K-isomers in heavy and superheavy nuclei

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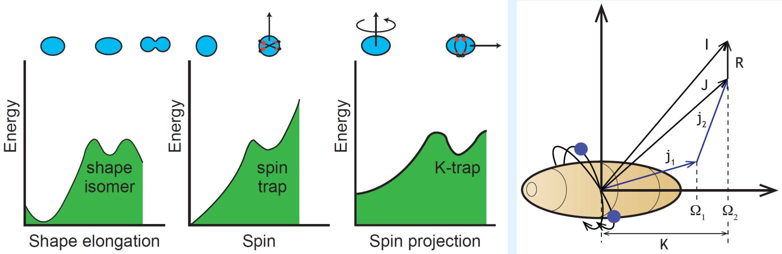
Nuclear deformation and K-isomers



P. Walker, G. Dracoulis, Nature **399**, 35 (1999); Rep. Prog. Phys. **79**, 076301 (2016)

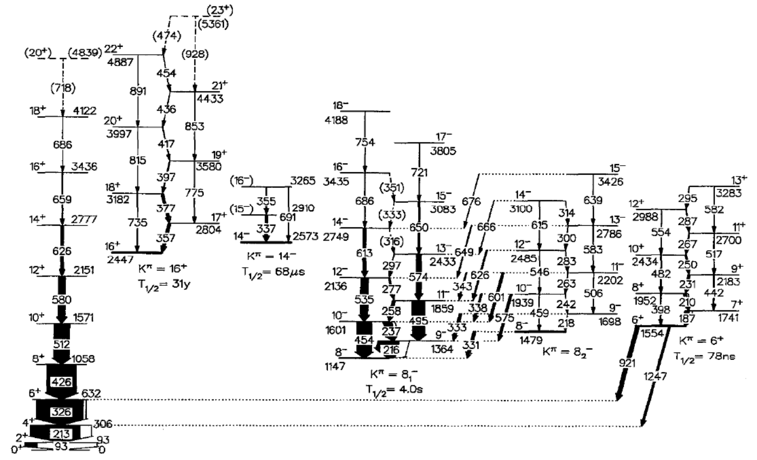
K-isomeric states in even-even nuclei:

Broken nucleon pairs $\Rightarrow$ coupled s.p. orbitals $\Rightarrow$ two- or multi-quasiparticle (qp) excitations with high K under axial symmetry conditions $\Rightarrow$ ΔK suppressed transitions $\Rightarrow$ K isomeric states

K-isomeric states in odd-mass nuclei:

Different K bandheads and axial symmetry

High-*K* isomers in ^{178}Hf



S. M. Millins, G. D. Dracoulis et al, PLB **400**, 401 (1997)

DSM+BCS analysis of 2qp energies and magnetic moments

DSM+BCS with quadrupole and octupole deformations

$$H = H_{\rm sp}(V_{\rm ws}(\beta_2,\beta_3)) + H_{\rm pair}$$

Pairing constants: $G_{n/p} = \left(g_0 \mp g_1 \frac{N-Z}{A}\right)/A, \quad g_0 = 17.8$ MeV, $g_1 = 7.4$ MeV

Two-quasiparticle energies

$$E^{K\pi}_{2qp} = E^{\Omega_1\pi_1}_{1qp} + E^{\Omega_2\pi_2}_{1qp}\ , \qquad E^{\Omega\pi}_{1qp} = \sqrt{(E^{\Omega\pi}_{sp}-\lambda)^2 + \Delta^2}$$

$K = \Omega_1 + \Omega_2;\ \pi = \pi_1 \cdot \pi_2 \ \ (\beta_3 = 0), \qquad \pi = {\rm sign}\langle\pi_1\rangle \cdot {\rm sign}\langle\pi_2\rangle \ (\beta_3 \neq 0)$

