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SHAPE COEXISTENCE AND ITS CAUSE IN ^{151}Gd*

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Abstract:

The $(\alpha,3n\gamma)$ reaction has been used to study the level structure of ^{151}Gd. Energy spacings and other information indicate a small deformation for the observed $i_{13/2}$ decoupled band; whereas, a large prolate deformation is indicated by the normal rotational band associated with the $h_{11/2}$ hole excitation. A simple explanation for these two shapes in ^{151}Gd is given, based on the Nilsson diagram, and the behavior is shown to be related to the well-known shape change occurring between 88 and 90 neutrons.

In order to obtain information about the moment of inertia of a nucleus from energy level spacings, the structure of the levels must be clear and reasonably simple. It has been pointed out that under certain conditions a system consisting of a single particle (or hole) with pure j coupled to an axially symmetric rotor gives rise to a particularly simple spectrum.[1-3] Specifically, for prolate deformations of intermediate size, a single-particle-plus-rotor system develops a band with spin sequence j, j+2, j+4, ··· and energy spacings equal to those in the ground-state band of the even-even core; whereas, a single hole coupled to such a rotor gives rise to a normal rotational band built on the state with $I = j$, having members with $\Delta I = 1$ and energy spacings approaching $I(I + 1)$ at moderately large deformations. An odd-A nucleus with the Fermi surface below (or above) the entire group of Nilsson orbitals that originate in a high-j unique parity spherical state very nearly constitutes such a particle- (or hole-) plus-rotor system, and thus the energy spacings of the lowest-lying band associated with the particular high-j shell can provide rather unambiguous information on the moment of inertia of that odd-A nucleus.

In ^{151}Gd, which has five neutrons beyond the N = 82 closed shell, the Fermi surface lies well outside both the $i_{13/2}$ and $h_{11/2}$ unique parity shells, which makes the interpretation of the bands associated with these excitations particularly unambiguous. From a study of these bands we determined the moments of inertia of ^{151}Gd in these two configurations, and the results suggest a marked difference in deformation between the two bands.

The experiments consisted of in-beam γ-ray measurements following the ^{150}Sm (α,3n) reaction. An enriched metallic ^{150}Sm target (≈ 10 mg/cm^2 thick)

was bombarded with 35-45 MeV α-particles provided by the Berkeley 88" cyclotron. The γ-ray measurements included excitation function and angular distribution studies, as well as γγ coincidence measurements. The coincidence and angular distribution data identified a strongly populated cascade of stretched E2 transitions based on a level at 851 keV, establishing a band with states having $\Delta I = 2$. About 25% of the γ-decay proceeds through this band. A second, weakly populated band (5% of the γ-decay) based on a level at 1210 keV was also identified. This latter band has very recently been seen in an independent (α,xnγ) experiment.[4] Observation of crossover as well as cascade transitions clearly establishes the $\Delta I = 1$ sequence for these band members, and their approximate I(I + 1) energy spacings suggest a normal rotational character. The remaining de-excitation intensity proceeds through a series of negative parity levels probably associated with the $f_{7/2}$ and $h_{9/2}$ shells. A partial level scheme for ^{151}Gd showing the bands and their prominent modes of decay is given in Fig. 1.

The ground-state spin of ^{151}Gd has recently been measured[5] to be 7/2, and the band-head spins assigned in Fig. 1 are in accord with the γ-ray data. They are independently supported by the results from an earlier ^{152}Gd(d,t)^{151}Gd experiment.[6] In that study high-ℓ transfer cross sections were observed with 7 and 29 μb/sr (at 90°) going to levels at 847 and 1204 keV, respectively, which we attribute to the two band heads established in the present experiment. The large cross section at 1204 keV excitation strongly suggests that it is associated with the $h_{11/2}$ hole state. The much smaller transfer cross section to the 847 keV level is compatible with an $i_{13/2}$ particle character for that excitation. These cross sections are in agreement with the predictions of the particle-rotor model as discussed below.

