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HIGH-SPIN CONFIGURATIONS IN  $^{147}\text{Gd}$  FROM ALIGNMENT OF SEVEN,  
NINE, AND ELEVEN PARTICLES

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Abstract

Detailed spectroscopic studies of the discrete  $\gamma$ -rays feeding the 550-ns isomer at 8.590 MeV in  $^{147}\text{Gd}$  are reported. The resulting decay scheme indicates single-particle nature of the states up to the highest observed spin  $79/2\text{ h}$  at 16.938 MeV of excitation energy. Comparison with Deformed Independent Particle Model calculations makes it possible to suggest configuration assignments to many of the levels. Five neutrons and six protons with their angular momenta aligned form the highest yrast states.

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## 1. Introduction

The regular rotational spectra of well deformed nuclei and the irregular ones of spherical shell-model nuclei exemplify two radically different ways of accommodating angular momentum in nuclei. In prolate deformed nuclei large amounts of angular momentum are accommodated with a minimum cost in excitation energy through collective rotational motion, while in spherical or oblate deformed nuclei it is achieved by alignment of the orbital angular momenta of the least bound (valence) nucleons<sup>1)</sup>. The two schemes are, however, not mutually exclusive. Pure collective rotation becomes uneconomic at high rotational frequencies, and single-particle angular momentum begins to contribute to the total spin through the mechanism of rotational alignment<sup>2)</sup>. Similarly, alignment of valence nucleons in a shell-model nucleus is equivalent to the formation of a "Saturn ring" of orbiting particles which induce macroscopic oblate deformations thereby opening the possibility for collective motion. One might therefore expect the two mechanisms for generating angular momentum to play their role in a cooperative fashion. Pure yrast spectra of either single particle or collective type should be rare.

This report presents results from  $^{147}\text{Gd}$  with  $N=83$  where the yrast angular momenta are constituted exclusively by alignment of single particles. Although five aligned nucleons suffice to generate a macroscopic (oblate) deformation with  $\epsilon = (-) 0.18$  and spin  $49/2$ ,<sup>3)</sup> the yrast structure up to spin  $79/2$  at almost 17 MeV of excitation is dominated by further alignment of nucleons involving altogether eleven aligned particles.

## 2. Experimental technique

The levels of  $^{147}\text{Gd}$  were populated by the  $^{122}\text{Sn}(^{30}\text{Si},5n)$  reaction with beams from the Argonne superconducting linac. Bombarding energies of 145, 153 and 161 MeV were used for a rough excitation function. The target had a thickness of 1  $\text{mg}/\text{cm}^2$   $^{122}\text{Sn}$  evaporated onto a  $50 \text{ mg}/\text{cm}^2$  foil of  $^{208}\text{Pb}$  thus stopping the recoiling evaporation residues within 2 ps. The results presented here were obtained at 153 MeV where the maximum angular momentum to the compound nucleus is 64  $\hbar$ , and the Q-value favours the 5n channel at the highest spins. At this energy an analysis of the singles spectra measured at  $55^\circ$  shows that the 550 ns isomer is populated with a probability which is 80% of the total channel yield. This high yield, and the fact that neighbouring nuclei do not have long-lived isomers, makes the  $T_{1/2} = 550 \text{ ns}$ ,  $I = 49/2 \hbar$  isomer at 8.590 MeV in  $^{147}\text{Gd}$  a unique case for studying yrast levels at even higher spins. By a pulsed beam technique it was required that the transitions observed from the decay of the compound nucleus were followed by several delayed transitions. The  $^{147}\text{Gd}$  reaction channel then comes out clearly, and a separation of the transitions for  $I > 49/2 \hbar$  from the complex decay<sup>4,5)</sup> between this level and the ground state is obtained.

The experimental setup consisted of four large Ge(Li) detectors at angles  $\mp 30^\circ$ ,  $150^\circ$  and  $210^\circ$  and an array of 14 NaI(Tl) detectors covering 47% of  $4\pi$ . A valid event was defined as a two-fold Ge coincidence within a beam burst followed by a two- or higher-fold delayed event recorded in the NaI-array. More than 30 million events of this type,

which starts the spectroscopy at spin  $49/2$  h, were recorded.