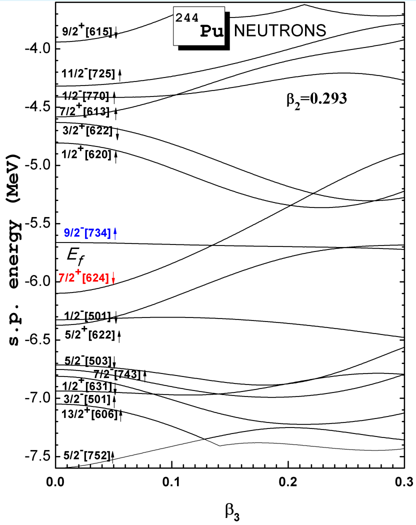
Magnetic moment of the 2qp configuration

$$\mu = \mu_N \left[g_R \frac{I(I+1)-K^2}{I+1} + g_K \frac{K^2}{I+1} \right]$$

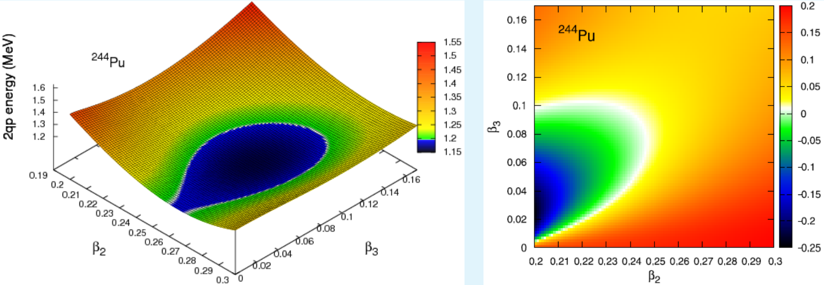
$$g_K = \frac{1}{K} \sum_{n=1,2} \langle \mathcal{F}_{\Omega_n} | g_s \cdot \Sigma + g_l \cdot \Lambda | \mathcal{F}_{\Omega_n} \rangle$$

$$g_R = Z/A, \quad g_s = 0.6 g_s^{\rm free}$$

Neutron s.p. levels in ^{244}Pu in dependence on the octupole deformation β_3 at fixed quadrupole deformation β_2

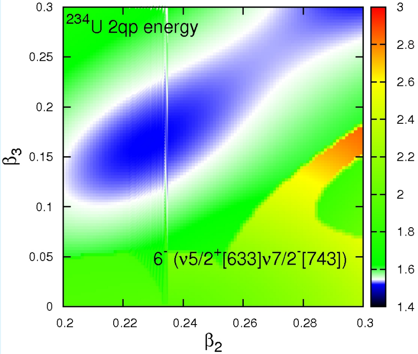


Two-quasiparticle energy and magnetic moment for the $K^\pi = 8^-$ $\{\nu 7/2[624] \otimes \nu 9/2[734]\}$ configuration in ^{244}Pu



[P. M. Walker and N. Minkov, Phys. Lett. B **694**, 119-122 (2010)]

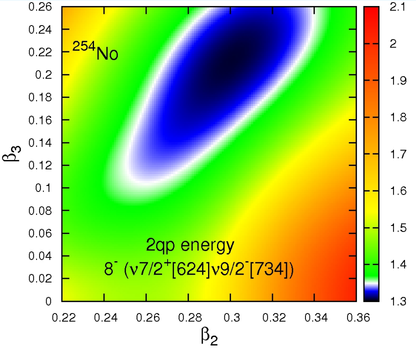
Two-quasiparticle energy and magnetic moment for the $K^\pi = 6^-$ $\{\nu 5/2[633] \otimes \nu 7/2[743]\}$ configuration in ^{234}U

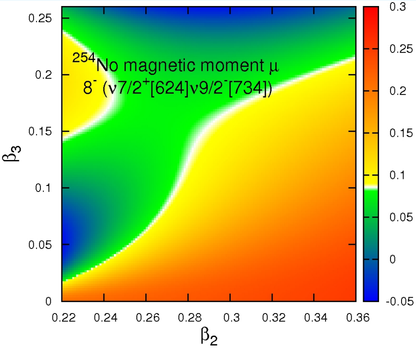


Other approaches:

- PES calculations by H. L. Liu and F. R. Xu, PRC **87**, 067304 (2013) – ($\beta_2 \sim 0.22$, $\beta_3 \sim 0.03$)
- Skyrme HFBCS calculations by L. Bonneau, P. Quentin, N. M. et al, Bulg. J. Phys. **46**, 366 (2019) – ($\beta_2 \sim 0.25$, $\beta_3 \sim 0.05$)

