Identification of levels in $^{162,164}$Gd and decrease in moment of inertia between $N = 98$–$100$

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Abstract. From prompt $\gamma$–$\gamma$–$\gamma$ coincidence studies with a $^{252}$Cf source, the yrast levels were identified from $2^+$ to $16^+$ and $14^+$ in neutron-rich $^{162,164}$Gd, respectively. Transition energies between the same spin states are higher and moments of inertia lower at every level in $N = 100$ $^{164}$Gd than in $N = 98$ $^{162}$Gd. These observations are in contrast to the continuous decrease in the $2^+$ energy to a minimum at neutron midshell ($N = 104$) in Er, Yb, and Hf nuclei.

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A $\gamma$–$\gamma$–$\gamma$ coincidence study of prompt $\gamma$ rays emitted in the spontaneous fission of $^{252}$Cf was carried out using Gammasphere [1] with $5.7 \times 10^{11}$ triples and higher coincidences recorded. Further experimental details are found in Luo et al. [2]. The yrast levels in neutron-rich $^{162,164}$Gd were identified for the first time from $2^+$ to $16^+$ in $^{162}$Gd and from $2^+$ to $14^+$ in $^{164}$Gd. The $^{162}$Gd transitions were established from our earlier 1995 Gammasphere data [3]. We searched with our new high-statistics data for $^{164}$Gd. We expected to find transitions with energies slightly below the energies in $^{162}$Gd by double gating on its 56Se partner, whose first two transitions are well known. We found no transitions with energies below those of $^{162}$Gd. Instead, we found $\gamma$ transitions with energies above those of $^{162}$Gd. The $^{162,164}$Gd intensities were checked against the relative yields as a function of neutron emission number.

The transitions in $^{162,164}$Gd are seen in double coincidence gates on the transitions identified in our work as the $6^+ \rightarrow 4^+$ and $8^+ \rightarrow 6^+$ in transitions $^{162}$Gd and $^{164}$Gd, as shown in fig. 1. The $2^+$ energy in known $^{160}$Gd is at $75.3$ keV and, from our data, in $^{162,164}$Gd at $71.6$ and $73.3$ keV, respectively. The transition energies from every level in $^{164}$Gd are higher than those from the same levels in $^{162}$Gd. These data show that there is the same decrease at every level of the moment of inertia in $N = 100$ $^{164}$Gd compared to $N = 98$ $^{162}$Gd. There is at least a local minimum in the $2^+$ energies and local maximum in the moments of inertia in Gd nuclei at $N = 98$ (see fig. 2). The $N = 98$, $100$ $^{164,166}$Dy [4] transition energies likewise increase from $N = 98$ to 100, and the $J_1$ and $J_2$ values of $^{166}$Dy similarly fall between those of $^{162,164}$Dy from $2^+ \rightarrow 0^+$ up to $12^+ \rightarrow 10^+$, then become less than those of $^{162}$Dy at $12^+$. However, Asai et al. [5] found that the $2^+$ and $4^+$ energies in $^{168}$Dy are lower than those of $^{166}$Dy, so the $J_1$ values of $^{168}$Dy for $N = 102$ are above the $N = 100$ values but still below the $N = 98$ values. In contrast, the $2^+$ energies for Hf and Yb isotopes have a minimum at $N = 104$ (midshell). Also, the Er values out to $N = 104$ follow this trend (see fig. 2). The energies from $2^+ \rightarrow 0^+$ to $14^+ \rightarrow 12^+$ all decrease from $N = 94$ to 98 in $^{156,158,160}$Sm, and their $J_1$ and $J_2$ MOIs increase in a systematic pattern. Unfortunately, the levels

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of $N = 100$ $^{162}$Sm are not yet known. In the Gd nuclei, the $J_1$ and $J_2$ moments of inertia as shown in fig. 3 for $N = 100$ fall below the $N = 96$ and 98 values at low spin and then drop below the $N = 96$ values above $10^+$. Similar behavior was found for Dy nuclei. In Er, the $N = 100$ $J_1$ values are systematically below the $N = 102$ values. Thus, $^{164}$Gd and $^{168}$Dy are more rigid with less stretching, i.e., less change in $J_1$ and $J_2$ with increasing $h\omega$ than their lighter-mass isotopes. In addition to at least a local minimum in $N = 98$ for $^{162}$Gd and $^{164}$Dy, one also notes that Er and Yb have a kink and change of slope above $N = 98$. This suggests an unusual effect, maybe a change in structure, at $N = 98$. Looking at the trends of the Gd and Dy $2^+$ energies in fig. 2, one would expect that their $N = 100$ and 102 $2^+$ energies would fall below those for similar-$N$ Sm, and perhaps even those of Nd nuclei. With the new Gd and Dy data, the lowest known $E(2^+)_s$ in this region for $N = 92$–110 now are for $Z = 60$ Nd, followed by $Z = 62$ Sm and then $Z = 64$ Gd, with $Z = 58$ Ce $E(2^+)_s$ curiously falling between the Gd and Dy values at $N = 92$ and 94 and with a much steeper slope.

The Nd isotopes, with $Z = 60$, are well removed from the proton midshell at $Z = 66$, and the most neutron-rich $N = 96$ is 8 neutrons away from midshell. Thus, our $^{162,164}$Gd data, along with the $^{164,168}$Dy [4] and $^{168}$Dy [5] data, raise a new question of why is it that the most neutron-rich known $Z = 60$, 62 Nd, Sm isotopes have the lowest $2^+$ energies, largest MOI, and presumably the largest deformation in the deformed region bounded by $Z = 50$–82 and $N = 82$–126.

In summary, from our work we identified levels in $^{162}$Gd and $^{164}$Gd. Each level and transition energy in $^{164}$Gd is higher than its counterpart in $^{162}$Gd. Although the known $2^+$ level energies have a minimum at midshell ($N = 104$) for Er, Yb, and Hf, our new data yield at least a local $2^+$ minimum at $N = 98$ for Gd. A local minimum also is seen there in Dy $2^+$ transitions established by Wu et al. [4]. Our $^{162,164}$Gd data likewise make clear that the known minimum $2^+$ energies in this region surprisingly are for $^{156}$Nd$_{96}$ and $^{162}$Sm$_{98}$. There is at least a local minimum (maybe total minimum) in $E(2^+)$ at $N = 98$ for Gd and Dy nuclei and a kink in Er and Yb nuclei there. Thus there is some new microscopic effect taking place at $N = 98$ that challenges microscopic theories.

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