# Identification of the $K^{\pi}=8^{-}$ rotational band in $^{138}$Gd

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A $K^{\pi}=8^{-}$ collective rotational band has been established upon the 6 $\mu$s isomeric state in the very neutron-deficient nucleus $^{138}$Gd. The band was observed using a technique involving the correlation of $\gamma$-ray transitions across the isomeric state. The single-particle configuration of the isomer has been deduced from the $\Delta I=2$ to $\Delta I=1$ intensity branching ratios. In addition, a series of other $\gamma$-ray transitions were observed which are reasoned to be part of a higher-lying four quasiparticle structure which decays through the $K^{\pi}=8^{-}$ isomeric state. The properties of the $K^{\pi}=8^{-}$ band are discussed in relation to the systematic properties of $K^{\pi}=8^{-}$ bands in the neighboring $N=74$ isotones. [S0556-2813(98)06608-4]

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## I. INTRODUCTION

High-$K$ multiquasiparticle isomers are a general feature of the midshell nuclei in the mass 170–180 region of the nuclear chart [1]. These $K$ isomers exist because of the large number of high-$\Omega$ orbitals around the $Z=72$–74 proton Fermi surface ($K$ is the projection of the total intrinsic angular momentum onto the nuclear symmetry axis of a deformed nucleus). As a consequence of the charge independence of the nuclear force, similar high-$K$ states are known to exist in the mass 130–140 region which are based upon the $N=72$–74 neutron orbits. For example, $K^{\pi}=8^{-}$ isomeric states are known in all of the even-even $N=74$ isotones, $^{128}_{54}$Xe [2], $^{130}_{56}$Ba [3], $^{132}_{58}$Ce [4], $^{134}_{60}$Nd [5], $^{136}_{62}$Sm [6], and $^{138}_{64}$Gd [7] with half-lives ranging from nanoseconds (Xe) to milliseconds (Ba,Ce). The half-lives of these states are a result of the $K$-selection rule which implies that $\gamma$-ray transitions involving large changes in $K$ are hindered [8]. Although the decay mode of these mass 130–140 isomeric $K^{\pi}=8^{-}$ states generally differs, in $^{130}_{56}$Ba, $^{134}_{60}$Nd, $^{136}_{62}$Sm, and $^{138}_{64}$Gd it proceeds via an $E1$ transition to the $I^{\pi}=8^{+}$ member of the yrast band. However, despite this similar decay mode the $B(E1)$ transition strengths are observed to vary by a factor of $\approx 40$. Reasons for this variation have been suggested to be due to either a change in the underlying structure of the isomeric state itself or that of the yrast $8^{+}$ state to which the isomer decays [7].

The observation of isomeric states, without the observation of the associated rotational band, is generally related to the conditions under which an experiment is performed. For example, in a previous study of $^{138}$Gd [7] a $K^{\pi}=(8^{-})$ isomer with half-life $6\pm1$ $\mu$s was observed. However, because that experiment was only concerned with detecting delayed $\gamma$-ray transitions, which were emitted by isomeric states, no prompt $\gamma$-ray transitions were collected, i.e., the experiment was insensitive to the prompt members of the $K^{\pi}=(8^{-})$ rotational band built upon the isomeric state. The importance of establishing the $K^{\pi}=8^{-}$ rotational band is that it allows the underlying single-particle configuration of the isomer to be confirmed through the $\Delta I=2$ to $\Delta I=1$ $\gamma$-ray intensity branching ratios. As a consequence, the single-particle configuration of the isomeric state in Ref. [7] was not unambiguously deduced. In another study of $^{138}$Gd [9], only prompt data were recorded and even though it might have been possible to observe the transitions in the rotational band it would not have been possible to link the band into the known level scheme.