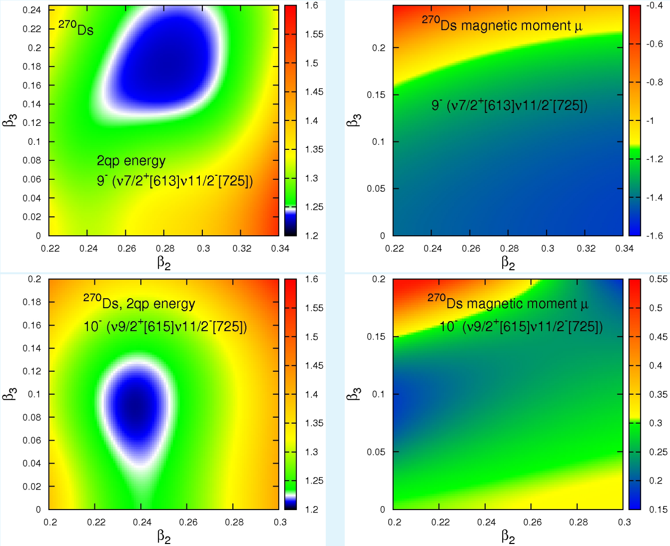
Two-quasiparticle energy and magnetic moment for the $K^{\pi} = 8^{-}$ $\{\nu 7/2[624] \otimes \nu 9/2[734]\}$ configuration in ^{254}No





[N. Minkov and P. M. Walker, Phys. Scripta **89**, 054021 (2014)]

2qp energy and magnetic moments for $K^{\pi} = 9^{-}, 10^{-}$ isomer in ^{270}Ds



[N. Minkov and P. M. Walker, Phys. Scripta **89**, 054021 (2014)]

Systematics of 2qp energy minima

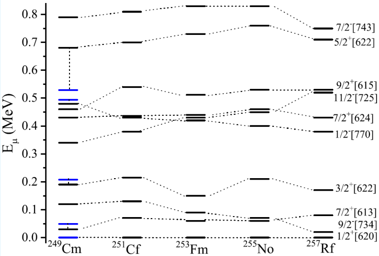
Phys. Scr. 89 (2014) 054021 N Minkov and P Walker

Table 1. Positions and depths of the 2qp energy minima in the (β_2, β_3)-surfaces obtained by DSM+BCS calculations for isomeric states of several heavy and superheavy nuclei. See the text for details.

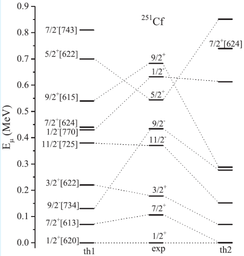
Nucleus	K^π	Configuration	β_2^{min}	β_3^{min}	Depth (MeV)
^{234}U	$K^\pi = 6^-$	$\{\nu 5/2[633] \otimes \nu 7/2[743]\}$	0.228	0.162	**0.432**
^{236}U	$K^\pi = 4^-$	$\{\nu 1/2[631] \otimes \nu 7/2[743]\}$	0.235	0.070	0.021
^{238}Pu	$K^\pi = 4^-$	$\{\nu 1/2[631] \otimes \nu 7/2[743]\}$	0.235	0.064	0.016
^{244}Pu	$K^\pi = 8^-$	$\{\nu 7/2[624] \otimes \nu 9/2[734]\}$	0.262	0.076	0.031
^{244}Cm	$K^\pi = 6^+$	$\{\nu 5/2[622] \otimes \nu 7/2[624]\}$	0.256	0.102	0.075
^{246}Cm	$K^\pi = 8^-$	$\{\nu 7/2[624] \otimes \nu 9/2[734]\}$	0.261	0.076	0.032
^{248}Cm	$K^\pi = 8^-$	$\{\nu 7/2[613] \otimes \nu 9/2[734]\}$	0.231	0.000	0.000
^{250}Fm	$K^\pi = 8^-$	$\{\nu 7/2[624] \otimes \nu 9/2[734]\}$	0.257	0.078	0.037
^{256}Fm	$K^\pi = 7^-$	$\{\pi 7/2[633] \otimes \pi 7/2[514]\}$	0.238	0.000	0.000
^{250}No	$K^\pi = 6^+$	$\{\nu 5/2[622] \otimes \nu 7/2[624]\}$	0.253	0.108	0.084
^{252}No	$K^\pi = 8^-$	$\{\nu 7/2[624] \otimes \nu 9/2[734]\}$	0.257	0.080	0.040
^{254}No	$K^\pi = 8^-$	$\{\nu 7/2[624] \otimes \nu 9/2[734]\}$	0.302	0.212	**0.317**
^{270}Ds	$K^\pi = 9^-$	$\{\nu 7/2[613] \otimes \nu 11/2[725]\}$	0.282	0.18	**0.139**
^{270}Ds	$K^\pi = 10^-$	$\{\nu 9/2[615] \otimes \nu 11/2[725]\}$	0.238	0.09	0.026
^{154}Nd	$K^\pi = 4^-$	$\{\nu 5/2[642] \otimes \nu 3/2[521]\}$	0.284	0.108	**0.137**
^{156}Nd	$K^\pi = 5^-$	$\{\nu 5/2[642] \otimes \nu 5/2[523]\}$	0.292	0.000	0.000
^{160}Sm	$K^\pi = 5^-$	$\{\nu 5/2[642] \otimes \nu 5/2[523]\}$	0.286	0.000	0.000
^{154}Gd	$K^\pi = 7^-$	$\{\nu 3/2[402] \otimes \nu 11/2[505]\}$	0.327	0.168	**0.137**
^{156}Gd	$K^\pi = 7^-$	$\{\nu 3/2[402] \otimes \nu 11/2[505]\}$	0.362	0.170	**0.126**

