Higher Spin States in Neutron Rich Nuclei

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ABSTRACT. Recent studies of the products produced in spontaneous fission (SF) have shown an unexpected richness of information about previously inaccessible higher spin studies in neutron rich nuclei. Recent evidence for octupole deformation in $^{144,146}$Ba, $^{164}$Yb and $^{226}$Ra have come from SF and other techniques. New insights into the structure of nuclei in the $A = 100-120$ and 136-152 regions have been obtained from two different SF $\gamma - \gamma$ coincidence studies of $^{252}$Cf in a Close Packed Ball with 20 Compton suppressed Ge detectors, where one experiment also included a fission fragment detector inside the ball at the Holifield Heavy Ion Research Facility, as well as a similar study at Argonne. New data resolve problems related to shape coexistence in $^{100}$Sr, $^{102}$Zr and provide new insights into the super deformation in this region. New high spin states up to $16^+$, a record in such neutron rich nuclei, were found in $^{138,140}$Xe, $^{140}$Ba, $^{146-150}$Ce and $^{150,152}$Nd in our HHIRF work and levels identified for the first time in $^{136}$Te and $^{149}$Ce. The $J_1$ moments of inertia for $^{148,150}$Ge and $^{150,152}$Nd exhibit an unexpected crossing pattern at high spins. These data also provide new insight into the fission process itself.

RESUMEN. Estudios recientes de los productos de la fisión espontánea (SF) han mostrado una riqueza inesperada de información sobre estados previamente inaccesibles de espines altos en núcleos ricos en neutrones. Evidencias recientes de la deformación octupolar en $^{144,146}$Ba, $^{164}$Yb y $^{226}$Ra se han obtenido de SF y otras técnicas. Nuevos puntos de vista en la estructura de núcleos en las regiones $A = 100-120$ y 136-152, se han obtenido de dos estudios diferentes sobre coincidencias $\gamma - \gamma$ en la SF de $^{252}$Cf en un “Close Packed Ball” con 20 detectores de Ge con supresión Compton; en donde uno de los experimentos también incluyó un detector de fragmentos de fisión dentro de la bola en el laboratorio de investigaciones de iones pesados de Holifield (HHIRF), así como un estudio similar en Argonne. Nuevos datos resuelven problemas relacionados a la coexistencia de formas en $^{100}$Sr, $^{102}$Zr y proporcionan visiones nuevas de la superdeformación en esta región. Se encontraron en trabajos en el HHIRF nuevos estados de espines altos hasta $16^+$, un record, en tales núcleos ricos en neutrones como $^{138,140}$Xe, $^{140}$Ba, $^{146-150}$Ce y $^{150,152}$Nd y se identificaron, por primera vez, niveles en $^{136}$Te y $^{149}$Ce. Los momentos de inercia $J_1$ para $^{148,150}$Ge y $^{150,152}$Nd exhiben un patrón de cruzamiento inesperado en espines altos. Estos datos también dan lugar a nuevas consideraciones sobre el proceso mismo de fisión.

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INTRODUCTION

Nuclei on the neutron rich side of beta stability have long been of interest for nuclear structure studies because they probe different regions of the single particle spectrum and different shell gap combinations for both spherical and deformed shapes. However, such nuclei have been a difficult challenge experimentally. Much information has been gained about the properties of neutron rich nuclei at low spin from the study of radioactive isotopes produced in neutron induced, and more recently, proton induced fission of uranium [1]. Such studies have been made possible by the use of isotope separators on line to reactors and more recently to low energy proton accelerators. More recently, new regions of radioactive neutron rich nuclei have been opened up for study through the use of multinucleon transfer reactions for examples, in the mass 50-80 and actinide regions [2,3].

However, to test many of the theoretical predictions of nuclear models one needs information about the higher spin states in nuclei in addition to their low spin states populated in radioactive decays. Higher spin states in neutron rich nuclei have been an even more difficult challenge than the lower spin states accessible through decay studies. One cannot reach the higher spin states in these nuclei by heavy ion fusion evaporation reactions as carried out extensively for proton rich nuclei. Until recently, untapped sources of information on higher spin states, as well as low spin states, of neutron rich nuclei have been the study of the prompt gamma rays from the fragments produced in spontaneous (SF) and induced (IF) fission of heavy elements.

