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New Structures at High Spin in ^{159}Er

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Abstract: The nucleus ^{159}Er was studied with the HERA system. Three bands were extended to higher spins, and three new bands were found. It is shown that specific orbitals rather strongly influence the high-spin behavior, some states remaining collective (somewhat triaxial), others evolving towards a non-collective oblate structure. One of the new bands is a higher-K band, similar to those found in heavier nuclei.

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The nucleus ^{159}Er is located in a transition region between lighter neighbors in which band terminations [1] (indicative of a non-collective structure) have been found around spin 40 and heavier ones which are thought to remain more collective up to the highest spins. In previous studies, the yrast, "A" band ($i_{13/2}$ neutron, favored signature) has been established [2] up to spin 89/2, whereas the "E" and "F" bands ($h_{9/2}$ neutron, favored and unfavored signatures) have been first seen [2] up to spins 65/2 and (correctly) to 55/2 respectively, and later extended [3] up to spins 89/2 and 67/2 respectively.* No clear sign of evolution towards a non-collective structure was seen. The study reported here is aimed at learning more about the structure of ^{159}Er in this critical region of spin, in particular, about the role played by the odd neutron, and about the shape evolution in the (heavier) nuclei as they become basically more collective. We find a branching of the yrast band at the highest spins (the first one observed in an odd nucleus) which is likely to indicate a terminating band. In contrast, the "E" band backbends at about the same spin (~ 81/2) but remains unbranched. This may indicate that the nature of the orbital occupied by the odd neutron plays an important role in determining the shape of the nucleus at the highest spins. Three new bands are also found in this nucleus and their structure will be discussed.

* In this paper (and also on the level scheme), each band (or sequence) is labeled by its structure in the lowest state. Backbends will occur at higher spins in these sequences (changing the structure), and in the text we sometimes will refer to a portion of a sequence by its more detailed structure. For example, the "E" sequence will be referred to in general as "E" but a particular region of it as EAB (the three quasiparticle structure between the AB neutron and the A_pB_p proton backbends).

The nucleus ^{159}Er was produced in the reaction ^{124}Sn (^{40}Ar, 5n) at 180 MeV at the 88-Inch cyclotron of the Lawrence Berkeley Laboratory. Three thin (0.5 mg/cm^2) self-supporting targets of ^{124}Sn were stacked, so that the γ-rays emitted by the recoiling products were fully Doppler-shifted. The γ-rays emitted were observed by the HERA array of 21 Compton-suppressed germanium detectors. Their gains were matched, according to their angles (to compensate for different Doppler shifts), so that the spectrum showed the true γ-ray energy for each detector. In this way, all the γ-ray pair combinations could be added (without loss of resolution) in a single E_γ-E_γ matrix, up to 4 MeV. Four hundred million three- and higher-fold events were recorded on tape. Angular correlation information was used where possible to determine the multipolarity of the transitions and the spin change, following the method of ref. 4.

The γ-rays in the yrast band can be seen in fig. 1a which shows a spectrum in coincidence with a single gate at 1096 keV. All the lines placed in the yrast ("A") band of fig. 2 (except the 1341 keV line which is weak) are visible. The 1152 keV line is very strong and was found to be in coincidence with itself. A comparison of the intensity of the 1152 keV line in the 1096 keV- and 1152 keV-gated spectra gives a ratio of 4:1 for the intensities of the two 1152 keV transitions. The intensities of the upper lines of the yrast band in the various spectra gated by these lines indicate the branching shown in fig. 2--in particular, there appears to be only one 1152 keV transition in coincidence with the 1231 keV γ-ray and two with the 1341 keV line. In addition, a group of three lines (1053, 1005, 941 keV) strongly in coincidence among themselves and marked by an asterisk in fig. 1a probably feeds on the $81/2^+$ level and is indicated as dashed lines in fig. 2. The "E" band was tentatively extended up to spin 97/2. In fig. 1b, the spectrum gated by the 1108 keV line clearly shows itself in coincidence. However, the relative order of these two lines and of the 1126 keV line is not established. Spectra gated on the 1102, 1144 and 1208 keV lines tentatively confirm their belonging to this band whereas the 1167 keV line (also seen in that spectrum) does not appear to belong to it. The "F" band has been extended up to spin 83/2. We have added an 857 keV line at spin 55/2 in that band based in particular on the coincidence spectrum with the 714 keV line and on intensity analyses in that band. The angular correlation ratios for most of the new lines (which are of order 1%) in these bands "A", "E", and "F" were not very reliable due to poor statistics but we will assume that these lines are of stretched E2 character, as is usual for transitions of this energy in this spin range.

