LBL-36158
UC-413
Preprint

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

Submitted to Physical Review Letters

Pair Excitations and a Proton Band-Crossing in Superdeformed ^{150}Gd

P. Fallon, C.W. Beausang, S. Clarke, P.J. Twin, F.A. Beck,
Th. Byrski, D. Curien, P.J. Dagnall, G. deFrance, G. Duchene,
P.D. Forsyth, B. Haas, M.J. Joyce, A.O. Macchiavelli, E.S. Paul,
J.F. Sharpey-Schafer, J. Simpson, J.P. Vivien, S. Aberg,
and W. Nazarewicz

June 1994

Prepared for the U.S. Department of Energy under Contract Number DE-AC03-76SF00098

LBL - 36158

Pair Excitations and a Proton Band-Crossing in Superdeformed ^{150}Gd

P. Fallon[1], C.W. Beausang[2], S. Clarke[2], P.J. Twin[2], F.A. Beck[3], Th. Byrski[3], D. Curien[3], P.J. Dagnall[2], G. deFrance[3], G. Duchene[3], P.D. Forsyth[2], B. Haas[3], M.J. Joyce[2], A.O. Macchiavelli[1], E.S. Paul[2], J.F. Sharpey-Schafer[2], J. Simpson[4] and J.P, Vivien[3]

(1) Nuclear Science Division, Lawrence Berkeley Laboratory, Berkeley , CA 94720 , USA
(2) Oliver Lodge Laboratory, University of Liverpool, L69 3BX, United Kingdom
(3) Centre de Recherches Nucleaires, F-67037 Strasbourg, CEDEX, France
(4) SERC Daresbury Laboratory, Warrington, WA4 4AD, United Kingdom

S. Aberg[5] and W. Nazarewicz[6,7†]

(5) Department of Mathematical Physics, Lund Institute of Technology,
S-22100 Lund, Sweden
(6) Joint Institute for Heavy Ion Research and Physics Division,
Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA
(7) Department of Physics, University of Tennessee, Knoxville, TN 37996, USA

Nuclear Science Division, Lawrence Berkeley Laboratory
University of California, Berkeley, California 94720, USA

June 16, 1994

This work was supported by the Director, Office of Energy Research Division of Nuclear Physics of the Office of High Energy and Nuclear Physics of the U.S. Department of Energy under Contract DE-AC03-76SF00098

Pair Excitations and a Proton Band-Crossing in Superdeformed ^{150}Gd.

P. Fallon[1], C.W. Beausang[2], S. Clarke[2], P.J. Twin[2], F.A. Beck[3], Th. Byrski[3], D. Curien[3], P.J. Dagnall[2], G. deFrance[3], G. Duchêne[3], P.D. Forsyth[2], B. Haas[3], M.J. Joyce[2], A.O. Macchiavelli[1], E.S. Paul[2], J.F. Sharpey-Schafer[2], J. Simpson[4] and J.P. Vivien[3].

[1] *Nuclear Science Division, Lawrence Berkeley Laboratory, Berkeley CA 94720, U.S.A.*

[2] *Oliver Lodge Laboratory, University of Liverpool, L69 3BX, United Kingdom.*

[3] *Centre de Recherches Nucléaires, F-67037 Strasbourg CEDEX, France.*

[4] *SERC Daresbury Laboratory, Warrington, WA4 4AD, United Kingdom.*

S. Åberg[5] and W. Nazarewicz[6,7,†]

[5] *Department of Mathematical Physics, Lund Institute of Technology, S-22100 Lund, Sweden*

[6] *Joint Institute for Heavy Ion Research and Physics Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831, U.S.A*

[7] *Department of Physics, University of Tennessee, Knoxville, TN 37996, U.S.A.*

(June 16, 1994)

Abstract

An excited superdeformed (SD) band in ^{150}Gd is associated with a 2p-2h proton excitation and provides the first evidence for collective proton pair excitations in a SD nucleus. This band is seen to exhibit a discontinuity in the γ-ray transition energies (backbending), which is interpreted as a band-crossing associated with the alignment of a pair of N=6 protons. There is further evidence that this excited SD band decays into the yrast SD band.

21.10 Re, 23.20 Lv, 27.70 +q

Typeset using REVTEX

Superdeformed (SD) nuclei, with a 2:1 axis ratio ($\beta_2 \approx 0.6$) around ^{152}Dy [1], are characterized by large shell gaps and high rotational frequencies ($\hbar\omega \geq 300$ keV) and consequently pair correlations are expected to be greatly reduced [2,3]. Indeed it is the single-particle characteristics of the nucleons, especially the so-called high-N intruder states (i.e., N=6 protons and N=7 neutrons) which appear to dominate the observed properties of SD bands in the mass 150 region [3,4]. In particular the variations in magnitude of the dynamical moments of inertia are attributed to differences in the number of high-N intruder orbitals occupied. There is evidence however that pair correlations play an important role in some mass 150 SD bands, for example the rapid rise in the dynamical moment of inertia and the discontinuity in the transition energies (backbending), seen at low frequency in ^{150}Gd [5] and ^{149}Gd [6,7] respectively, have been interpreted as paired band-crossings arising from the alignment of a pair of N=7 quasineutrons. Nonetheless, the evidence for pairing in this region of SD nuclei is clearly limited and the precise role of pair correlations at superdeformations and large rotational frequencies remains uncertain.