This paper describes the result of an experiment which populated high-spin states in $^{138}$Gd in order to establish the $K^{\pi}=8^{-}$ rotational band. $^{138}$Gd is the most neutron-deficient $N=74$ nucleus which can realistically be studied using a stable beam and stable target combination with a fusion-evaporation reaction [9]. In this experiment, a $K^{\pi}=8^{-}$ rotational band was established in $^{138}$Gd by using a technique of correlating prompt and delayed $\gamma$-ray coincidences across the 6 $\mu$s isomeric state. From the intensity branching ratios of the prompt transitions in the $K^{\pi}=8^{-}$ rotational band, $|(g_K-g_R)/Q_0|$ values have been extracted which confirm the underlying single-particle configuration of the isomer. In addition, a series of higher-lying transitions was observed which is reasoned, on the basis of the systematics of similar bands in this region, to be associated with a four-quasiparticle structure. These additional transitions also decay through the $K^{\pi}=8^{-}$ two-quasiparticle isomeric state in accordance with the $K$-selection rule [8]. This measurement represents only the fourth case where a rotational band has been observed built upon a $K^{\pi}=8^{-}$ isomeric state in the $N=74$ chain of isotones.

## II. EXPERIMENT

States above the $K^{\pi}=8^{-}$ isomer in $^{138}$Gd were populated with the $^{106}$Cd($^{36}$Ar,$2p2n$) reaction. The target consisted of a single foil of $^{106}$Cd of thickness 550 $\mu$g/cm$^2$. The $\approx 1$ pnA, 180 MeV, $^{36}$Ar beam was supplied by the K130 cyclotron at the University of Jyväskylä, Finland. Prompt $\gamma$ rays were detected with 23 escape-suppressed germanium detectors of the JUROSPHERE spectrometer which consisted of 13 EUROGAM type-I detectors (of relative efficiency $\approx 70\%$) [10] and 10 TESSA-type detectors [11] (of relative efficiency $\approx 25\%$). The total photo-peak efficiency of the JUROSPHERE array was measured to be $\approx 1.5\%$ at 1.3 MeV. The recoiling nuclei were separated from the beam particles by the RITU spectrometer [12] and were implanted into a 80 mm$\times$35 mm silicon (Si) strip detector at the focal plane of RITU. Two EUROGAM-type detectors, without Compton suppression shields, were placed as close as possible to the Si-strip detector in order to detect isomeric or delayed $\gamma$ rays which were emitted from the decay of the $K^{\pi}=8^{-}$ state within $\approx 20$ $\mu$s of a recoiling nucleus being detected in the Si detector.

Data were recorded with the condition that either (a) a single prompt $\gamma$-ray transition was detected in the JUROSPHERE array and a recoiling nucleus was detected in the Si detector, and/or (b) a recoiling nucleus was detected in the Si detector and a delayed $\gamma$ ray was detected up to 20 $\mu$s later in the two EUROGAM detectors at the focal plane. The rate of recoiling nuclei implanted into the Si detector was limited to $\approx 4000$ per second which corresponded to a prompt $\gamma$-$\gamma$ rate of $\approx 500$ per second in the JUROSPHERE spectrometer. In the experiment, a total of $5.6\times10^{5}$ prompt events were correlated with delayed events in $\approx$5–6 days of beam time. Energy and efficiency calibrations were obtained with $^{133}$Ba and $^{152}$Eu radioactive sources which were placed both at the JUROSPHERE target position and at the Si detector position at the focal plane of RITU.

## III. DATA ANALYSIS AND RESULTS

A series of two-dimensional matrices were created and the analysis was performed with the ‘‘UPAK’’ [13] software package. In particular, a recoil-gated $\gamma-\gamma$ matrix was created, which contained only those prompt events which were detected in JUROSPHERE in coincidence with a recoiling nucleus in the Si detector. In this matrix, it was observed that the $\gamma$-ray yrast transitions in $^{138}$Gd corresponded to only $\approx 9\%$ of the total number of events. The other main channels were $^{138}$Sm ($\approx 21\%$), $^{138}$Eu ($\approx 28\%$), $^{137}$Sm ($\approx 14\%$), and $^{139}$Eu ($\approx 8\%$). These data were also sorted into a series of prompt ($\gamma$-ray-detected in JUROSPHERE) versus delayed ($\gamma$-ray-detected at the focal plane) matrices with various time limits, from zero up to three half-lives of the isomeric state ($\approx 20$ $\mu$s), after a recoiling nucleus was implanted into the Si detector.

