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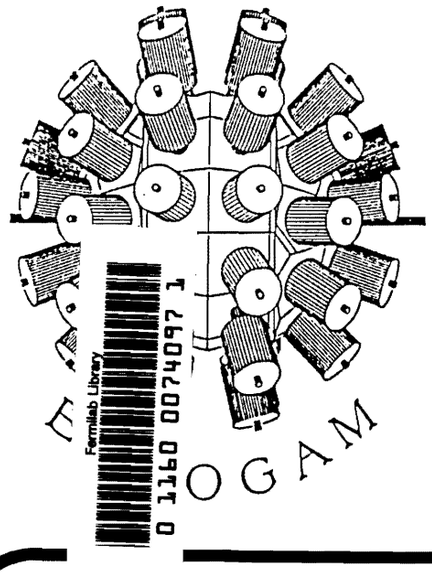

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Rotational Inertia of Superdeformed Nuclei: Intruder States, Pairing, and Identical Bands

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Abstract

The phenomenon of identical bands is studied by analyzing the distributions of fractional changes in the dynamical moments of inertia of pairs of bands in superdeformed (SD) nuclei. These distributions are found to exhibit a peak with a centroid at nearly zero. Their widths increase in going from SD bands in the mass A$\sim$150, to SD bands in the mass $\sim$190, and to normally-deformed bands in the rare-earth region. Consequently, there exists a significant excess of identical bands in SD nuclei compared to normally-deformed nuclei at low spins. This is attributed to the weaker pairing correlations and the stabilizing role of intruder orbitals on the structures of SD bands.

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Observation of rotational bands in different nuclei which have nearly identical moments of inertia (MoI) and, occasionally, nearly identical γ-ray energies has been one the most exciting discoveries in low-energy nuclear physics in recent years [1]. These identical bands exist at both low- and high-spins, and span a wide variety of shapes [2–11]. The first pair of identical bands (IB's) discovered in 1990 [2] was an excited superdeformed (SD) band in ^{151}Tb whose γ-ray energies are identical to those in the yrast band of ^{152}Dy to within $\sim$1.5 keV over 20 transitions. This similarity implies that the dynamical MoI of the two bands are the same to within a few parts per thousand. (The dynamical MoI, $\mathcal{J}^{(2)}$, is defined as $4/\Delta E_\gamma$, where ΔE_γ is the difference in the energies of two consecutive γ rays in a band composed of stretched E2 transitions.) This is extremely surprising since the variation just due to the mass difference between the two nuclei is expected to be one order of magnitude larger. The discovery of IB's implies that, contrary to expectations, in some cases the valence particles (or holes) have only a very weak effect on the corresponding core. That is, they play the role of weakly-coupled spectators. So far, despite intense theoretical efforts aimed at the understanding of the IB phenomenon, no definitive scenario has yet emerged [1].

Since the advent of new and highly efficient γ-ray spectrometers such as Eurogam, Gammasphere, and Ga.Sp, numerous pairs of IB's have been discovered in the SD mass regions $A\sim130$, $A\sim150$, and $A\sim$ 190 nuclei. With the availability of a relatively large set of data on IB's, it is now possible to investigate if there exists an excess of IB's among superdeformed nuclei versus normally-deformed nuclei. Moreover, if significant differences were observed, can they be traced to any of the special properties of the SD bands such as the presence of large shell effects or reduced pairing correlations? This study provides affirmative answers to both of these questions.

In this work, we have adopted the general definition that two bands are *identical* if they exhibit an anomalously small difference (as defined later) in their $\mathcal{J}^{(2)}$. We shall use the following notation to indicate that band (n) in nucleus X and band (m) in nucleus Y are identical: $\{\mathrm{X(n)}, \mathrm{Y(m)}\}$. To assess the degree of similarity between the MoI's of two bands X(n) and Y(m), we have first evaluated the fractional change (FC) in their $\mathcal{J}^{(2)}$:

$$FC_{\mathrm{X(n),Y(m)}} \equiv \left[\mathcal{J}^{(2)}_{\mathrm{X(n)}} - \mathcal{J}^{(2)}_{\mathrm{Y(m)}}\right] / \mathcal{J}^{(2)}_{\mathrm{X(n)}} = \Delta\mathcal{J}^{(2)} / \mathcal{J}^{(2)}_{\mathrm{X(n)}}. \tag{1}$$