Three new bands have been observed in ^{159}Er. A new band of the same spins and parities as the "E" band (but with an intensity of 3% of the 209 keV line at spin 33/2 compared to 15% for the "E" band) feeds into the "E" band at the level of the EAB backbend at spin $25/2^-$. The location of this band is further confirmed by the transitions of 665 keV and 744 keV to the "A" band. A weaker band ($\leq$ 2% at the bottom 570 keV line) of four transitions consistent with a stretched E2 character also feeds the same $25/2^-$ state. Finally, another new band was found, which has a structure different from all the others, with a series of cascade and cross-over transitions (see fig. 1c). The location of this band is well established by four decay pathways and the spins and parities are established from the multipolarity of the interband transitions deexciting the 2.52 MeV level ($25/2^-$). The angular correlation of the 1270 keV transition is consistent with an unstretched dipole character, that of the 806 keV line is consistent with a stretched dipole, and that of the 1042 keV with a stretched quadrupole, although these transitions are weak (the $27/2^-$ to $25/2^-$, 162 keV line is 3% of the intensity of the 209 keV line). The only alternative would be a value of $23/2^-$ (instead of $25/2^-$) for the 2.52 MeV level, but the angular correlations and the absence of a direct transition to the $21/2^+$ level of the "A" band do not favor that hypothesis.

The structure of the various bands in ^{159}Er indicates a rich variety of behaviors. Of all the bands seen, only the yrast appears to branch at high spins. However, there is no gain in energy for these levels relative to an appropriate rigid-rotor reference for the two left most branches. There is however a sizable gain in energy for the dashed levels, about as much as in the terminating band in ^{158}Er [5]. The general tendency, as the mass number increases and nuclei become more collective, is that the terminating levels would gain less and less energy as shown [4,5] by a comparison of ^{156}Er and ^{158}Er. Nevertheless, at least one branching is observed in ^{159}Er, which indicates a competition between two different structures. At least one of them is likely to have a small collectivity, as indicated by our lifetime measurements using the DSAM method, with a ^{124}Sn lead-backed target. The yrast lines, at least up to the 1152 keV line, have a stopped component indicative of a rather long lifetime ($\geq$ 2 ps), and this requires a loss of collectivity in or above that spin region. So, we are probably seeing some kind of terminating structure at this branching.

In contrast, the "E" band, which is extended to about the same spin as the yrast band, does not show any branching. Instead there is a strong upbend at a frequency $\hbar\omega \simeq 0.55$ MeV (see fig. 3a) in which at least 6 $\hbar$ are aligned, and the energies of the highest transitions suggest that a band structure may persist even beyond that alignment. The most likely candidates for such a strong upbend in that frequency region are the $h_{9/2}$ or $i_{13/2}$ proton orbitals coming from the empty shell above the valence shell. It is very interesting that such an alignment is not seen at all in the "F" band (see fig. 3a) which is also known in the same frequency region. The only reason we can envision why it would be present in the "E" band and not in the "F" band is that the "E" band is more triaxial driving [6] in this mass region, and the empty $h_{9/2}$, $i_{13/2}$ proton orbitals are favored [7] by triaxial shapes. Another possible interpretation for the irregularities of the states at $81/2^-$ in the "E" band has been suggested [8], which assumes that the deformation decreases in these states and therefore the nucleon (mostly proton) configuration is rearranged accordingly. These states are then described as terminating states obtained by adding one neutron to the known terminating configurations in ^{158}Er. We do not know which of these two possibilities corresponds to the observed behavior in the "E" band, but we feel that they both probably exist, the first one occurring in bands where the nucleus remains strongly deformed and collective (though somewhat triaxial), and the second one where it moves toward band termination.

