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An enhanced-deformation (ED) rotational band with unusual characteristics has been discovered in the odd-Z nucleus ^{131}Pr. The dynamical moment of inertia $\mathcal{J}^{(2)}$ = 50-to-60 $\hbar^2$MeV^{-1} and the extracted quadrupole moment $Q_0 = 5.5 \pm 0.8$ eb (β_2=0.32±.05) are comparable with other ED bands (sometimes called 'superdeformed') in the mass A∼130 region. The two signature partners of the ED band are connected by dipole transitions which can be followed down to a $K = 9/2$ band-head. This band is unlike all other ED bands in the A∼130 region in that the $i_{13/2}$ intruder neutron orbital is unoccupied.

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In the mass 130 region 'superdeformed bands' or 'enhanced deformation' (ED) bands seem to be concentrated mainly in even-Z nuclei (Ce-Nd-Sm-Gd). These bands exhibit regular sequences of E2 transitions with $\mathcal{J}^{(2)}$ values ranging from 45-60 $\hbar^2$MeV^{-1}, and measured lifetimes indicating quadrupole moments in the range 4.0-7.5 eb [1][2]. To date, it has been widely accepted that the occupation of the highly alignable $i_{13/2}[660]_{1/2}$ neutron intruder orbital plays the crucial role in stabilising the shape by polarizing the core [3]. Indeed, all such ED bands in this mass region are thought to have at least one $\mathrm{i}_{13/2}$ neutron involved in their valence configuration.

In this paper we report the observation of a strongly-coupled ED band in the odd-Z nucleus ^{131}Pr. Enhanced deformation was inferred from its high dynamical moment of inertia, $\mathcal{J}^{(2)}$ = 50-to-60 $\hbar^2$MeV^{-1}, and was confirmed by measurement of its quadrupole moment, $Q_0 = 5.5 \pm 0.8$ eb. Although these values are comparable to other mass-130 ED bands, we believe that the $\nu i_{13/2}[660]_{1/2}$ orbital is not occupied in ^{131}Pr. This leads us to suggest that the appearance of an ED shape-minimum in ^{131}Pr depends only on the existence of an excited ED even-Z,N core (i.e. a strong shell energy correction) since it cannot be caused by the polarization of the $\mathrm{i}_{13/2}$ neutron orbital.

A similar band with $\mathcal{J}^{(2)} \simeq 55$ $\hbar^2$MeV^{-1} was found earlier in ^{129}Pr [4], but neither spin assignments nor lifetime measurements were reported. The estimated spins ($\sim$10-to-20 $\hbar$ if $\mathcal{J}^{(1)} = \mathcal{J}^{(2)}$) were consistent with a configuration that could include $\mathrm{i}_{13/2}$ neutrons. A strongly-coupled band observed in ^{133}Pm [5] also has similarities with the bands in ^{129,131}Pr but has a lower $\mathcal{J}^{(2)} \sim 45$ $\hbar^2$MeV^{-1} and no discrete linking transitions were observed and no lifetimes of the states were measured.

High-spin states in ^{131}Pr were populated via the reaction ^{98}Mo(^{37}Cl,4n). A beam of ^{37}Cl ions at a bombarding energy of 155 MeV was provided by the MP tandem of the TASCC facility at Chalk River. This reaction had a grazing angular momentum

L_{gr} = 56$\hbar$, and left the ^{135}Pr* compound nucleus with an average excitation energy E* = 74 MeV. The main channels in the decay of the compound nucleus were $4n$ into ^{131}Pr (31% of the yield), $p3n$ into ^{131}Ce (29%), $p2n$ into ^{130}Ce (15%) and $3n$ into ^{132}Pr (8%).

Gamma-ray spectroscopy was performed with the 8π spectrometer. This instrument consists of an inner ball of 71 bismuth germanate (BGO) crystals providing sum energy (H) and fold (K) information and an array of twenty high-resolution Compton-suppressed HPGe detectors. A valid event required a two-fold (or higher) Ge-coincidence with a condition of K$\geq$10 on the BGO ball. Approximately 2×10^8 events were accumulated with a target of two stacked self-supporting ^{98}Mo foils which each had a thickness of 0.5 mg/cm^2. A further $\sim$$2 \times 10^8$ events were collected with a 1 mg/cm^2 ^{98}Mo foil on a 12 mg/cm^2 lead backing.

