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Superdeformed Band in ^{135}Nd

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Abstract: A superdeformed band (ß≈0.4-0.5) was found in ^{135}Nd, the first one in an odd-mass nucleus. It consists of 13 transitions with an average moment of inertia $\Im^{(2)}\approx 59\ \hbar^2\mathrm{MeV}^{-1}$, and gathers at its bottom ~10% of the reaction events leading to ^{135}Nd. Of the three known superdeformed bands, it is the most strongly populated and the one observed to the lowest spins. It has a moment of inertia very similar to that of the superdeformed band in ^{132}Ce. The less-deformed part of the decay scheme of ^{135}Nd is also given.

A nucleus may take on a variety of shapes, and understanding their origin has been the subject of extensive studies. One of the most interesting "curiosities" is nuclei with very large deformations. Prolate shapes with a 2:1 ratio of principal axes ("superdeformed shapes") were first found in fission isomers in the Pu-Am region some twenty years ago.[1] In this paper, the definition of superdeformation is generalized to refer to the larger prolate deformation when there is a second deformed well in the potential-energy surface (but not necessarily with 2:1 axes). Calculations have predicted that superdeformed shapes might also be found in rare-earth nuclei at high angular momenta.[2-5] Indeed, unresolved features as well as discrete bands originating from superdeformed shapes were recently found[6,7] in ^{152}Dy and[8] in ^{132}Ce. A detailed spectroscopy of the superdeformed bands is just beginning, and several questions remain to be answered by experimental studies. For example, do other nuclei also develop low-lying superdeformed bands at high spins, or is the second minimum in the potential energy surface restricted to a specific ("magic") number of neutrons and protons? How does the population of these bands depend on the HI,xn reaction through which the excited nucleus was formed? Is the feeding out of these bands statistical, as suggested by ref. 6? How large are the pairing effects in the superdeformed bands? In this letter we present evidence for another superdeformed band, in ^{135}Nd, the first such band in an odd-N nucleus, together with the level scheme of the less-deformed states of the nucleus.

The nucleus ^{135}Nd was produced by the ^{100}Mo (^{40}Ar,5n) reaction, at 173 and 177 MeV bombarding energy. The beam was provided by the LBL 88-inch cyclotron, and two stacked thin foils (0.5 mg/cm^2 each) were used as a target. The gains of the 21 Compton-suppressed Ge-detectors from the HERA array[9] were matched on-line to compensate for the Doppler-shifts of the γ rays. The different angles of the detectors provided angular correlation information, and spin and parity assignments were made using the method described in ref. 10. A total of ~700 million three- and higher-fold events was recorded, of which approximately 25% came from the 5n channel.

Standard coincidence techniques were used to extract the less-deformed part of the level scheme of the nucleus, Fig. 1. Only a few states were known previously[11] in ^{135}Nd. We extended the ground-state $\Delta I=1$ structure with the odd $h_{11/2}$ neutron beyond the first backbend up to spin 47/2, and found a second $\Delta I=1$ structure which we followed up to spin 39/2. The transitions connecting this band to the yrast band behave like pure stretched dipoles; that feature and the absence of any possible crossover transitions establish the parity to be positive. Most of the cascade transitions in the positive- and negative-parity bands have angular correlations which are rather close to the value expected for stretched dipoles, although they may have small quadrupole admixtures. These cascade transitions carry the major part of the intensity, whereas the quadrupole crossovers are quite weak in general, except for the lowest-spin states of negative parity and all the highest-spin states. This behavior can be qualitatively understood from the configuration of the bands. The first backbend in the negative-parity bands (sharp increase in the moment of inertia in Fig. 3) is due to proton alignment ($h_{11/2}$), which will enhance the M1-component. The strong cascade transitions and the absence of this backbend (c.f. Fig. 3) suggest that the positive-parity bands are based on the $h_{11/2}$ neutron plus a pair of protons, one of which is also $h_{11/2}$. The other proton could either occupy a $g_{7/2}$ or a $d_{5/2}$ orbital. This configuration could be lowered in energy by the admixture of octupole phonons. The lower part of this scheme is basically in agreement with parallel work.[12]