This letter reports on the observation of an excited SD band in ^{150}Gd which exhibits a pronounced discontinuity (backbending) in the γ ray transition energies. This is interpreted as a band-crossing associated with the alignment of a pair of N=6 protons and provides the first evidence for collective proton pair excitations in a SD nucleus. Moreover, at the backbend, this excited SD band is seen to decay into the yrast SD band.

High spin states in ^{150}Gd were populated by the reaction ^{26}Mg $+^{130}$Te at a beam energy of 149 MeV. Two stacked ^{130}Te targets, each 600 μg/cm^2 with a 300 μg/cm^2 Au backing (support) were used. The beam of 1-2pnA was supplied by the tandem accelerator at the Daresbury Laboratory Nuclear Structure Facility and the Eurogam spectrometer [8] was used to record the coincident γ-ray energies. An unsuppressed Ge fold $\geq$7 was required before accepting an event and the resulting event rate was $\sim 5 \times 10^3$ events per second, yielding a total of $\sim 1 \times 10^9$ suppressed coincidence events with Ge fold $\geq$3.

Five SD bands, assigned to ^{150}Gd, have been observed in this data set. Four of the SD bands have been reported previously [5,9–11], the fifth is the subject of this letter. This new SD band has an intensity of ~40% relative to the yrast SD band (band 1) and a partial spectrum of ^{150}Gd band 5 is shown in Fig. 1a. Above E_γ=1 MeV the transition energy spacing is regular ($\Delta E_\gamma \approx 49$ keV) and thus its dynamical moment of inertia, $\Im^{(2)} \equiv 4\hbar^2/\Delta E_\gamma$, (Fig. 2) is constant as a function of rotational frequency ($\hbar\omega \equiv E_\gamma/2$) and similar to that of the yrast SD band (band 1) in ^{152}Dy. Since the $\Im^{(2)}$ moment of inertia is sensitive to the occupation of specific high-N intruder states, band 5 in ^{150}Gd is assigned the same intruder configuration ($\pi 6^4 \nu 7^2$) as ^{152}Dy band 1. In addition, at high spins, the transition energies in band 5 are similar to those in ^{152}Dy band 1. Fig. 3 indicates that the most likely excitation involving two N=6 protons can be associated with the two-particle two-hole (2p-2h) proton excitation from the $[301]\frac{1}{2}$ level to the $[651]\frac{3}{2}$ intruder level and thus, at least at high spins, the configuration of band 5 is considered to be two proton holes in the ^{152}Dy yrast SD core.

Although the higher energy γ rays provide the evidence for the similarities between band 5 in ^{150}Gd and band 1 in ^{152}Dy, there are large differences at lower spins. Band 5 exhibits a pronounced irregularity in the $\Im^{(2)}$ moment of inertia (Fig. 2) indicating that a band-crossing (interaction) has occurred. The band interaction involves two pairs of partially resolved transitions (Fig. 1a) at approximately 966 and 997 keV. These peaks are broader than other SD peaks in the spectrum and coincidence data (Fig. 1b) show that they each correspond to two transitions. Although it is not possible to uniquely determine the ordering of the transitions within the two doublets, a proposed decay sequence, consistent with the data, is 1046.0, 998.6, 967.6, 994.8, 964.5 and 909.9 keV. The resulting discontinuity in the transition energies is termed a backbend. It is important to note that a re-ordering of the transitions within a doublet (or between the doublets) still results in a clear irregularity in the transition energy spacing and hence does not alter the physics interpretation presented below.

The two $[301]\frac{1}{2}$ proton holes in the ^{150}Gd band 5 configuration are expected to carry a very small amount of intrinsic angular momentum and therefore, since both band 5 in ^{150}Gd and band 1 in ^{152}Dy have very similar transition energies above $E_\gamma \approx 1300$ keV, we assume that the relative angular momentum alignment (angular momentum difference) between these bands is close to zero in this region. The absolute spin values for ^{152}Dy are taken from ref. [12] and the resulting angular momentum curves for ^{150}Gd band 5 and ^{152}Dy band 1 are shown in Fig. 4 as a function of rotational frequency. At low frequencies, below the band-crossing, ^{150}Gd band 5 has less angular momentum (at a given frequency) than ^{152}Dy band 1. At the crossing point band 5 suddenly gains ~4 units of angular momentum, whereas band 1 in ^{152}Dy shows no sudden change in alignment.