These different behaviors suggest that the nature of the odd neutron orbital plays an important role in determining the structure of the nucleus, even up to the highest spins. Indeed, the other orbitals involved at lower frequencies are nearly the same in the "A", "E" and "F" bands: they all experience the $h_{11/2}$ A_pB_p proton alignment at a frequency of 0.44 MeV (see fig. 3). In all cases the neutron A and B orbitals are present, since the first backbend is the AB neutron alignment in the "E" and "F" bands, and it is the BC neutron alignment in the "A" band. Therefore, it seems that the E, F and C neutron orbitals are the critical ones. The C orbital is thought [9] to be prolate driving in that region and it may be that with this orbit occupied the nucleus cannot so easily make use of the high-j proton orbitals from the next shell to generate angular momentum and therefore branches into more prolate (collective) and more oblate (terminating) structures.

Of the two new bands connected to the "E" band, the short one (with four transitions), least favored in energy, could be the continuation of the "E" band (parallel to the EAB backbend) and is not populated up to very high spins. The most logical assignment for the other band would be "GAB", with G being the next neutron orbital above the E orbital (having the same signature), originating from the $5/2^-[523]$ orbital. Such bands may have been seen also in the neighboring [10] nucleus ^{163}Yb and [11] in ^{165}Hf, but not up to such high spins. It is interesting that this "G" band follows rather closely (see fig. 3a) the "E" band. The bands EAB and FAB depopulate strongly (80% for "E", 100% for "F") into the A and B bands at the level of the AB backbend. This suggests that the interactions between the one- and three-quasiparticle bands (E → EAB and F → FAB) are weak, as some calculations [12] indicate.

In the third new band, the strong dipole cascade transitions (of the same intensity as the cross-over transitions at the bottom, and gradually decreasing) suggest a proton component of the configuration, and the absence (fig. 3b) of the A_pB_p backbend, (which is seen in all the other bands) indicates that an $h_{11/2}$ proton is occupied. The most probable odd neutron orbital is $i_{13/2}$ since the AB backbend is not seen at the proper frequency, probably being delayed by the occupation of an $i_{13/2}$ neutron. Indeed, in fig. 3b, it is apparent that this band and the yrast "A" band follow each other closely, suggesting an A neutron component for this band. The proposed configuration could be the coupling of an A neutron to the low-lying two quasiproton 7- state (7/2- [523] $\otimes$ 7/2+ [404]) known in the neighboring [13,14] even nuclei ^{162,164}Er. However, the proton configuration cannot have too high a K value at spin 25/2 since this band decays without measurable delay ($\lesssim$ 5 ns) towards the "A" (and "B" and "E") bands at spins for which the odd neutron is mostly aligned. This is supported by the cranking [15] calculations which show that the $7/2^-$ [523] $h_{11/2}$ proton orbital does align (reducing the K value) but, like the $7/2^+$ [404] orbital, has very little signature splitting as is observed in this band. A similar band may have been observed [16] in ^{163}Er but it is somewhat surprising to observe it in ^{159}Er since its structure is more characteristic of that of the heavier nuclei where prolate shapes "rotating around the symmetry axis" giving rise to high-K band-heads are observed.

In conclusion, we observe a variety of behaviors at high spins in the nucleus ^{159}Er. There are indications that the yrast band is terminating, whereas the "E" band seems to remain more collective (triaxial) and makes use of the high-j orbitals in the next empty shell to generate angular momentum. The "F" band also probably remains collective at the same frequencies as the "E" band but does not backbend (yet). Finally we begin to see higher-K bands, as in the heavier (more collective and prolate) nuclei. Our results indicate that the individual orbitals (and in particular the odd neutron) influence rather strongly the shape and collectivity of this "transitional" nucleus. Further studies to increase the maximum spins in $^{159,160}Er$ should give us a chance to understand in more detail the role played by particular orbits in the transitions from the "terminating" regime in the lighter nuclei to a more collective regime in the heavier ones.