In order to ascertain which transitions feed the $K^{\pi}=8^{-}$ isomeric state, the prompt versus delayed matrix was used.

TABLE I. The energies and intensities for all of the prompt $\gamma$-ray transitions which were correlated with the delayed transitions from the decay of the $K^{\pi}=8^{-}$ isomeric state in $^{138}$Gd. The errors on the energies and intensities have been deduced from the spread in their distribution in a series of different spectra. The top panel shows the transitions which are placed in the level scheme and the bottom section shows the unplaced transitions which are most likely part of the higher-lying four-quasiparticle bands.

| $E_{\gamma}$ (keV) | Normalized $I_{\gamma}$ (%) | $I_i \rightarrow I_f$ |
|---|---|---|
| | $K^{\pi}=8^{-}$ | |
| 395.5(2) | 100(7) | $(9^{-})\rightarrow(8^{-})$ |
| 414.8(1) | 49(6) | $(10^{-})\rightarrow(9^{-})$ |
| 427.6(1) | 41(5) | $(11^{-})\rightarrow(10^{-})$ |
| 433.0(3) | 40(5) | $(12^{-})\rightarrow(11^{-})$ |
| 810.5(5) | 39(6) | $(10^{-})\rightarrow(8^{-})$ |
| 843.2(5) | 54(14) | $(11^{-})\rightarrow(9^{-})$ |
| 860.7(5) | 23(4) | $(12^{-})\rightarrow(10^{-})$ |
| | Unplaced higher-lying rotational band | |
| 172.6(4) | 27(5) | |
| 208.9(3) | 36(4) | |
| 229.4(6) | 23(4) | |
| 252.6(2) | 39(6) | |
| 260.8(3) | 34(4) | |
| 284.8(4) | 32(4) | |
| 298.5(4) | 12(4) | |
| 342.7(2) | 32(4) | |
| 402.0(2) | 41(5) | |
| 832.4(2) | 58(7) | |

Gates set on the previously observed [9] delayed 220.8-, 384.4-, 489.1-, and 555.6-keV yrast transitions and the delayed 583.2-keV transition in $^{138}$Gd, identified a total of 17 new prompt transitions which feed the $K^{\pi}=8^{-}$ isomeric state. These prompt transitions are listed in Table I and a $\gamma$-ray spectrum is shown in Fig. 1. The prompt $\gamma$ rays in this spectrum appear to form a sequence of *two* rotational bands. The transitions which lie directly on top (with the largest intensity) of the $K^{\pi}=8^{-}$ isomeric state have $M1$ transitions around 396–433 keV with the corresponding $E2$ crossover transitions between 811 and 861 keV. The second band, which lies at higher excitation energy (with a lower intensity) has $M1$ transitions around 173–343 keV. The corresponding $E2$ transitions (which are expected at 440–560 keV) were not observed in this work. The only other new transition in these spectra, which is not expected to be an interband $M1$ or an in-band $E2$ transition, based on the known bands in this region, is the 832.4-keV transition shown in the inset to Fig. 1. In comparison, in $^{136}$Sm [14] there is an 866.8-keV transition which links the low-lying $K^{\pi}=8^{-}$ and higher-lying $K^{\pi}=(12^{+})$ isomeric states. By analogy this is the most likely explanation for the 832.4-keV transition in $^{138}$Gd. Figure 2 shows the partial level scheme, which concentrates on the decay of the $K^{\pi}=8^{-}$ isomeric state in $^{138}$Gd, deduced from this work. It should be noted that there were neither sufficient statistics to perform angular correlations nor to check the coincidence relations between these prompt transitions. This is partly because the band has