Coriolis mixing in 1qp isomers of $N = 153$ isotones, T. Shneidman, N. M., G. Adamian, N. Antonenko PRC 106, 014310 (2022)

TCSM



TCSM DSM



$$^{251}\mathrm{Cf}\text{: } I^\pi, K^\pi[Nn_z\Lambda] = 7/2^+, 1/2^+[620] \to E = 105.7 \text{ keV};$$

$$I^\pi, K^\pi[Nn_z\Lambda] = 7/2^+, 7/2^+[613] \to E = 106.3 \text{ keV}$$

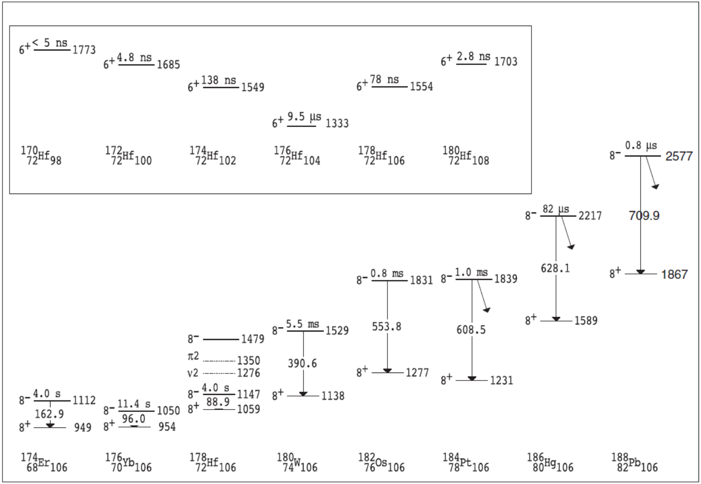
Nucleus	^{249}Cm	^{251}Cf	^{253}Fm
$E_{7/2^+}$ (keV)	39.0 (58.8)	105.9 (106.3)	118.2
$B(E2, 7/2^+ \to 3/2^+_{K=1/2})$ (W.u.)	0.93×10^{-3} (2.7×10^{-3})	0.124 (0.47)	0.368×10^{-3}
$B(E2, 7/2^+ \to 5/2^+_{K=1/2})$ (W.u.)		0.017 (<0.032)	0.762×10^{-3}
$B(M1, 7/2^+ \to 5/2^+_{K=1/2})$ (W.u.)		4.66×10^{-5} ($>2.1\times10^{-5}$)	4.91×10^{-7}
$T_{1/2}$	73.4 μs (23 μs)	45 ns (38 ns)	3.65 μs

Skyrme HFBCS in K-isomers

- Hartree-Fock (HF) plus BCS energy-density functional
- Selfconsistent blocking of two s.p. states (2qp isomer configuration)
- SIII Skyrme force with spin and current vector time-odd fields
- Deformed HO basis with axial symmetry: $N_0 + 1 = 17$ (for actinides and SH) and $N_0 + 1 = 15$ (for rare-earths) major oscillator shells; NG_z=30 (Gauss - Hermite in z), NG_r=15 (Gauss–Laguerre in $\perp$) quadrature mesh points; basis parameters b, q optimized
- Pairing strengths G_n, G_p: overall adjustment to experimental MoI $1/(2\mathfrak{J}) = E(2_1^+)/6 \rightarrow G_n = 16$ MeV, $G_p = 15$ MeV in r-earths
- HFBCS 2qp K-isomer energy: $E^*_{\mathrm{th}}(K^\pi) = E^{2qp}_{\mathrm{tot}}(K^\pi) - E^{\mathrm{GS}}_{\mathrm{tot}}$