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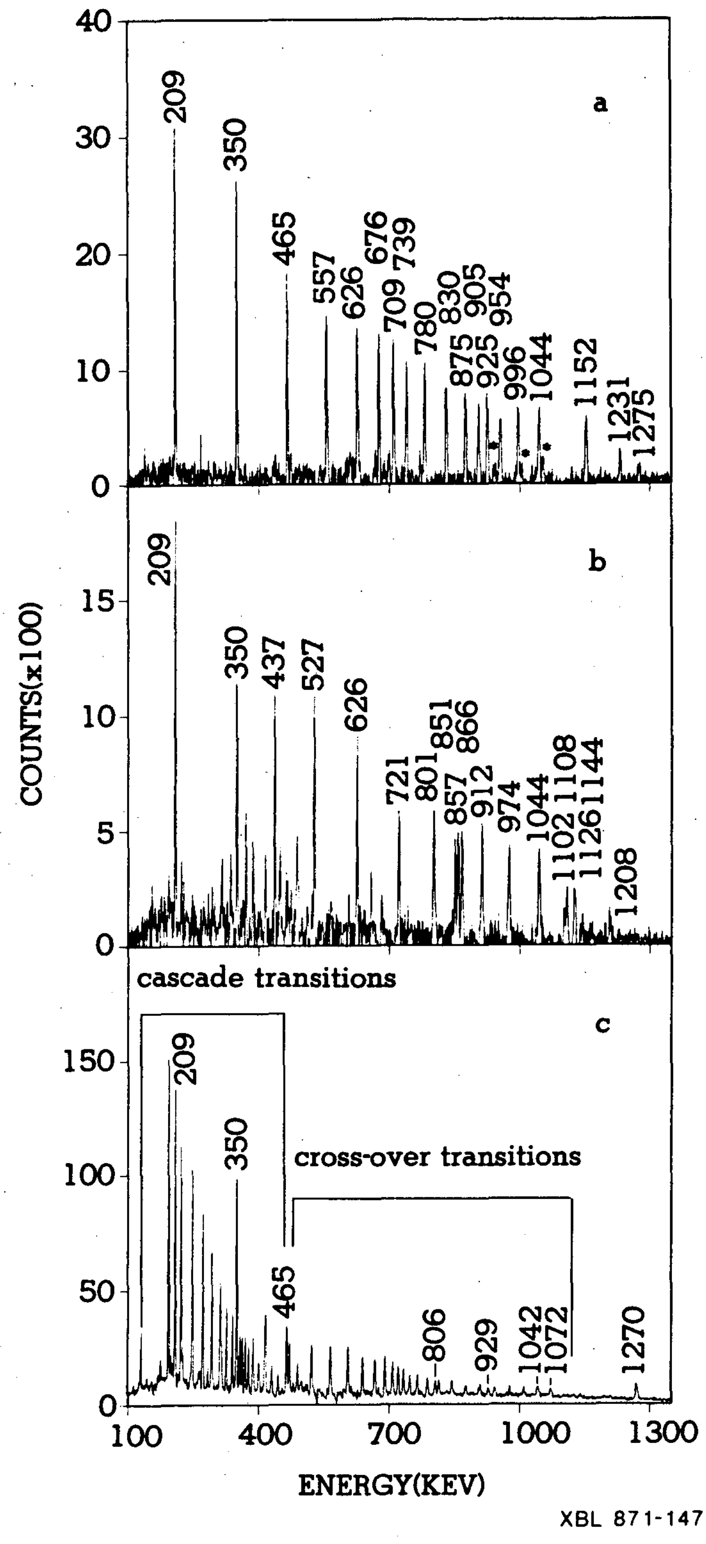
Figure Captions

Fig. 1 The γ-ray spectra in coincidence with a) the 1096 keV line; b) the 1108 keV line; c) the 162 keV line. Only the interband transitions and the "A" band are labeled in the last spectrum.

Fig. 2 Level scheme of ^{159}Er. For clarity, the (known) $\Delta I = 1$ transitions between E and F, and between B and A are not shown.