In addition, however, we observed a series of γ rays with an average energy spacing of 67.5 keV, leading to the superdeformed band depicted in Fig. 1. At its bottom, where the lowest in-band transitions gather approximately 10% of the reaction events leading to ^{135}Nd, this band branches out in many pathways, each carrying less than 1-2% intensity. This behavior indicates already that the structure of this band is very different from that of the other low-lying bands in the nucleus, since it does not decay preferentially to a particular state (with most similar configuration). To obtain a very clean spectrum of this band, the triples data were sorted in a special way. Two gates were required, one on an in-band transition, the other either in-band or on a low-lying state seen in coincidence with the band in single-gated spectra. Figure 2 shows a background-subtracted spectrum of the third γ ray in coincidence with these double gates where we have summed the clean-gate combinations. All the lines in this double-coincidence spectrum come from ^{135}Nd and are related to the superdeformed band. We are reasonably confident of one depopulation path (the 620 keV - 1184 keV sequence feeding the $19/2^-$ state), which at the same time requires energy differences from the lowest band-members to other states that match several lines left over in the clean spectrum of Fig. 2. Angular correlations indicate that the in-band transitions are stretched quadrupoles and that the 620 keV line is most likely a stretched quadrupole. We do not have good angular correlation values for the 1184 keV transition. However, the spins given in Fig. 1 are favored, because, if the 1184 keV were a stretched quadrupole also, the 767 keV line would have to be an E3 or M2. If the 1184 keV transition were unstretched, the spins would be lowered by, at most, one unit. With the given spin assignments the superdeformed states become yrast at spin 45/2. It is around this spin, that the intensities of the superdeformed band and the negative-parity states become comparable. One would a priori expect roughly equal intensities where the two bands cross. Table I lists the intensities of the γ rays of the superdeformed band and the depopulating transitions, some of which could not be placed in the scheme.

The moment of inertia of the superdeformed band is very different from that of the other bands in the nucleus ^{135}Nd, as illustrated in Fig. 3. Not only is it considerably larger, but also much smoother. The three-quasiparticle bands reach kinetic moments of inertia ($\Im^{(1)}$) around 40 $\hbar^2$MeV^{-1}, whereas the superdeformed band reaches a value of 55 $\hbar^2$MeV^{-1}, and has a dynamic moment of inertia ($\Im^{(2)}$) around 59 $\hbar^2$MeV^{-1}, also shown in Fig. 3. Calculating the deformation from the moment of inertia is always uncertain, since the result depends strongly on the mass flow pattern inside the nucleus, which is not known. Quadrupole moments have less ambiguity in determining the deformation. Lifetime measurements in the superdeformed band of ^{132}Ce indicate[8] a deformation of $\beta \approx 0.5$. Since the moments of inertia in the superdeformed bands are very similar in ^{135}Nd and ^{132}Ce, we assume their deformations are also similar. The dynamic moment of inertia shows two maxima over the range of the superdeformed band. The first one occurs at the lowest band member. Possibly an alignment takes place at that frequency which energetically favors the superdeformed shape. That might explain why the band cannot be followed to lower spins. The second maximum, which occurs around spin 49/2, might be indicative of a weak alignment. However, calculations[13] predict an alignment only at considerably higher spins. We do not observe the other signature partner of the superdeformed band, which suggests that the odd neutron occupies a unique-parity orbital with low-Ω, where the signature splitting is large. The two superdeformed bands in ^{135}Nd and ^{132}Ce seem much more similar to each other than to the one in ^{152}Dy, which is more deformed.[6,14] Also the bands become yrast at about the same spin, even though the one in ^{135}Nd lies about 1.5 MeV lower in excitation energy. Whether the superdeformed minimum in ^{135}Nd really lies lower in the potential energy surface is not very clear, because one has to correct for pairing, liquid drop and rotational energies; the last of which depends strongly on the spin assignments.

