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Abstract

High–spin states in ^{136}Nd were populated via the ^{100}Mo(^{40}Ar,4n) reaction at beam energies of 176 and 182 MeV, and resulting γ–rays were detected using the GAMMASPHERE spectrometer. Analysis of the data has revealed the existence of an excited superdeformed (SD) band in ^{136}Nd. The yrast SD band in ^{136}Nd has been extended by the addition of four (possibly five) transitions at high frequency. The new band displays the remarkable property of having transition energies identical (to within ±1 keV) to those of the half–points of the yrast SD band of ^{136}Nd. Possible explanations in terms of cranked Woods–Saxon single–particle calculations are discussed.

The existence of superdeformed (SD) nuclei around A$\sim$130 is now well established. The first evidence came with the observation of a sequence of narrowly spaced γ–rays ($\Delta E_\gamma \sim$70 keV) in ^{132}Ce [1]. The occurrence of these strongly deformed prolate shapes ($\beta_2 \sim$0.3–0.4) arises in part from the shell structure at large deformations being energetically favourable when compared with that at normal deformation. Neutron $i_{13/2}$ intruder orbitals play an important role in polarizing the core, thereby enhancing and stabilizing the superdeformed shape [2]. Until recently no excited SD bands had been found in nuclei near A$\sim$130. This was surprising since multiple SD bands had been found in several nuclei of the A$\sim$150 and A$\sim$190 regions (for a recent compilation of superdeformed bands see [3]; for the most recent review of superdeformation in nuclei around A$\sim$150 and A$\sim$190 see [4]). However, high–statistics experiments on GAMMASPHERE and EUROGAM have revealed excited SD sequences in $^{131-133}$Ce [5, 6, 7] and ^{133}Pr [8]. These results provide important information on the proton and neutron level structure close to the Fermi surface at this large deformation.

Recent experiments with the GAMMASPHERE array, aimed at investigating superdeformation in $^{135-137}$Nd, have resulted in the observation of an excited SD band, which has been assigned to ^{136}Nd. The known yrast SD band in ^{136}Nd [9] has also been extended to higher frequency by the addition of four (possibly five) new transitions. The new excited band is at the half–point energies of the ^{136}Nd yrast SD sequence (to within $\pm$1 keV) over the entire observed frequency range. This is the first observation of a pair of 'identical' SD bands in the Nd isotopes. This letter presents the evidence for this new excited band. The properties of the band, in particular its relationship to the yrast SD structure, will be discussed within the framework of cranked Woods–Saxon single–particle calculations [10, 11].

High–spin states in ^{136}Nd were populated via the ^{100}Mo(^{40}Ar,4n) reaction at beam energies of 176 and 182 MeV. The beam, which was accelerated by the 88–Inch Cyclotron at the Lawrence Berkeley Laboratory, was incident on a stack of two self–supporting ^{100}Mo foils, each of thickness $\sim$500 μgcm^{-2}. Coincident γ–rays, emitted during the decay of high–spin states, were detected with the early implementation phase of the GAMMASPHERE array [12]. For the experiments at 176 MeV and 182 MeV, the array consisted of 36 and 24 large–volume (relative efficiency ~80%), Compton–suppressed, HPGe detectors, respectively. Approximately 1.8×10^9 and 1.0×10^9 events with a suppressed Ge–fold of ≥3 were recorded at the lower and higher beam energies, respectively. The data for each beam energy were sorted into γ–γ matrices and also into γ–γ–γ cubes, to allow a search for new high–spin structures.

Analysis of these data has revealed the presence of a new weakly populated sequence, with energy spacings characteristic of SD bands in the Nd nuclei. Due to insufficient statistics, it has proved impossible to perform a directional correlation analysis for this new structure. Therefore, in the following we make the reasonable assumption that it is a SD sequence of E2 transitions. Fig. 1 shows spectra for the new band and the known SD band in ^{136}Nd. The inset of Fig. 1 shows the extension of the yrast SD band to higher frequency. The γ–ray energies for both of the bands are summarized in Table 1.