The backbending in ^{150}Gd implies an interaction (band-crossing) between configurations with different intrinsic alignments. The unpaired single-particle routhians [3] for both protons and neutrons do not show any evidence of an interaction. However, cranked-shell-model calculations including pairing,[1] performed for ^{150}Gd at the deformation calculated for band 5 ($\beta_2 = 0.62, \beta_4 = 0.12$), predict a band-crossing associated with the alignment of a pair of N=6 intruder protons ($[651]\frac{3}{2}$). The calculated crossing frequency and alignment are $\hbar\omega \approx 0.6$ MeV and $i \approx 4\hbar$ respectively. This band-crossing is predicted in the calculations even when a much reduced proton pairing gap is used (Δ_p~450 keV). In the limit of very weak pairing such calculations have rather limited applicability, however, the cranked-shell-model with reduced pairing may be used, in some cases, to give a qualitative description of the band-crossing. Additional information relating to the nature of the band-crossing in ^{150}Gd band 5 can be obtained by comparing ^{150}Gd band 5 with ^{152}Dy band 1. Since, (i) ^{150}Gd and ^{152}Dy are isotones (N=86), (ii) Total Routhian Surface (TRS) calculations [3] predict that ^{150}Gd band 5 and ^{152}Dy band 1 have similar deformations, and (iii) ^{152}Dy band 1 does not show any evidence for a band-crossing, then we may rule out the possibility that the backbend in ^{150}Gd band 5 is due to the alignment of a pair of neutrons. In contrast, the constant $\Im^{(2)}$ for ^{152}Dy is well reproduced by calculations [4] which do not include pairing and this is consistent with the expectation that the large Z=66 (^{152}Dy) shell gap at $\beta_2 \approx 0.6$

---

[1] Since, in general, the BCS (static) pair gaps in mass 150 SD nuclei are expected [2,3] to be quenched at low frequencies, the dynamic pairing or pair fluctuations are important.

should greatly reduce the proton pairing (similarly, we expect weak neutron pairing for both ^{150}Gd band 5 and ^{152}Dy band 1 due to the large N=86 gap).

Above the backbending, the structure of band 5 in ^{150}Gd can be understood in terms of a $(^{152}\mathrm{Dy})_{yrast}\otimes\pi([301]\frac{1}{2})^{-2}$ configuration. In this region, the dynamic proton pair correlations in band 5 are expected to be weaker than in ^{152}Dy band 1 due to the blocking of the $[301]\frac{1}{2}$ pair (see, e.g., Ref. [13] for a discussion of dynamic pairing and blocking effects). Consequently, just above the backbending, band 5 is expected to carry more angular momentum than ^{152}Dy band 1 (see insert to Fig. 4), and its $\Im^{(2)}$ moment of inertia should be lower than in ^{152}Dy (see Fig. 2 and discussion in ref. [2]). At higher rotational frequencies pair correlations decrease and both bands become 'identical'.

Below the backbending, the nature of band 5 is probably more complex. The SD ground state of ^{150}Gd can be associated [14] with the large Z=64 SD shell gap in the single-particle proton spectrum (Fig. 3) and the first excited I^{π}=0$^+$ state is the 2p-2h excitation from $\pi([301]\frac{1}{2})^2$ to $\pi([651]\frac{3}{2})^2$. In the presence of pairing, such an excitation is a two-quasiparticle K^{π}=0$^+$ seniority-zero state. This situation strongly resembles the excited *deformed* intruder configurations in neutron-deficient isotopes of Sn, Hg, and Pb, which are understood in terms of proton pair excitations across closed shells (see ref. [15], Sec. 2.1.4 and 2.2.8). We propose that the low frequency part of the SD band 5 in ^{150}Gd may also be built on such an intruder state, which is slightly more deformed than the SD yrast band. Due to the low density of single-particle states around the Z=64 SD shell gap the pair excitation is expected to be of a dynamical character, i.e., the quasiparticle picture resulting from static (ie., non-zero BCS) pairing is probably not appropriate.

A proton backbending involving the lowest N=6 intruder orbital has been reported recently in a SD band in ^{144}Gd [16], once more illustrating the importance of pairing at superdeformations. The SD band in ^{144}Gd is presumably the lowest (yrast) configuration, whereas the structure of band 5 in ^{150}Gd is based on an excited 2-proton configuration. In our opinion, the ^{150}Gd data provides additional important information related to the role of pairing around SD shell gaps and may even shed some light on elementary modes of nuclear excitations involving the pair field.

A SD band in ^{149}Gd [7] (band 4) has also been associated with a 2p-2h proton excitation from the [301]1/2 to the [651]3/2 intruder orbital, coupled to a 1p-1h neutron excitation from the $[651]\frac{3}{2}$ into the $[770]\frac{1}{2}$ intruder. In this example the observed $\Im^{(2)}$ is very constant (and identical to ^{152}Dy band 1) and the fact that no band-crossing has been seen in the ^{149}Gd SD band 4 is puzzling. However, TRS calculations predict a deformation of $\beta_2 = 0.59, \beta_4 = 0.10$ for ^{149}Gd band 4 and at this deformation the cranked-shell-model, including pairing, predicts a smooth gain in alignment for ^{149}Gd band 4 which is consistent with the data. Although the results obtained from the cranked-shell-model (which describes the pair correlations within a static pair field) are highly qualitative, a possible explanation for the absence of a backbending in ^{149}Gd band 4 (in contrast to ^{150}Gd band 5) may thus be related to the deformation driving effects of the $[651]\frac{3}{2}$ neutron hole.