Data from the self-supporting target experiment were replayed into a γ-γ coincidence matrix with the condition of 15$\leq$H(MeV)$\leq$30 on the BGO sum-energy. The interactive data-analysis codes ESCL8R and LF8R [9] were used to construct a level scheme. With these codes it was possible to analyze the complex coincidence relationships involving many multiple assignments of unresolved γ-ray transitions. A least-squares fit was performed directly on the γ-γ coincidence matrix to extract intensities and energies in the proposed level schemes which included 525 γ-ray transitions distributed amongst several nuclides including ^{131}Pr, ^{132}Pr, ^{130}Ce and ^{131}Ce. The assignment of transitions to specific nucleides was facilitated by comparison to charged-particle-γ coincidence data from the ^{105}Pd(^{32}S,x$nypz\alpha$) reaction at 155 MeV [8].

The γ-γ lead-backed data were sorted into a matrix with the same H-condition described above and containing only coincidences between a ±37° detector (closest to the beam axis) and a ±79° detector. A Directional Correlation from Oriented states

(DCO) [10] analysis was carried out. This allowed the assignment of multipolarities to many transitions. Measurements of the attenuated Doppler shifts for fast transitions that are emitted as the nucleus slows down in a material provide information on the mean lifetimes of nuclear states. Two more γ-γ coincidence matrices from the backed data were made which contained events from detectors at ±79° against events in detectors at +37° or −37°. A Doppler-shift (DSAM) analysis was done to measure lifetimes for the ED-band.

Transitions assigned to ^{131}Pr were organized into seven rotational sequences that comprised one decoupled and three strongly-coupled bands. A partial level-scheme is shown in figure 1, where the sequences have been labelled numerically. Some strong transitions in bands 1 and 2/3 have been observed in previous studies [6][7]. In this paper the discussion will focus on the properties of the ED-band, band 4/5. A spectrum obtained by summing gates chosen to cleanly select the band is shown in figure 2. Band 6/7 will be briefly discussed because of its unusual decay (evident in figure 2) *into* the ED-band. We intend to discuss the remaining bands in a later publication.

The ED-band has a number of unusual features. These are its low excitation energy, the occurrence of strong dipole transitions between its signature partners, the decay to what we believe is the band-head state with $I = K = 9/2$, the simple decay pattern of the ED band-head to 'normal-deformed' states, and the decay of a normal-deformed structure (band 6/7) into ED states at high spin. The ED band is not yrast at high spin and its population is too weak to be observed above $\hbar\omega \sim$ 450 keV. Typically in this mass region the bands persist to $\hbar\omega \sim$ 700 keV or even $\hbar\omega \sim$ 1000 keV in the case of ^{132}Ce.

The simple decay of the ED-band into band 2/3 has allowed us to determine the low excitation-energy and spin of the ED band-head. With reference to figure 1, the flux into the band-head ($I_\gamma 181$ + $I_\gamma 378$ = 8±1 %) equals the flux out ($I_\gamma 529$ + $I_\gamma 726$ + $I_\gamma 526$ = 8± 1%), where the intensities are relative to $I_\gamma 256$ (15/2 → 11/2). DCO ratios for the linking transitions were determined in spectra obtained by summing selected gates on stretched quadrupole transitions of the ED band (namely E_γ = 411, 444, 515 and 551 keV). In general only when the DCO ratio (R_{DCO}) is less than approximatedly 0.65 does the method produce an unambiguous assignment and in that case the transition can only be stretched L2/L1 with a mixing ratio δ = L2/L1 ≤ 0 (see reference [10]). Amongst the linking transitions, only the 526 keV transition matches this criterion, $R_{DCO} = 0.49 \pm 0.09$. The transition at 450 keV has $R_{DCO} = 0.91 \pm 0.15$ and is assigned stretched E2. Since this transition goes to the $3/2^+$ ground state, the spin of the ED bandhead is assigned 9/2. Although the mixing ratio for the 526 keV transition is nearly zero, perhaps suggesting a parity change, the DCO ratios for the other linking transitions, namely $\gamma 529$ and $\gamma 726$, imply considerable L2/L1 mixing for I=9/2, hence a positive parity assignment is indicated.