All the γ–rays of the new band are in coincidence with known low–lying transitions of the yrast sequence in ^{136}Nd (see Fig. 1) [13]. Known lines in ^{135,137}Nd [14, 15, 16, 17, 18] are not seen consistently in triple gated spectra formed from gates on band members. This favours the assignment of the new band to ^{136}Nd. However, the intensities of the ^{136}Nd yrast γ–rays are anomalously high indicating some contamination of the gates. To verify the assignment of the new structure to ^{136}Nd the ratio of the intensity of the new SD band in the 176 MeV data to its intensity in the 182 MeV data was determined. This ratio was compared to the one for the yrast SD bands of ^{135}Nd [15] and ^{136}Nd [9]. The results are summarized in Table 2. Clearly, the intensity of the new band follows that of the known ^{136}Nd SD band, lending convincing support to our isotopic assignment. We estimate that the excited band has approximately 20% the intensity of the yrast SD band.

As yet, linking transitions to the normal deformed states have not been found for the two sequences. Consequently, the excitation energies, spins, and parities of states in the bands are not known. The dynamic moment of inertia, $\Im^{(2)}$=dI/dω (=4/ΔE$_\gamma$), is a spin independent quantity that can be readily deduced and used to compare the behaviour of the bands. Fig. 2a shows the $\Im^{(2)}$'s of the two SD bands in ^{136}Nd plotted as functions of rotational frequency. The behaviour of the $\Im^{(2)}$ has been described in terms of the combined effect of gradual proton ($h_{11/2}$) and neutron ($h_{9/2}$+$h_{11/2}$) alignments [2]. The yrast SD band shows a low frequency irregularity which has been associated with the depopulation of the band [9]. The new excited SD sequence is not seen to as low a rotational frequency as the yrast band.

The excited SD band has transition energies at the half–points of the yrast SD band in ^{136}Nd (see Figs. 1 and 2, and Table 1). Similar 'identical' bands (by identical we mean transition energies that lie at the half, quarter, three–quarter points, or are the same as those of some other reference band) have been found in both the A$\sim$150 and A$\sim$190 regions [4]. Very recently, identical bands have also been found in $^{131-133}$Ce [5, 6, 7] and ^{133}Pr [8]. Stephens et al. [19, 20] have pointed out that identical SD bands have quantized differences in aligned spin, I_x (a multiple of 1/2). Since both bands we observe are in ^{136}Nd, and the excited band is at the half–points of the yrast SD band, the difference in aligned spin must be integer. To show the quantized alignment difference Stephens et al. [20] suggest considering the 'incremental alignment' defined by:

$$\Delta i = \frac{2\Delta E_\gamma}{\Delta E^0_\gamma} \qquad (1)$$

where ΔE$_\gamma$ is obtained by subtracting E$_\gamma$(I) (the transition energy under consideration) from the nearest transition energy in the reference band (the yrast SD sequence in ^{136}Nd in this case) which has a lower value. The energy difference between the two closest reference transitions is given by ΔE^0_γ=E^0_γ(I+2)–E^0_γ(I). The results of this analysis are presented in Fig. 2b. The incremental alignment is 1.00(7) over the entire frequency range of the excited band.

To gain an understanding of this behaviour cranked Woods–Saxon calculations [10, 11] have been performed. Single–particle routhians with β_2=0.3 and γ=0° (a representative deformation for the SD structures in the Nd isotopes [16, 21, 22]) for both protons and neutrons are presented in Fig. 3. Changing β_2 by up to 10%, or introducing a small triaxial deformation ($\gamma \sim 5^\circ$), does not significantly alter the alignments of the orbitals described in the discussion below. Since the quantized alignment difference is integer over the entire observed frequency range of the excited band, the different orbitals involved in the two configurations should have the same curvature. This is clear since the alignment of an orbital is given by $i = -de/d\omega$. By examining the single–particle plots one sees that for ^{136}Nd (Z=60, N=76) significant shell gaps, of comparable size, exist at both the proton and neutron Fermi surfaces. The calculations predict that the proton shell gap is slightly larger. We now examine the most likely proton and neutron excitations that can give rise to excited bands.

