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Abstract: Superdeformed bands were found in ^{134}Nd and ^{136}Nd. The dynamic moments of inertia ($\mathfrak{I}^{(2)}$) of these bands are about as large as those of the known superdeformed bands in ^{135}Nd and ^{132}Ce, corresponding to $\beta \approx 0.4-0.5$. A high probability for staying in band is measured for the bands in ^{134}Nd and ^{136}Nd.

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Much attention has been paid to the recent discovery of superdeformed bands in the rare earths -- bands that originate from a second prolate minimum in the potential-energy surface of the nucleus (at larger deformation). So far, such bands have been observed in two different regions; a discrete band with $\beta \approx 0.6$ was reported [1] in ^{152}Dy, and a band with $\beta \approx 0.4-0.5$ was found [2-4] in ^{132}Ce and in ^{135}Nd. Furthermore, unresolved features (ridges) indicative of bands with superdeformed moments of inertia were seen in the correlation matrices of several rare-earth nuclei [4-6]. Although the existence of superdeformed shapes in rare-earth nuclei at high angular momenta had been predicted by cranked-shell-model calculations [7-9], their detailed understanding is as yet incomplete. To find out how the superdeformed minimum is related to proton and neutron numbers (and thus to specific orbitals), we have made a search in the Nd isotopes. In this paper, we present evidence for superdeformed bands in ^{134}Nd and ^{136}Nd. A systematic comparison of the behavior of these bands is now possible.

High-spin states in ^{134}Nd and ^{136}Nd were populated by the ^{98}Mo(^{40}Ar,4n) and ^{100}Mo(^{40}Ar,4n) reactions, at beam energies of 173 MeV and 176 MeV, respectively. The beam was provided by the 88-inch cyclotron of the Lawrence Berkeley Laboratory. In both experiments two enriched molybdenum foils (0.5mg/cm^2) were used as a target, such that the evaporation residues recoiled into vacuum. The 21 Compton-suppressed Ge detectors of the HERA array [10] were gain matched on-line to correct for the different Doppler shifts of the γ rays. The peak-to-total ratio of the Ge counters was improved by 10% in the ^{134}Nd experiment by adding NaI nose cones to the individual BGO shields which resulted in better suppression of the Compton-edge peak. In the ^{134}Nd case ~80 million triple and higher-fold events were recorded on tape, and there were ~700 million such events in the ^{136}Nd case. In both experiments, the 4n-channel was the most strongly populated.

Each set of data was initially sorted into a correlation matrix, whereby every triple event was broken into three independent E_γ-E_γ pairs. For a first search, uncorrelated events were removed from this matrix by the method of ref. [11]. Projections parallel to the diagonal (ridge cuts) at various distances (corresponding to different moments of inertia) in such a matrix were helpful to select candidates for γ-ray energies belonging to a regularly spaced sequence. Then standard projections, parallel to an energy axis, were tried on the γ-ray energies at which peaks had appeared in the ridge cuts. This way, the two new superdeformed bands shown in fig. 1 were found. However, the single-gated spectra were not clean because of other strong lines which accidentally overlapped in energy with the gates. In order to assign the new bands to a particular nucleus, special use of the triple γ-ray coincidences was made. For each event, every γ ray was tested against gates centered at the energies of the superdeformed band, and if two γ rays were within these gate limits, the third one was updated in a spectrum. Individual spectra were kept for each gate combination of two in-band γ rays, so as to have the possibility of dropping contaminated combinations later. All these individual spectra were summed in the ^{134}Nd case, and only a few combinations (that are also present in other bands or other nuclei) were rejected in the ^{136}Nd case. As a background, the sum of spectra that were single gated on the same energies of the superdeformed in-band transitions (appropriately normalized), was used. This method provides a high-statistics background which takes "peak-background" as well as "background-background" components into account. The resulting background-subtracted spectra of the superdeformed bands are shown in fig. 2. It is very clear that the two bands are in ^{134}Nd and in ^{136}Nd, respectively. Table 1 gives the relative intensities of the superdeformed transitions, obtained from a (detector-efficiency corrected) sum spectrum containing all gate combinations in both cases. Gates on low-lying yrast transitions in these nuclei indicate intensities of ~4-5% (of the $2^+ \rightarrow 0^+$) for the average of the lower superdeformed band-members in ^{134}Nd and ~2% for those in ^{136}Nd. We were not able to find the linking transitions between the superdeformed bands and the observed yrast transitions, in contrast to ^{135}Nd. This is not too surprising, since the superdeformed band in ^{135}Nd decays through many pathways at its bottom, each carrying less than a fifth of the intensity of the lowest in-band transitions (which have an intensity of ~10%) [4]. Without the direct links the spin assignments given in fig. 1 have to be regarded as tentative. Also, angular correlation measurements were not possible for the superdeformed in-band transitions because of their low intensities. However, their regular pattern suggests that they form a rotational band and are therefore of stretched electric quadrupole character.