The discrete superdeformed band reaches the intensity level of 1% - about the limit of detection - at transition energies around 1.3 MeV, but there is evidence for superdeformed shapes in the continuum up to 1.6 MeV. A series of cuts perpendicular to the diagonal in the two-dimensional array $E_{\gamma 1}$-$E_{\gamma 2}$ is shown in Fig. 4. These spectra are dominated by the 4n and 5n products of the reaction (^{136}Nd and ^{135}Nd). At lower spins (E_γ below 1.2 MeV), continuous ridges 136 keV apart ($\mathfrak{I}^{(2)} \approx 59\ \hbar^2$MeV^{-1}) are seen, which contain more intensity than the observed discrete band. Even the second and third ridges, as marked in Fig. 4, are quite strong. Above 1.3 MeV, where the discrete superdeformed band fades out, ridges are still present 144 keV apart ($\Im^{(2)} \approx 56\ \hbar^2 MeV^{-1}$). In addition, much weaker ridges from a less-deformed structure can be seen. Thus, there must be many unresolved transitions from states which have the same moment of inertia as the discrete (cold) superdeformed band. The presence of higher ridges means that there are comparatively long strings of in-band transitions, and consequently a slow cooling to the yrast line. From 1.3 MeV up to the highest γ-ray energies where ridges can be seen, their separation does not change appreciably. This is a quite different behavior from the discrete superdeformed band, whose dynamic moment of inertia drops by 25% in ^{132}Ce over the same range.[8] In the discrete bands this drop in $\Im^{(2)}$ can be understood, since the angular momentum of the high-j orbitals becomes mostly aligned, and thus contributes less to the collective moment of inertia.[16] The states giving rise to the continuous structure must, in contrast, involve various additional high-j orbitals in order to maintain the $\Im^{(2)}$ value.

In conclusion, we have observed the first superdeformed band in an odd-mass nucleus, ^{135}Nd, and the second one in the lighter rare-earth region. Of all observed superdeformed bands, this one goes to the lowest spins and is populated the strongest, which enabled us to connect it to the rest of the level scheme. Its deformation corresponds most likely to $\beta \approx 0.4$-0.5. The two superdeformed bands in ^{135}Nd and ^{132}Ce seem to have very similar moments of inertia. Continuous ridges are found in the data, which indicate that most of the continuum is also emitted by superdeformed states. Systematics will tell us more about the origin and the configuration of these very deformed bands.

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Figure captions:

Figure 1: Level scheme of ^{135}Nd as obtained from the present work. Transition energies are given in keV.

Figure 2: Superdeformed band in ^{135}Nd labeled by transition energies. Lines belonging to the less-deformed states are marked by #-signs, (possible) linking transitions by "l"s. The double-gated background-subtracted spectrum is a sum of clean-gate combinations, which affects the relative intensities.

Figure 3: Moments of inertia (in units of $\hbar^2$MeV^{-1}) of the bands in ^{135}Nd. Full squares (circles) mark the $\mathfrak{I}^{(1)}$ of the negative- (positive-) parity bands of negative signature (open symbols represent the other signature), and triangles (asterisks) the $\mathfrak{I}^{(1)}$ (respectively $\mathfrak{I}^{(2)}$) of the superdeformed band.

Figure 4: Cuts perpendicular to the diagonal in the symmetrized $E_{\gamma 1}$-$E_{\gamma 2}$ matrix at 4keV/ch; top:1-1.2 MeV, middle:1.2-1.4 MeV, bottom:1.4-1.6 MeV. The matrix was unfolded and the uncorrelated γ rays were subtracted by the method described in ref. 15. The arrows indicate the position of the ridges.

Table I: Intensities of superdeformed in-band and depopulating transitions in percent of reaction events leading to ^{135}Nd.

E_γ (keV)	Intensity (%)	E_γ (keV)	Intensity (%)
545.9	8.3 (8)	620.3	1.0 (3)
602.7	10.5 (10)	1184	1.2 (4)
676.5	8.0 (8)	529.4	2.0 (6)
749.2	7.5 (8)	549.6	1.8 (6)
817.4	6.5 (7)	(616)	
882.5	6.6 (7)	(767)	< 1 (for 616, 767, 949)
946.6	5.5 (7)	(949)	
1011.1	4.2 (6)	(282.6)	
1078.2	3.3 (6)	(514)	not placed (282.6, 514, 566)
1145.9	2.5 (6)	(566)	
1215.6	1.6 (5)		
1287.5	0.9 (4)		
(1362)	< 1		