Many years ago prompt SF studies were used to suggest for the first time that $^{98}$Sr and $^{100}$Zr had unusually large ground state deformations [4]. The availability of higher efficiency multi-detector arrays of Compton suppressed Ge detectors has brought on a renewed interest in studies of the prompt gamma rays of the fragments from spontaneous and induced fission. Groups at Argonne, Daresbury, and a Vanderbilt-Oak Ridge-Idaho-Dubna collaboration have carried out several such studies from spontaneous [5-9] and heavy-ion induced [10] fission which have revealed new insights into our knowledge of neutron rich nuclei [5-10]. This paper is primarily a review of these studies, including recent, unpublished results [6,9].

Much of the work presented here comes from two experiments carried out at the Holifield Heavy Ion Research Facility (HHIRF) in the 20 Compton suppressed Ge detector Close-Packed Ball array [6,9] with $^{252}$Cf SF sources. In the first experiment a $^{252}$Cf source with 3,900 fission events/sec was coated on the inside surface of a gas-filled ionization chamber which was placed inside the Ge ball to allow fission-fragment-$\gamma$-$\gamma$-coincidences to be recorded [6]. A total of $1.5 \times 10^7$ fragment-$\gamma$-$\gamma$-coincidences were recorded. New, higher spin studies up to $14^+$ in some cases, were observed in 19 nuclei, and the levels of $^{136}$Te were established for the first time. These data allow one to study the changes from vibrational to deformed structures and to see the influence of rotation aligned structures at higher spins from only a short run. In order to improve the statistics and to see higher spin states, a stronger $^{252}$Cf source was run in the same Close-Packed Ball and $1.9 \times 10^9$ $\gamma$-$\gamma$ events were recorded [9]. In these data states to $16^+$, a record for neutron rich nuclei, were observed in some of the level schemes. A number of new insights are obtained from these data.
Stable ground state octupole deformations have been one of the exciting recent new insights into nuclear structure with the discovery of parity doublets in the regions of At, Ra and Th nuclei (see review of Nazarewicz, Ref. [11]). Nuclei with permanent octupole deformation do not have reflection symmetry (see the classic paper of Leander et al., Ref. [12]). Reflection asymmetry gives rise to a doubling of states with opposite parity in odd-A nuclei, as first observed in the actinide elements, for example $^{223}$Th (Ref. [13]).

The sequences of rotational states in $^{223}$Th can be understood as the coupling of an octupole deformed core with an unpaired neutron. In even-even nuclei one observes even- and odd-parity rotational bands, as shown in Fig. 1. The GSI Coulomb excitation group have Coulomb excited the radioactive target $^{226}$Ra($t_{1/2} = 1600$ yr) with a $^{208}$Pb beam [14]. They extracted electric quadrupole, hexadecapole, and, for the first time, octupole

**FIGURE 1.** Coulomb excited levels in $^{226}$Ra (Ref. [14]).

**TABLE I.** Reduced transition probabilities and charge deformation parameters in $^{226}$Ra (Ref. [14]).

<table>
<thead>
<tr>
<th>$\lambda$</th>
<th>$B(E\lambda; 0 \rightarrow \lambda)[e^2b^\lambda]$</th>
<th>$\beta_\lambda$ (exp)</th>
<th>$\beta_\lambda$ (Ref. [12])</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>5.15(14)</td>
<td>0.165(2)$^a$</td>
<td>+0.164</td>
</tr>
<tr>
<td>3</td>
<td>1.10(11)</td>
<td>0.104(5)$^a$</td>
<td>-0.112</td>
</tr>
<tr>
<td>4</td>
<td>1.08(15)</td>
<td>0.123(8)</td>
<td>+0.096</td>
</tr>
</tbody>
</table>

$^a$Sign of deformation parameter not determined experimentally.
transitions moments up to spin 18. Their extracted $\beta_2$, $\beta_3$, and $\beta_4$ deformations for $^{226}$Ra, in Table I, are in excellent agreement with theoretical calculations [12] for a stable octupole deformation.