For such a low spin-value, it is most likely that the ED-band has a one-quasiparticle rather than a three-quasiparticle structure. This rules out the possibility that the band contains the first pair of aligned $i_{13/2}$ neutrons, since they alone would contribute ~10$\hbar$ of angular momentum. The only nearby proton orbital that is signature degenerate over a wide range of rotational frequency is the positive-parity $\pi g_{9/2}$ $[404]_{9/2}$ orbital. Confirmation of the $g_{9/2}$ character is provided by the large B(M1)/B(E2) ratios, which lie in the range 1-2 $(\mu_N/\mathrm{eb})^2$ and rule out all other plausible one-proton assignments. The mixing ratios of the intraband E2/M1 transitions are positive, and so indicate a prolate shape.

With the lead-backed target data we have performed a Doppler-shift (DSAM) analysis of the γ-ray shifts observed in the ±37° rings of HPGe detectors, to extract a quadrupole moment for the ED-band and for band 1. The electronic stopping powers used were those of Northcliffe and Schilling [11] normalised to the α stopping powers of Ziegler and Chu [12]. The nuclear stopping power was calculated from the LSS [13] formalism, and large-angle scattering was treated by the Blaugrund [14] method. The data were analyzed assuming a constant quadrupole moment for a given band and the results are shown in figure 3. Band 1 is best represented by a quadrupole moment of 3.9 ± 0.3 eb. With the relationship of reference [15] it corresponds to β_2=0.23±.02, i.e. "normal" deformation. The data for the ED-band are best represented by a quadrupole moment of $Q_0 = 5.5 \pm 0.8$ eb, indicating an enhanced deformation of β_2=0.32±.05. At this deformation, in a Woods-Saxon potential the $\pi g_{9/2}$ $[404]_{9/2}$ orbital is expected to lie near the Fermi surface for Z = 59, as can be seen in figure 4.

The same Woods-Saxon potential, but with pairing correlations included, was used in Total Routhian Surface calculations (TRS [16]). For positive-parity configurations two minima in the (β_2,γ) deformation plane occur over a wide range of frequency. One minimum has $\beta_2 = 0.24$, $\gamma \sim 1^\circ$ which we associate with the $[411]_{3/2}$ configuration and assign to band 2/3; the other has $\beta_2 = 0.33$, $\gamma \sim 1^\circ$ which is consistent with the deformation obtained for the ED-band from the DSAM analysis. We identify this higher deformation minimum with the $[404]_{9/2}$ configuration assigned to the ED-band.

We have performed similar calculations using the modified oscillator potential with the formalism of reference [17]. These calculations allow particular configurations to be tracked as a function of spin, but pairing correlations are not included. Both the normal and ED bands can be followed to zero spin in these calculations. For spins I~15-20 figure 1 shows that the ED band is observed to lie about 750 keV above yrast, whereas the calculation predicts this to be about 700 keV.

The stability and relatively low excitation-energy of the ED minimum at zero rotational frequency is most likely associated with the shell-correction energy at Z=59, rather than a polarisation effect caused by the occupancy of a particular orbital. Both the modified oscillator and the Woods-Saxon calculation at $\hbar\omega$=0, shown in figure 4, give substantial shell gaps for Z=58 (centred at β_2=0.42) and Z=60 (centred at β_2=0.33) which are presumably involved in the ED structures of Ce and Nd isotopes. These proton gaps can be reinforced by gaps in the neutron shell energy at N=70 and N=72. In the calculation it is the more deformed N=72 gap (cf. figure 4) that is associated with the ED-band. At the deformation associated with the ED-band, the $i_{13/2}[660]_{1/2}$ neutron intruder orbital is high in energy. A 2p-2h excitation into this intruder orbital would require ~4 MeV of excitation, and hence we rule out this possibility for the ED-band.

The ED-band exhibits no sharp alignment gain up to a rotational frequency of $\hbar\omega\sim$ 400 keV; this is close to the frequency where the proton $h_{11/2}$ crossing should occur according to our CSM calculations at the appropriate deformation. Presumably we lose sight of the band experimentally at this crossing. A general feature of band crossings which occur off the yrast line is that little intensity flows from the band above the crossing to that below. The behaviour of band 2/3 in figure 1 illustrates this point.