The SD band 5 in ^{150}Gd is seen (Fig. 5) to lose $\sim$ 50% of its intensity in the backbending region and may de-excite completely after the 909.9 keV transition. At the same time there is a build up of intensity in the yrast SD band (^{150}Gd band 1) which can not be associated with gating transitions set accidentally on band 1. Therefore we suggest that band 5 decays primarily into band 1 rather than into the normal deformation states. This transfer of intensity occurs throughout the backbending region, where the N=6 protons align. It is reasonable to assume that the excited SD band (band 5) is likely to be a few hundred keV above the yrast SD band in the SD band population region and thus we can estimate that the linking transitions, connecting band 5 to band 1, would be in the energy range 1.7 - 2.2 MeV. However these data do not contain sufficient statistics in order to enable us to make a positive identification of any linking transitions. In our opinion the observation of such inter-band decays may, with a more detailed measurement, allow us to obtain direct information on the nature of the correlations present in SD nuclei.

In summary we have observed an excited SD band in ^{150}Gd which, at high spins, is assigned a $\pi 6^4 \nu 7^2$ high-N intruder configuration coupled to two proton holes in the $[301]\frac{1}{2}$ level, i.e. two proton holes in the ^{152}Dy yrast SD core. This new band undergoes a backbending at low frequencies which we interpret as an alignment of a pair of N=6 protons. Thus these data provide the first evidence for K^{π}=0^+ proton pair excitations in a SD nucleus. In addition, at the band-crossing, this excited SD band is seen to decay into the yrast SD band rather than directly to the normal deformation states.

EUROGAM is funded jointly by the SERC (U.K.) and IN2P3 (France). Three of us (SC, PJD, and MJJ) acknowledge receipt of SERC postgraduate studentships during the course of this work. PF, AOM and W.N acknowledge support from the U.S. Department of Energy under contract numbers DE-AC03-76SF00009, DE-AC05-84OR21400, DE-FG05-87ER40361, and DE-FG05-93ER40770. Discussions with D. Bés, S. Frauendorf, B. Mottelson, and R. Wyss are gratefully acknowledged. S.A and W.N thank the European Centre for Theoretical Studies in Nuclear Physics and Related Areas (ECT*) in Trento for its hospitality and for partial support for this project.

REFERENCES

† Permanent address: Institute of Theoretical Physics, Warsaw University, Hoża 69, 00-681 Warsaw, Poland; Institute of Physics, Warsaw Institute of Technology, Warsaw, Poland.

[1] P.J.Twin *et al.*, Phys. Rev. Lett. **57**, 811 (1986).

[2] Y.R.Shimizu, E.Vigezzi and R.A.Broglia, Phys. Lett. **198B**, 33 (1987); Nucl. Phys. **A509** 80 (1990).

[3] W.Nazarewicz, R.Wyss and A.Johnson. Phys. Lett. **225B**, 208 (1989); Nucl. Phys. **A503**, 285 (1989).

[4] T.Bengtsson, S.Åberg and I.Ragnarsson, Phys. Lett. **208B**, 39 (1989).

[5] P.Fallon *et al.*, Phys. Lett. **218B**, 137 (1989); Phys. Lett. **257B**, 269 (1991).

[6] B.Haas *et al.*, Phys. Rev. **C42**, R1817 (1990).

[7] S.Flibotte *et al.*, Phys. Rev. Lett. **71**. 688 (1993).

[8] C.W.Beausang *et al.*, Nucl. Instrum. and Meth., **A313**, 37 (1992); F.A.Beck, Prog. Part. Nucl. Phys. **28**. 443 (1992).

[9] T.Byrski *et al.*, Phys. Rev. Lett. **64**, 1650 (1990).

[10] W.Nazarewicz, P.J.Twin, P.Fallon and J.D.Garrett, Phys. Rev. Lett. **64**, 1654 (1990).

[11] C.W.Beausang *et al.*, Phys. Rev. Lett. **71**, 1800 (1993).

[12] I.Ragnarsson, Nucl. Phys. **A557**, 167c (1993).

[13] Y.R.Shimizu, J.D.Garrett, R.A.Broglia, M.Gallardo and E.Vigezzi, Rev. Mod. Phys. **61**, 131 (1989).

[14] S.Åberg, Nucl. Phys. **A488**. 147c (1988).

[15] J.L.Wood, K.Heyde, W.Nazarewicz, M.Huyse and P.van Duppen, Phys. Rep. **215**, 101 (1992).

[16] S.Lunardi *et al.*, Phys. Rev. Lett. **72**, 1427 (1994).

FIGURES

FIG. 1. (a) Double gated coincidence spectrum of ^{150}Gd SD band 5 expanded around the proposed backbending region. The transition energies are given in both the figure and the accompanying table and have typical errors ranging from ± 0.4 keV in the lower energy region to ± 0.7 keV at higher energies. The resolved energies of the proposed doublets are shown in the spectrum and the table (indicated by "*"). Peaks corresponding to transitions in the yrast SD band of ^{150}Gd are labeled by "(b1)" and their energy. Also shown is the 780 keV peak associated with the decay of the normal deformed yrast $I = 23^-$ state in ^{150}Gd. Other peaks, labeled A-D, correspond to decays of transitions in normal deformed states in ^{150,151}Gd. (b) Double gated spectra in coincidence with the unresolved doublets at 964-968 and 995-999 keV, expanded around the region containing the doublets. Gating on the doublets was confined to one half of a given doublet as indicated in the figure and to all other SD band members. The other component of the unresolved doublet is clearly seen.