The first evidence for ground state octupole deformation outside the At-Ru-Th region was found in $^{144,146}$Ba from studies of the prompt $\gamma$-ray from SF of $^{252}$Cf. Positive- and negative-parity bands with enhanced E1 crossing transitions were observed as shown in Fig. 2 (Ref. [5]). For completeness, while theoretical and experimental investigations of octupole deformations have focused on the Ra-Th ($Z \approx 88, N \approx 134$) and Ba-Sm ($Z \approx 56, N \approx 88$) nuclei, there exists some evidence that indicates an instability with respect to the octupole degree of freedom for $N \approx 94$ nuclei. In $^{162}$Er and $^{164}$Yb, the lowest negative-parity band is seen to be systematically depressed about 200 keV relative to the next lowest negative-parity band, and there is a lack of signature splitting in the lowest negative-parity decay sequence in the neighboring odd-$N$ isotopes. To clarify the possibility of strong interaction between the octupole and aligned quasineutron configurations observed in the $N = 94$ erbium and ytterbium, $B(E1)/B(E2)$ branching ratios
were extracted from our $^{164}$Yb lifetime data [15]. As a result of the strong octupole band character, one might expect enhanced E1 transitions from the (-, 1)-band to the yrast band. The E1/E2 branching ratios were extracted for $^{162,166}$Yb and $^{164}$Yb and, indeed, the branching ratios in $^{164}$Yb are enhanced by more than a factor of 4 with respect to the neighboring isotopes. Furthermore, the absolute B(E1) values of $^{164}$Yb are of the order of $10^{-3}$ W.u. comparable to those observed in the Ba-Sm nuclei. The enhanced octupole strength for $^{164}$Yb probably is the result of the proximity of the second pair of octupole-driving orbitals; i.e. the $\Omega = 3/2$ components of the $\nu_{i13/2}$ and $\nu_{f7/2}$ states near the Fermi level for $N = 94$. However, the octupole instability in $^{164}$Yb is less pronounced than for Ba-Sm nuclei [$\pi(i_{13/2} \otimes d_{5/2})$ and $\nu(i_{13/2} \otimes f_{7/2})$] and Ra-Th nuclei [$\pi(i_{13/2} \otimes f_{7/2})$ and $\nu(j_{15/2} \otimes g_{9/2})$], where at least one set of the octupole driving orbitals both have $\Omega = 1/2$. These systematics indicate that the larger spacial localization of the $\Omega = 1/2$, high-j configurations probably is important in stabilizing the octupole shape. So, $^{164}$Yb provides an example of enhanced octupole deformation arising from the less pronounced pair of octupole-driving orbitals, i.e. $\nu(i_{13/2} \otimes f_{7/2})$ with $\Omega = 3/2$.

**NEUTRON RICH NUCLEI IN THE A = 100-120 REGION**

New levels were observed in $^{100,102}$Zr (independently reported in Ref. [8]), $^{104,106}$Mo, $^{108,110,112}$Ru, $^{112,114,116}$Pd and $^{120}$Cd in our first experiment [6]. Some of the level schemes are given in Table II. As reported in Refs. [7,16], Peker and Hamilton [17] analyzed the data [6] for $^{98}$Sr, $^{100,102}$Zr, $^{104-106}$Mo and $^{106-110}$Ru in terms of $\Delta E_\gamma = E_{2\gamma} - E_{1\gamma}$ vs. spin. This function is very sensitive to shape changes [18] and is a smoothly decreasing function of spin for a single band with breaks when there is a band crossing or interaction. There had been a puzzle for $^{98}$Sr and $^{100}$Zr in that, while their $2_+^+ - 0^+$ energies all indicated they were strongly deformed, their $E_4/E_2$ ratios were 2.99 and 2.67, respectively, considerably lower than the 3.3 predicted in a pure rotational model. These two nuclei have the lowest $0_+^+$ excited states known in any nucleus, 215 and 331 keV, respectively. These excited $0_2^+$ states are near spherical in nature. With the new $8^+$ and $10^+$ levels [6], the $\Delta E_\gamma$ values as shown in Fig. 3 for $^{102}$Zr, $^{104,106}$Mo, $^{106-110}$Ru and the recently discovered $^{104}$Zr (Ref. [8]) are all smoothly decreasing functions of spin (with some small fluctuations for $^{104}$Mo) to indicate a single rotational band characteristic of deformed rotors up to the highest spin observed. However, both $^{98}$Sr and $^{100}$Zr have quite different $\Delta E_\gamma$ patterns. Their $\Delta E_\gamma$'s exhibit a break at the lowest spin. This break was interpreted [17], just as for $^{74,76}$Kr (Ref. [19]) as arising from the interaction of near-spherical excited and superdeformed ground states to shift the $0_{gs}^+$ down and $0_{gs}^+$ up. By assuming that $\Delta E_\gamma$ for $^{100}$Zr and $^{98}$Sr vary in the same way at higher spins and extrapolating that variation back to low spins, we found the superdeformed ground state to be pushed down 20 and 40 keV in $^{98}$Sr and $^{100}$Zr, respectively [17]. After correcting for these shifts, the $E_{4_+}/E_{2_+}$ ratios are 3.3 and 3.1, which are compatible with the rigid rotor value. Following our work, Mach et al. [20] analyzed all the lifetime data for the $2_+^+$, $0_2^+$ and $4_1^+$ levels in these nuclei. They also found that the superdeformed ground states only weakly mix with the excited near-spherical $0_2^+$ states. Their extracted shifts of 23.3 and 46.9 keV, for $^{98}$Sr and
$^{100}$Sr, respectively, are in excellent agreement with our values [7,16] determined earlier from $\Delta E_\gamma$. This close agreement demonstrates the power of $\Delta E_\gamma$ plots to yield detailed and quantitative information on energy level patterns, changes in structures, and shape coexistence. Similar analysis indicate perhaps only 5-10 keV shifts in $^{100}$Sr and $^{102}$Zr (see Ref. [16] for additional details and discussion of mass 70 nuclei). There remains the important question of why the excited near-spherical and superdeformed ground states which are so close in energy in $^{98}$Sr and $^{100}$Zr interact so weakly (20-50 keV shifts) when they interact so strongly (200 keV shifts) in $^{74,76}$Kr where these same two shapes are much farther apart [7,16]. It is difficult to understand these differences in interaction strengths since the origin of the superdeformation in both cases relates to the reinforcement of the N (38,60) and Z (38) shell gaps at $\beta \sim 0.4$ and possibly the same $g_{9/2}$ and $g_{7/2}$ intruder orbitals [7].

