Multiparticle high-K structures in odd-A rare earth nuclei

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Long-lived excited states (isomers) occur in axially symmetric quadrupole deformed nuclei mainly as a consequence of conservation of $K=\sum_i\Omega_i$ (with $\Omega$ denoting a Nilsson orbital) quantum number. High $K$ multi-quasiparticle (mqp) structures arise from coupling of angular momenta of broken pairs in even-even nuclei and valence nucleons. Long-lived K isomers result when these mqp high $K$ structures occur at low energies competing with collective yrast states, or when their decay is $K$-hindered.

Jain et al.[1] had reported the first listing of $3qp$ structures in 1990 and Singh et al. [2] published an exhaustive compilation, as of July 2005, of $3qp$ band levels observed in odd-A rare earths. Numerous mqp ($m=1$-$9$) K-isomers with $t_{1/2}$ ranging from ns to years have been identified to-date in several nuclei across the periodic table [3]. Presently we focus on K-isomers with $t_{1/2} \geq \mu s$ in odd-A rare earth nuclei.

Significant advances in identification of such isomers have come about during the past decade mainly due to improved/new technologies, which include:

(a) use of Gammasphere multidetector array in (HI,xn) reaction studies [4];
(b) multiparticle transfer reactions [5];
(c) deep inelastic reactions [6];
(d) relativistic projectile fragmentation (RPF) [7,8];
(e) RPF with a storage ring [9].

To illustrate the mqp structures observed in odd-A nuclei, we list in Table 1 K-isomers with $t_{1/2} \geq \mu s$ identified so far [3-9] in the $Z=72$ (Hf) and $Z=73$ (Ta) isotopic sequences. To unravel these structures, we first look at the available $1qp$ configuration space sketched in Fig. 1. Interestingly at almost halfway between $Z=60$ & 82 (at $Z=72$) and between $N=82$ & 126 (at $N=106$), we find close lying $\Omega=7/2$ & $9/2$ orbitals. This fact explains the observation [3] of low-lying (~1MeV) $K^z=8$ pp isomers in all even-even $Z=72$ (Hf) isotopes and $K^z=8$ nn isomers in all $N=106$ isotones from $Z=68$ ($^{174}_{72}$Er) through $Z=82$ ($^{188}_{72}$Pb). The classic (first reported in 1968) longest-lived even-even isomer ($t_{1/2} = 31y$) observed in $^{178}_{72}$Hf (2446 keV) has $K^z=16^+$ with

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**Table 1**: Presently identified long-lived ($t_{1/2} \geq \mu s$) high spin ($J \geq 17/2$) multiparticle isomers in odd-A $^{175}_{72}$Hf and $^{177}_{73}$Ta isotopes

<table>
<thead>
<tr>
<th>$^{A}\chi$</th>
<th>$E_x$ (keV)</th>
<th>$t_{1/2}$</th>
<th>$K^z$</th>
</tr>
</thead>
<tbody>
<tr>
<td>[A]: Odd A $^{175}_{72}$Hf isotopes</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{175}<em>{72}$Hf$</em>{103}$</td>
<td>1433</td>
<td>1.1\mu s</td>
<td>19/2+</td>
</tr>
<tr>
<td></td>
<td>3015</td>
<td>1.2\mu s</td>
<td>35/2-</td>
</tr>
<tr>
<td></td>
<td>4636</td>
<td>2.8\mu s</td>
<td>45/2+</td>
</tr>
<tr>
<td></td>
<td>7455</td>
<td>&gt;7\mu s</td>
<td>(57/2-)</td>
</tr>
<tr>
<td>$^{177}<em>{72}$Hf$</em>{105}$</td>
<td>1342</td>
<td>56\mu s</td>
<td>19/2+</td>
</tr>
<tr>
<td></td>
<td>1315</td>
<td>1.1s</td>
<td>23/2+</td>
</tr>
<tr>
<td></td>
<td>2740</td>
<td>51.4\mu m</td>
<td>37/2-</td>
</tr>
<tr>
<td>$^{179}<em>{72}$Hf$</em>{107}$</td>
<td>1106</td>
<td>25d</td>
<td>25/2-</td>
</tr>
<tr>
<td></td>
<td>3775</td>
<td>15\mu s</td>
<td>43/2+</td>
</tr>
<tr>
<td>$^{181}<em>{72}$Hf$</em>{109}$</td>
<td>1044</td>
<td>~100\mu s</td>
<td>17/2+</td>
</tr>
<tr>
<td></td>
<td>1742</td>
<td>1.5ms</td>
<td>25/2-</td>
</tr>
<tr>
<td>$^{183}<em>{72}$Hf$</em>{111}$</td>
<td>1464</td>
<td>10s</td>
<td>27/2-</td>
</tr>
<tr>
<td>$^{187}<em>{72}$Hf$</em>{115}$</td>
<td>?</td>
<td>0.27\mu s</td>
<td>?</td>
</tr>
</tbody>
</table>