The lowest single–particle excitation of the protons is predicted to be from the [541]3/2 state to the [411]3/2 orbital across the Z=60 gap (see Fig. 3a). The [411]3/2 levels have no significant curvature and very little alignment. The [541]3/2 orbital is curved at low frequency but over the energy range for which the excited band is seen ($\hbar\omega \sim 0.45 \rightarrow 0.75$ MeV) the curvature is less pronounced. The calculations indicate that, if the [411]3/2 excitation is responsible, the signature partner of the first excited band should also be seen. The two signatures of the [411]3/2 state show very little splitting and the second excited band would lie under the yrast SD band over much of the observed frequency range. Since the first excited band has only 20% the intensity of the yrast SD band, it would be difficult to identify its signature partner. The peaks in the yrast band are not anomalously wide, and we can find no evidence for the signature–partner band. The favoured signature of the [532]5/2 state also lies close to the proton Fermi surface. The curvature of this orbital is very similar to that of the [541]3/2 level. This is clearly seen in Fig. 2b which shows the resulting differences from integer alignment for the various excitations described. Clearly, the excitation to the [532]5/2 level gives a near integer difference in aligned spin over the entire observed frequency range of the excited band. Excitations to the [411]3/2 levels do not give as good an agreement. In particular the low frequency deviation reflects the increasing curvature of the [541]3/2 level at low frequency.

The lowest single–particle neutron excitation would be from the [402]5/2 level to the [530]1/2 orbital across the N=76 gap. The signature partner band of the [530]1/2 state might also be populated. The splitting between the two signatures of the [530]1/2 level is large (see Fig. 3b), and no candidate for a second excited band has been found. Similar considerations to those outlined above can again be applied. The favoured [530]1/2 orbital has significant curvature at the lowest frequencies of the calculation; however, the curvature is much less over the observed frequency range of the excited band. The [402]5/2 level has a near–zero curvature over the appropriate frequency range. The difference from integer alignment for this excitation is also plotted in Fig. 2b . This is near integer only at the lowest frequency with the deviation becoming more pronounced at higher frequency.

On the basis of the discussion above the favoured explanation for the occurrence of the excited SD band at the half–points of the yrast SD band involves the excitation of a proton from the [541]3/2 orbital to the [532]5/2 orbital. However, it is probably not possible to use these simple calculations to decide upon the correct scenario. One particular concern is the role of pairing in these structures. If some pairing is present then this will affect the alignment of orbitals. However, the nature (whether static or dynamic) and magnitude of the proton and neutron pairing remains unclear. The situation is further complicated by possible effects from the strong residual proton–neutron (pn) interaction between the $i_{13/2}$ neutrons and low–K $h_{11/2}$ protons. For instance, the pn interaction is thought to have a sizeable quenching effect on the static proton pairing in the Sm (Z=62) nuclei [23].

To summarize, an excited SD band has been found and assigned to ^{136}Nd. It displays the remarkable property of having transition energies identical to the half–points of the yrast SD sequence in ^{136}Nd (to within ±1 keV). The incremental alignment difference between the two structures is found to be integer. The occurrence of the excited band can be explained in terms of either single–particle proton or neutron excitations. The difference in the alignments of orbitals involved in the excitation turn out to be roughly integer (a proton excitation to the [532]5/2 orbital best fulfils this requirement). Important experimental imperatives are to determine the relative spins of the two bands and also to measure the deformations of both the yrast and excited SD structures. This may be of considerable help in characterizing their nature further.