FIG. 2. Dynamic moments of inertia, $\Im^{(2)}$, for the yrast SD band in ^{152}Dy (circles) and ^{150}Gd SD band 5 (squares) as a function of rotational frequency. The moments of inertia are similar at high frequencies but a sudden discontinuity occurs in ^{150}Gd band 5 at a frequency of ~0.5 MeV. Only the transition energies above the backbending in ^{150}Gd are used.

FIG. 3. Single-particle proton levels at the Fermi surface for SD bands around Z=64-66. At β_2 ~0.62 the low-N $[301]\frac{1}{2}$ and the second N=6 intruder ($[651]\frac{3}{2}$) orbitals are degenerate. We propose that ^{150}Gd SD band 5 corresponds to the excitation of two protons from the $[301]\frac{1}{2}$ orbital into the N=6 intruder level.

FIG. 4. A plot of the level spin versus rotational frequency for the yrast SD band in ^{152}Dy (circles) and ^{150}Gd SD band 5 (squares). Above 1300 keV the transition energies (frequencies) are very similar and therefore the spin difference in this region is assumed to be zero. At the backbending, ^{150}Gd SD band 5 gains ~4 units of spin which we propose is due to the alignment of a pair of N=6 protons. The inset shows the relative alignment (ΔI) between the bands.

FIG. 5. Relative inband intensities as a function of rotational frequency for ^{150}Gd SD band 5 (filled squares) illustrating a loss of intensity over the backbending region and a corresponding increase in the intensity of transitions associated with the yrast SD band in ^{150}Gd (open squares).

