has an $i_{13/2}$ target configuration, hence the S-band members are expected to be populated with appreciable strength. In an earlier study [2] of the ^{161}Dy(^{3}He,α)^{160}Dy reaction candidates for the low-spin members of the S-band in the nucleus ^{160}Dy were proposed. The spin assignments for the 6^+ and 8^+ S-band members in ^{160}Dy are consistent with a later ^{158}Gd(α,2nγ)^{160}Dy study [3]. These previous studies related to low spin S-band members in ^{160}Dy have prompted a new investigation [4] where $i_{13/2}$ components of states in the nucleus ^{162}Dy are searched for in the ^{161}Dy(α,^{3}He)^{162}Dy stripping reaction. For comparison also the ^{163}Dy(^{3}He,α)^{162}Dy reaction was measured.

S-band members for ^{162}Dy were proposed in a previous study of the ^{160}Gd($\alpha, 2n\gamma$)^{162}Dy reaction [5].

2. Experimental procedures and results

For the measurements isotopically enriched targets of ^{161}Dy and ^{163}Dy on 20 - 40 μg/cm^2 thick C-backings were used. In the case of ^{161}Dy, the target thickness was $\sim$160 μg/cm^2 and the isotopic purity was 95.94%, while the corresponding values for ^{163}Dy were $\sim$240 μg/cm^2 and 96.85%.

Both experiments were carried out at the KVI cyclotron in Groningen, where 50 MeV α and ^{3}He beams were provided. The particle spectra were recorded with the QMG/2 magnetic spectrograph, equipped with a two-dimensional detector system, that made it possible to discriminate between outcoming α and ^{3}He particles. In both experiments data were recorded at six angles in the angular range of 5° – 40° relative to the beam axis. The resolution (FWHM) of the spectra ranged from 20 to 30 keV. A sample spectrum for the ^{161}Dy(α,^{3}He)^{162}Dy reaction is given in fig. 3.

The resulting excitation energies for the ^{161}Dy(α,^{3}He)^{162}Dy reaction are given in table 1.

The cross-sections were normalised by comparing to elastic angular distributions which were measured over the range from 10° to 30°. For absolute normalisation, these were in turn compared to the results of optical model calculations.

Along with excitation energies and adopted assignments, the experimental cross-sections for one angle are given in table 1, which summarizes the levels observed in the ^{161}Dy(α,^{3}He)^{162}Dy reaction. For more experimental details, see Andersen et al. [4].

3. Interpretation

For light-ion induced single-particle transfer reactions in the rare-earth region the experimental cross-sections are in general well described by the Nilsson model combined with the DWBA predictions. When the target nucleus has an odd number of particles, the calculated cross-sections are summed over

Table 1: Energy levels observed in the ^{161}Dy(α,^{3}He)^{162}Dy reaction

Energy (keV)		$d\sigma/d\Omega$[b] (μb/sr)		Assignment			
previous[a]	present	exp.	calc[c]	l	I^π	K	rot. band
80.66	81	8	6	6	2^+	0	ground state band
265.66	266	64	57	6	4^+	0	ground state band
548.53	548	176	169	6	6^+	0	ground state band
920.99	922	28	38	6	8^+	0	ground state band
1357.77	1363	12	14	5(,6)	3^-	0	$\frac{5}{2}^+[642] - \frac{5}{2}^-[523]$
1485.71	1488	12	11	5(,6)	5^-	5	$\frac{5}{2}^+[642] + \frac{5}{2}^-[523]$
1518.80	1521	14	11	5	5^-	0	$\frac{5}{2}^+[642] - \frac{5}{2}^-[523]$
1574.1	1578	44			4^+	0	S-band?
1576.11			25	5,6	6^-	5	$\frac{5}{2}^+[642] + \frac{5}{2}^-[523]$
1683.88	1682	54	19	5,6	7^-	5	$\frac{5}{2}^+[642] + \frac{5}{2}^-[523]$
1755.5			1		7^-	0	$\frac{5}{2}^+[642] - \frac{5}{2}^-[523]$
1766.5	1759	57	4	5,6	3^-	3	$\frac{5}{2}^+[642] + \frac{1}{2}^-[521]$
1767.4					6^+	0	S-band?
1826.7	1828	14	9	5	4^-	3	$\frac{5}{2}^+[642] + \frac{1}{2}^-[521]$
1985.9	1990	17			8^+	0	S-band?
2002			8	5	6^-	3	$\frac{5}{2}^+[642] + \frac{1}{2}^-[521]$
	2085	19		5,4			
	2260	21		4			
	2292	14		5,6			
	2351	11		6,5			
	2381	10		3			
	2429	17		4			
	2455	10					
	2505	18	33.5	6,5	7^+	6	$\frac{5}{2}^+[642] + \frac{7}{2}^+[633]$
	2532	22		4			
	2623	33	51.5	6	6^+	1	$\frac{5}{2}^+[642] - \frac{7}{2}^+[633]$
	2647	37		5			
	2697	21		4(,5)			
	2726	27		4,5			
	2755	47	72.5	6	8^+	6	$\frac{5}{2}^+[642] + \frac{7}{2}^+[633]$
	2785	27		4,5			
	2812	24		5			
	2847	35	49.8	6	7^+	1	$\frac{5}{2}^+[642] - \frac{7}{2}^+[633]$
	2901	21		5			
	2930	3[illegible]	54.8	6	9^+	6	$\frac{5}{2}^+[642] + \frac{7}{2}^+[633]$