Fig. 3 Spin versus frequency plots for various bands in ^{159}Er: a) band "E" (o), band E continuation (■), band "F" (●), and band "G" (□); b) band "A" (∇), its branching at the $85/2^+$ level (Δ), and the signature 1/2 (⊕) and -1/2 (○) members of the band labeled An $(7/2-[523] \otimes 7/2+[404])_p$.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626
676
709
739
780
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954
996
1044
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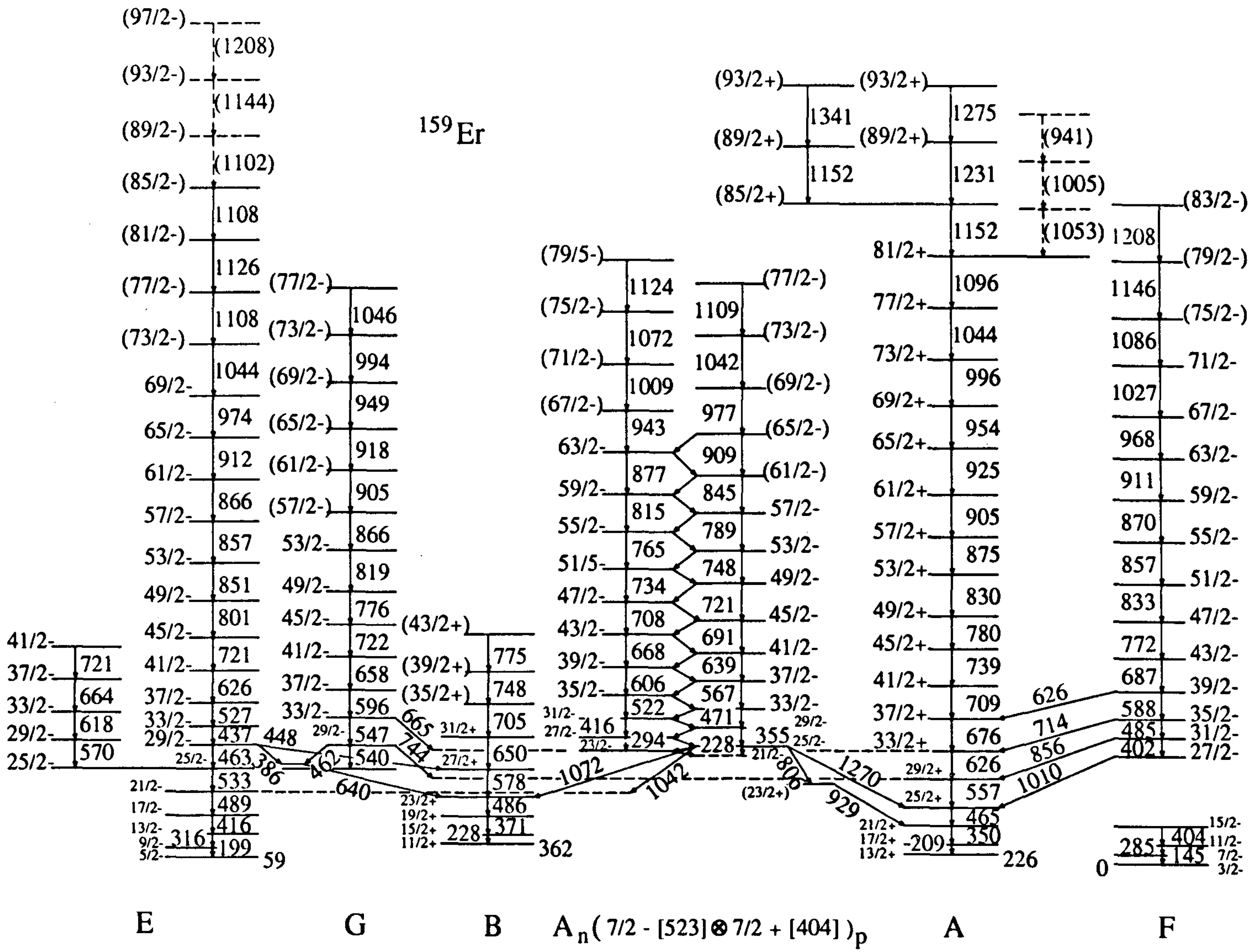
1231
1275
b
209
350
437
527
626
721
801
851
857
866
912
974
1044
1102
1108
1126
1144
1208
c
cascade transitions
cross-over transitions
209
350
465
806
929
1042
1072
1270
COUNTS(x100)
ENERGY(KEV)
XBL 871-147