The nucleus Y, to which the reference band belongs, was taken to be the lighter of the two nuclei. The quantity FC has the advantage of being independent of the *absolute* spin, I. Instead, it depends only on the relative spin alignments of the two bands defined as $i(\omega) = I_{\mathrm{X(n)}}(\omega) - I_{\mathrm{Y(m)}}(\omega)$, where $\hbar\omega = E_\gamma/2$ is the rotational frequency. Since the absolute spin values of SD bands have not yet been experimentally determined, one can alternatively use the effective spin alignment $i_{\mathrm{eff}} = i \bmod 1$. As shown in Ref. [12], the FC is related to the effective alignment by the relation

$$FC_{\mathrm{X(n),Y(m)}} = di/dI_{\mathrm{X(n)}} = di_{\mathrm{eff}}/dI_{\mathrm{X(n)}} \tag{2}$$

In situations where i_{eff} is a linear function of I, the average slope of this linear function yields the *average fractional change*, $\overline{FC}$. In this work, we have extracted $\overline{FC}$ via a linear least-squares fit to i_{eff}. This technique is particularly useful when comparing MoI of SD bands which typically consist of long ($\sim$15 transitions on average) cascades of γ rays.

We imposed two successive conditions to select the IB's. First, to ensure that a good least-squares fit is obtained, we required that the resulting standard deviation must be less than 0.05. (In situations where band interactions introduced local discontinuities in $\mathcal{J}^{(2)}$, we excluded from the least-squares fit up to 20% of the data points.) The second condition required that for two SD bands to be *identical*, their $\overline{FC}$ value should be less than half the expected change in the MoI of two rigid bodies due to their mass difference, ΔA.

The data set considered for this analysis consisted of 18 highly-deformed bands in the mass $A\sim$130 region, 54 SD bands in the mass $A\sim$150 region, and 45 SD bands in the mass $A\sim$ 190 region [13]. Several comparisons of the identical bands found in each of these regions were performed which will be discussed below.

In the first step of the analysis, we compared the MoI's of *all* possible pairs of SD bands belonging to different nuclei in a given region. As shown in the first rows of Tables I and II, of the 1250 (790) possible pairs in the mass $A\sim$150 (190) region, nearly 32% (61%) produced satisfactory least-squares fits with a standard deviation of $\sigma < 0.05$. The resulting

distributions for the $\overline{FC}$ values in all three mass regions are shown in Fig. 1. These all exhibit a nearly Gaussian peak centered at $\overline{FC}\sim 0$. Applying our second condition, we found 17 (24%), 73 (6%), and 92 (12%) pairs of IB's in the mass $A\sim 130$, 150, and 190 regions, respectively. To gain further insight into the origin of these identical bands, a more detailed analysis of the structures of the IB's in the $A\sim 150$, and 190 regions was performed. A detailed analysis of the bands in the $A\sim 130$ region was not possible due to lack of statistics.

In SD nuclei in the mass $A\sim 150$ region, pairing correlations are believed to be greatly reduced [14,15]. Consequently, SD bands in this region may be labeled using the high-$\mathcal{N}$ intruder occupation quantum numbers. ($\mathcal{N}$ is the principal oscillator quantum number and the intruder orbitals are those orbitals which originate from the higher-lying shells which have a larger $\mathcal{N}$.) For example, the yrast band ^{152}Dy(1), and the excited bands ^{151}Tb(2) and ^{151}Dy(4) in the adjacent nuclei all contain 4 protons from the $\mathcal{N}$=6 and two neutrons from the $\mathcal{N}$=7 shells. (This configuration will be denoted as $\pi 6^4 \nu 7^2$.) Relative to the yrast band ^{152}Dy(1), these excited bands in ^{151}Dy and ^{151}Tb are based on a single hole in a low-$\mathcal{N}$ neutron and proton orbital, respectively. It has been previously suggested that the high-$\mathcal{N}$ intruder orbitals ($\mathcal{N} > 5$) have a major influence on the magnitude and spin dependence of the $\mathcal{J}^{(2)}$ of SD bands in the Gd-Dy region [16]. As described below, the present analysis strongly corroborates this suggestion.