a) Ref. [6].

b) The cross-sections are given at a laboratory angle of 15°.

c) See text.

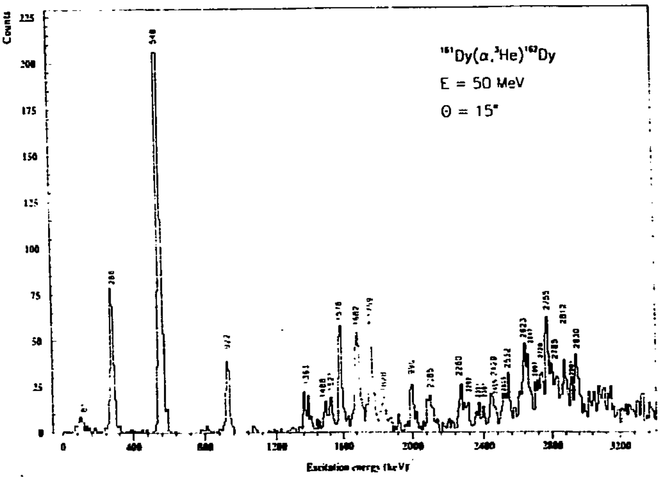

Figure 3: Spectrum of ^{3}He-particles from the ^{161}Dy(α,^{3}He)^{162}Dy reaction at 15°

the l-dependent single-particle DWBA cross-sections and the spherical shell model components of the Nilsson states. To evaluate the Nilsson wave functions and the cross-sections for each member in the rotational bands based on the various Nilsson configurations, the computer code EVE [7] was employed.

The DWBA calculations were carried out with the computer code DWUCK4 [8] using a standard optical potential [4].

The over-all normalisation factor, N, of the theoretical cross-sections is poorly known for the class of 'mismatch' reactions as the present (^{3}He,α) and (α,^{3}He) reactions. We have determined its values from comparisons of the theoretical calculations to the experimental cross-sections. The values obtained in this way are N = 63 for the ^{161}Dy(α,^{3}He)^{162}Dy reaction and N = 33 for the ^{163}Dy(^{3}He,α)^{162}Dy reaction. These numbers give good agreement for the other identified rotational bands and are in reasonable agreement with commonly used values.

The dominant l-transfer for each state was determined by comparing the experimental angular distributions with the DWBA calculations. As the angular distributions are rather similar for high l-transfers, it is difficult to distinguish between $l = 5$ and 6 and unless the angular distribution is a very 'typical' $l = 6$ transfer even $l = 4$ may not be ruled out and vice versa. This uncertainty is reflected in the 'best-fit' l-values given in table 1.

In the ^{161}Dy nucleus the unpaired neutron is blocking the $\frac{5}{2}^+$[642] Nilsson orbital, while the orbital is occupied in the ^{163}Dy nucleus. For ^{163}Dy the unpaired neutron occupies the $\frac{5}{2}^-[523]$ orbital. As stripping reactions populate particle states and pickup reactions hole states, only the ground state band and the $\frac{5}{2}^+[642]\pm\frac{5}{2}^-[523]$ rotational bands are expected to be appreciably populated in both reactions. These bands are already well known from the literature [6,9], and we observe the higher spin members of each of these bands. Both in the ^{163}Dy(^{3}He,α)^{162}Dy and in particular in the ^{161}Dy(α,^{3}He)^{162}Dy reactions the 7^- member of the $K = 5$ band is populated considerably stronger than accounted for in the Nilsson model.