A remarkable anomaly of the ^{131}Pr case is the observation of the decay of band 6/7 into the ED band. Band 6/7 has an $\mathcal{J}^{(2)}$ consistent with normal deformation. Energetically this comes about because the ED-band gains no angular momentum from aligned particles in the spin range we observe. Therefore, any band that lies reasonably close to yrast and does exhibit an alignment gain can become more yrast than the ED band. We propose that band 6/7 presents such a case. The measured DCO ratios are consistent with a stretched E2 assignment for γ560 keV and a stretched E2/M1 with significant mixing $+0.4 < \delta < +2.5$ for γ294 keV. Thus, we assign positive parity to band 6/7. Evidently, the decay from band 6/7 to the ED-band is caused by mixing of the levels assigned $23/2^+$ at 2600 keV (in sequence "4" of the ED-band) and 2609 keV (in sequence "6" of band 6/7), since they have the same spin and parity. These levels are observed to be 9±1 keV apart, and will be strongly mixed by even a weak interaction, e.g., 4.5 keV if the levels were exactly degenerate before mixing.

Band 6/7 has large B(M1)/B(E2) ratios in the range 3-6 $(\mu_N/\mathrm{eb})^2$, and its dipole transitions have negative E2/M1 mixing ratios, which are characteristics of high-K structures. Several such bands are known in ^{133}Pr [18] where they have been assigned oblate shapes with a $\nu h_{11/2}^2 \otimes \pi h_{11/2}$ structure. However, these bands have negative parity and therefore cannot be identified with bands 6/7 seen here. An alternative possibility is the prolate structure $\pi h_{11/2} \otimes \nu[404]_{7/2}[523]_{7/2}$ where the neutron quasiparticles form a low lying $K = 7^-$ band in the core ^{130}Ce [19] . TRS calculations show there is a minimum with a $\beta_2 = 0.25$ for such a three-quasiparticle configuration. The lack of signature splitting and the calculated B(M1)/B(E2) ratios are in good accord with this assignment. In the Dönau-Frauendorf model, this structure would produce a negative E2/M1 mixing ratio for a prolate shape [20].

In summary, we have found a strongly-coupled band in ^{131}Pr that has an enhanced-deformation of $\beta_2 = 0.32 \pm 0.05$. The low-excitation energy and spin of the band-head lead us to conclude that the $i_{13/2}[660]_{1/2}$ intruder orbital is neither aligned nor occupied in this structure. This is unlike all the other enhanced-deformation bands in the A = 130 region. The key aspect is the large gain in shell-energy for the $\pi g_{9/2}$ configuration at Z=59 when the core deforms out to β_2= 0.33. This provides a stable rotational platform, without aligned particles, which allows us to follow the γ-decay sequence down to the $I = 9/2$ band-head.