In the rare earth region, only a small number of the pairs histogrammed in Fig. 1(b) have negative $\overline{FC}$ values. This indicates that the MoI's of SD bands in this region generally increase with mass. As far as the ΔA-distribution of the 73 pairs of IB's is concerned, there are 19, 25, 12, 7, 7, 2, and 1 IB's for mass differences of 1 to 7, respectively. Using configuration assignments based on the cranked mean field calculations [14,16,17], more than 85% of these identical bands were found to have the same high-$\mathcal{N}$ intruder content. In adjacent nuclei, the high-$\mathcal{N}$ content of a configuration is preserved by the creation of a single particle or hole in a low-$\mathcal{N}$ orbital.

An interesting feature of Fig. 1(b) is the appearance of a second sharp peak which is

centered at $\overline{FC}\approx 0.1$. Interestingly, nearly $\sim$85% of the band pairs that comprise this peak are predicted to differ by two high-$\mathcal{N}$ intruders (namely, a $\mathcal{N}$=7 neutron and a $\mathcal{N}$=6 proton orbital), irrespective of their mass difference. Similarly, many of the pairs that comprise the third peak at $\overline{FC}\approx 0.16$ differ by three high-$\mathcal{N}$ intruders. These correlations clearly highlight the dominant influence of the high-$\mathcal{N}$ intruder orbitals on the MoI's of the SD bands in the $A\sim 150$ region.

In the next step of the analysis, we studied the distribution of the $\overline{FC}$ values when the reference nuclei were taken to be the adjacent nuclei with one less nucleon. A comparison of *all* bands in nucleus X (mass $A_{\rm X}$) with *all* bands in the nucleus $A_{\rm X}-1$ identified 19 pairs (5%) of identical SD bands (cf the third row in Table I). This percentage is similar to that found in the first row, where all possible pairs of nuclei were considered. A further restriction of one of the bands to be the yrast band in either nucleus $A_{\rm X}$ or $A_{\rm X}-1$ resulted in 54 band-pairs which fulfilled the conditions of a good least-squares fit (cf the fourth row in Table I). The distribution of the $\overline{FC}$ values for these 54 pairs are shown in Fig. 2(a). Similar to the distribution shown in Fig. 1(b), this distribution, too, shows two distinct peaks at $\overline{FC}\sim 0$ and $\overline{FC}\sim 0.1$. Remarkably, when at least one of the bands was restricted to the yrast configuration, the number of pairs of IB's decreased from 19 to 17 despite the fact that the number of combinations dropped from 369 to 140. Again, all of the 17 pairs of identical bands are predicted to have the same high-$\mathcal{N}$ intruder content. Therefore, we conclude that a necessary condition for generating IB's in the mass $A\sim 150$ region is to have the same number of high-$\mathcal{N}$ intruder proton and neutron orbitals.

A similar analysis performed for the SD bands in the mass $A\sim 190$ region leads to different conclusions (cf Table II). For example, Fig. 1(c) shows that the distribution of $\overline{FC}$ for all possible pair combinations has only a single broad peak which is centered at $\overline{FC}\sim 0$. The full width at half maximum of this distribution is $\sim$0.05 as compared to the value of 0.025 obtained for the $A\sim 150$ region [18]. In comparison with Fig. 1(b), the noteworthy differences include: (i) the condition of a good least-squares fit is satisfied more often (61%)

and does not change the overall shape of the distribution even though some background is removed; (ii) the secondary structures are much less pronounced; and (iii) the distribution is more symmetric around zero. This pattern does not change qualitatively when only adjacent nuclei are compared [see Fig. 2(b)]. Interestingly, many of the pairs that fulfilled the requirement of identical bands have been predicted to have very *different* high-$\mathcal{N}$ contents [20]. The present study suggests that (i) most of the active orbitals in the mass $A\sim190$ region have a constant effective alignment in the observed frequency range, and (ii) the condition of identical high-$\mathcal{N}$ occupancy is no longer a good criterion for selecting IB's. This means that in the case of SD bands in this region, the configuration-mixing interactions such as pairing are strong enough to effectively smooth out the individual single particle occupations; thus, reducing the influence of high-$\mathcal{N}$ states. Another contributing factor is that, compared to the $A\sim150$ region, the high-$\mathcal{N}$ intruders in the $A\sim190$ region have larger values of K [20] (K is the projection of the single-particle angular momentum on the symmetry axis). These intruder orbitals, therefore, do not significantly change the deformation of the core and are only weakly influenced by the Coriolis interaction.