The intensity of the superdeformed band in ^{134}Nd is about the same as that of the band in ^{132}Ce [3], which gathers ~5% of the $4^+ \rightarrow 2^+$ intensity. The superdeformed band in ^{136}Nd is considerably weaker, whereas the one in ^{135}Nd stands out being about twice as strongly populated. This difference is also reflected in the feeding pattern. The superdeformed band in ^{135}Nd is fed all the way to the lowest transitions; in the three even nuclei no feeding occurs below spin ~26 and their feeding pattern is very similar (see table 1 and ref. [3]). The feeding out of the superdeformed band is very sudden in all cases. One might think that the differences in the population of these bands are related to the energy of the band. The fact that the ^{135}Nd band with the largest intensity appears to have the lowest excitation energy at a given spin points in that direction. Whether this is due to the alignment that the odd particle contributes or to a pairing effect (e.g., unpaired superdeformed bands) is not clear.

In fig. 3 the spin of the superdeformed states is plotted versus rotational frequency for the four cases in the Ce and Nd isotopes. Although the absolute spin values carry an uncertainty of about $2\hbar$, the overall similarity of the curves is apparent. They are all very smooth, overlap over a wide spin range and have similar moments of inertia. However, they are not perfectly straight and do not extrapolate to zero, which reflects that the kinetic and dynamic moments of inertia do not coincide over much of these bands. The bands in ^{134}Nd and ^{135}Nd go somewhat lower in spin (frequency) than the other two bands. In fig. 4 the dynamic moments of inertia, $\mathfrak{I}^{(2)} \approx 4\hbar^2/\Delta E_\gamma$ (which are independent of the assigned spin), of the four bands are compared. For that purpose the moments of inertia were scaled to the one for A=134, assuming an $A^{5/3}$ dependence. The band in ^{134}Nd seems to have the smallest moment of inertia, and the band in ^{132}Ce the largest. Still, the difference amounts only to about 10%. The average moments of inertia of the superdeformed bands in ^{135}Nd and ^{136}Nd are very much the same and lie in between. For the lowest transition a large irregularity of $\Im^{(2)}$ is seen in three of the four cases. These "kinks" at the bottom of the bands may be a sign of mixing connected with the depopulation; or they may indicate that a band crossing happens at that frequency and another band becomes favored in energy. The large fall-off of the moments of inertia in all bands at higher frequencies is a dominant feature in fig. 4. Nevertheless lifetime measurements [3] in ^{132}Ce are consistent with a constant deformation of $\beta \approx 0.5$ up to the top transitions, and due to the similarities we assume the bands in the other nuclei have a similar (constant) deformation. The decrease of $\Im^{(2)}$ can then be explained by the gradual alignment of high-j orbitals, whose contribution to the collective moment of inertia is thereby removed [12].

