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 Ω 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 mpq 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 mpq (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 $t_{1/2} \geq$ μs 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 $t_{1/2} \geq$μs 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 Ω=7/2 & 9/2 orbitals. This fact explains the observation [3] of low-lying (~1MeV) $K^\pi=8^-$pp isomers in all even-even Z=72 (Hf) isotopes and $K^\pi=8^-$nn isomers in all N=106 isotones from Z=68 (^{174}Er) through Z=82 (^{188}Pb). The classic (first reported in 1968)

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

^{A}X	E_x (keV)	$t_{1/2}$	K^π
[A]: Odd A $_{72}$Hf isotopes			
$^{175}Hf_{103}$	1433	1.1μs	19/2+
	3015	1.2μs	35/2-
	4636	2.8μs	45/2+
	7455	>7ns	(57/2-)
$^{177}Hf_{105}$	1342	56μs	19/2+
	1315	1.1s	23/2+
	2740	51.4m	37/2-
$^{179}Hf_{107}$	1106	25d	25/2-
	3775	15μs	43/2+
$^{181}Hf_{109}$	1044	~100μs	17/2+
	1742	1.5ms	25/2-
$^{183}Hf_{111}$	1464	10s	27/2-
$^{187}Hf_{115}$	?	0.27μs	?
[B]: Odd A $_{73}$Ta isotopes			
$^{175}Ta_{102}$	1568	2μs	21/2-
$^{177}Ta_{104}$	1355	5.3μs	21/2-
	4656	133μs	49/2-
$^{179}Ta_{106}$	1328	1.6μs	23/2-
	1317	9ms	25/2+
	2640	54.1ms	37/2+
$^{181}Ta_{108}$	1483	25μs	21/2-
	2228	210μs	29/2-
$^{183}Ta_{110}$	1311+x	0.9μs	19/2+
$^{185}Ta_{112}$	1273	11.8ms	21/2-
$^{187}Ta_{114}$	1789	22s	27/2-
	2935	>5m	41/2+
$^{189}Ta_{116}$	?	0.6μs	?
	?	1.6μs	?

longest-lived even-even isomer ($t_{1/2}$ = 31y) observed in ^{178}Hf (2446 keV) has $K^\pi=16^+$ with

4qp[pp8^-⊗nn8^-] structure and is seen as an yrast trap, since it occurs lower in energy than any other I=16 level. Further, a $K^\pi=22^-$ isomer ($t_{1/2}$=43μs) in ^{176}Hf at 4864 keV is interpreted as a 6qp [4qp 16^+ ⊗ nn6^-] structure [4].

The observed mqp 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^+⊗n$5/2^-$] structure. The $K^\pi=49/2^-$ isomer ($t_{1/2}$=192μs) at 4656 keV in ^{177}Ta has been given the structure 7qp[6qp22^-⊗p$5/2^+$]. 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 ^{175}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≥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^-⊗n$11/2^+$]. The 2935 keV ^{187}Ta isomer is identified [9] as a 5qp structure $K^\pi=41/2^+$[ppp8^-⊗$5/2^+$: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 ^{187}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.

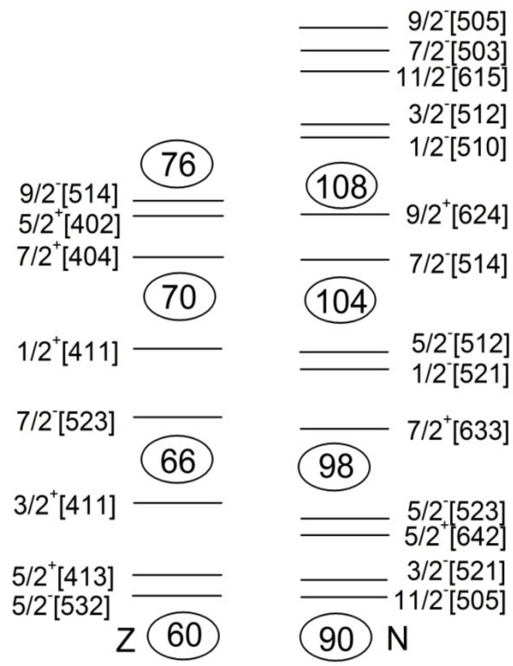

Fig. 1: Schematic (not to scale) single particle level diagram for rare earth nuclei. The energy ordering of levels is only qualitative.

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