It is expected that [21,24] pairing correlations play a more important role here than in the $A\sim150$ region. A crucial factor is that SD bands in the $A\sim150$ region occur at very high angular momenta where pairing correlations are strongly quenched [14,15]. In contrast, SD bands in the $A\sim190$ region extend down to rather low spins ($I\sim8$), where static pairing correlations are important. Indeed, the smooth rise in $\mathcal{J}^{(2)}$ as a function of rotational frequency has been attributed [21,24] to the successive alignment of high-$\mathcal{N}$ particles in the presence of pair correlations.

The statistics given in Table II indicate that $\sim$12% of the SD bands from the Hg-Pb region satisfy the IB's criteria compared to the 6% in the rare earth region. This difference is again the consequence of the enhanced pairing correlations which tend to reduce the role of the high-$\mathcal{N}$ orbitals. In other words, the polarization effects due to high-$\mathcal{N}$ orbitals are significantly reduced in this mass region.

The study in Ref. [12] examined the $\overline{FC}$ values for about 180 normally-deformed odd-

proton bands in the rare-earth region with known spins, energies and configuration assignments. The reference band in each case consisted of the yrast band in the adjacent even-even nucleus with one less proton. A similar study for nearly 200 of the odd-neutron normally-deformed bands in the rare-earth region has been also recently reported in Refs. [1]. In the present study, the results of these two surveys are combined to obtain the distribution of the $\overline{FC}$ values for the odd-A normally-deformed bands (neutron numbers N=90-109 and proton numbers Z=62-78). In Fig. 2, this distribution (stars) is superimposed on the corresponding distributions of $\overline{FC}$ values for SD bands in the $A\sim150$ and 190 regions. This histogram, represents an approximately Gaussian distribution with a centroid of $\overline{FC}\simeq5\%$, and a full width at half maximum of $\simeq28\%$. However, this distributions is considerably wider than that for the SD bands. The most striking feature of Fig. 2 is the presence of an excess of IB's in SD bands as compared to the low-spin normally-deformed bands. Again, this difference can be attributed to pairing correlations: the present analysis of the odd-A rare-earth bands covers the low-spin states where pairing correlations are indeed very important.

To summarize, the distributions of fractional changes in MoI of both SD and normally-deformed bands are found to exhibit a nearly Gaussian peak centered at approximately zero The widths of these distributions increase form 0.025 for SD bands in $A\sim150$, to 0.05 for SD bands in $A\sim190$, to 0.28 for normally-deformed bands in the rare-earth region. As a result, there exists a large excess of identical bands in SD nuclei compared to normally-deformed nuclei at low spins. This is attributed to the increasing strength of pairing correlations. A unique feature of the SD bands in the $A\sim150$ region is that their underlying shell structure (i.e., their high-$\mathcal{N}$ intruder content) is clearly reflected in their moments of inertia. Indeed, there exists a very nice correspondence between the theoretical single-particle shell structure, occurrence of IB's, and the observed fine structures (peaks) in the distribution of fractional changes in MoI. This feature, however, is lost in the $A\sim190$ SD bands where configuration mixing due to pairing correlations smears out the individuality of each band.

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FIGURES

FIG. 1. Distributions of average fractional changes ($\overline{FC}$) in the MoI's of pairs of SD bands in the mass regions: (a) $A\sim130$; (b) $A\sim150$; and (c) $A\sim190$. All possible pairs of bands belonging to nuclei in a given region which could be fitted with a standard deviation of $\sigma < 0.05$ are shown in these plots.

FIG. 2. Distributions of average fractional changes ($\overline{FC}$) in the MoI's of pairs of SD bands in the mass regions $A\sim150$ (left) and $A\sim190$ (right). Bands in a nucleus X with mass A_X are compared with bands in the neighbouring nucleus with A_X-1, one of the bands being restricted to the yrast configuration. The stars show the corresponding distribution for nearly 400 odd-A normally-deformed bands in the rare-earth region. All three distributions are normalized separately to have a total count of one.