Information about the probability of staying in the superdeformed band was obtained from the double-gated spectra. For that purpose, we summed the combinations corresponding to the first through fourth ridge (adjacent transitions, one apart, two apart and three apart) and compared it with a spectrum gated by the fifth and higher ridge combinations after background subtraction. One can calculate the intensity ratio expected for these two spectra assuming that the relative intensities are those of table 1. Within the experimental uncertainty (which is estimated to be ~30%) the calculated and measured ratios agree for the superdeformed band in ^{134}Nd and in ^{136}Nd. We can thus exclude a strong feeding in and out at every state; rather the decay path remains in the superdeformed band once it hits one of its members. In fact, we can deduce that the probability for staying in band at each step is greater than ~90% (except for the lowest in-band transition). This is what one might expect with large in-band B(E2)'s associated with the large deformations and relatively small inter-band transition probabilities due to the significant difference in shape of the lower-lying states in the nucleus.

It is consistent with this picture (in which the resolved superdeformed bands can be thought of as "yrast" states for their shape) that unresolved features (ridges) having a superdeformed moment of inertia were found in the correlation matrices from both experiments. The ones originating from the continuum of ^{135}Nd and ^{136}Nd were reported earlier [4]. In the matrix resulting from the ^{98}Mo + ^{40}Ar experiment the high-spin continuum is mainly due to ^{134}Nd, since the $(\alpha,4n)$ channel competes well against the 5n and (p,4n) channels, and the α particle removes a sizeable fraction of the initial angular momentum of the compound nucleus. Ridges from a superdeformed structure are visible between ~1.0 MeV and ~1.5 MeV, the upper limit being caused by statistics. The ridge separation is 134 keV (corresponding to $\Im^{(2)} \approx 60$ $\hbar^2$MeV^{-1}) at 1.05 MeV and becomes larger with increasing transition energies, i.e., 138 keV at 1.15 MeV, and 146 keV at 1.3 MeV. These ridges seem to consist of unresolved bands besides the discrete superdeformed band in ^{134}Nd, because they look rather continuous in the correlation matrix, and the second and possibly higher ridges, though present, are considerably weaker than the first ridge in contrast to the discrete band. Also, the moment of inertia deduced from the ridge separation drops less over the same transition energy range than that of the resolved transitions (see fig. 4). As in ^{135}Nd [4], this may be explained by a variety of configurations in the unresolved bands so that the admixture of various additional high-j orbitals is possible or larger deformations are induced.

In conclusion, we have found superdeformed bands in ^{134}Nd and ^{136}Nd which are very similar to the previously known bands in ^{135}Nd and ^{132}Ce. The abundance of superdeformed bands in the Nd isotopes suggests that the superdeformed minimum is a general feature of nuclei in this region. This may be in constrast to ^{152}Dy, where apparently a strong shell effect causes the minimum at very large deformation [13] to be especially deep in that particular case.

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Figure Captions

Fig. 1: Superdeformed bands and some yrast transitions in ^{132}Ce, ^{134}Nd, ^{135}Nd and ^{136}Nd. The dashed arrows indicate unobserved linking transitions. Energies are given in keV, parentheses indicate that a transition is tentative. The data for ^{132}Ce and ^{135}Nd are taken from refs. [3] and [4].

Fig. 2: Superdeformed bands in ^{134}Nd (top) and ^{136}Nd (bottom) labeled by transition energies. The less-deformed yrast transitions populated in each of the nuclei are labeled by the spin of the initial state. The background-subtracted spectra are a sum of double-gate combinations. (See text.)

Fig. 3: Spin versus rotational frequency for superdeformed bands: Open (filled) squares represent ^{134}Nd (^{136}Nd), and open (filled) circles represent ^{132}Ce (^{135}Nd). The data for ^{132}Ce and ^{135}Nd are taken from refs. [3] and [4].

Fig. 4: Dynamic moments of inertia of superdeformed bands scaled to A=134, as described in the text. For labeling and references see caption of fig. 3.