Fig. 1

Fig. 2



XBL 871-145

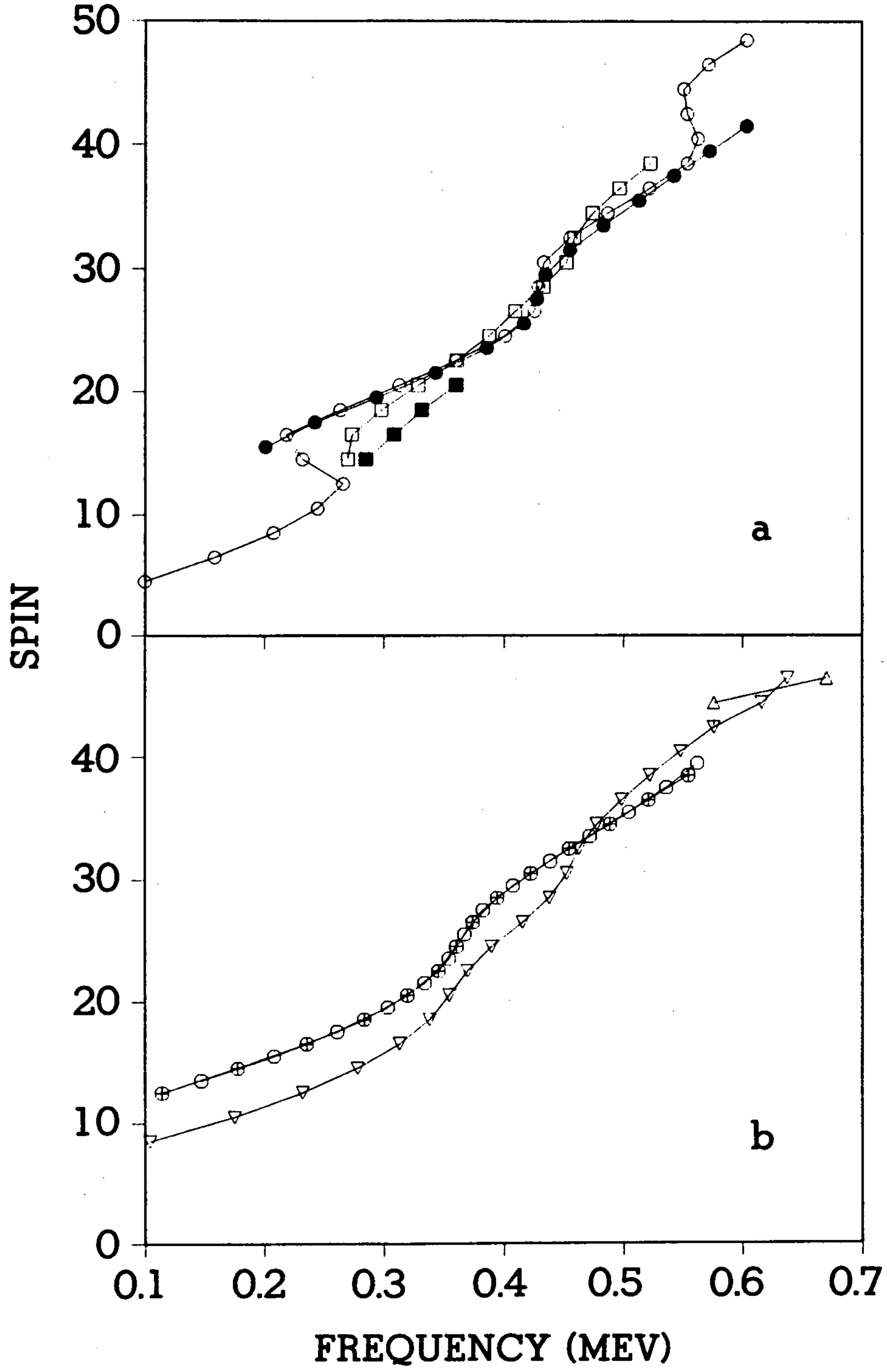


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Fig. 3