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

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Abstract. From prompt γ-γ-γ 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.

PACS. 21.10.Re Collective levels – 27.70.+q $150 \leq A \leq 189$

A γ-γ-γ coincidence study of prompt γ rays emitted in the spontaneous fission of ^{252}Cf was carried out using Gammasphere [1] with 5.7×10^{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 γ transistions with energies slightly below the energies in ^{162}Gd by double gating on its ^{84}Se partner, whose first two transistions are well known. We found no transitions with energies below those of ^{162}Gd. Instead, we found γ 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

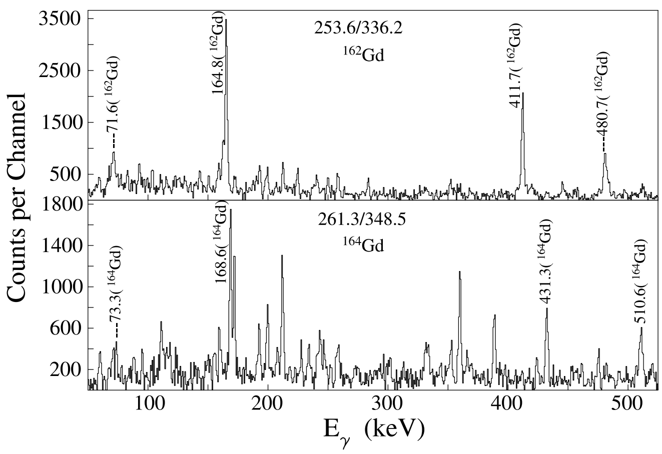

Fig. 1. Top: double gate on 253.6 keV and 336.2 keV in ^{162}Gd. Bottom: double gate on 261.3 keV and 348.5 keV in ^{164}Gd. All gates have gate width = 0.33 keV.

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 constrast, 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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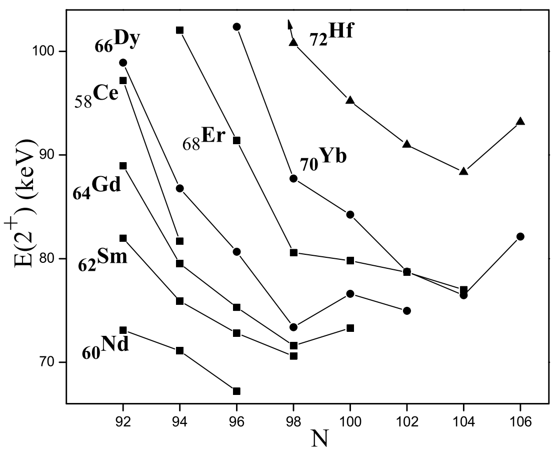

Fig. 2. Plot of 2^+ level energies *vs.* neutron number.

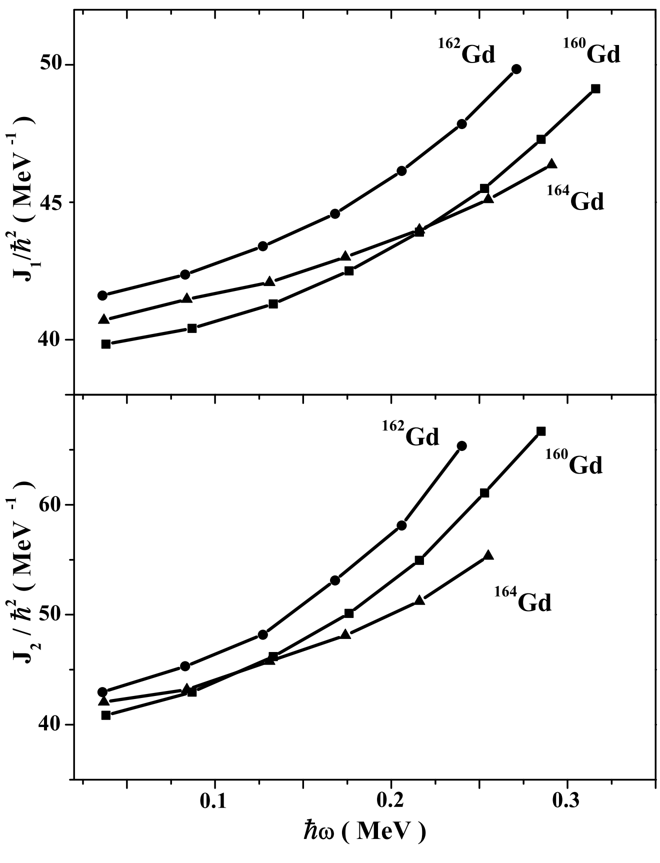

Fig. 3. Plot of J_1 (upper) and J_2 (lower) *vs.* $\hbar\omega$ for ^{160,162,164}Gd.

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 between 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 ^{166}Dy are more rigid with less stretching, *i.e.*, less change in J_1 and J_2 with increasing $\hbar\omega$ 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 [6] 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 ^{164,166}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 $^{156}_{60}\mathrm{Nd}_{96}$ and $^{160}_{62}\mathrm{Sm}_{98}$. 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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