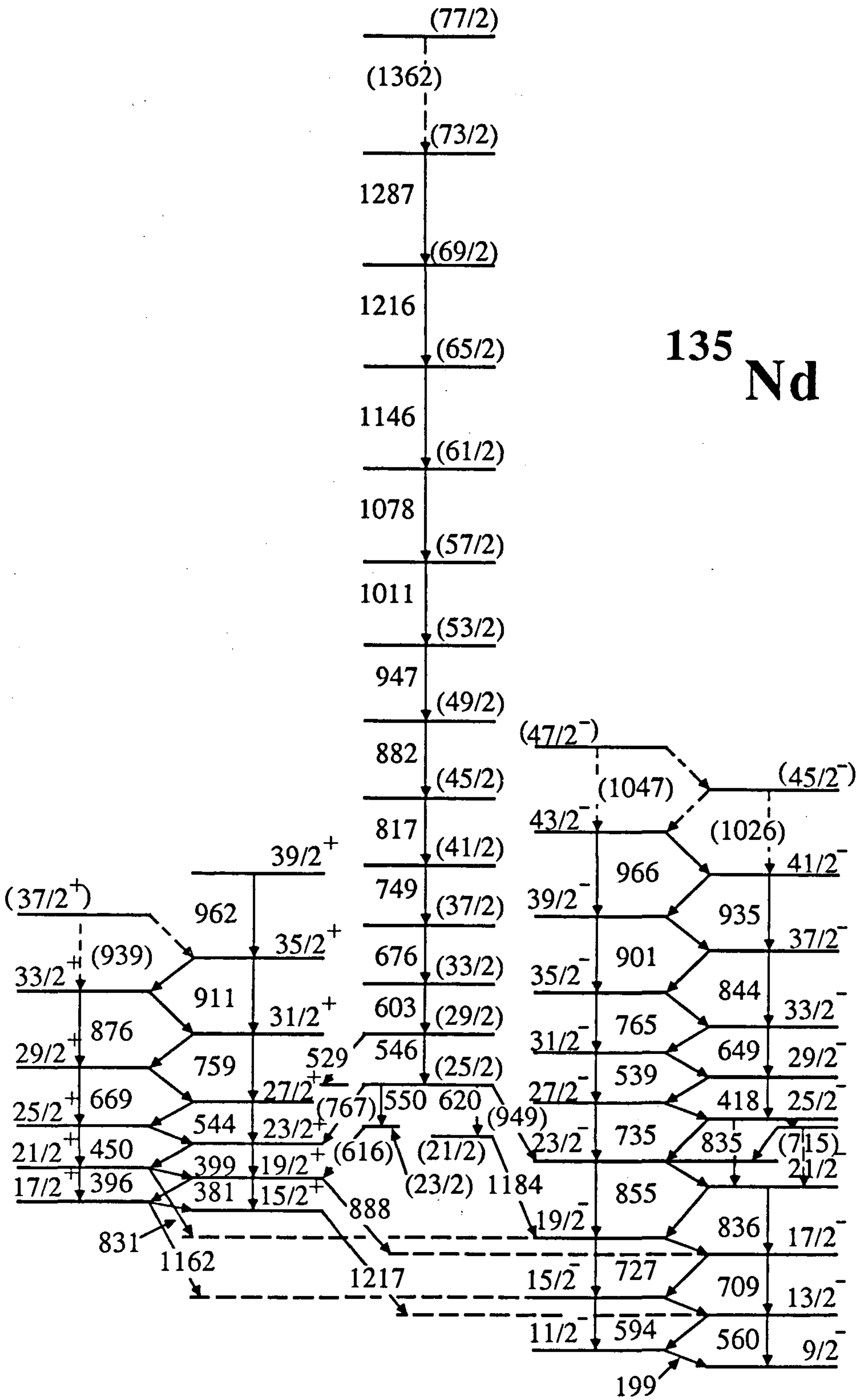
135 Nd
(77/2)
(1362)
(73/2)
1287
(69/2)
1216
(65/2)
1146
(61/2)
1078
(57/2)
1011
(53/2)
947
(49/2)
882
(45/2)
817
(41/2)
749
(37/2)
676
(33/2)
603
(29/2)
546
(25/2)
550
620
(767)
(616)
(23/2)
(21/2)
(949)
1184
(47/2⁻)
(1047)
(45/2⁻)
43/2⁻
(1026)
966
41/2⁻
39/2⁻
935
901
37/2⁻
35/2⁻
844
33/2⁻
765
31/2⁻
649
29/2⁻
539
27/2⁻
418
25/2⁻
735
835
(715)
23/2⁻
21/2
855
19/2⁻
836
17/2⁻
727
15/2⁻
709
13/2⁻
594
11/2⁻
560
9/2⁻
199
(37/2⁺)
39/2⁺
962
35/2⁺
(939)
33/2⁺
911
876
31/2⁺
29/2⁺
759
529
27/2⁺
669
25/2⁺
544
23/2⁺
450
21/2⁺
399
19/2⁺
396
17/2⁺
381
15/2⁺
888
831
1162
1217