In a subsequent experiment employing the same delayed trigger technique and the same target, angular distributions of the  $\gamma$ -rays feeding the  $I = 49/2$  h level were measured over the angles  $0^\circ$ ,  $23^\circ$ ,  $45^\circ$ ,  $60^\circ$  and  $90^\circ$ . A single gamma-x detector (17%) surrounded by a symmetric anti Compton shield, made from bismuth germanate, replaced the four Ge(Li) counters in this measurement. The distance between the target and the surface of the gamma-x crystal was 10 cm.

Finally, spectra were measured at  $0^\circ$  with the same counter arrangement but with a special  $300 \text{ } \mu\text{g}/\text{cm}^2$  self-supporting  $^{122}\text{Sn}$  target foil. From this target the recoiling evaporation residues could fly freely for 125 and 600 ps, and the spectra were analyzed for Doppler-shift effects.

### 3. Results

The selectivity of the experimental technique is illustrated in fig.1. The upper panel shows the spectrum of all  $\gamma$ -rays following the  $^{122}\text{Sn} + ^{30}\text{Si}$  reaction at 153 MeV while the middle and lower panels show the feeding and the depopulating lines, respectively. The highly improved peak to background ratios also include the effect of the anti Compton shield.

Comparisons of the  $0^\circ$  spectra obtained with the different target arrangements show that all the observed  $\gamma$ -rays are emitted later than 2 ps, but for transitions above  $I = 59/2$  h earlier than 125 ps after fusion. This is a strong indication that all  $\gamma$ -rays are of single-particle nature because a typical rotational cascade of stretched E2 transi-

tions terminating with a  $E_{\gamma} > 500$  keV transition at about spin 25 h is emitted within less than 2 ps. This result is corroborated by analysis of the  $\gamma$ - $\gamma$  coincidence spectra which shows no evidence of regular sequences of rotational transitions. In addition only few lines are found to have the angular distribution typical of stretched E2 transitions.