In the *^{161}Dy(α,^{3}He)^{162}Dy reaction, higher spin members* of the bands based on the $\frac{5}{2}^+[642]\pm\frac{1}{2}^-[521]$ configuration are also seen at energies previously known.

Above ~2 MeV of excitation energy the calculations predict the strongest population for the bands based on the $\frac{5}{2}^+[642]\pm\frac{7}{2}^+[633]$ configurations. Experimentally, these bands seem likely to be found among the group of levels observed in the region of 2.5–3.0 MeV of excitation energy. We, somewhat tentatively, assign some of the strongest peaks in that region to these bands, as shown in table 1. The observed cross-sections are only 65 % of the calculated values, the strength might therefore be shared among a number of the experimental groups in a different way than suggested. If the same assignments were also given to the strongest unassigned groups, the total cross-section would in fact be in excellent agreement with the prediction.

The experimental cross-sections of the identified levels from both reactions are shown along with the predictions in fig. 4.

4. Discussion

Generally, the agreement between theory and experiment seems to be very good, as much as 88% of the cross-section below 2.5 MeV of excitation energy has been accounted for in the ^{161}Dy(α,^{3}He)^{162}Dy reaction and 93% in the ^{163}Dy(^{3}He,α)^{162}Dy reaction. However, the level at 1759 keV assigned both to the 7^- member of the $\frac{5}{2}^+[642]+\frac{5}{2}^-[523]$ rotational band and the 3^- member of the $\frac{5}{2}^+[642]+\frac{1}{2}^-[521]$ rotational band is populated much stronger in the ^{161}Dy(α,^{3}He)^{162}Dy reaction than explained theoretically as shown in fig. 5 and table 1. The larger fraction of the strength of the 1759 keV level may thus be attributed to the level at 1767.5 keV, tentatively associated with a 6^+ member of the S-band in an (α,2nγ) study [5] of ^{162}Dy. Also, tentative 4^+ and 8^+ members were suggested at excitation energies of 1573.5 keV and 1986.1 keV. In the present work the levels at1578 keV and 1990 keV are populated more strongly than expected from strength calculations for Nilsson states assigned to these particle groups and thus may be associated with the 4^+ and 8^+ levels.

In the previous study [2] of the ^{161}Dy(^{3}He,α)^{160}Dy reaction, the three levels at excitation energies 1607, 1723 and 1974 keV were proposed to be