Fig. 1

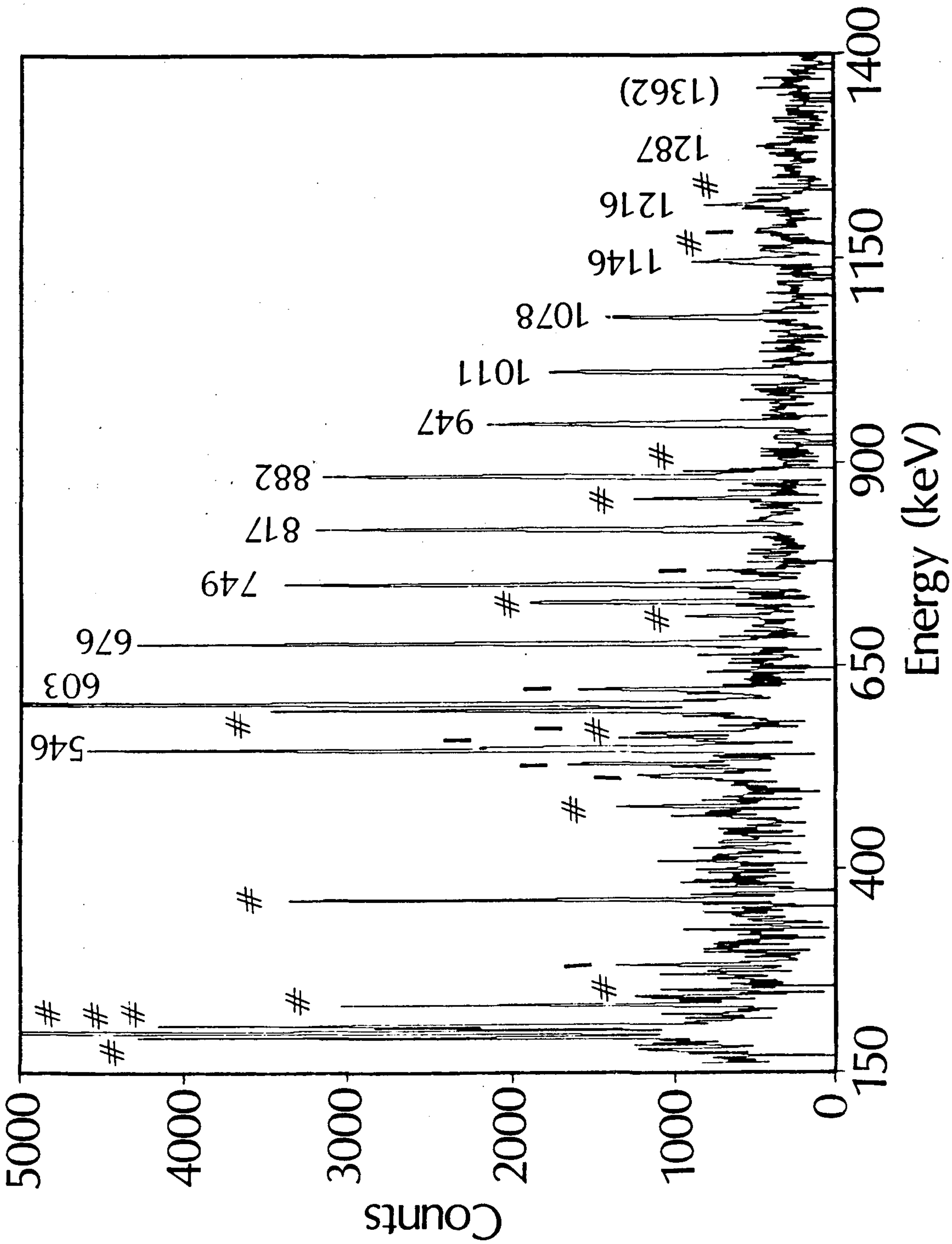

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