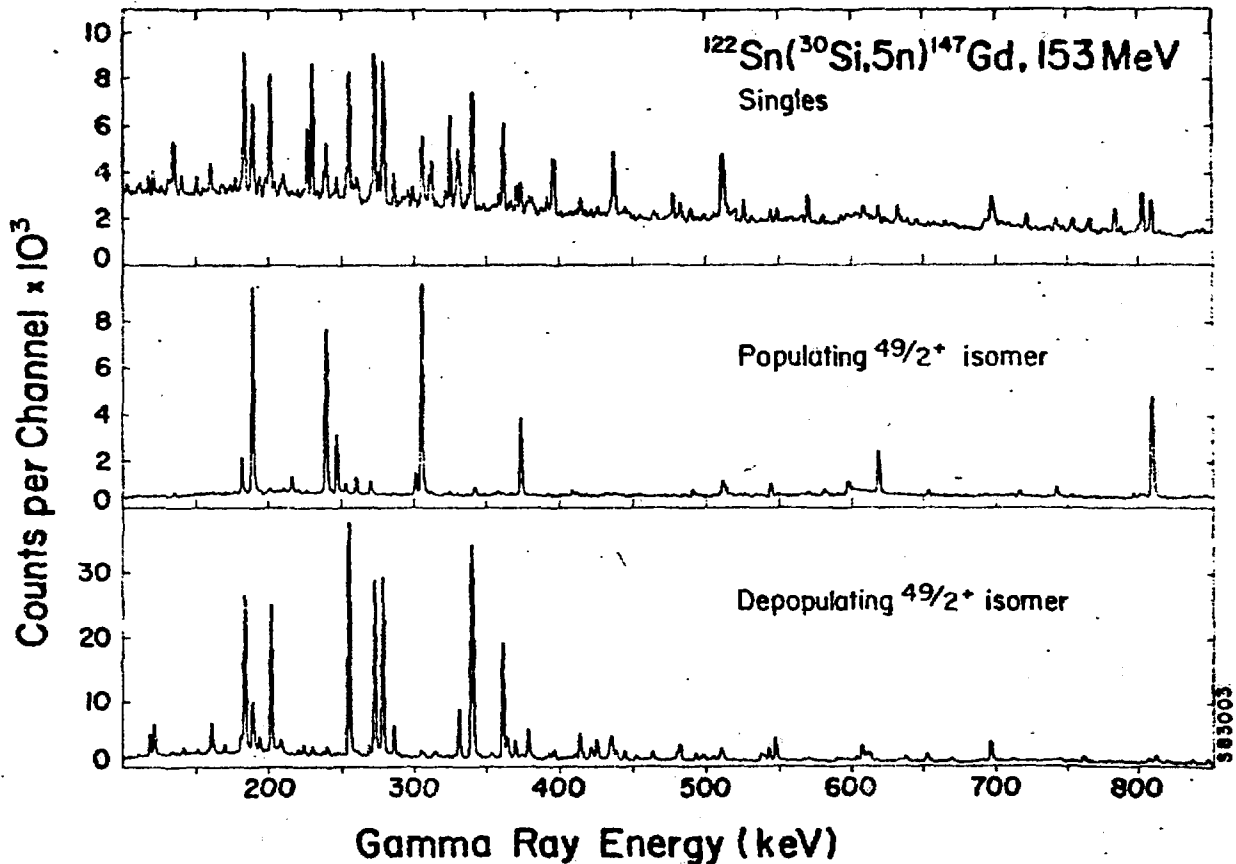


Fig.1. Spectra at  $0^\circ$ . The upper panel is a pure singles spectrum. The middle panel shows  $\gamma$ -rays preceding the delayed trigger and prompt with respect to the beam. The lower panel shows the  $\gamma$ -spectrum in the beam off period and in coincidence with the delayed trigger. The two lower spectra are Compton suppressed.

Fig.2 shows the main features of the decay based on the coincidence and angular distribution measurements. Selected examples of the angular distributions are shown in fig.3.