The band based on the level at 851 keV is analogous to similar decoupled bands recently identified in the odd-A lanthanum nuclei,[7] in that the level spacings very closely resemble those of the neighboring even isotopes (Fig. 2). It was already indicated in the heavier lanthanum isotopes that the decoupled-band energy spacings follow those of the even-even ground band even if the latter deviate significantly from the I(I + 1) spacings of a perfect rotor. This is also demonstrated by the $13/2^+$ band in ^{151}Gd, and by a similar decoupled $13/2^+$ band in ^{149}Gd identified in a parallel experiment (cf. Fig. 2 and Ref. 8). Using the very general empirical relationship[9] between the 2^+ energies and the E2 transition lifetimes, which essentially all even-even nuclei follow, we can estimate[1] the deformation β as:

$$\beta \approx \sqrt{\frac{1225}{A^{7/3} \cdot 6(\hbar^2/2\mathfrak{J})}} \quad , \qquad (1)$$

where $\hbar^2/2\mathfrak{J}$ is in MeV. For the $13/2^+$ decoupled band in ^{151}Gd we have $E_{17/2 \rightarrow 13/2} = 6(\hbar^2/2\mathfrak{J}) = 0.493$ MeV, which gives $\beta_{13/2} = +0.14$.

The negative-parity band based on the 1210 keV $11/2^-$ hole state is analogous to similar bands observed in several odd-N rare-earth nuclei around N = 91. The level energies for this band, based on a single hole in the high-j shell, are predicted to approach $\hbar^2/2\mathfrak{J}$ times I(I + 1), as mentioned above. The absence in the observed energies of an oscillating term suggests that the $11/2^-$ band in ^{151}Gd is rather close to that limit. From the first level spacing $E_{13/2 \rightarrow 11/2} = 13(\hbar^2/2\mathfrak{J}) = 0.252$ MeV we calculate, with Eq. (1), $\beta_{11/2} = +0.29$. This value would be lowered by 5-10% if the Coriolis mixing were taken into account.

From the remaining negative parity states no definite conclusions on the moment of inertia can be drawn at present. These levels also exhibit a band-like pattern, but the occurrence of a very fast $11/2^- \rightarrow 11/2^-$ transition clearly indicates that the $h_{9/2}$ and $f_{7/2}$ shells both contribute heavily to the level wave functions, which greatly complicates the analysis. Such strongly-mixed wave functions are indeed expected; Nilsson model calculations give rather complete mixing of these two j-values at deformations as low as $\beta \approx 0.1$.

The occurrence of the two different deformations derived from the $11/2^-$ and $13/2^+$ bands is a very unusual result. Our conclusions so far are based on the moment-of-inertia parameters extracted from rotational energy spacings, which we expect to be especially reliable in these particular bands as discussed above. Independent support for these deformations comes from the single-neutron pickup cross sections[6] for the two band heads, and from energy systematics in this region.

From the data in Ref. 6 we deduce the spectroscopic strengths, $S_{11/2} = 0.18 \pm 0.06$ (2j+1) or $C^{eff}_{11/2} = 1.1 \pm 0.3$, and $S_{13/2} \geqslant 0.61$ (2j+1) or $C^{eff}_{13/2} \geqslant 4.3$. For this estimate we have used $\Delta(^{152}Gd) = 1.08$ MeV and assumed a 30% uncertainty in the experimental cross sections. As the deformation of ^{152}Gd is between those of the $11/2^-$ and $13/2^+$ configurations in ^{151}Gd we have assumed a unity overlap integral between the target and final nuclear wave functions. In the particle-rotor model these values give the deformations, $\beta_{11/2} \geqslant 0.23$ and $-0.10 < \beta_{13/2} < +0.15$, in agreement with the results obtained from the energy spacings in the bands.