Acknowledgements

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Table 1: The transition energies (in keV) for the two SD bands in ^{136}Nd. Also given, in the third column, are the half-point energies of the ^{136}Nd yrast SD band.

^{136}Nd (Yr)	^{136}Nd (Ex)	1/2-points
716.5(2)		
794.9(2)		
856.7(3)		
918.3(3)	888(1)	887.5(2)
982.7(3)	951(1)	950.5(2)
1049.4(2)	1017(1)	1016.0(2)
1117.5(2)	1081(1)	1083.5(2)
1185.8(3)	1151(1)	1151.7(2)
1255.1(4)	1221(1)	1220.5(3)
1325.2(3)	1290(1)	1290.2(3)
1398.5(4)	1364(1)	1361.9(3)
1476.6(4)	1438(1)	1437.6(3)
1558.2(4)		
1643.5(5)		
1732.6(7)		
1815(1)		

Table 2: The ratio of the intensity of each SD band in the 176 MeV data to the intensity of the same band in 182 MeV data.

Structure	$\frac{I(176)}{I(182)}$
^{135}Nd	1.83(20)
^{136}Nd	3.56(20)
New	3.22(20)

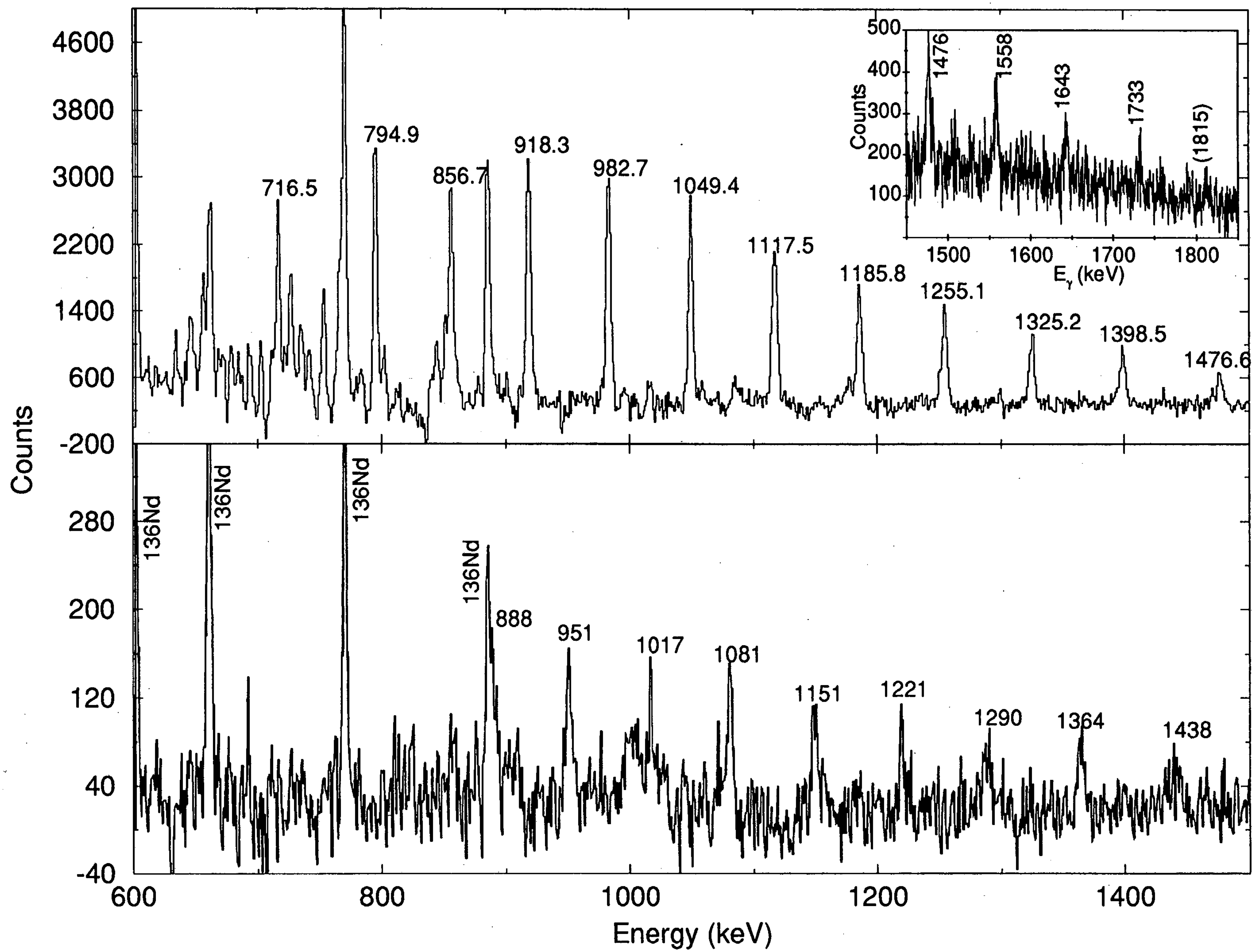
Figure Captions

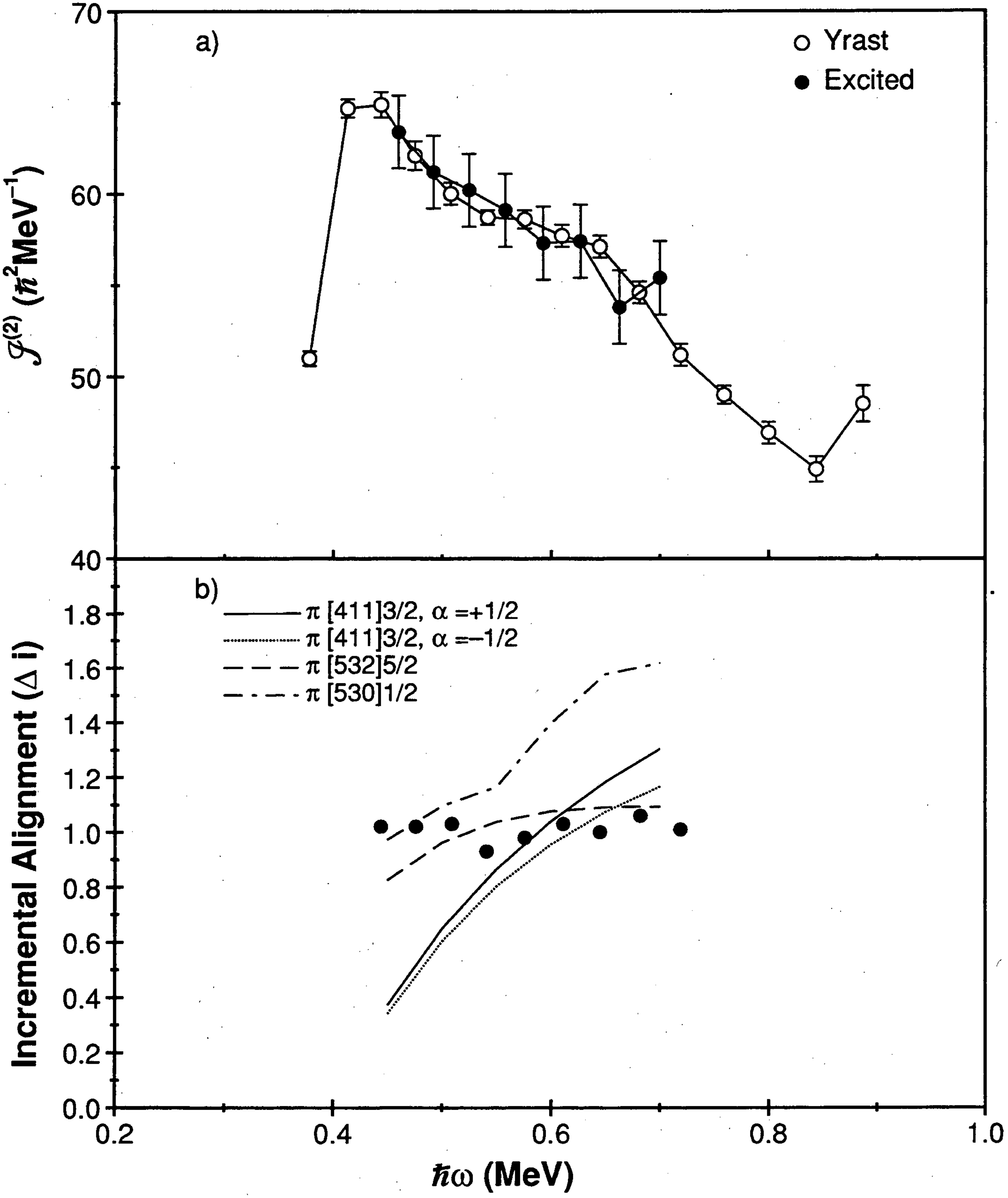
Figure 1: Coincidence spectra, obtained from triples data, showing a) the known SD band in ^{136}Nd (formed from a sum of all gates on known in–band transitions), and b) the new excited band (formed from a sum of gates on the 1151, 1221, 1290, and 1364 keV transitions). Band members are labelled with their energies in keV. Known low–lying transitions in ^{136}Nd are also marked. The inset shows the additional new γ–rays at the top of the yrast SD band. All the γ–ray energies for both bands are presented in Table 1.