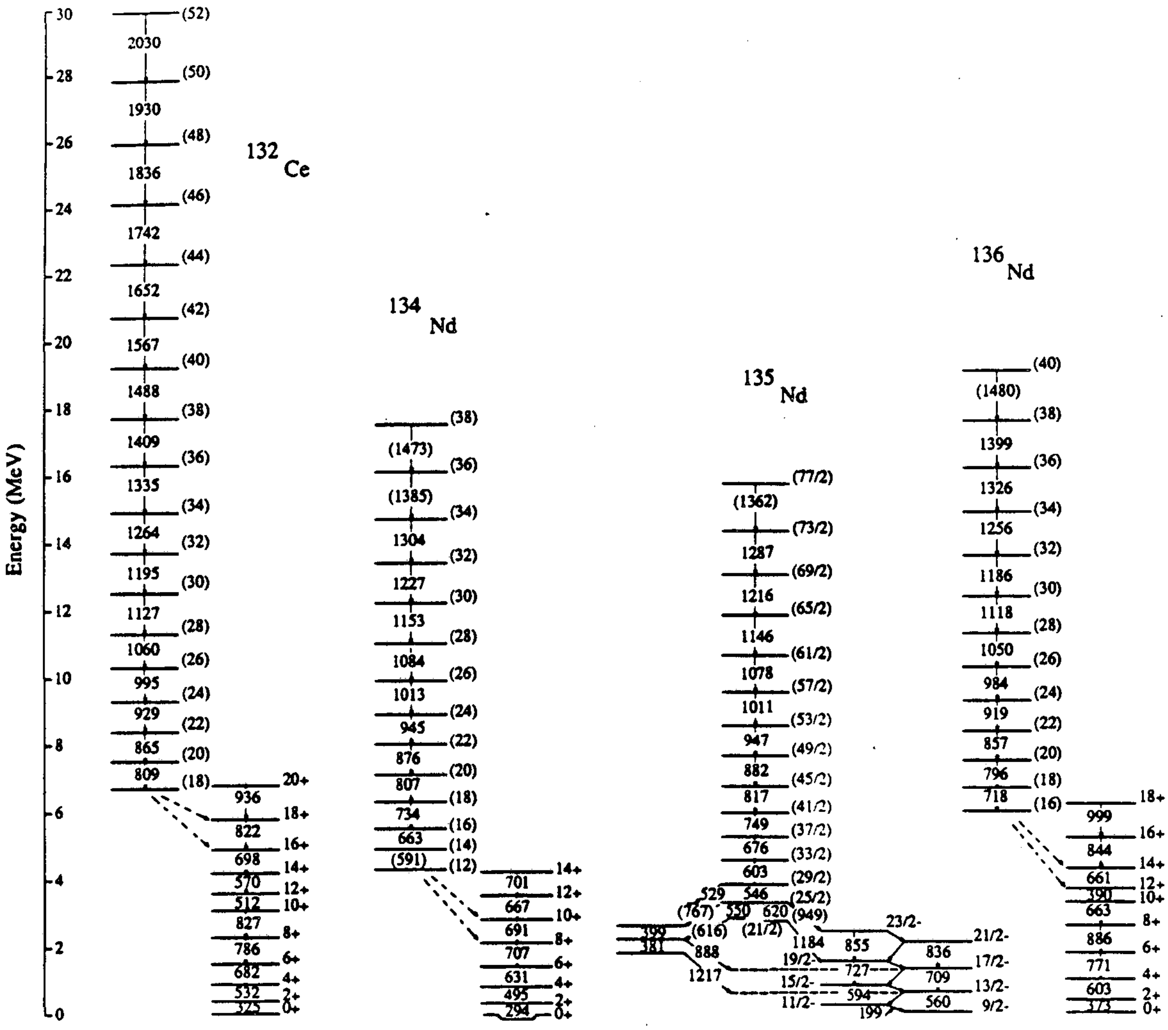
Table 1: Relative intensities of superdeformed in-band transitions

^{134}Nd(a)		^{136}Nd(b)	
Energy (keV)	Relative Intensity(c)	Energy (keV)	Relative Intensity(c)
(591)	0.5	718	0.4
663	1.0	796	1.0
734	1.1	857	1.1
807	0.9	919	1.0
876	1.0	984	0.9
945	1.1	1050	0.8
1013	1.0	1118	0.7
1084	0.8	1186	0.6
1153	0.6	1256	0.5
1227	0.5	1326	0.4
1304	0.5	1399	0.3
(1385)	0.3	(1480)	0.2
(1473)	0.4		

(a) 1.0 corresponds to ~4-5% of the $2^+ \rightarrow 0^+$ in ^{134}Nd.