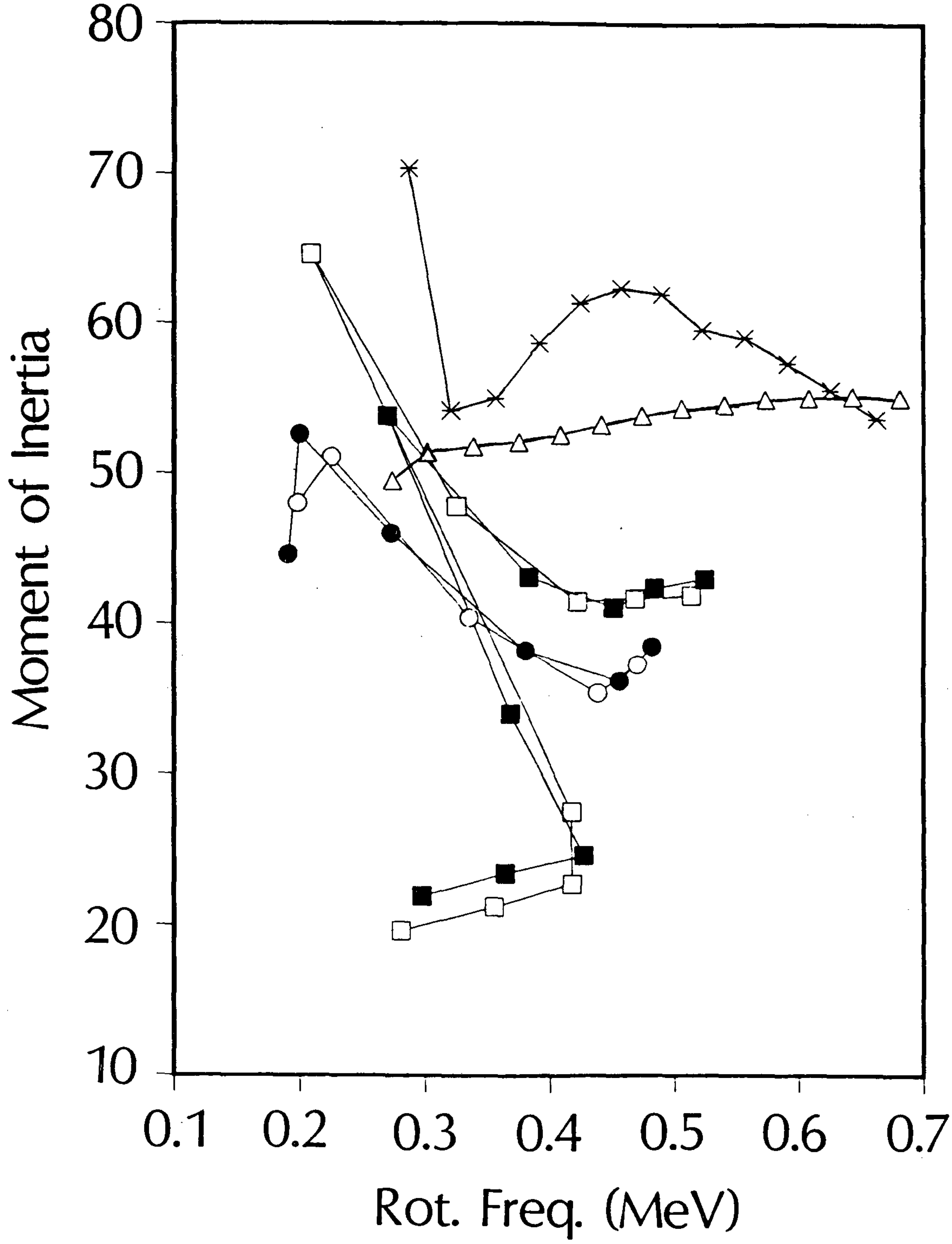
Fig. 2