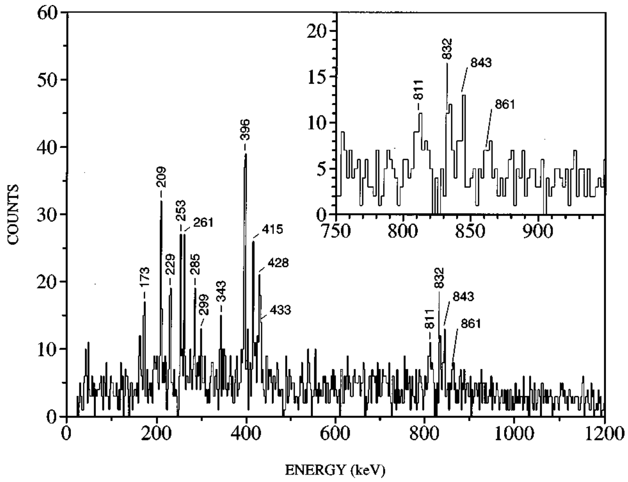


FIG. 1. A sum spectrum of prompt transitions detected in the JUROSPHERE array by gating on the delayed 220.8-, 384.4-, 489.1-, and 555.6-keV yrast transitions and the delayed 583.2-keV transition in $^{138}$Gd. The spectrum was also gated by the region of time from 0 to 9 $\mu$s after a recoiling nucleus was implanted into the Si detector and was background subtracted with the later time region 9 to 18 $\mu$s.

a small intensity ($\approx 1.4\%$) relative to the yrast band in $^{138}$Gd and therefore, corresponds to a very small percentage of the total fusion $\gamma$-ray yield. These transitions have only been observed due to the highly selective method of correlating prompt with delayed transitions across the isomeric state. However, in support of the ordering of the transitions in the $K^{\pi}=8^{-}$ band, the sum of any two adjacent $M1$ $\gamma$-ray transition energies is equal to the corresponding $E2$ transition energy as expected for these high-$K$ bands.

In order to confirm that these prompt transitions are definitely from $^{138}$Gd, they have to be correlated with the delayed decays from the isomeric state. This was achieved by gating on the new prompt transitions in the prompt versus delayed matrix and projecting out the delayed transitions. Figure 3 shows the sum of gates on the new prompt transitions in this matrix. In the figure it is evident that the only transitions which are in coincidence with these new prompt transitions are the delayed members of the yrast band in $^{138}$Gd. Indeed, there are no other transitions in the entire spectrum. As a control it was also checked that by setting random gates on the prompt axis of this matrix the delayed $^{138}$Gd yrast transitions were not observed.

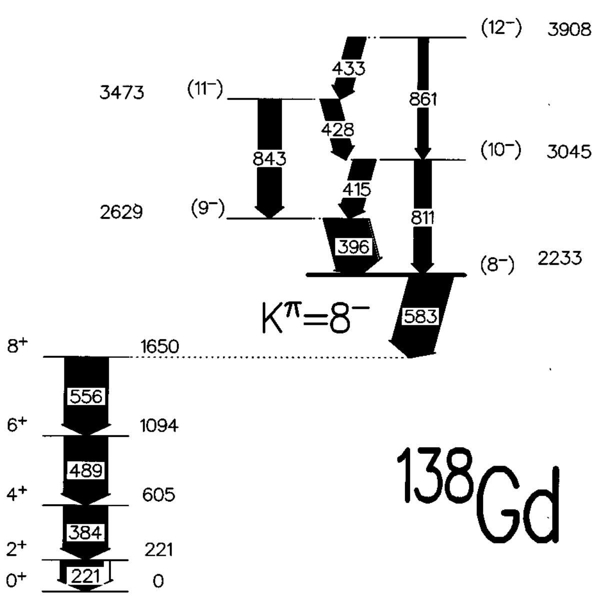


FIG. 2. A partial level scheme of $^{138}$Gd which focuses on the prompt transitions in the $K^{\pi}=8^{-}$ rotational band established in this work.