Figure 2a: Plots of the dynamic moment of inertia, $\Im^{(2)}$, as functions of rotational frequency, ω, for the two SD bands in ^{136}Nd.

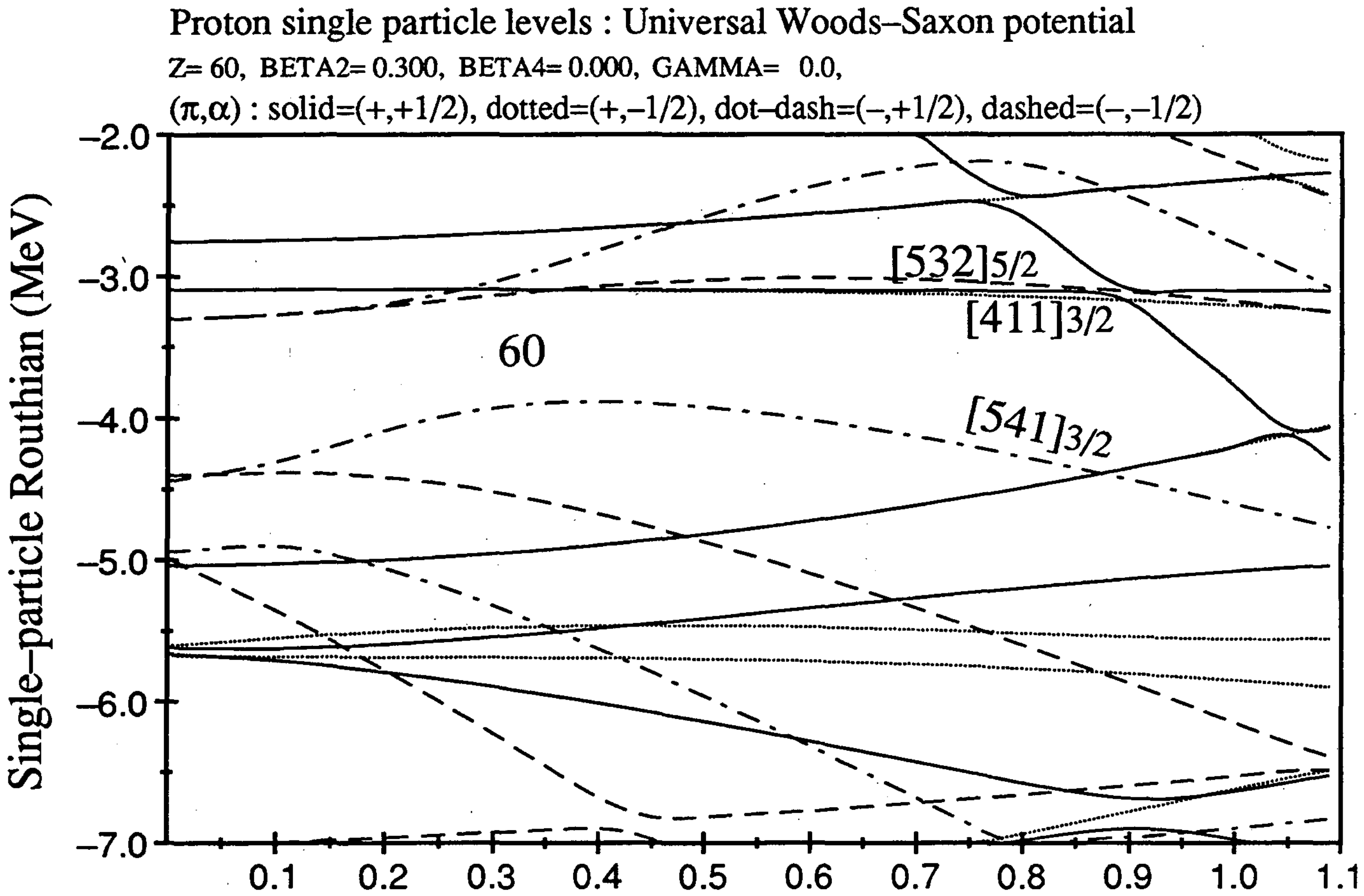
Figure 2b: The solid circles represent the incremental aligned angular momentum (see text) as a function of rotational frequency for the excited SD band relative to the yrast SD band in ^{136}Nd (errors are roughly the same size as the circles). Also shown are the calculated curves for the difference from integer alignment resulting from an excitation of: a) a proton from the [541]3/2 level to the [411]3/2 α=+1/2 level (solid line), [411]3/2 α=–1/2 level (dotted line), or [532]5/2 level (dashed line); b) a neutron from the [402]5/2 level to the [530]1/2 level (dot–dashed line).

Figure 3: Single–particle Woods–Saxon Routhian diagrams for a) protons and b)neutrons calculated with deformation parameters β_2=0.3 and γ=0. Parity and signature (π,α) of the levels are indicated in the following way: solid=(+,+1/2), dotted=(+,–1/2), dot–dashed=(–,+1/2), and dashed=(–,–1/2)


4600
3800
3000
2200
1400
600
-200
Counts
716.5
794.9
856.7
918.3
982.7
1049.4
1117.5
1185.8
1255.1
1325.2
1398.5
1476.6
500
400
300
200
100
Counts
1476
1558
1643
1733
(1815)
1500
1600
1700
1800
E_γ (keV)
280
200
120
40
-40
136Nd
136Nd
136Nd
136Nd
888
951
1017
1081
1151
1221
1290
1364
1438
600
800
1000
1200
1400
Energy (keV)