A comparison with the energy systematics of particular 0^+ bands in the even-even nuclei, which is shown in Fig. 2, gives further support for our interpretation. First, it can be seen that the $13/2^+$ decoupled-band energy spacings in ^{151,149}Gd (N = 87,85) follow rather closely those of the even-even ground bands. Secondly, Fig. 2 also shows the energy spacings of bands built on excited deformed 0^+ states. Such deformed states have been identified[10,11] in the N = 86 and 88 isotopes of Gd and Sm by two-neutron pickup studies, and in some cases the associated 2^+ and 4^+ rotational states are also known. The correlation of the $2^+ \rightarrow 0^+$ separation in this band with the $13/2^- \rightarrow 11/2^-$ separation in the 11/2 |505| band seems likely to be significant. We note, however, that the moment-of-inertia parameters for the 11/2 |505| bands are distinctly larger than those of the deformed 0^+ bands, particularly for the lower-mass isotopes.

The very different deformations in ^{151}Gd resulting from a single neutron in the $i_{13/2}$ shell or a single hole in the $h_{11/2}$ shell may be qualitatively understood in terms of the Nilsson diagram. Figure 3 shows the portion of the diagram around the N = 82 closed shell. Occupation of the 11/2 |505| orbital with its strong upward slope will favor a spherical nuclear equilibrium shape, whereas the orbitals immediately above N = 82 generally slope downwards and thus favor deformation. In its ground state ^{151}Gd has two pairs and the odd particle occupying the down-sloping orbitals above N = 82. Promotion of the odd neutron from the ground-state orbital to the lowest $i_{13/2}$ orbital represents a promotion from a moderately down-sloping orbital to a similar down-sloping orbital. Such a change in occupation should leave the nuclear deformation relatively unaffected. In the $11/2^-$ configuration, however,

a neutron has been lifted above the N = 82 gap. The nucleus now has three pairs in the down-sloping orbitals and the 11/2 |505| orbital has become 50% unoccupied. Both consequences of this rearrangement produce a very strong tendency towards deformation.

The considerable difference in ground-state deformation of even-even nuclei observed as one goes from 88 to 90 neutrons was first theoretically interpreted by Mottelson and Nilsson[12] as a consequence of the similar transfer of a pair of neutrons from the 11/2 |505| orbital to the down-sloping orbitals above the 82 shell. We would assume that the excited deformed 0^+ states, in the N < 90 nuclei, similarly involve, to a considerable extent, the removal of a neutron pair from the 11/2 |505| Nilsson orbital. However, this mechanism is complicated in the even-even nuclei by the pairing correlations which smear out the occupation probabilities. The uncertainty is reduced in an odd-A nucleus, where the presence of an odd particle unambiguously determines a 50% occupation probability. Thus, whereas it is difficult to specify the configuration of the deformed 0^+ states in these even-even nuclei, the connection of a specific orbital to the deformed shapes is clear in an odd-A nucleus like ^{151}Gd.

This more detailed picture of the origin of shape coexistence in an odd-A nucleus might provide the means to identify similar phenomena in other regions of the nuclear chart. Bands similar to those in ^{151}Gd should generally appear whenever the nuclear potential is soft towards β-deformation and the Fermi surface lies between two spherical j-shells, and recently identified[13,14] bands in ^{45}Sc and ^{75}Se might be interpreted in this way.

FOOTNOTES AND REFERENCES

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†On leave from Physik Department, Technische Universität, München, Germany.