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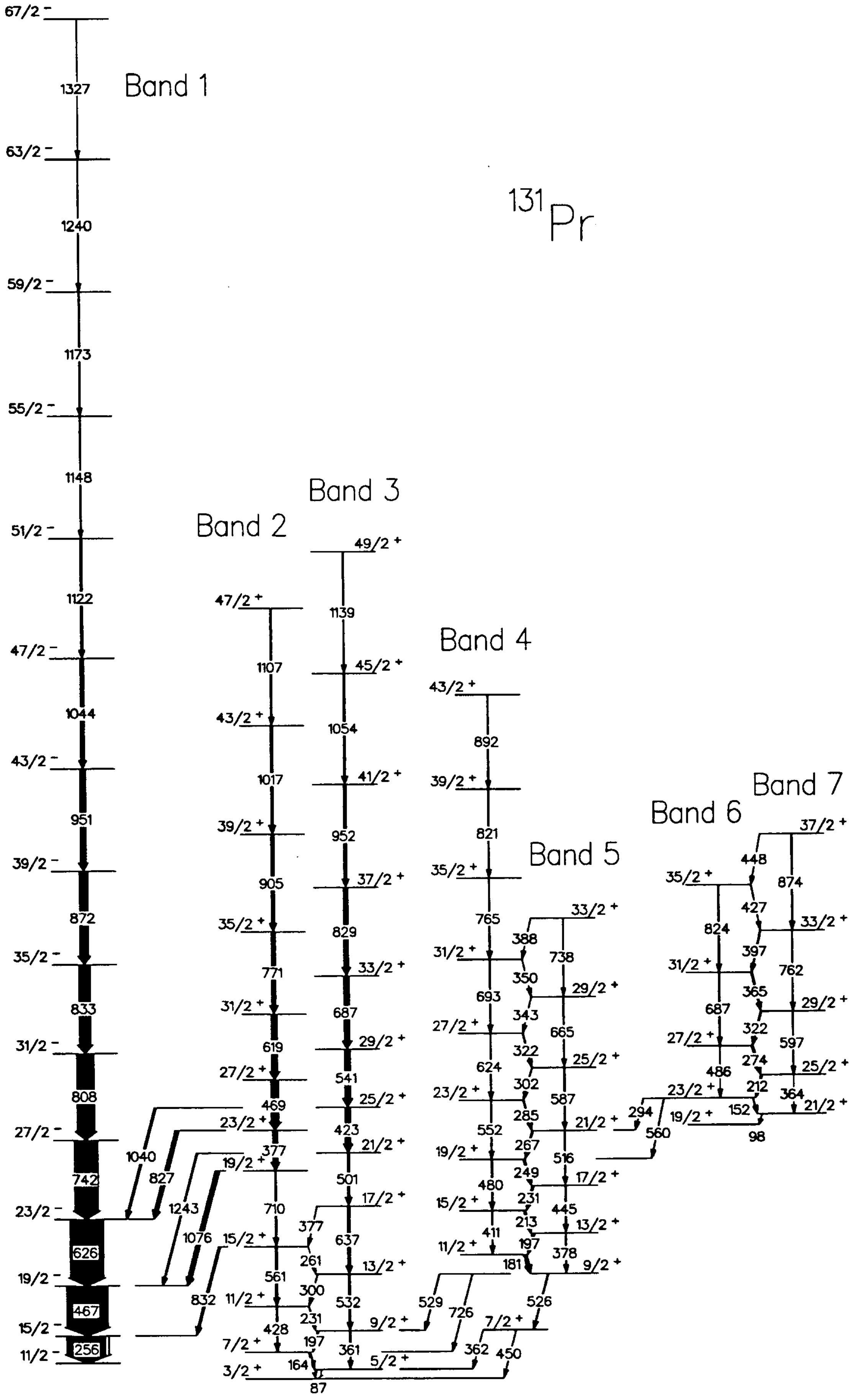
FIGURES

FIG. 1. Proposed partial level scheme for ^{131}Pr.

FIG. 2. Coincidence γ-ray spectrum for the sum of gates set on transitions at 181, 213, 231, 249, 411, 526, and 529 keV chosen to select the enhanced-deformation band, band 4/5. Transitions are labelled as follows: Energy (no label) = band 4/5. Energy A = band 6/7. Energy L = link from band 4/5. Energy N = band 2/3 fed by band 4/5.

FIG. 3. Fractional Doppler shift of γ rays in the ED band (filled circles) and in band 1 (open circles). The calculated curves have been obtained assuming a constant quadrupole moment $Q_0 = 5.5$ eb (solid line) and $Q_0 = 3.9$ eb (dashed line).

FIG. 4. Woods-Saxon calculations centred at Z=59 N=70. Note the shell gaps at Z=58 and Z=60 which are separated by the upsloping $[404]_{9/2}$ orbital. Neutron shell gaps appear at N=70 and N=72 separated by the downsloping $[541]_{1/2}$ orbital.