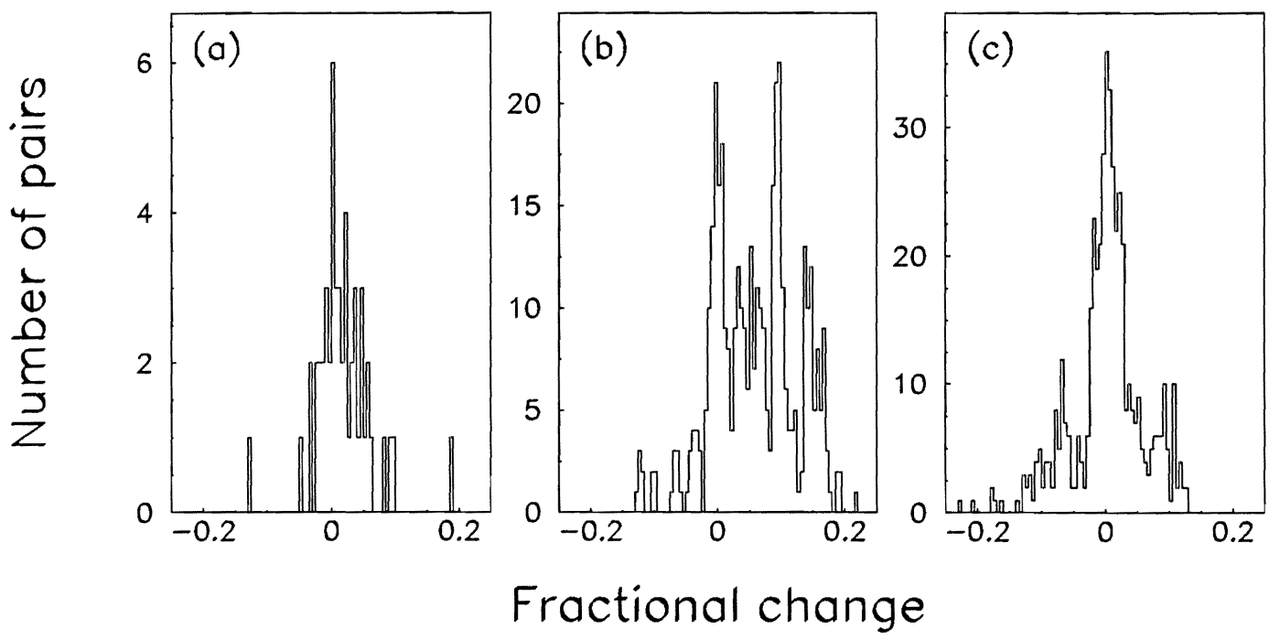
TABLES

TABLE I. Numbers of pairs of SD bands in the $A{\sim}150$ region when *all (a)* bands in nucleus X with mass A_X are compared with *all (a)* bands (rows 1 and 3) in the reference nucleus Y with mass A_Y. The notation $A_Y \neq A_X$ means that bands belonging to all different nuclei were analyzed. The notation $A_Y{=}A_X{-}1$ means that the reference consisted of the band(s) in the adjacent nucleus with one less nucleon. In rows 2 and 4, at least one of the bands is restricted to the *yrast (y)* configuration. The numbers correspond to: (first column) no condition applied; (second column) requiring the resulting standard deviation from the least-squares fit to be smaller than 0.05; and (third column) imposing the additional requirement that selects the identical bands.

$A \sim 150$		no condition	$\sigma < 0.05$	IB's
$A_X(a)$ vs. $A_Y(a)$;	$A_Y \neq A_X$	1250	406 (32%)	73 (6%)
$A_X(a/y)$ vs. $A_Y(y/a)$;	$A_Y \neq A_X$	544	155(28%)	32 (6%)
$A_X(a)$ vs. $A_Y(a)$;	$A_Y{=}A_X{-}1$	369	103 (28%)	19 (5%)
$A_X(a/y)$ vs. $A_Y(y/a)$;	$A_Y{=}A_X{-}1$	140	54 (39%)	17 (12%)

TABLE II. Same as Table I except for the mass $A \sim 190$ region.