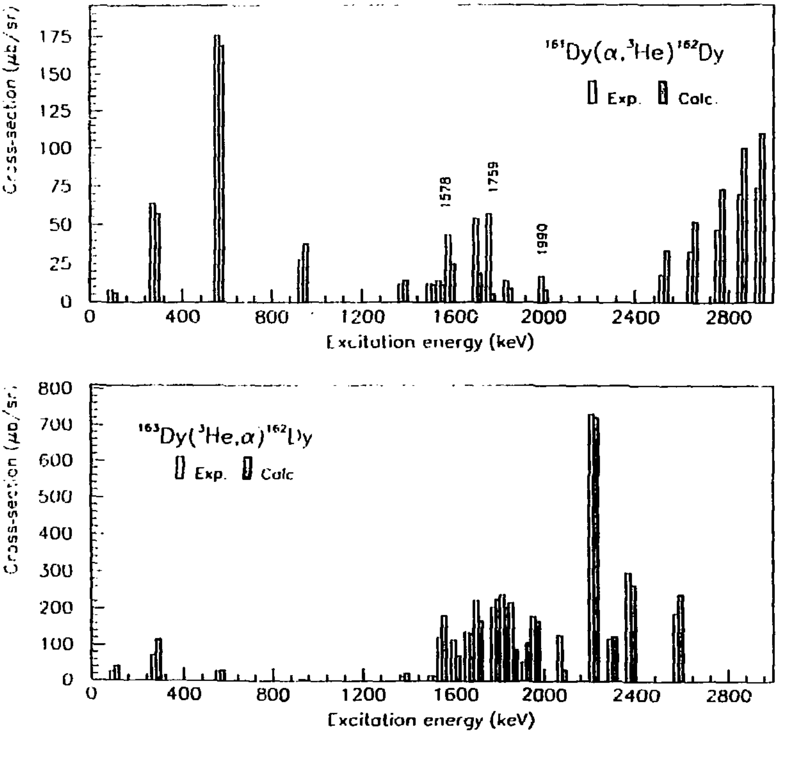

Figure 4: Comparison of experimental and theoretical cross-sections

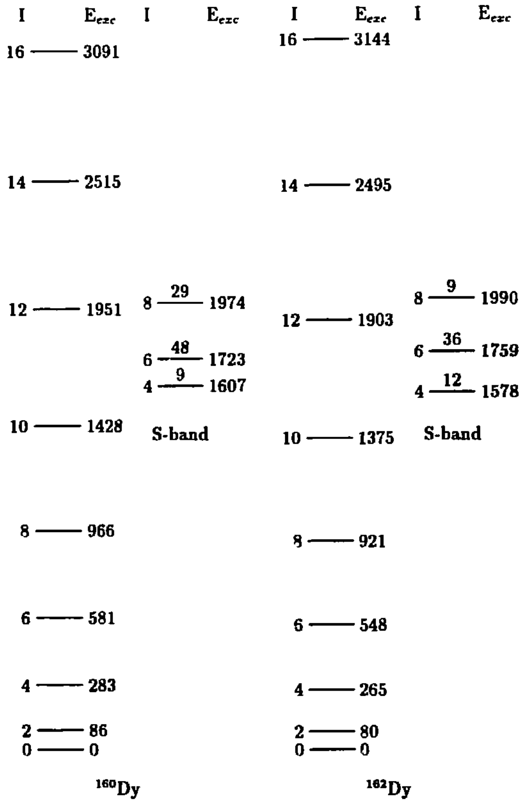

Figure 5: Ground state and low spin S-band members. Spins and excitation energies (keV) are listed. For the S-band members Q-value corrected population strengths relative to the summed strength of the 4^+, 6^+ and 8^+ members of the ground state band are given

low-spin members of a superband, and these suggestions are consistent with a later (α,2nγ) study [3] where the spin assignments were confirmed. In fig. 5 the triplet of states at 1578 keV, 1759 keV and 1990 keV, presently observed in ^{162}Dy is compared to the previously [2] proposed S-band members in ^{160}Dy.

The similarity both in excitation energy and population strengths for the proposed S-band members in ^{160}Dy and ^{162}Dy strongly indicates that these are states of similar nature. A more detailed comparison of the two bands may be performed using the band members of the present work and the previous (α,2nγ) studies [3,5]. Figure 6 displays the extracted Routhian e' and spin alignment i as function of rotational frequency $\hbar\omega$. The ground bands are used as references with the parameters [1] $\Theta_0 = 34\hbar^2$ MeV^{-1} and $\Theta_1 = 138\hbar^4$ MeV^{-3} for ^{160}Dy and $\Theta_0 = 37\hbar^2$ MeV^{-1} and $\Theta_1 = 97.6\hbar^4$ MeV^{-3} for ^{162}Dy. This set of parameters gives an extremely good fit to the ground band transitions below the 12^+ states (e' varies between 2 and 7 keV).

The interpretation of levels belonging to the S-band in ^{162}Dy is supported by fig. 6, the two Routhians are parallel to within 40 keV. Furthermore, the alignments increase strongly as a function of $\hbar\omega$ and reach about $5\hbar$ around $\hbar\omega = 0.15$ MeV. Above $\hbar\omega = 0.1$ MeV the spin alignment is $\approx 1/2\hbar$ lower in ^{162}Dy than in ^{160}Dy.

From the plot of $i(\omega)$ in fig. 6 it is evident that the alignment process for the two $i_{13/2}$ neutrons is far from smooth contrary to the predictions [1] of the cranked shell model.