^{131}Pr
Band 1
Band 2
Band 3
Band 4
Band 5
Band 6
Band 7
67/2 −
1327
63/2 −
1240
59/2 −
1173
55/2 −
1148
51/2 −
1122
47/2 −
1044
43/2 −
951
39/2 −
872
35/2 −
833
31/2 −
808
27/2 −
742
23/2 −
626
19/2 −
467
15/2 −
256
11/2 −
1040
827
1243
1076
832
47/2 +
1107
43/2 +
1017
39/2 +
905
35/2 +
771
31/2 +
619
27/2 +
469
23/2 +
377
19/2 +
710
15/2 +
561
11/2 +
428
7/2 +
164
3/2 +
87
377
261
300
231
197
49/2 +
1139
45/2 +
1054
41/2 +
952
37/2 +
829
33/2 +
687
29/2 +
541
25/2 +
423
21/2 +
501
17/2 +
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13/2 +
532
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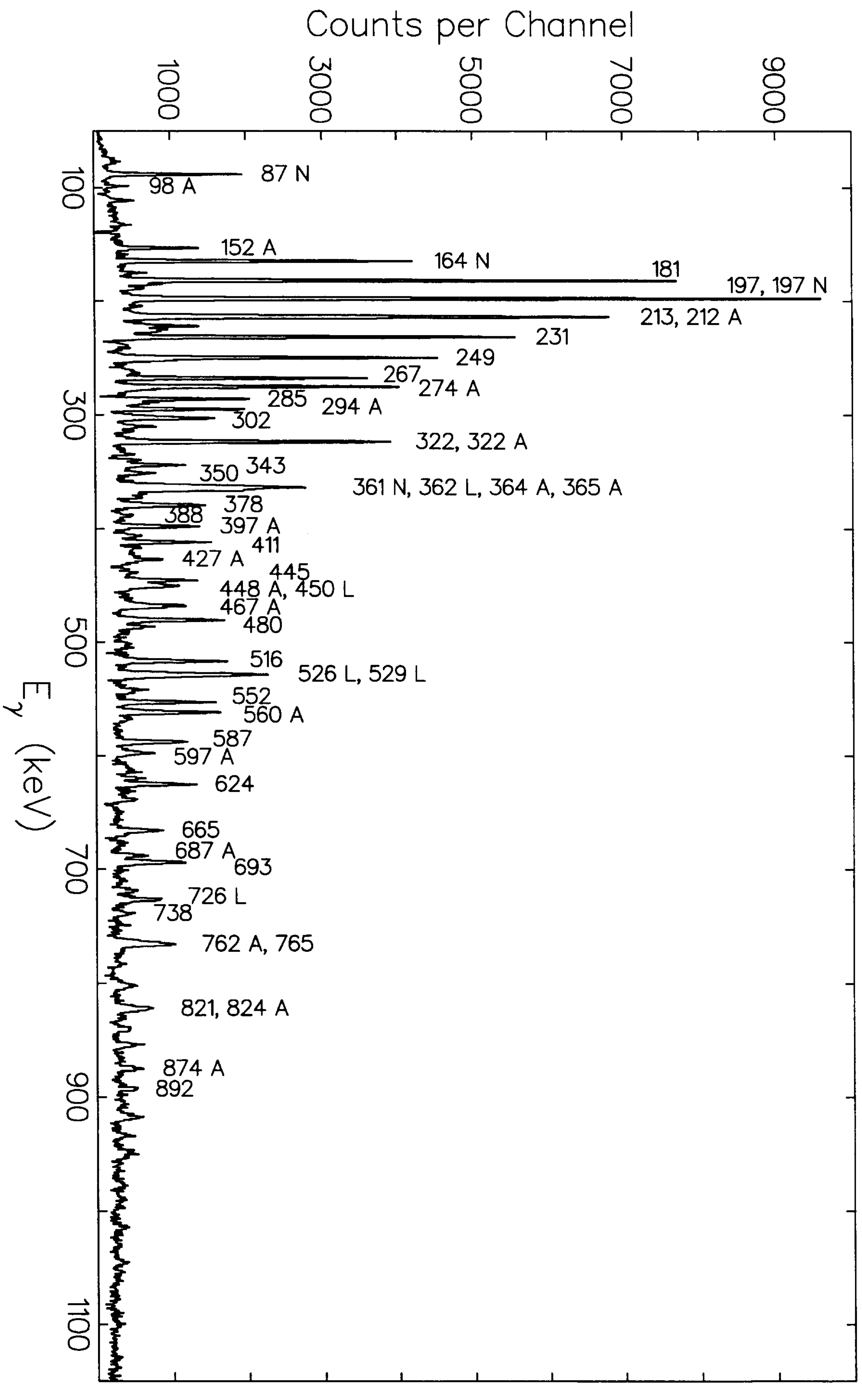
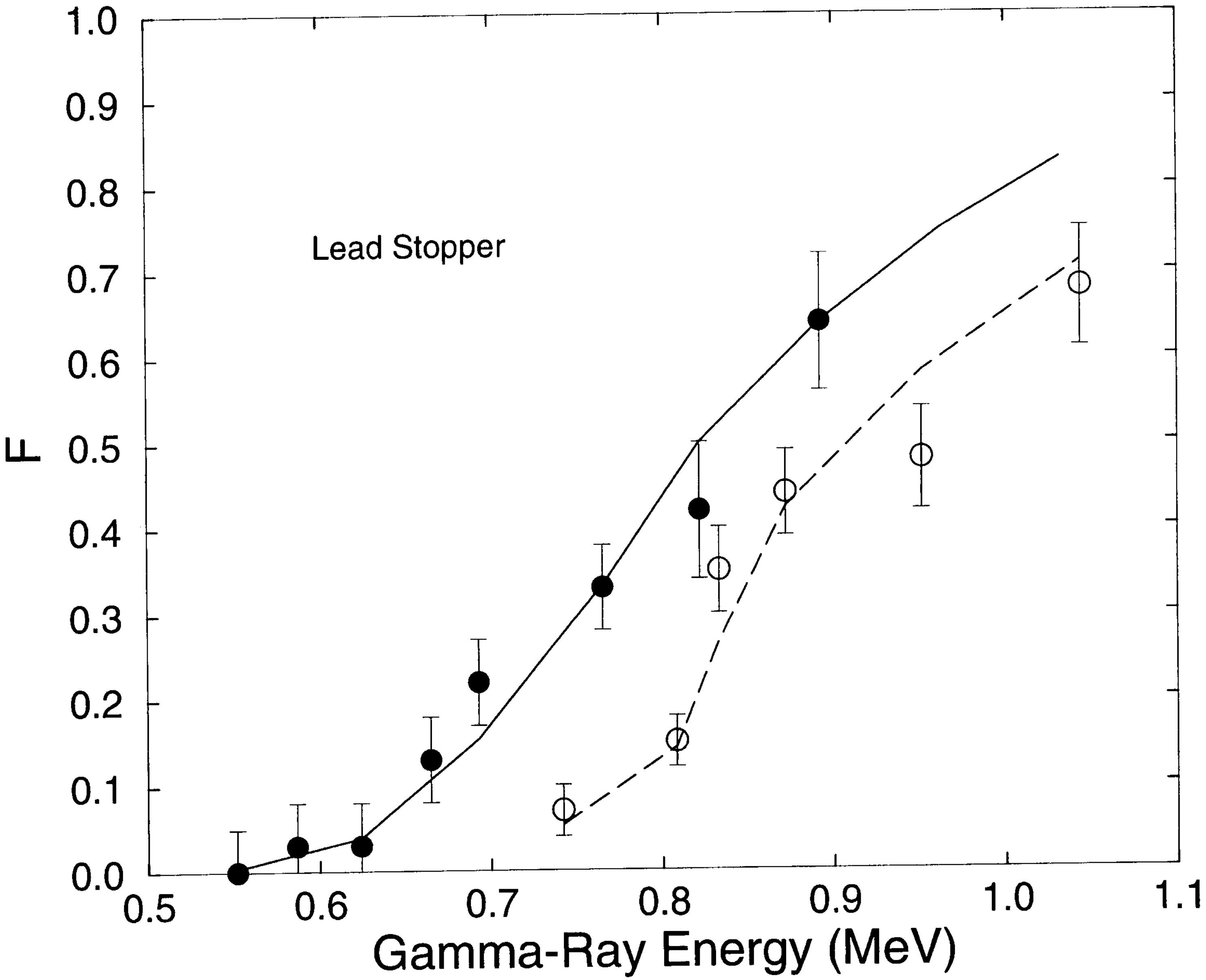
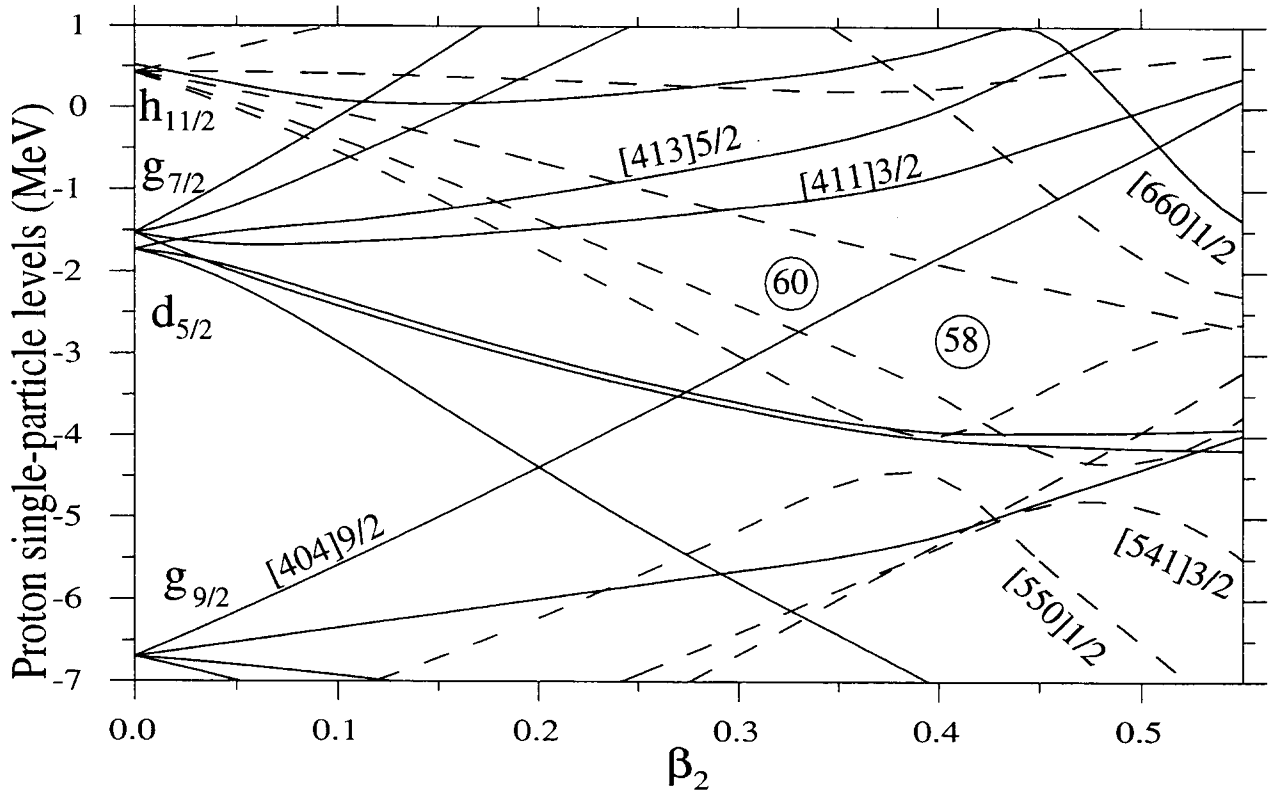
5/2 +
529
726
362
450
43/2 +
892
39/2 +
821
35/2 +
765
31/2 +
693
27/2 +
624
23/2 +
552
19/2 +
480
15/2 +
411
11/2 +
181
388
350
343
322
302
285
267
249
231
213
197
33/2 +
738
29/2 +
665
25/2 +
587
21/2 +
516
17/2 +
445
13/2 +
378
9/2 +
526
7/2 +
294
560
35/2 +
824
31/2 +
687
27/2 +
486
23/2 +
19/2 +
152
98
448
427
397
365
322
274
212
37/2 +
874
33/2 +
762
29/2 +
597
25/2 +
364
21/2 +


Counts per Channel
1000
3000
5000
7000
9000
E$_\gamma$ (keV)
100
300
500
700
900
1100
87 N
98 A
152 A
164 N
181
197, 197 N
213, 212 A
231
249
267
274 A
285
294 A
302
322, 322 A
350
343
361 N, 362 L, 364 A, 365 A
378
388
397 A
411
427 A
445
448 A, 450 L
467 A
480
516
526 L, 529 L
552
560 A
587
597 A
624
665
687 A
693
726 L
738
762 A, 765
821, 824 A
874 A
892

Fractional Doppler Shifts



Woods-Saxon levels for protons central Z=59
Solid : π=+. dashed : π=-



Woods-Saxon levels for neutrons central N=72
Solid : π=+. dashed : π=-