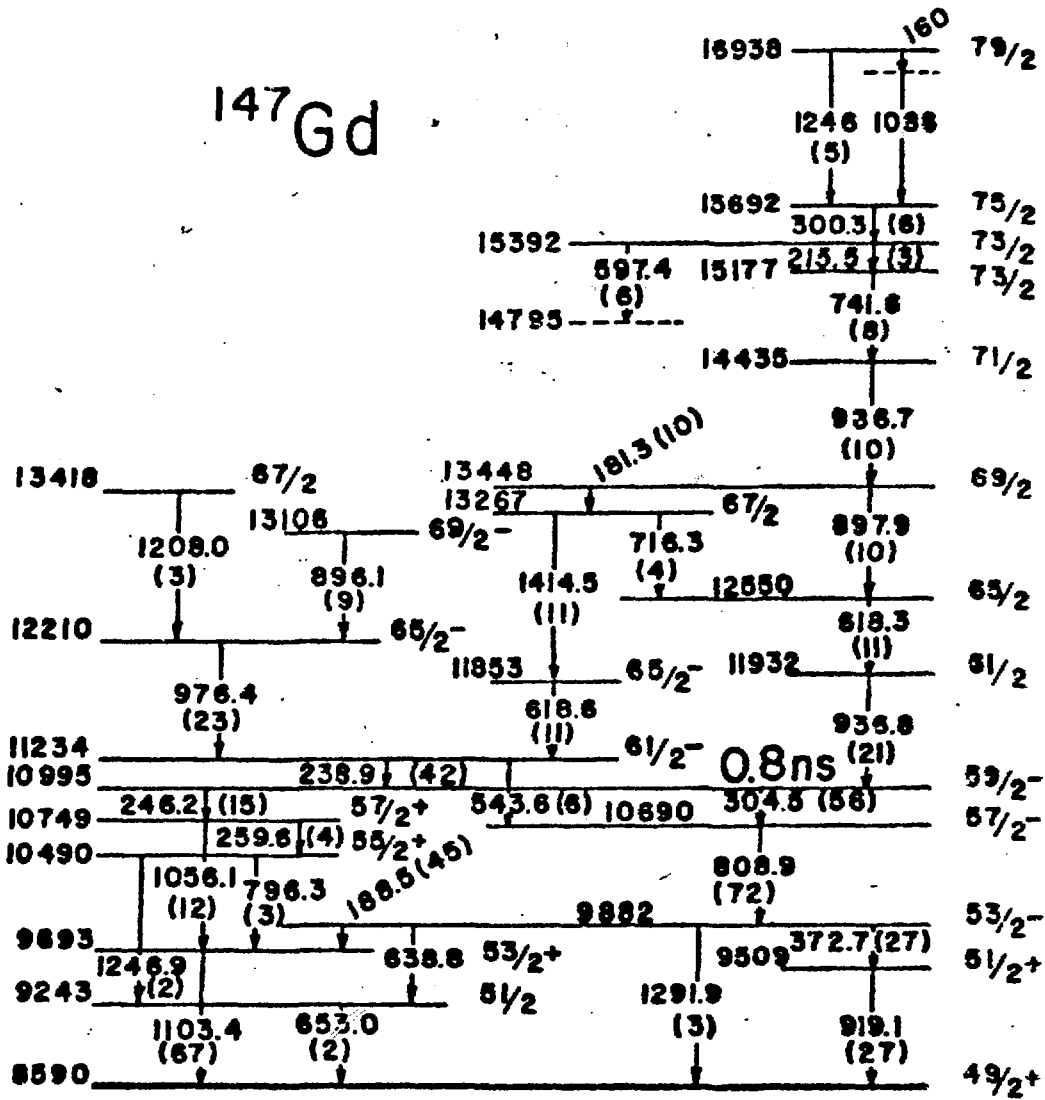


Fig. 2. Partial level scheme of  $^{147}\text{Gd}$  beyond 8.590 MeV. The levels below are shown in refs. 4 and 5. The intensities are not corrected for internal conversion.