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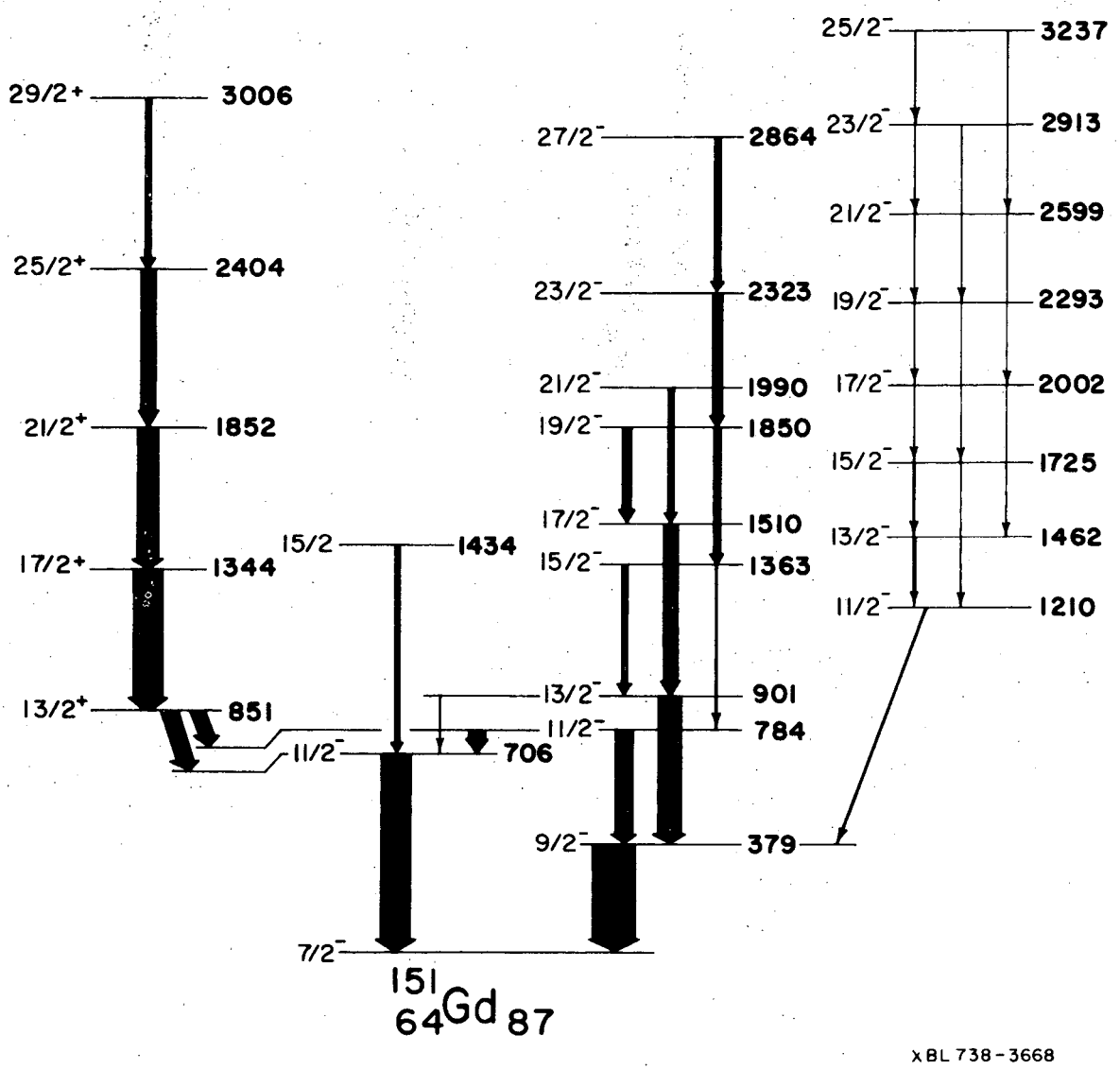
FIGURE CAPTIONS

Fig. 1. The level scheme of ^{151}Gd.

Fig. 2. Energy systematics of selected rotational states in the N = 88 region. The solid and dashed lines show the energy separations in the ground and excited 0^+ bands in the even-even Gd and Sm nuclei (see Ref. 8). The circles show the analogous separations in the $i_{13/2}$ decoupled bands in ^{149}Gd and ^{151}Gd. This band in ^{149}Gd is reported in Ref. 8, and has members: I^{π} (E in keV); $13/2^+$ (955); $17/2^+$ (1739); $21/2^+$ (2400); and $25/2^+$ (3292). The triangles and dotted line show the 13/2 to 11/2 separation in the $11/2^-$ |505| bands in odd-A Gd and Dy nuclei.