However, the $^{101,103}$Zr levels [8] provide evidence for the importance of the $h_{11/2}$ intruder orbital in the superdeformation in this region, as earlier proposed in Ref. [16]. Hotchkis et al. [8] propose that the side band in $^{101}$Zr and the ground band in $^{103}$Zr have $5/2^-$ band heads associated with the $5/2^- [532]$ intruder configuration ($\nu h_{11/2}$). These results

**Figure 3.** $\Delta E_\gamma = E_{\gamma 2} - E_{\gamma 1}$ as function of spin [6,8,9]
are consistent with the predictions of mean-field calculations [21-23] and correspond with predicted minima in the potential energy surfaces [22,23] at $\beta_2 \approx 0.4$. The near degeneracy of the $5/2^-$ [532] orbital with the ground state in $^{101}$Zr, they propose, suggests substantial occupancy in $^{100}$Zr of the $\Omega = 1/2$ and $3/2$ Nilsson orbitals of the $h_{11/2}$ intruder. So, in $^{102-104}$Zr they suggest there should be significant occupancy of the $\Omega = 1/2^-, 3/2^-$ and $5/2^-$ orbitals to support predictions of deformed mean field calculations that the $h_{11/2}$ orbit near the Fermi surface provides the driving force toward large deformation. This is in contrast to shell model calculations which attribute the deformation to the $g_{7/2}$ orbit with the only small occupancy of the $h_{11/2}$ orbit. Earlier, it was pointed out [24] that it is the strong down-sloping, $\nu h_{11/2}$ orbit and to a lesser extent the $\nu g_{7/2}$ orbit which should be important in driving the deformation, and that it is not clear what this does to the p-n coupling scheme interpretation [25] of the strong deformation in Zr nuclei.

Neutron Rich Nuclei in the A = 136-150 Region

Table II. Yrast gamma-ray energies of neutron-rich $^{104}$Mo to $^{142}$Ba with $A \sim (100-150)$ in prompt even-even products of $^{252}$Cf spontaneous fission. The new $^{142}$Xe data are Ref. [26] and confirmed in our work [9], and the others Ref. [6,9]. New transitions are indicated by *. The $^{142,144}$Ba data are Ref. [5] (and confirmed here). Some of the higher spin assignments are tentative.