a)
○ Yrast
● Excited
$\mathcal{J}^{(2)}$ ($\hbar^2$MeV^{-1})
70
60
50
40
b)
π [411]3/2, α =+1/2
π [411]3/2, α =−1/2
π [532]5/2
π [530]1/2
Incremental Alignment (Δ i)
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0.2
0.4
0.6
0.8
1.0
ħω (MeV)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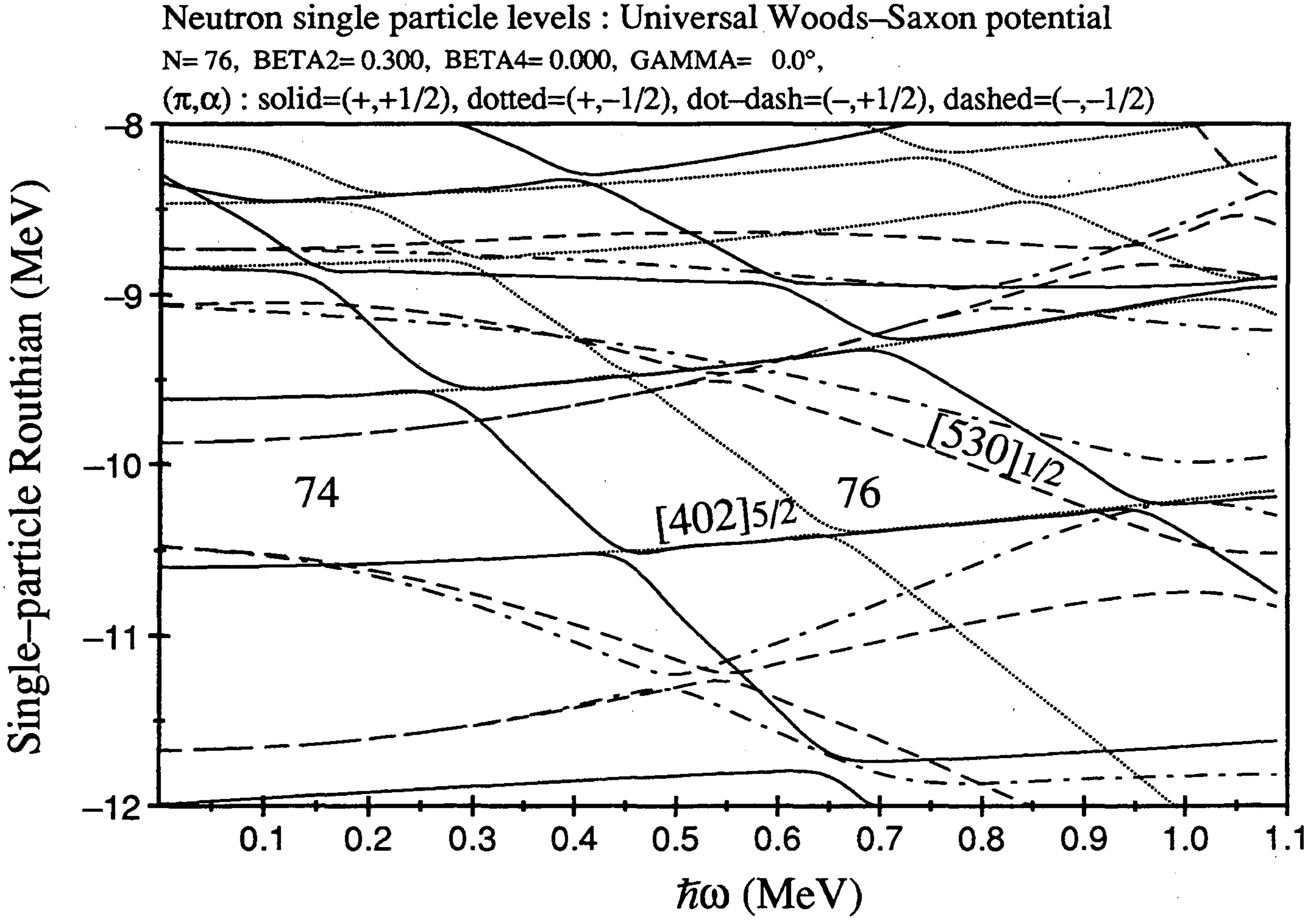
Neutron single particle levels : Universal Woods–Saxon potential
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(π,α) : solid=(+,+1/2), dotted=(+,–1/2), dot–dash=(–,+1/2), dashed=(–,–1/2)

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