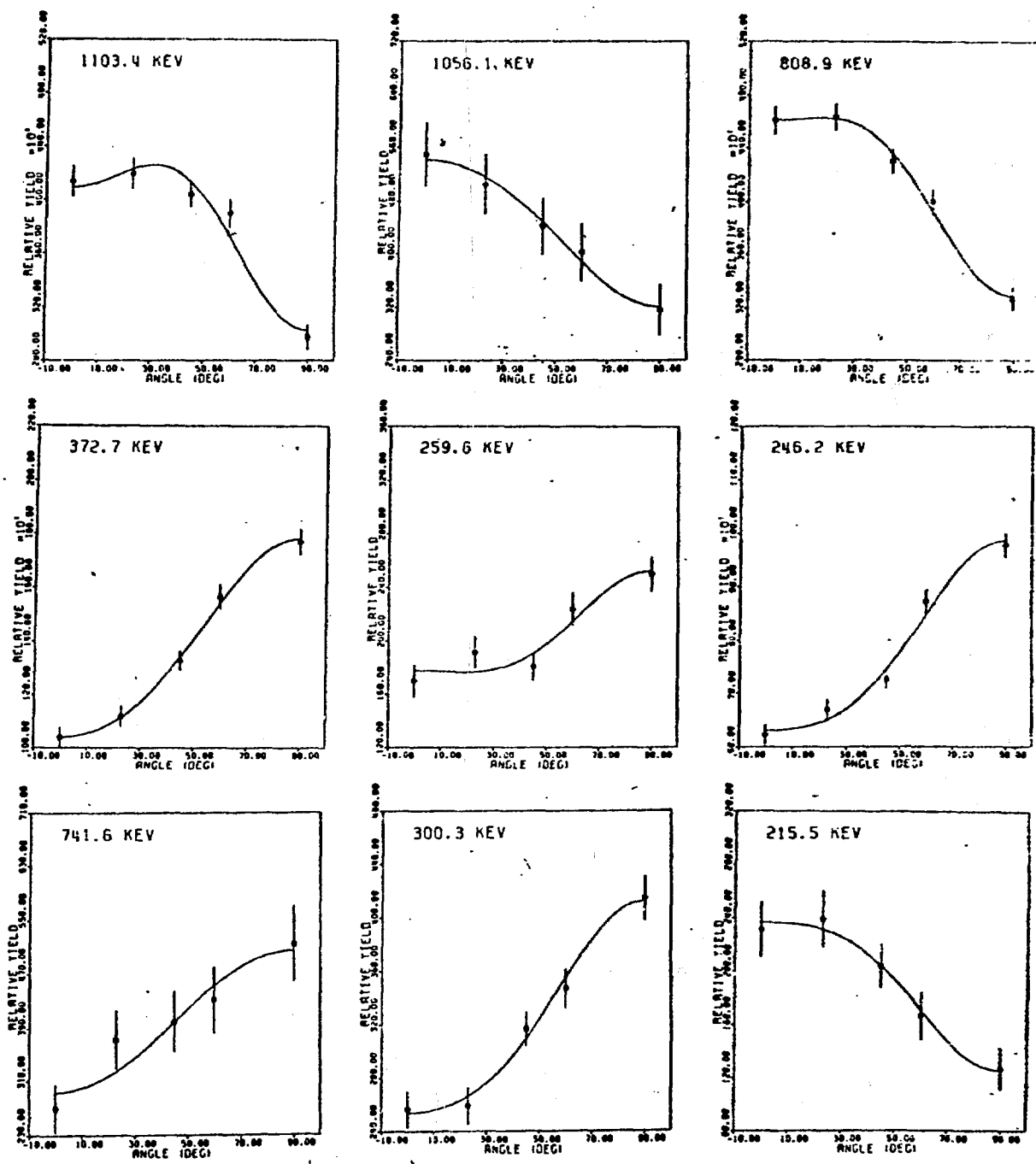


Fig.3. Angular distributions of selected transitions in  $^{147}\text{Gd}$ . Note that the 3 lower transitions are at  $I > 71/2$  with intensities  $< 8\%$ .

#### 4. Discussion

The level structure from  $49/2^+$  to the  $59/2^-$  level at 10.995 MeV agrees with the results of ref. <sup>6)</sup>. Beyond spin 69/2 a drastic decrease in the  $\gamma$ -ray intensity with increasing spin is observed. This appears to be connected with a strong dispersion of the cascade pattern above this spin in analogy with previous observation at lower spins in neighbouring nuclei<sup>7)</sup>.

Spin and parity assignments come from the angular distributions assuming stretched cascades. Consistency within loops in the decay scheme, where strong, pure  $\lambda=2$  transitions (1103.4, 1056.1 and 808.9 MeV) and pure  $\lambda=1$  transitions (246.2, 372.7 and 259.6 keV) are the main building bricks, provide the spin and parity assignments up to the  $59/2^-$  isomeric level at 10.995 MeV. The pure  $\lambda=1$  238.9 keV transition and the  $\lambda=2$  543.6 keV with a half life of  $\sim 25$  ps, ref. <sup>6)</sup>, assigns  $61/2^-$  to the 11.234 MeV level. Both the 976.4 and the 618.6 keV doublet are pure  $\lambda=2$  with half lives <sup>6)</sup> that exclude M2 and assign  $65/2^-$  to both the 11.853 and the 12.210 MeV levels.

Parity assignments to the levels beyond these have not been possible because of the M1/E1 ambiguity in the  $\lambda=1$  angular distributions. The 215.5 keV transition at  $I=73/2$  h is either an unstretched dipole or a stretched quadrupole transition, but an E2 transition would imply  $t_{1/2}(s.p.) \sim 10$  ns which is not observed and leaves  $\lambda=1$  ( $\Delta I=0$ ) as the only choice.