Figure 7 shows the low spin S-band members in ^{160}Dy and ^{162}Dy. The 0^+ and 2^+ levels associated with the S-band in ^{162}Dy are also populated in the ^{160}Dy(t,p)^{162}Dy reaction [10]. Similarly in the ^{158}Dy(t,p)^{160}Dy reaction, levels populated at 1457 keV and 1513 keV are probably the 0^+ and 2^+ members of the S-band [10]. A closer inspection of the S-band in ^{162}Dy (fig. 7) shows that the 4^+–6^+–8^+ part of the S-band structure appears somewhat irregular, which indicates the possibility of yet another band crossing around I = 6.

A comparison of the proposed S-bands in ^{160}Dy and ^{162}Dy demonstrates almost identical structures (fig. 7). The S-bands and ground state bands converge with increasing spin values, and extrapolations of the S-bands indicate possible crossings with the ground state bands at spin values $I \geq 20$. Thus, it is interesting that "backbending" plot for ^{162}Dy show no sign of backbending, while ^{160}Dy starts to upbend already at I = 12 (fig. 8). Such a difference in the backbending plots for ^{160}Dy and ^{162}Dy indicate significantly different coupling matrix elements between the S-band and ground state band in these isotopes. The wave functions for the S-bands and ground state band levels are however expected to be similar in the two Dy isotopes, and thus a large difference in the matrix elements is not expected. In fig. 9 a calculation [11] of matrix elements in a modified harmonic oscillator picture is presented. The model predicted matrix elements are very similar for N = 94 and N = 96 nuclei, at variance with the experimental data for the S-bands.

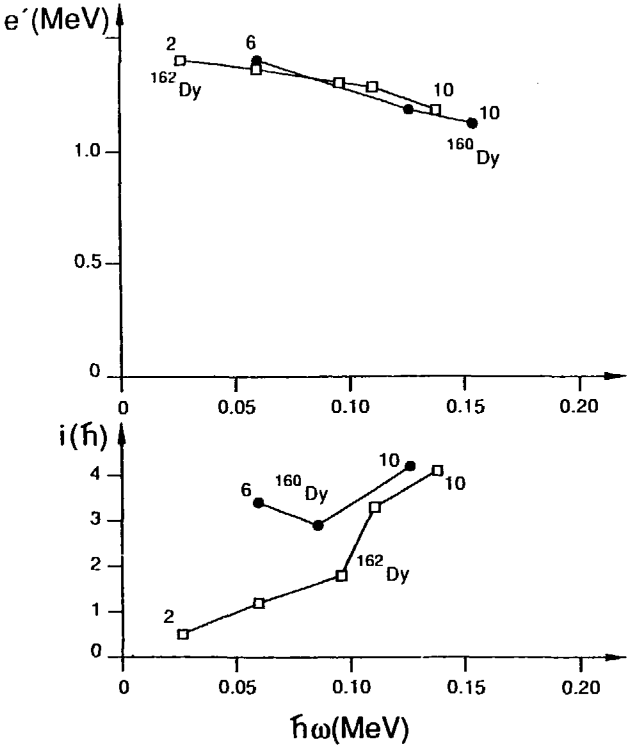

Figure 6: Experimental Routhians and alignments for the low spin members of the proposed S-bands in ^{160,162}Dy

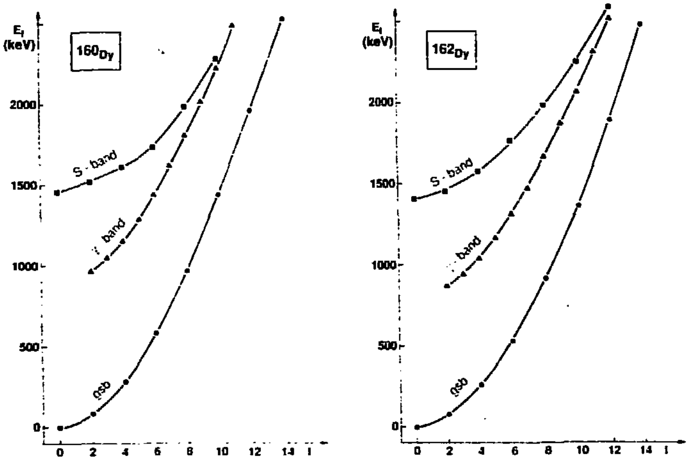

Figure 7: Level energies versus spin for S-band, γ-band and ground state band in ^{160}Dy and ^{162}Dy