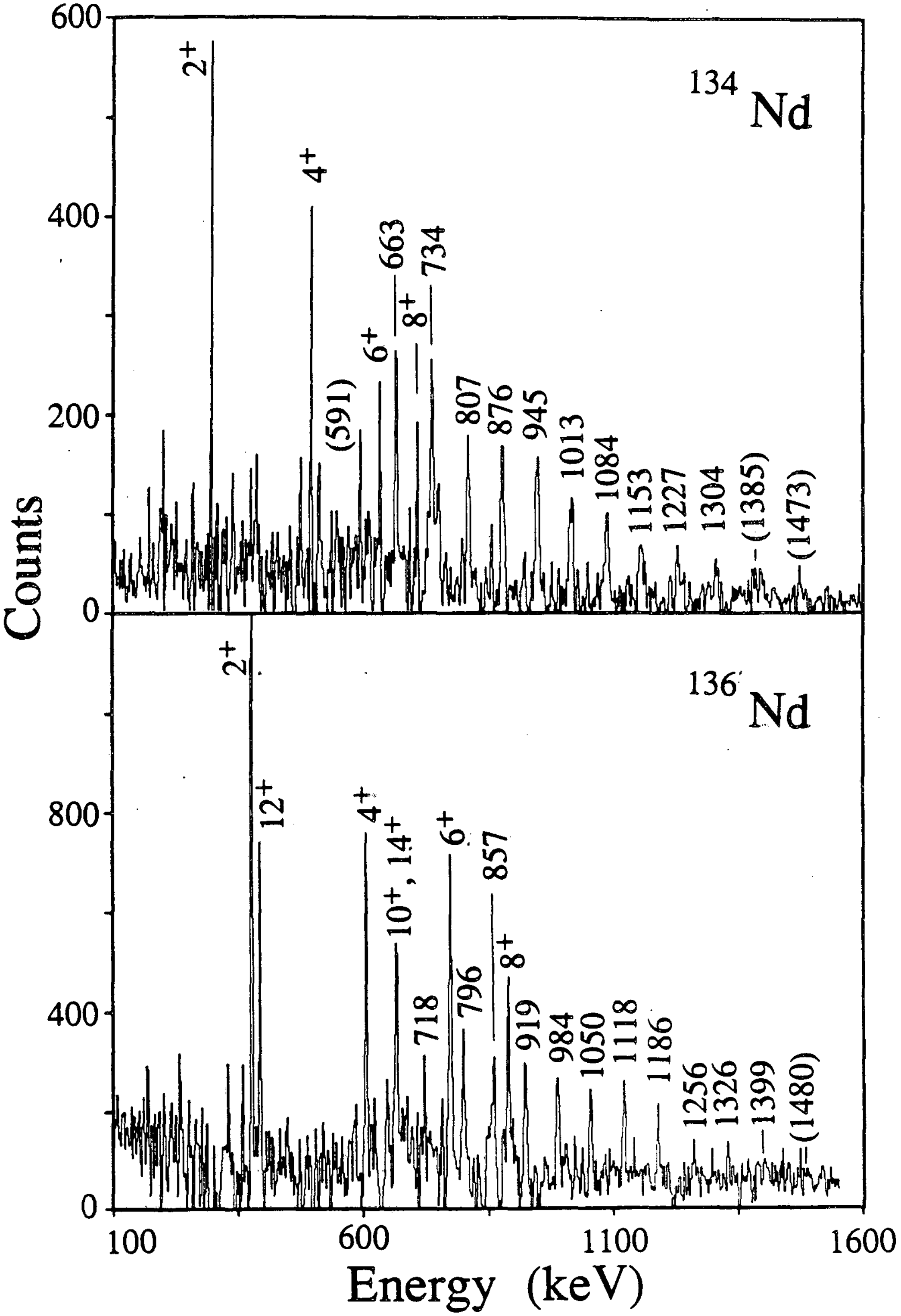
(b) 1.0 corresponds to ~2% of the $2^+ \rightarrow 0^+$ in ^{136}Nd.