<table>
<thead>
<tr>
<th>$I^\pi$, $I_f^\pi$</th>
<th>$I_i^\pi$</th>
<th>$I_f^\pi$</th>
<th>$I_i\pi$, $I_f\pi$</th>
<th>$I^\pi$</th>
<th>$I_f^\pi$</th>
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<tbody>
<tr>
<td>$^{104}$Mo</td>
<td>$^{106}$Mo</td>
<td>$^{108}$Ru</td>
<td>$^{110}$Ru</td>
<td>$^{112}$Ru</td>
<td>$^{112}$Pd</td>
</tr>
<tr>
<td>2+</td>
<td>0+</td>
<td>242.3</td>
<td>241.8</td>
<td>237.5</td>
<td>349.0</td>
</tr>
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<td>4+</td>
<td>2+</td>
<td>369.0</td>
<td>351.1</td>
<td>423.3</td>
<td>423.2</td>
</tr>
<tr>
<td>6+</td>
<td>4+</td>
<td>519.7</td>
<td>511.6</td>
<td>576.1*</td>
<td>576.2*</td>
</tr>
<tr>
<td>8+</td>
<td>6+</td>
<td>642.7*</td>
<td>655.1*</td>
<td>702.6*</td>
<td>706.0*</td>
</tr>
<tr>
<td>10+</td>
<td>8+</td>
<td>734.1*</td>
<td>785.1*</td>
<td>815.8*</td>
<td>722.9*</td>
</tr>
<tr>
<td>$^{120}$Cd</td>
<td>$^{136}$Te</td>
<td>$^{138}$Xe</td>
<td>$^{140}$Xe</td>
<td>$^{142}$Xe</td>
<td>$^{144}$Ba</td>
</tr>
<tr>
<td>2+</td>
<td>0+</td>
<td>506.3</td>
<td>1134.5*</td>
<td>589.5</td>
<td>377.0</td>
</tr>
<tr>
<td>4+</td>
<td>2+</td>
<td>697.0</td>
<td>288.8*</td>
<td>484</td>
<td>458.2</td>
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<tr>
<td>6+</td>
<td>4+</td>
<td>830.4*</td>
<td>573.6*</td>
<td>482*</td>
<td>583.1*</td>
</tr>
<tr>
<td>8+</td>
<td>6+</td>
<td>925.6*</td>
<td>1697.0*</td>
<td>730.4*</td>
<td>567.3*</td>
</tr>
<tr>
<td>10+</td>
<td>8+</td>
<td>688.6*</td>
<td>608.1*</td>
<td>610.4*</td>
<td>574.0</td>
</tr>
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<td>12+</td>
<td>10+</td>
<td>599.8*</td>
<td>679*</td>
<td>671.7*</td>
<td>622.6</td>
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<tr>
<td>14+</td>
<td>12+</td>
<td>848.8*</td>
<td></td>
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New, higher spin states have been found in $^{138,140}$Xe, $^{140}$Ba, $^{146,148,150}$Ce, $^{150,152}$Nd and $^{158}$Sm in our HHIIRF work [6,9] and the levels in $^{136}$Te (Ref. [6]) and $^{142}$Xe (Ref. [26]) established for the first time, as shown in Table II and Fig. 6 shown later. Transitions in $^{149}$Ce also have been identified for the first time [9]. One can see from Fig. 4 the influence of the $N = 82$ spherical shell gap and the increase in deformation as a function of $N$ and as one $Z$ goes away from the $Z = 50$ shell gap for a given $N$. There are some anomalies,
however. Note for \( N = 82 \) the first excited \( 2^+ \) energy for the \( N = 82 \) isotones increases as one goes away from the \( Z = 50 \) shell closure, 1280\((Z = 52)\), 1314\((54)\), 1436\((56)\) and 1596\((58)\). The \( 2^+ \) energy in the \( N = 84 \) isotones shows a similar increase as \( Z \) increases from \( 54 \) to \( 58 \). For \( N = 86 \) the \( 2^+ \) energy oscillates but is highest for \( Z = 58 \). For \( N = 88 \) the \( 2^+ \) energy is again higher in \( ^{146}\text{Ce} \( (Z = 56) \) than in \( ^{148}\text{Ba} \( (56) \). Then the \( 2^+ \) trend reverses for \( N = 90 \) for \( ^{146}\text{Ba} \) and \( ^{148}\text{Ce} \). If one looks at the moment of inertia, the \( \Delta E_\gamma \) plots or the \( \gamma \) ray energies as a function of spin, one sees some other interesting features. Note (Table II) for \( N = 84 \) there is a backbend in the moment of inertia as a function of \( h\omega \) (break in \( \Delta E \), Fig. 5) at the \( 4^+ \) level for \( ^{138}\text{Xe} \) and \( ^{140}\text{Ba} \) to indicate some type of band crossing at low spin. Then in \( ^{138}\text{Xe} \) there is a second backbend at \( 10^+ \). For \( N = 86 \) there is no backbend in \( ^{140}\text{Xe} \) and \( ^{142}\text{Ba} \), but \( ^{140}\text{Xe} \) has a backbend at \( 8^+ \), but \( ^{142}\text{Ba} \) does not! One also sees that while \( ^{140}\text{Xe} \) starts out with slightly smaller deformation at the \( 2^+ \) level than \( ^{142}\text{Ba} \) (a higher \( 2^+ \) energy), the levels and their depopulating transitions at \( 4^+ \) and above are lesser in energy (presumably larger deformation) than those in the ground band of \( ^{142}\text{Ba} \). By \( N = 88 \), \( ^{144}\text{Ba} \) already looks like a good soft rotor. As already stressed recently [1], the sharp jump in deformation between \( N = 88 \) and 90 noted many years ago for \( \text{Sm, Gd and Dy isotopes is a shell gap reinforcement effect where the } Z = 64 \text{ spherical subshell gap at Gd keeps these nuclei spherical further from the } N = 82 \text{ spherical shell gap until there is a sudden change between } N = 88 \text{ and 90 for those three nuclei, just as the } N = 56 \text{ spherical shell gap is reinforced by the } Z = 40 \text{ subshell gap to keep the } \text{Sr and } \text{Zr nuclei spherical furtherl from } N = 50 \text{ until there is a sudden switch (onset of deformation) between } N = 58 \text{ and 60 in the } \text{Sr and } \text{Zr nuclei} [1]. \text{This difference also is}
Figure 5. Moments of inertia $J_1$ and $J_2$ and $\Delta E_\gamma$ for $^{138-142}\text{Xe}$ and $^{142-146}\text{Ba}$. 
seen in laser spectroscopy measurements of the mean square charge radii where there is no sudden jump in deformation between $N = 88$ and 90 in the Ba-Ce region like there is in Sm-Dy nuclei (see Ref. [1]).