$A \sim 190$		no condition	$\sigma < 0.05$	IB's
$A_X(a)$ vs. $A_Y(a)$;	$A_Y \neq A_X$	790	481 (61%)	92 (12%)
$A_X(a/y)$ vs. $A_Y(y/a)$;	$A_Y \neq A_X$	479	268 (56%)	37 (8%)
$A_X(a)$ vs. $A_Y(a)$;	$A_Y{=}A_X{-}1$	333	197 (59%)	26 (8%)
$A_X(a/y)$ vs. $A_Y(y/a)$;	$A_Y{=}A_X{-}1$	182	96 (53%)	7 (4%)


(a)
(b)
(c)
Number of pairs
Fractional change
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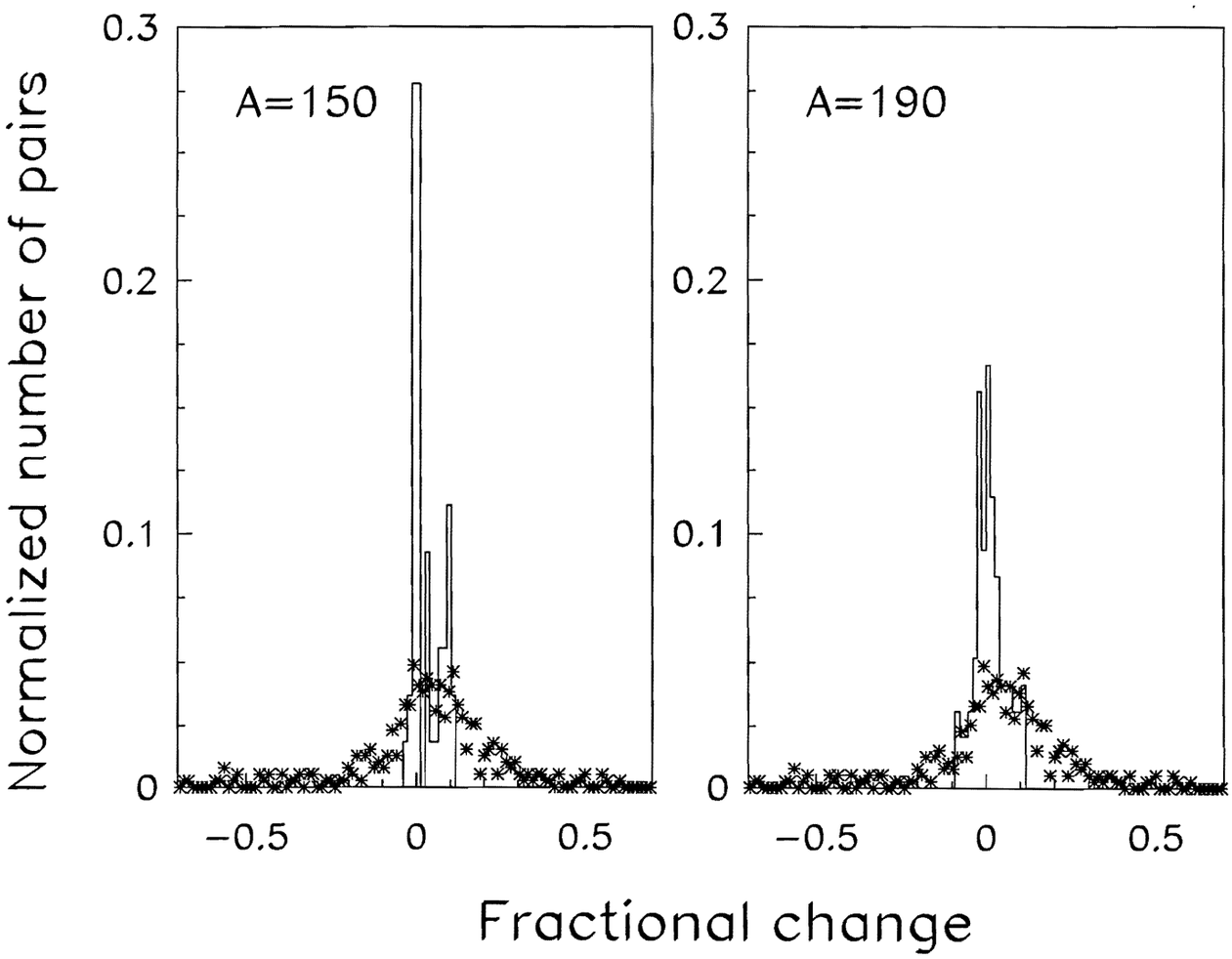
4
6
0
5
10
15
20
0
10
20
30
−0.2
0
0.2


A=150
A=190
Normalized number of pairs
Fractional change
0.3
0.2
0.1
0
−0.5
0
0.5