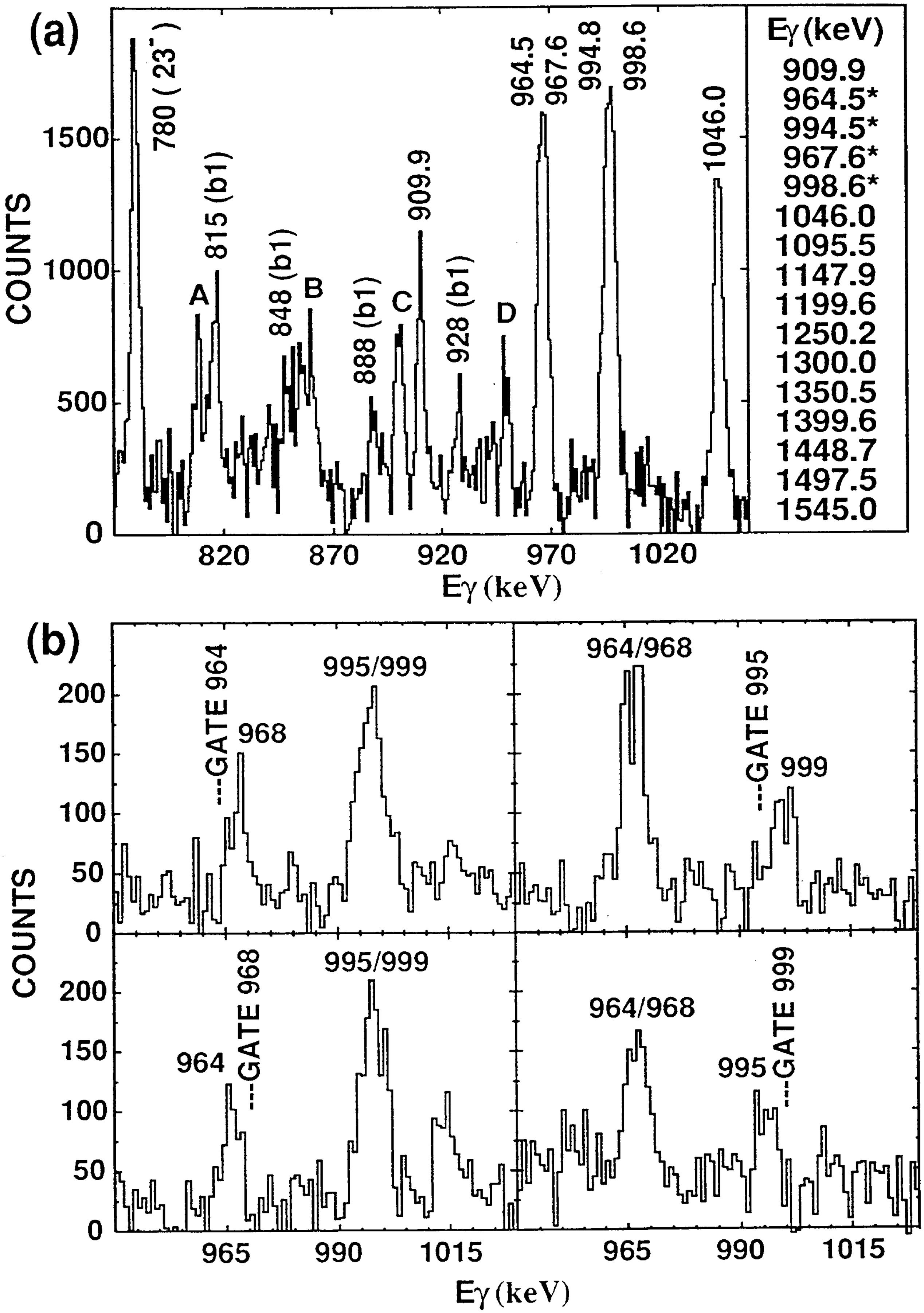

(a)
780 (23⁻)
815 (b1)
A
848 (b1)
B
888 (b1)
C
909.9
928 (b1)
D
964.5
967.6
994.8
998.6
1046.0
Eγ (keV)
909.9
964.5*
994.5*
967.6*
998.6*
1046.0
1095.5
1147.9
1199.6
1250.2
1300.0
1350.5
1399.6
1448.7
1497.5
1545.0
COUNTS
0
500
1000
1500
820
870
920
970
1020
Eγ (keV)
(b)
---GATE 964
968
995/999
964/968
---GATE 995
999
964
---GATE 968
995/999
964/968
995
---GATE 999
COUNTS
0
50
100
150
200
965
990
1015
965
990
1015
Eγ (keV)

Figure 2

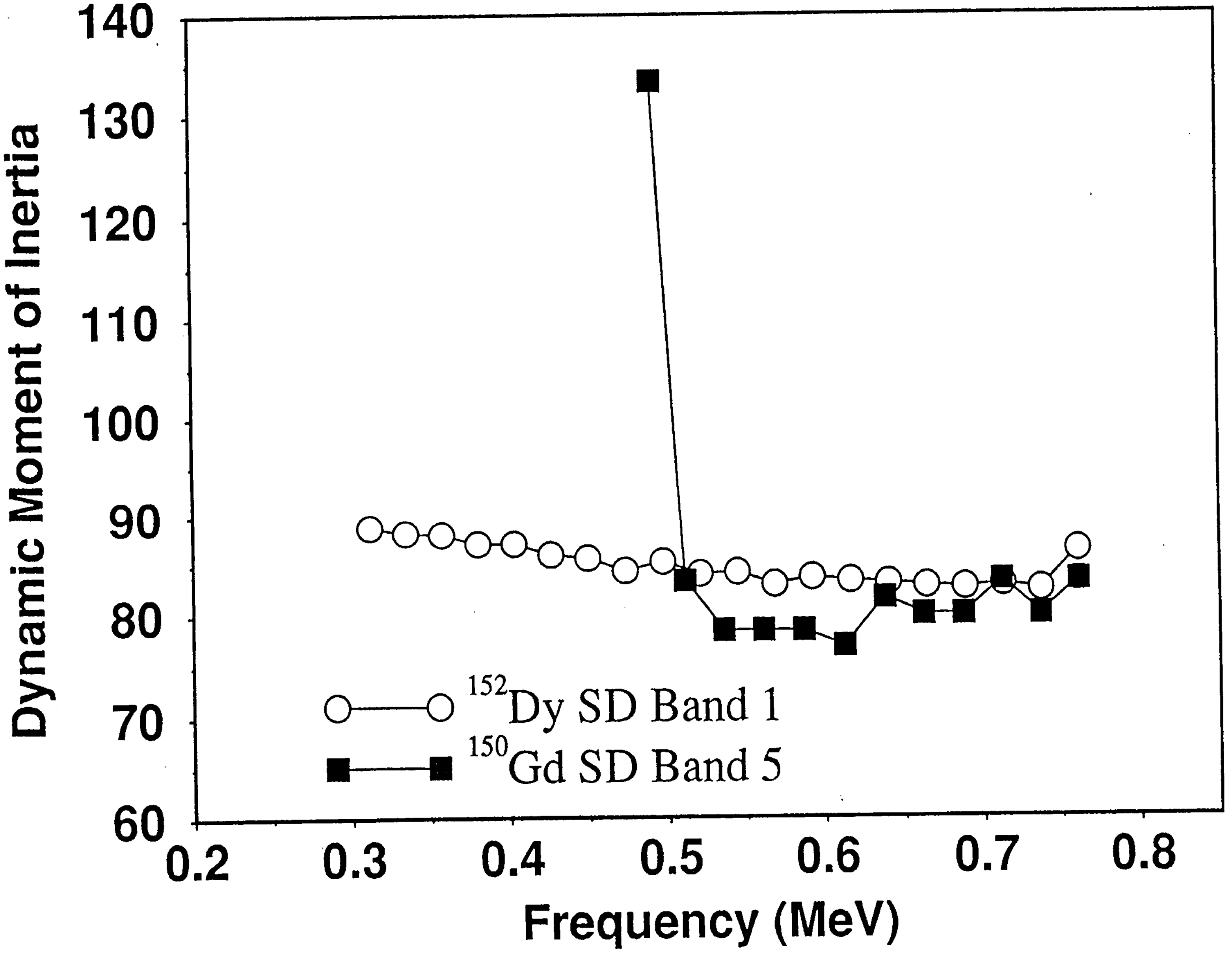

Dynamic Moment of Inertia
140
130
120
110
100
90
80
70
60
0.2
0.3
0.4
0.5
0.6
0.7
0.8
Frequency (MeV)
^{152}Dy SD Band 1
^{150}Gd SD Band 5