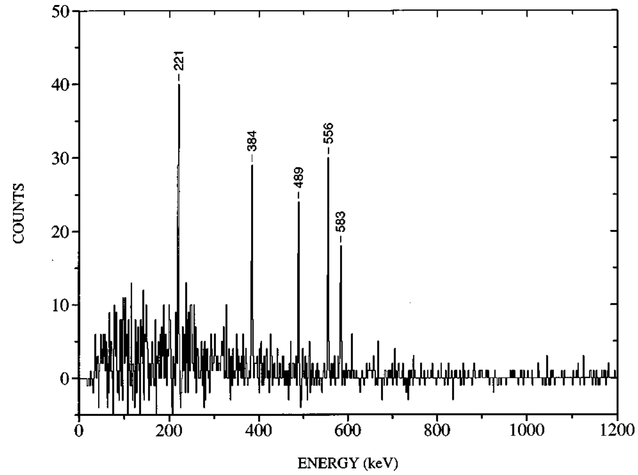


FIG. 3. A spectrum of delayed yrast transitions in $^{138}$Gd observed by gating on the prompt 172.6-, 208.9-, 229.4-, 252.6-, 260.8-, 284.8-, 298.5-, 395.5-, 402.0-, and 414.8-keV transitions in the newly established $K^{\pi}=8^{-}$ band.

## IV. DISCUSSION

In order to establish the configuration for the new band the systematics of $K^{\pi}=8^{-}$ bands in this mass region have been considered. In addition, $|(g_K-g_R)/Q_0|$ values have been deduced from the $\Delta I=2$ to $\Delta I=1$ $\gamma$-ray intensity branching ratios, see Table I. The amount of quadrupole admixture in the dipole ($\Delta I=1$) transitions was calculated in the strong-coupling limit of the rotational model with

$$\frac{\delta^2}{(1+\delta^2)}=\frac{2K^2(2I-1)}{(I+1)(I-1+K)(I-1-K)}\frac{E_1^5}{E_2^5}\frac{I_2^{\gamma}}{I_1^{\gamma}}, \qquad (1)$$

where $\delta$ is the quadrupole/dipole mixing ratio, $E$ and $I^{\gamma}$, respectively, refer to the transition energies (in MeV) and intensities and the subscripts 1,2 refer to $\Delta I=1,2$ transitions, respectively. The ratio of the $g$ factors to the quadrupole moment, $Q_0$ is then calculated by

$$\frac{(g_K-g_R)}{Q_0}=0.933\frac{E_1}{\delta\sqrt{I^2-1}}. \qquad (2)$$

These equations assume a well-defined $K$ and Eq. (1) only yields the magnitude of $\delta$ and not its sign. In this work the sign of $|(g_K-g_R)|$ remains ambiguous because it was not possible to measure angular correlation ratios to determine $\delta$ for the transitions in the band. However, the negative sign of $\delta$ was reasoned from a comparison with the angular correlation measurements for the transitions in the $K^{\pi}=8^{-}$ band in $^{136}$Sm [14], and the theoretical $g$ factors, discussed below.