(c) Relative intensities have an uncertainty of ~ ± 0.1.



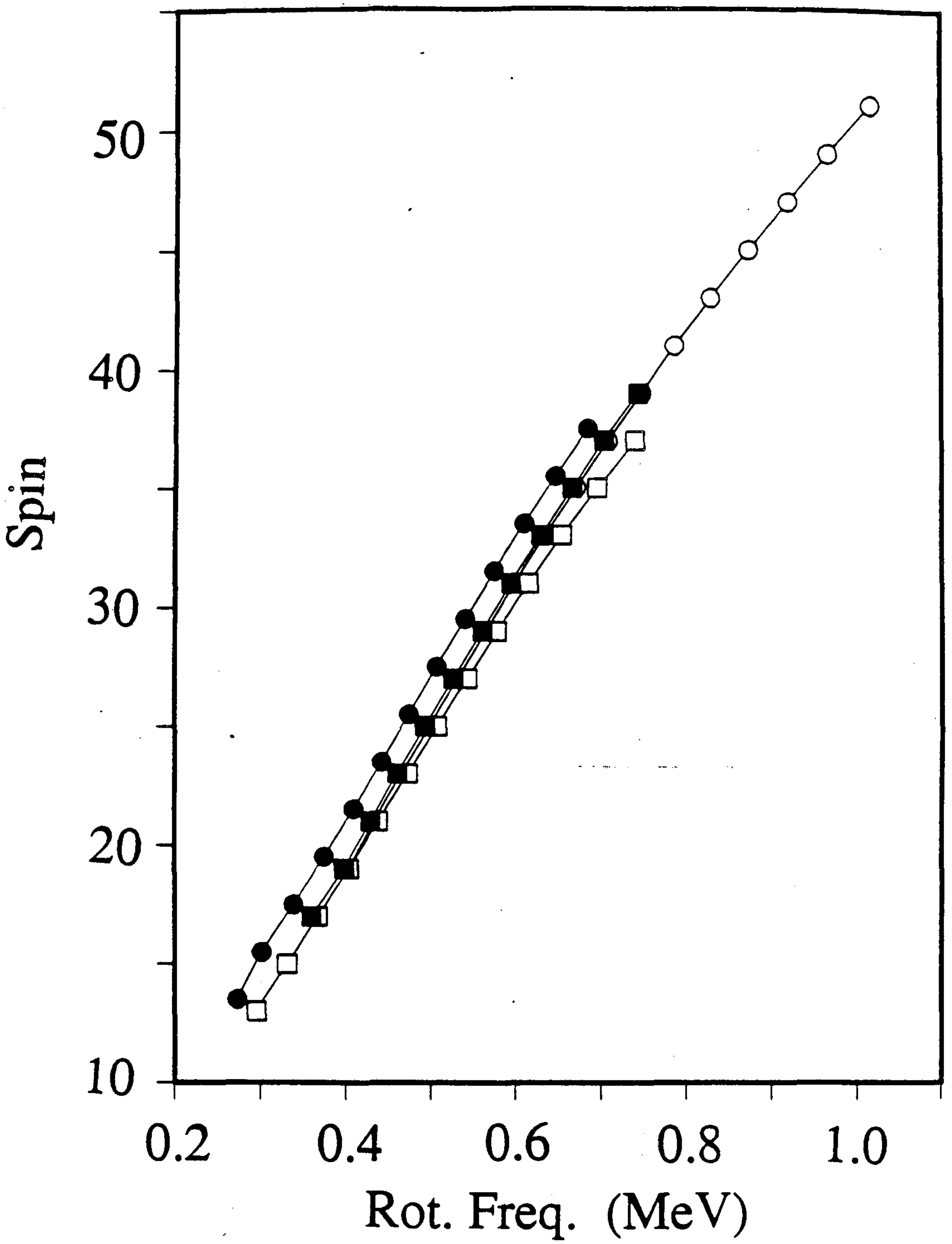
XBL 873-700

Fig. 1



XBL 873-703

Fig. 2



XBL 873-702