Fig 3 [illegible]

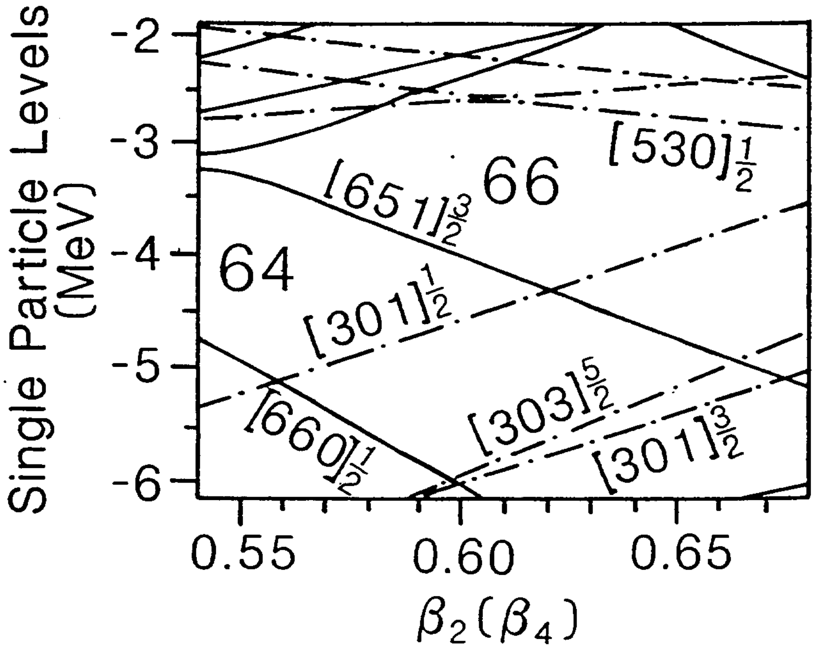

Single Particle Levels (MeV)
-2
-3
-4
-5
-6
0.55
0.60
0.65
$\beta_2(\beta_4)$
64
66
$[651]\frac{3}{2}$
$[530]\frac{1}{2}$
$[301]\frac{1}{2}$
$[660]\frac{1}{2}$
$[303]\frac{5}{2}$
$[301]\frac{3}{2}$