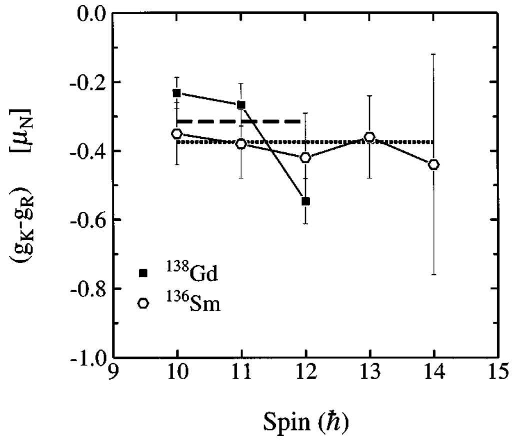


FIG. 4. $(g_K-g_R)$ values for the new $K^{\pi}=8^{-}$ band in $^{138}$Gd and the established $K^{\pi}=8^{-}$ band in $^{136}$Sm [14]. The weighted average of the ratio is shown by the dashed line for $^{138}$Gd and the dotted line for $^{136}$Sm.

Figure 4 shows the $(g_K-g_R)$ values for the $K^{\pi}=8^{-}$ band in $^{138}$Gd (filled squares) and the weighted average value, $-0.31\pm0.03$, is shown by the thick-dashed line in the figure. Also shown in Fig. 4 are the $(g_K-g_R)$ values for the $K^{\pi}=8^{-}$ band (open hexagons) in $^{136}$Sm [14] and its weighted average value, $-0.37\pm0.05$, indicated by the thick-dotted line. In the calculation, it is assumed that $Q_0=4.5e$ b from the lifetime measurements of the lowest $I^{\pi}=2^{+}$ state in $^{136}$Sm [15]. The similarity in the $(g_K-g_R)$ values for the $K^{\pi}=8^{-}$ bands in these neighboring $N=74$ isotones permits the following conclusions to be drawn: The $(g_K-g_R)$ values for $^{138}$Gd all lie close to $-0.4$, and assuming a prolate shape [15], the most favorable configuration for the $K^{\pi}=8^{-}$ isomer is the two quasineutron [514]9/2⊗[404]7/2 configuration which has a theoretical $(g_K-g_R)$ value of $-0.4$, consistent with the experimental value. As noted in Ref. [14], any other configurations around the neutron Fermi surface at these deformations have $(g_K-g_R)=-0.7$ and any proton orbits which could couple to $K^{\pi}=8^{-}$ have $(g_K-g_R)=+0.6$, both of which are inconsistent with the present data. In summary, the $(g_K-g_R)$ values favor a two-quasineutron [514]9/2⊗[404]7/2, $K^{\pi}=8^{-}$ configuration for the new band in $^{138}$Gd.

The experimental aligned angular momentum, $i_x$, (or alignment) [16] for the yrast and $K^{\pi}=8^{-}$ bands in $^{138}$Gd are shown in Fig. 5(a). A reference band with Harris parameters $\Im_0=11.0\hbar^2/\mathrm{MeV}$ and $\Im_1=25.8\,\hbar^4/\mathrm{MeV}^3$ has been subtracted from each band. Also shown in this figure are the aligned angular momentum of the yrast, $K^{\pi}=8^{-}$ and $K^{\pi}=(12^{+})$ bands in (b) $^{136}$Sm [14] and (c) the $K^{\pi}=8^{-}$ and $K^{\pi}=12^{(-)}$ bands in $^{134}$Nd [5,17], respectively. The gain in alignment observed in the yrast band near $\hbar\omega\approx0.3$ MeV has been shown to be due to the $h_{11/2}$ proton crossing; the lowest neutron configurations are expected to align at a higher rotational frequency [18]. The initial alignment of the $K^{\pi}=8^{-}$ band in $^{138}$Gd, at low rotational frequencies, is about 2–3$\hbar$ and is consistent with that expected from the coupling of the two quasineutron [514]9/2⊗[404]7/2 configuration. The alignment of this band is also very similar to that of the other $K^{\pi}=8^{-}$ bands in $^{136}$Sm and $^{134}$Nd, see Figs. 5(b) and 5(c). These similarities, when taken together with the $(g_K-g_R)$ values, give evidence that the new transitions are based on a two quasineutron $K^{\pi}=8^{-}$ [514]9/2⊗[404]7/2 configuration in $^{138}$Gd.