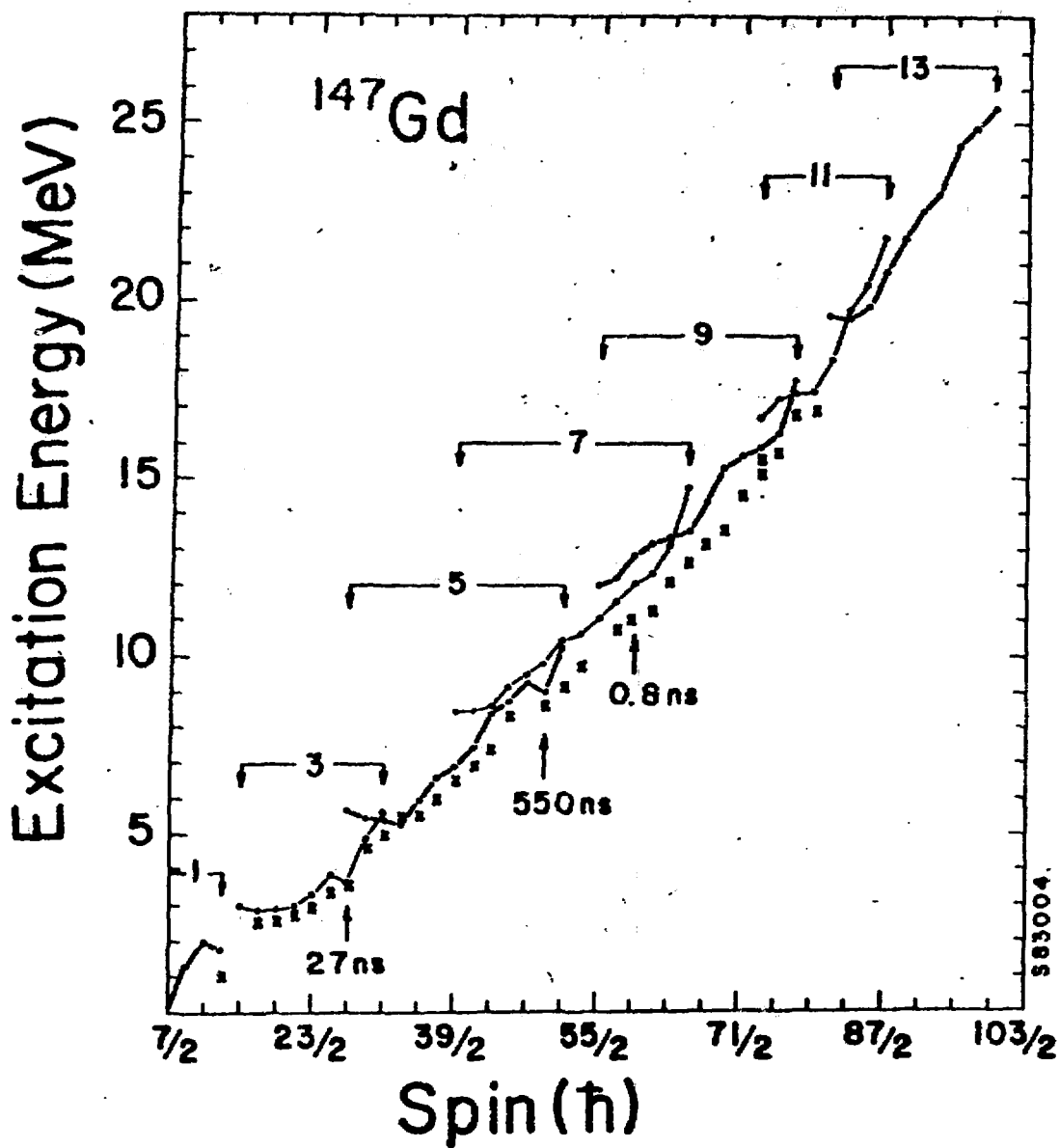


Fig.4. Comparison of the observed yrast level sequence from ref.4 and the present work with model calculations by T. Døssing et al.<sup>8)</sup>.

Fig.4 is a comparison of the observed yrast<sup>4</sup> level sequence with the results of a model calculation of Døssing, Neergaard and Sagawa<sup>8)</sup>. It is a Deformed Independent Particle Model calculation with inclusion of pairing, where the effect of further residual interaction is described in terms of a deformation of the binding field. The minimum energy and the deformation of each trial configuration is determined varia-

tionally. This model is expected to be particularly realistic in describing the stretched configurations. The numbers of (more or less stretched) particles contributing to the various segments of the theoretical yrast line are indicated on fig.4. From spin 49/2 these configurations are oblate deformed with  $\epsilon$  typically around -0.2, whereas at lower spins they are nearly spherical.