| [B]: Odd A $^{175}_{73}$Ta isotopes |
| $^{175}_{73}$Ta$_{102}$ | 1568 | 2\mu s | 21/2- |
| $^{177}_{73}$Ta$_{104}$ | 1355 | 5.3\mu s | 21/2- |
| | 4656 | 133\mu s | 49/2- |
| $^{179}_{73}$Ta$_{106}$ | 1328 | 1.6\mu s | 23/2- |
| | 1317 | 9\mu s | 25/2+ |
| | 2640 | 54.1\mu s | 37/2+ |
| $^{181}_{73}$Ta$_{108}$ | 1483 | 25\mu s | 21/2- |
| | 2228 | 210\mu s | 29/2- |
| $^{183}_{73}$Ta$_{110}$ | 1311+x | 0.9\mu s | 19/2+ |
| $^{185}_{73}$Ta$_{112}$ | 1273 | 11.8\mu s | 21/2- |
| $^{187}_{73}$Ta$_{114}$ | 1789 | 22s | 27/2- |
| | 2935 | >5\mu m | 41/2+ |
| $^{189}_{73}$Ta$_{116}$ | ? | 0.6\mu s | ? |
| | ? | 1.6\mu s | ? |

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4qp\[pp8\otimes nn8\]

structure and is seen as an yrast trap, since it occurs lower in energy than any other I=16 level. Further, a K\(^\pi\)=2\(^{-}\) isomer (t\(_{1/2}\)=43\,\mu s) in \(^{176}\)Hf at 4864 keV is interpreted as a 6qp [4qp 16\(^{+}\) \otimes nn6\] structure [4].

The observed mpq structures, listed in Table 1, are interpreted as arising from the coupling of the valence nucleon with the (m-1)qp broken pair structures in the core (A-1) even-even nucleus. For instance, the 3qp isomers in \(^{177}\)Hf(23/2\(^{+}\)), \(^{179}\)Hf(25/2\(^{-}\)) and \(^{181}\)Hf(17/2\(^{+}\)) arise from the coupling of 2qp K\(^\pi\)=8\(^{-}\)(pp) structure with the respective valence neutron orbital (as seen in Fig.1), namely 7/2\(^{-}\)(N=105), 9/2\(^{+}\)(N=107) and 1/2\(^{-}\)(N=109). The K\(^\pi\)=37/2\(^{-}\) isomer in \(^{177}\)Hf has the 5qp[4qp16\otimes nn5\] structure. The K\(^\pi\)=49/2\(^{-}\) isomer (t\(_{1/2}\)=43\,\mu s) at 4656 keV in \(^{177}\)Ta has been given the structure 7qp\[6qp22\otimes pp5\] + . The 4636 keV (45/2\(^{+}\)) and 7455 keV (57/2\(^{-}\)) isomers in \(^{175}\)Hf are interpreted [3] as 7qp and 9qp isomers respectively. Two superdeformed (SD) bands at 3726 keV (31/2\(^{-}\) to 83/2\(^{-}\)) and 12688 keV (79/2\(^{-}\) up to 127/2\(^{-}\)) have also been identified [10] in \(^{173}\)Hf.

Relativistic projectile fragmentation (RPF) [7-9] and deep inelastic reactions [6] are effective processes to investigate very neutron-rich nuclei. The storage ring technology [9] has a further advantage in that it can identify longer-lived (>1m) isomers in these exotic species. For Hf and Ta n-rich (N\(\geq\)110) nuclides, the 11/2\(^{+}\)[615] n-orbital also comes into play resulting in higher K-values. For instance, the 1712 keV \(^{183}\)Hf isomer (t\(_{1/2}\)=10s) is assigned [9] the 3qp structure K\(^\pi\)=27/2\[^{[}\]pp8\otimes nn11/2\] \(\ast\). The 2935 keV \(^{187}\)Ta isomer is identified [9] as a 5qp structure K\(^\pi\)=41/2\[^{[}\]pp8\otimes 5/2\[^{[}\]\otimes nn10 (9/2\(^{+}\) \@ 11/2\(^{+}\))]; a 5qp structure with such a high K occurring below 3 MeV is seen to be even longer-lived (>5m) than the 183\(^{1}\)Ta ground state (2.3m). The recent RPF publication [8] leads us to an interesting observation: 56 scientists from 23 institutions of 11 nations teamed up to identify 49 isomers in 23 nuclides of 8 elements in this experiment!

Confirmation of the suggested isomer configuration is sought from other experimental quantities e.g. decay transition rates, (g\(_K\)
g\(_R\)) values, reduced K-hindrance factors etc. Critical analysis of all available isomer data is being undertaken to deduce distinctive characteristics of this phenomenon.

Fig. 1: Schematic (not to scale) single particle level diagram for rare earth nuclei. The energy ordering of levels is only qualitative.

References

[3] ENSDF, XUNDL, NWC and NUDAT, continuously updated data bases at NNDC (Brookhaven NY) June 2012 version