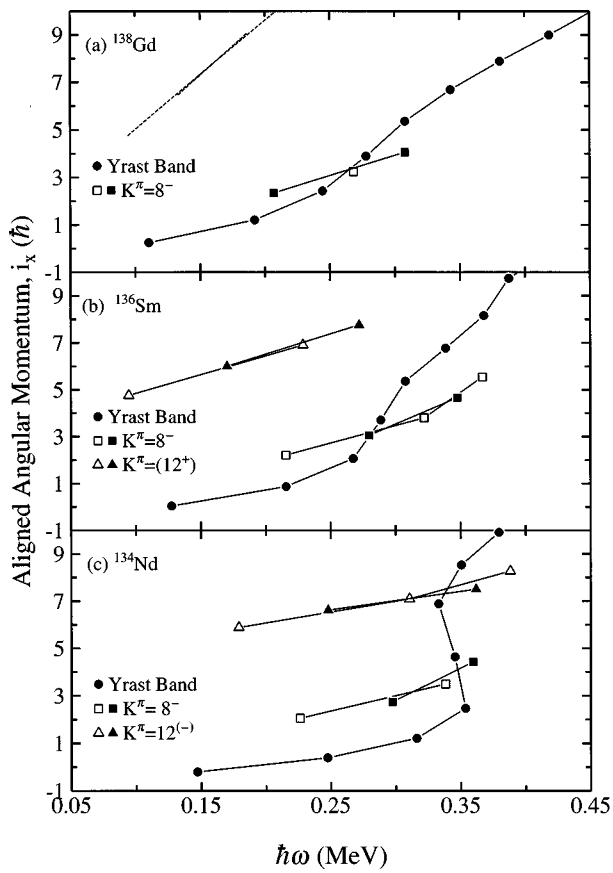


FIG. 5. The experimental aligned angular momentum, $i_x$ for (a) the yrast and $K^{\pi}=8^{-}$ bands in $^{138}$Gd, (b) the yrast, $K^{\pi}=8^{-}$ and $K^{\pi}=(12^{+})$ bands in $^{136}$Sm (Ref. [14]), and (c) the yrast, $K^{\pi}=8^{-}$ and $K^{\pi}=12^{(-)}$ bands in $^{134}$Nd (Ref. [17]). See text for the explanation of the dashed line in panel (a).

In contrast the aligned angular momentum of the higher-lying transitions (assuming they form a rotational band with ascending $\gamma$-ray transition energies of 209, 229, 253, 261, 285, and 299 keV) does not appear to follow the expected trend based on the systematics of other four-quasiparticle $K=12$ bands in the region. Figure 5 shows that the alignment of a band with these properties [dotted lines in Fig. 5(a)] would increase too rapidly, with rotational frequency, relative to the behavior of the four-quasiparticle bands in the neighboring isotones. This is most likely because these higher-lying transitions arise from more than one four-quasiparticle structure like those observed in $^{134}$Nd [17] and $^{136}$Sm [14]. Unfortunately the present experiment did not have sufficient statistics to unravel this complicated behavior.

## V. CONCLUSIONS

In summary, the correlation of prompt versus delayed $\gamma$-ray coincidences across an isomeric state has been shown to be a very powerful technique for selecting low-intensity rotational bands. A $K^{\pi}=8^{-}$ collective rotational band has been established upon the 6 $\mu$s isomeric state in the most neutron-deficient $N=74$ nucleus $^{138}$Gd. The two-quasineutron [514]9/2⊗[404]7/2 single-particle configuration of the isomeric-bandhead state has been deduced from the $(g_k-g_R)$ values and aligned angular momentum properties. In addition, a series of other transitions was observed which is most likely part of a four-quasiparticle structure which could not be fully established in this work.

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