XBL 8612-5060

Fig. 3

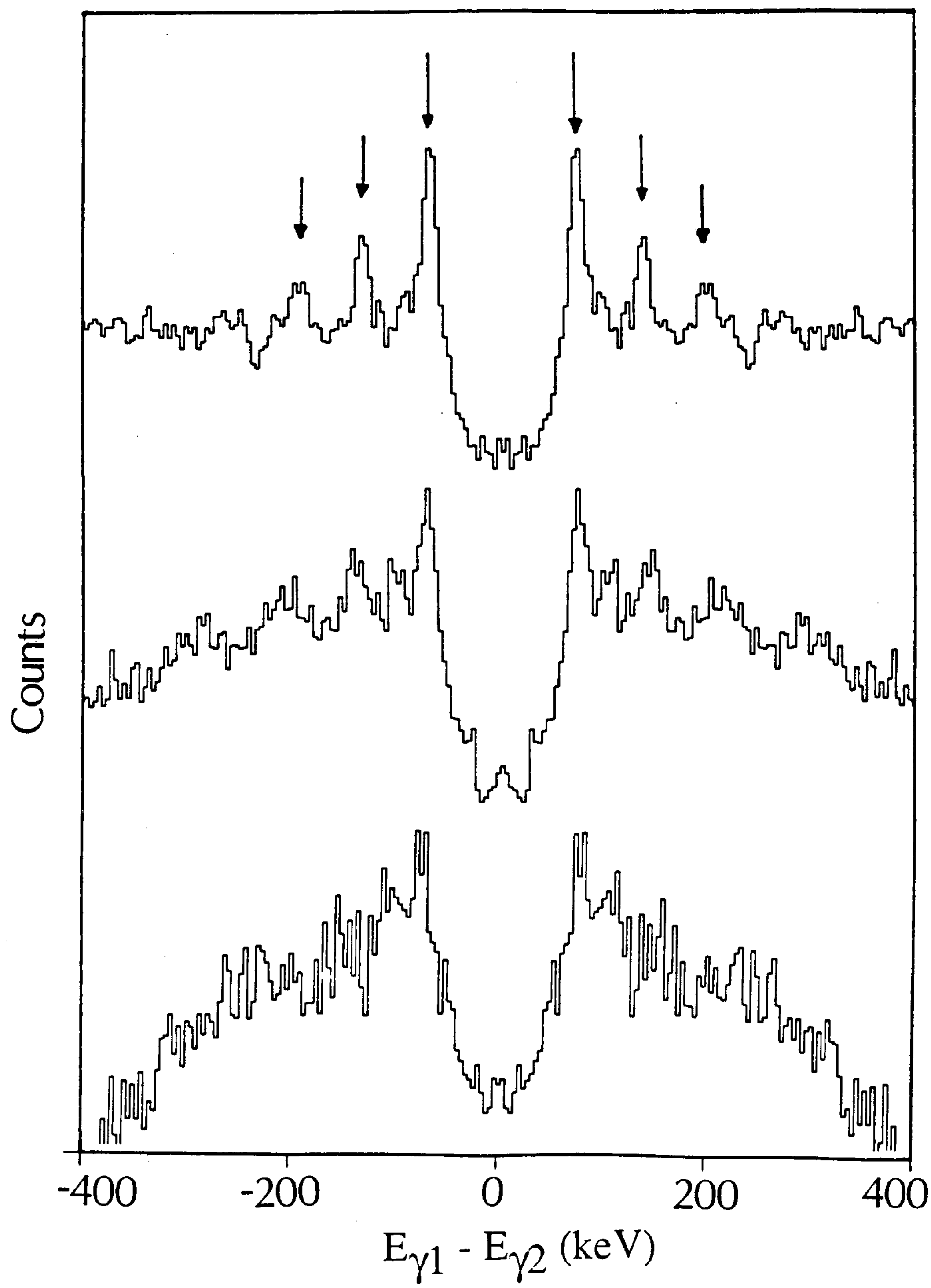


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Fig. 4

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