Fig. 3

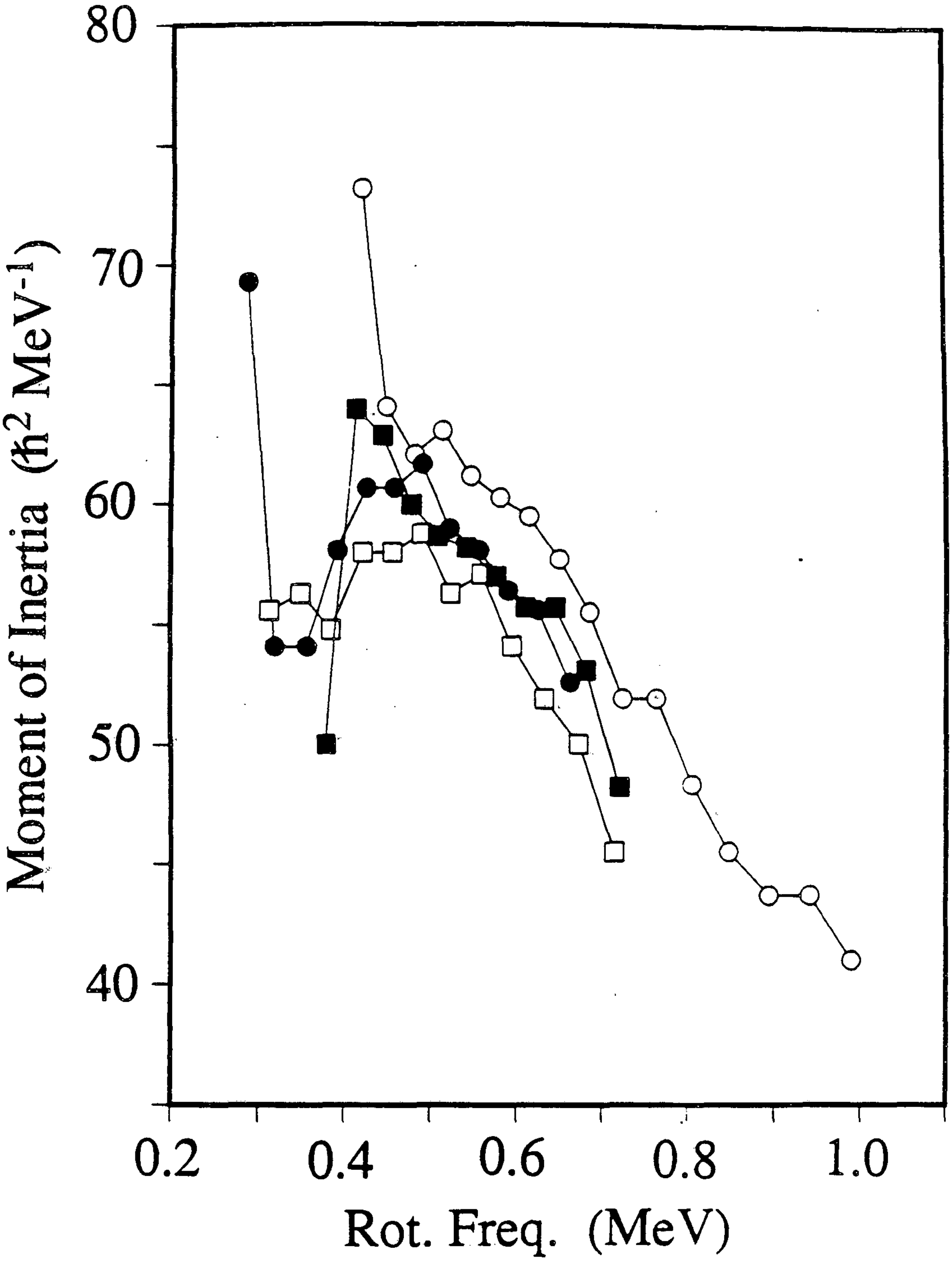


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Fig. 4

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