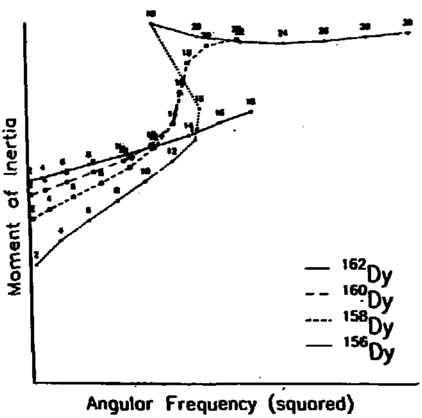

Figure 8: Moment of inertia J versus ω^2 for dysprosium isotopes

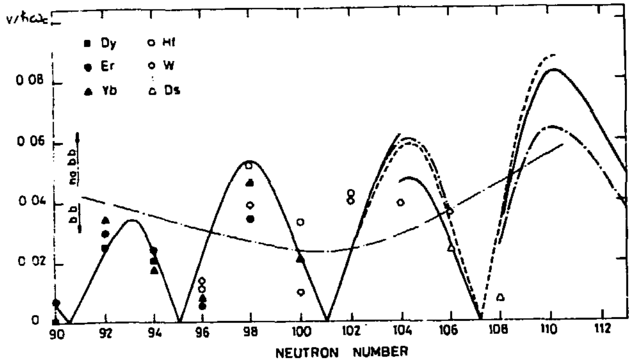

Figure 9: Matrix elements V between the S-band and ground state band. The limit for backbending is shown by the thin dot-dash curve. The figure is quoted from ref. [11]

The γ-band (included in fig. 7) and other K = 0 bands may perturb the S-band and the ground state band near the crossing. Such perturbations must be taken into the evaluation of matrix elements, but will probably not alter significantly the conclusions drawn above.

5. Concluding remarks

Complete low spin S-band sequences (I = 0 → 10 for ^{160}Dy and I = 0 → 12 for ^{162}Dy) are established and presented. The levels may be arranged in rather regular rotational bands. A "kink" in the proposed S-band in ^{162}Dy may indicate yet another band crossing.

There appear to be significant coupling between the S-band and the ground state band in ^{160}Dy and almost no coupling in ^{162}Dy, at variance with theoretical predictions.

In order to get a deeper understanding of the coupling between the S-band and the ground band, experimental information on the levels close to the crossing and on both sides of the crossing is desirable.

Also it would be interesting to have matrix elements between the S-band and the ground state band calculated for N = 94 and N = 96 in more realistic models (e.g., Saxon-Wood potential), to check whether they explain better the present data.

References

[1] R. Bengtsson and S. Frauendorf, Nucl. Phys. **A327** (1979) 139

[2] J. Gen-Ming and J.D. Garrett and G. Løvhøiden T.F. Thorsteinsen, J.C. Waddington and J. Rekstad. Phys. Rev. Lett. **46** (1981) 222

[3] H.J. Riezebos, M.J.A. de Voigt, C.A. Fields, X.W. Cheng, R.J. Peterson, G.B. Hagemann and A. Stolk. Nucl. Phys. **A465** (1987)1

[4] E. Andersen. H. Helstrup, G. Løvhøiden, T.F. Thorsteinsen, M. Guttormsen, S. Messelt, T.S. Tveter, M.A. Hofstee, M. Schippers, S.Y. van der Werf, Nucl. Phys. (in print)

[5] C.A. Fields, K.H. Hicks, R.A. Ristinen, F.W.N. De Boer, P.M. Walker, J. Borggreen and L.K. Peker, Nucl. Phys. **A389** (1982) 218

[6] R.G. Helmer, Nuclear Data Sheets **64** (1991)79

[7] R. Hirning, *The Computer Code EVE*, McMaster University, Hamilton, Ontario, Canada

[8] P.D. Kunz, *The Computer Code DWUCK4*, University of Colorado, Denver, Colorado, USA

[9] A. Bäcklin, A. Suarez, O.W.B. ScHulz, B.P.K. Maier, U. Gruber, E.B. Shera, D.W. Hafemeister, W.N. Shelton and R.K. Sheline, Phys. Rev. **160** (1967) 1011

[10] D.G. Burke, G. Løvhøiden and T.F. Thorsteinsen, Nucl. Phys. **A483** (1988) 221

[11] R. Bengtsson, Journal de Physique **41** (1980) C10