Figure 4

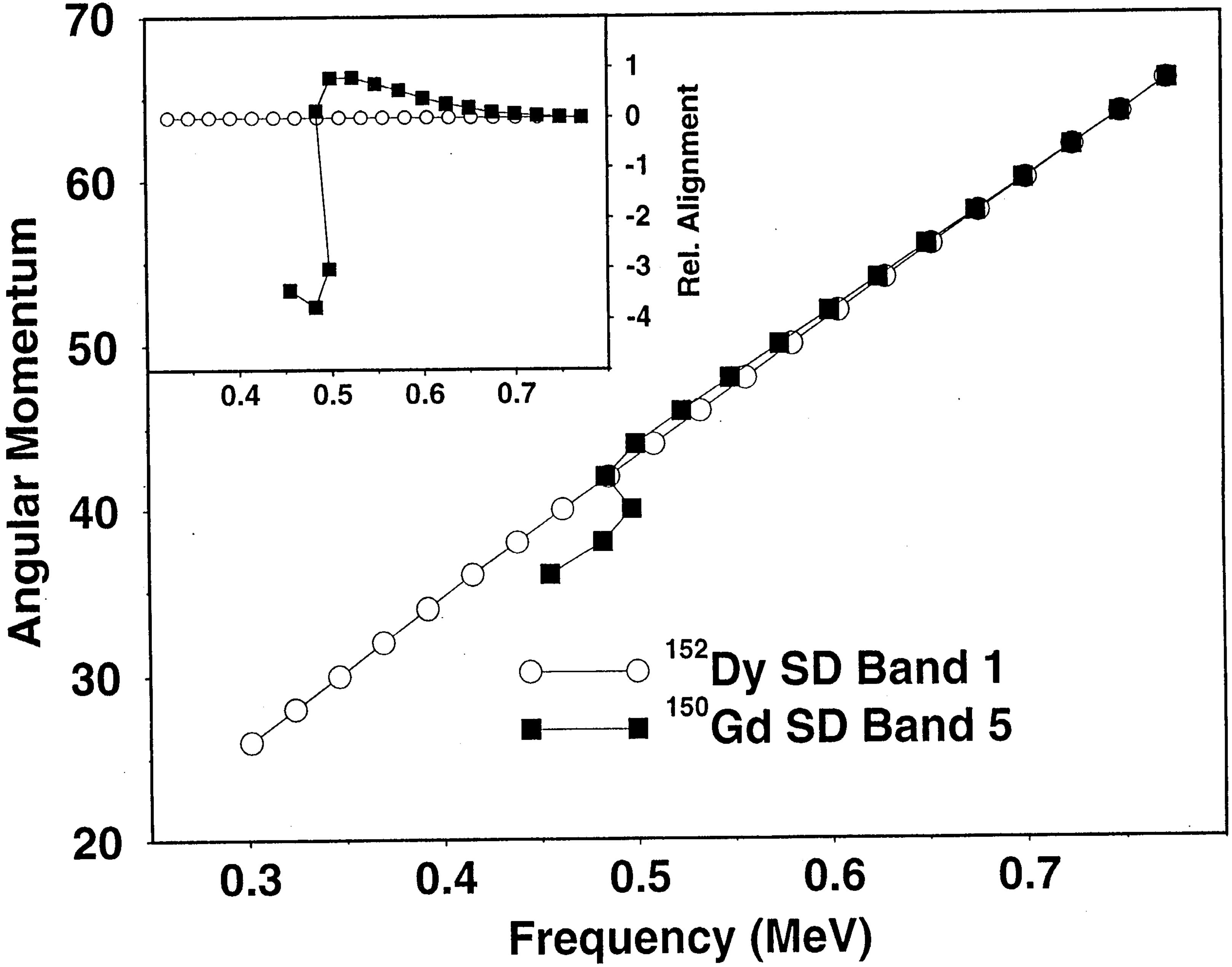
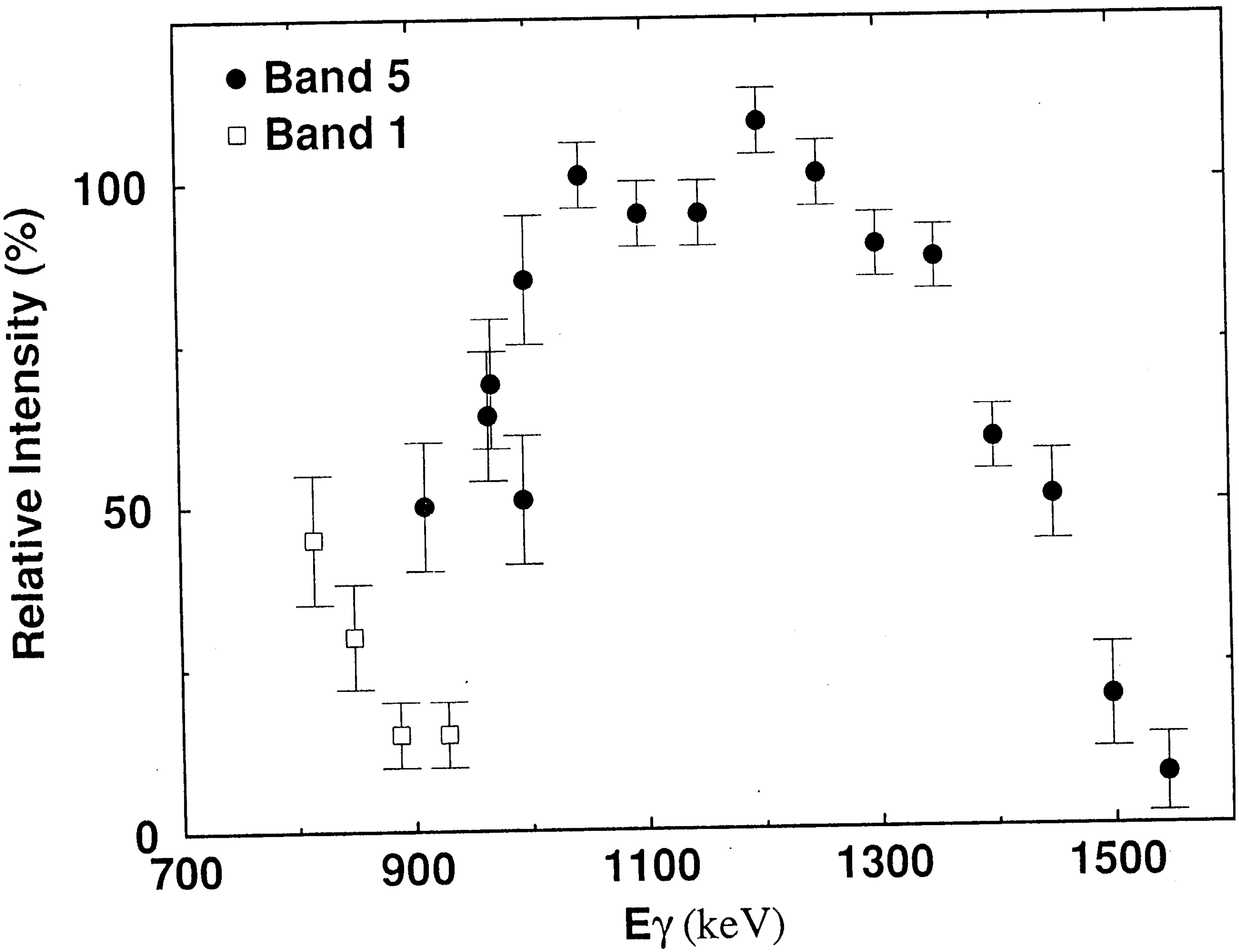

Angular Momentum
70
60
50
40
30
20
0.3
0.4
0.5
0.6
0.7
Frequency (MeV)
^{152}Dy SD Band 1
^{150}Gd SD Band 5
Rel. Alignment
1
0
-1
-2
-3
-4
0.4
0.5
0.6
0.7

Fig 5


● Band 5
□ Band 1
Relative Intensity (%)
0
50
100
700
900
1100
1300
1500
Eγ (keV)