Fig. 3. Nilsson diagram for the N = 82 region. The inserts show the intrinsic configurations of the $13/2^+$ and $11/2^-$ band heads at $\beta \approx 0.14$, where the Fermi levels, λ, are estimated to be those calculated for N = 86 and N = 88, respectively.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25/2+ 2404
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17/2+ 1344
13/2+ 851
15/2 1434
11/2- 706
7/2-
27/2- 2864
23/2- 2323
21/2- 1990
19/2- 1850
17/2- 1510
15/2- 1363
13/2- 901
11/2- 784
9/2- 379
25/2- 3237
23/2- 2913
21/2- 2599
19/2- 2293
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11/2- 1210
151 64 Gd 87
XBL 738-3668

Fig. 1

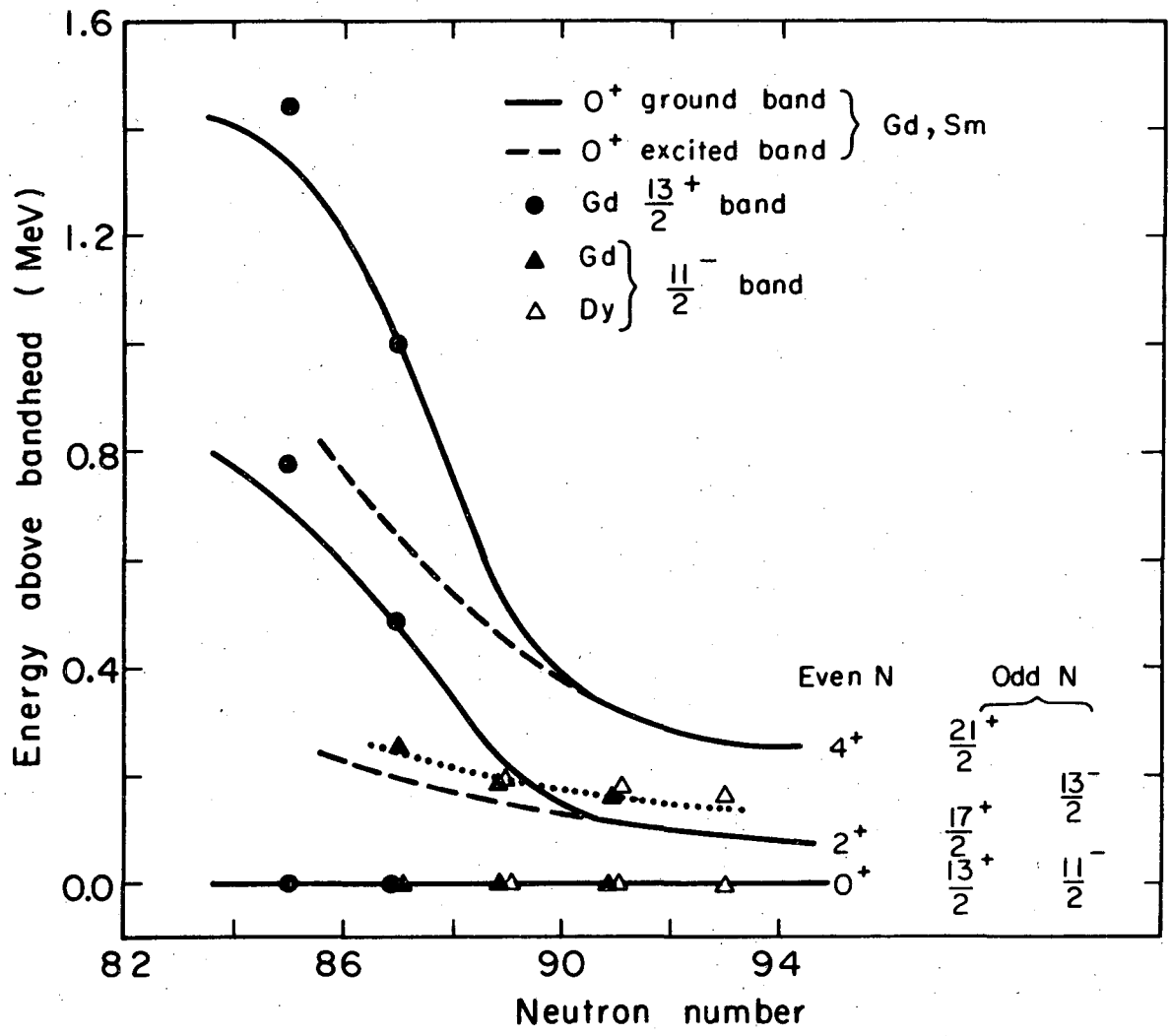

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Fig. 2

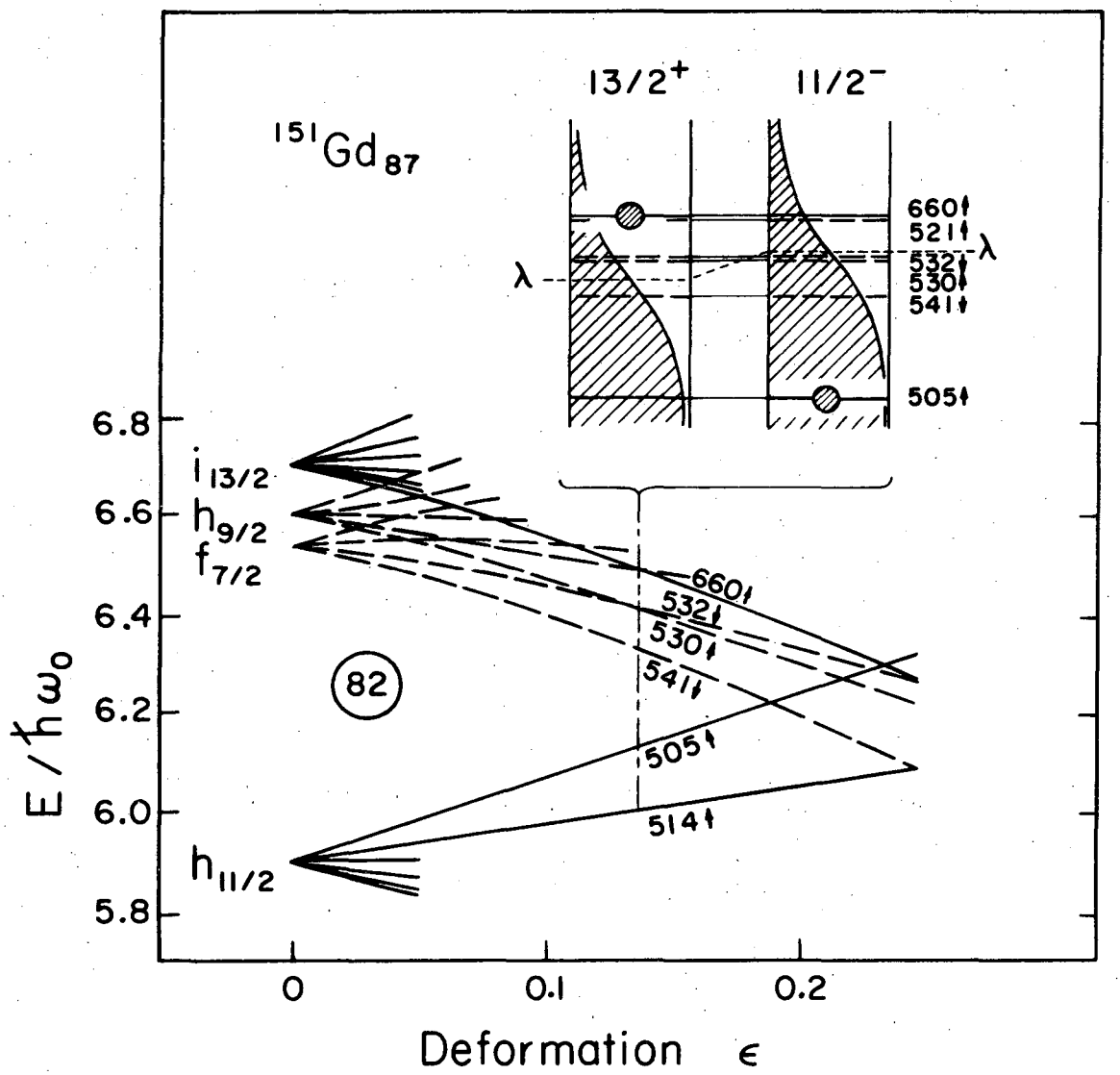

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Fig. 3

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