As one sees from fig.4, there is rather good agreement between calculated and experimental yrast energies. In order to see whether the agreement extends to the actual configurations of the states, we have made a detailed analysis of the transition rates and branching ratios of the gamma rays feeding the 49/2 isomeric state, which we assume to have the  $\nu(f_{7/2}h_{9/2}i_{13/2})\pi(h_{11/2})^2$  stretched configuration. The lifetime measurements of ref.<sup>6)</sup> have been included in this analysis.

On this basis we suggest that the level sequence  $51/2^+$ ,  $53/2^+$ ,  $55/2^+$  and  $57/2^+$  terminating at 10.749 MeV has the multiplet structure

$$\nu(f_{7/2}h_{9/2}i_{13/2})\pi(d_{5/2}^{-2}h_{11/2}^2).$$

For the  $51/2^+$  level at 9.509 MeV depopulated by the mixed (M1+E2) 919.1 keV transition we suggest the structure

$$\nu(f_{7/2}h_{9/2}i_{13/2})\pi(d_{5/2}^{-1}g_{7/2}^{-1}h_{11/2}^2).$$

This implies  $\Delta L=2$  and hindrance for  $M1$ , but can explain the 25%  $E2$  admixture for the 919.1 keV transition.

The  $53/2^-$  level at 9.882 MeV we propose as

$$v(f_{7/2}h_{9/2}i_{13/2})\pi(h_{11/2}^2) \otimes 3^-$$

This level decays to the  $49/2^+$  with the mixed ( $M2+E3$ ) 1291.9 keV transition. The reduced transition probability of the  $E3$  is

$$B(E3) = (4\pm 2) \cdot 10^4 e^2 fm^6$$

as compared to the 997.4 keV transition to the ground state

$$(f_{7/2} \otimes 3^- \rightarrow f_{7/2})$$

$$B(E3) = 5.6 \cdot 10^4 e^2 fm^6$$

Intrinsic configuration assignments beyond these levels become increasingly speculative, but the pure 808.9 keV stretched  $E2$  and the 0.8 ns half life of the 10.995 MeV level suggests

$$57/2^- : v(f_{7/2}i_{13/2}^2)\pi(d_{5/2}^{-2}h_{11/2}^2)$$

and

$$59/2^- : v(f_{7/2}h_{9/2}i_{13/2})\pi(g_{7/2}^{-1}h_{11/2}^3)$$

or

$$v(f_{7/2}h_{9/2}i_{13/2})\pi(d_{5/2}^{-1}h_{11/2}^3)$$

to the 10.690 MeV and 10.995 MeV levels respectively.

At the highest spins as much as 11 particles, 5 neutrons and 6 protons, are contributing, and the structures are probably of the type

$$\nu(d_{3/2}^{-1}f_{7/2}h_{9/2}i_{13/2}^2)\pi(d_{5/2}^{-3}h_{11/2}^3).$$

Recent calculations by Chasman<sup>9)</sup> have also been compared to the data, and the good agreement of these independent predictions of level spins and energies suggests that unique structure assignments will be possible near spin 40 and 17 MeV of excitation energy when more spectroscopic details are obtained.

## 5. Conclusion

The main result of this study is the experimental identification of yrast states of very high spin values with excitation energy reaching approximately 17 MeV. There is no indication of collective motion contributing to the buildup of the total angular momentum. On the contrary, the gamma-decay pattern remains typical of emission from single-particle excited states. This is in contrast to studies of unresolved  $\gamma$ -spectra<sup>10)</sup> at these and higher spins which include transitions above the yrast line and suggest the presence of collective structures. The yrast energies measured in the present work agree on the average with the energies expected for a system of independent nucleons with oblate deformation  $\epsilon = -0.2$  and with the spin pointing parallel to the symmetry axis. The highest observed state appears to result from the alignment of eleven nucleons, five neutrons and six protons.

The nucleus  $^{147}\text{Gd}$  thus offers an example of "rotation" of a fermion system, where the entire angular momentum is carried by the least bound particles orbiting in same plane around the core, inducing a considerable oblate deformation.

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