From our second $^{252}$Cf SF experiment, $\gamma$ rays have been identified from states up to a record 16+ for very neutron-rich nuclei as shown in Fig. 6 where our new level schemes for $^{148,150}$Ce and $^{152,154}$Nd are given [9]. Plots of $J_1$ and $J_2$ moments of inertia are shown in Fig. 7. Note the moment of inertia plots where $J_1$ starts out considerably smaller for $^{148}$Ce than $^{150}$Ce, but as $I$ increases $J_1$ reaches and passes $J_1$ for $^{150}$Ce. In $^{152}$Nd, $J_1$ also shows the same crossing pattern but at lower spin and less sharp but more definite crossing. The $J_2$ for $^{148}$Ce exhibits a striking increase at the two highest spins. As another example, the levels in $^{142}$Xe have been identified from the Argonne $^{248}$Cf SF data and have been used to test the prediction of the $N_pN_n$ scheme [26]. Finally, as seen in Fig. 8 significant information about the spontaneous fission process itself can be gained from these studies. The fact that one sees states up to 16+ carries significant information about the necks at fission. The neck must be reasonably thick in order to impart such large angular momentum. As seen in Fig. 8, one also gains information about the relative
neutron emission channels. Note in Fig. 8 one sees transitions associated with levels from $^{103}$Zr, the 1n channel, to $^{98}$Zr (not shown), the 6n channel.

These data demonstrate that studies of the prompt $\gamma$ rays from the fragments produced in SF can provide considerable important information to test our theoretical models, including the interplay of spherical and deformed shapes and single particle orbitals as a
function of spin and N and Z in addition to the fission process itself. We have just begun to look at these data theoretically in order to identify the different structures involved. There also is considerable more information including the identification of additional new isotopes in the present data sets. We are continuing our analysis. Also, heavy-ion induced fission should provide an even wider mass range of fission fragments for study. Our INEL collaborators have prepared, for the first time, a $^{242}$Pu SF source (essentially the world’s supply) which will be run at HIRIF soon. This source, with its different mass distribution, should yield additional valuable insights.

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