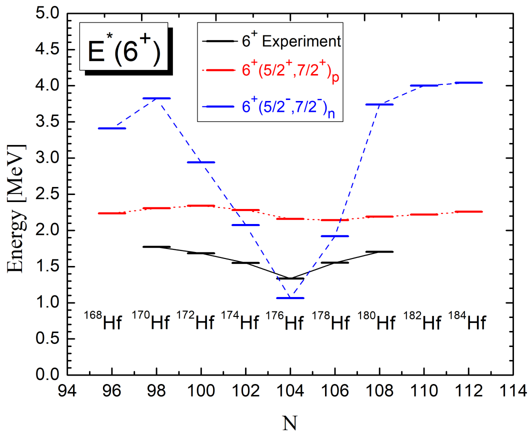
$K^\pi = 6^+$ and $K^\pi = 8^-$ isomers in Hf isotopes and $N = 106$ isotones

Rep. Prog. Phys. 79 (2016) 076301 Review



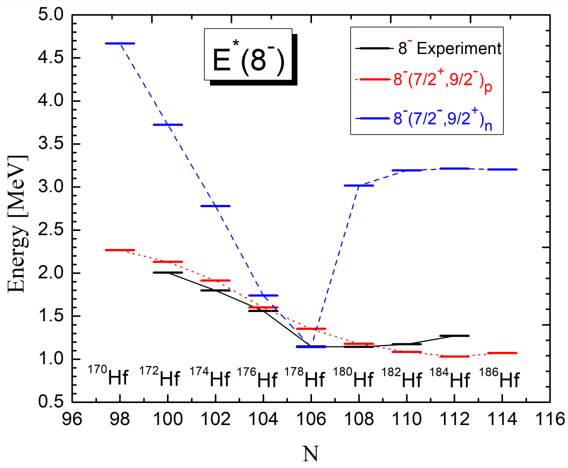
P. Walker, G. Dracoulis, Rep. Prog. Phys. **79**, 076301 (2016)

HFBCS description of $K^\pi = 6^+$ isomer energies in Hf isotopes. Configurations: $\nu 5/2^-[512] \otimes \nu 7/2^-[514]$; $\pi 5/2^+[402] \otimes \pi 7/2^+[404]$

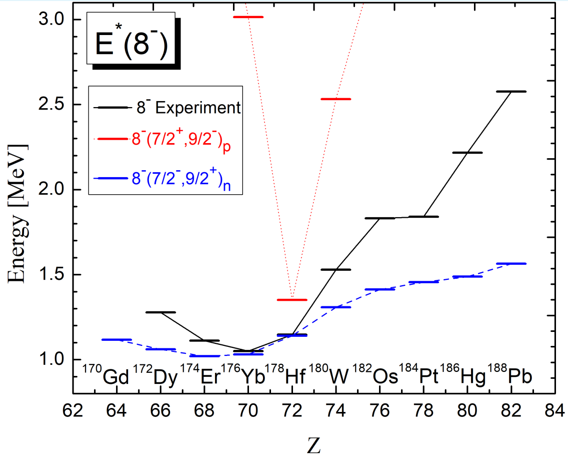


[N.M., L. Bonneau, P. Quentin, J. Bartel, H. Molique, M.-H. Koh, Phys. Rev. C **109**, 064315 (2024)]

HFBCS description of $K^\pi = 8^-$ isomer energies in Hf isotopes. Configurations: $\nu 7/2^-[514] \otimes \nu 9/2^+[624]; \pi 7/2^+[404] \otimes \pi 9/2^-[514]$



HFBCS description of $K^\pi = 8^-$ isomer energies in $N = 106$ isotones. Configurations: $\nu 7/2^-[514] \otimes \nu 9/2^+[624]; \pi 7/2^+[404] \otimes \pi 9/2^-[514]$



HFBCS description of energies and magnetic moments in $K^\pi = 6^+$ and $K^\pi = 8^-$ isomers in Hf isotopes and $N = 106$ isotones

A	N	K^π	E^{*n}_{th}	E^{*p}_{th}	E^*_{exp}	μ^n_{th}	μ^p_{th}
168	96	6^+	3.409	2.236	—	1.832	5.740
		8^-					
170	98	6^+	3.824	2.306	1.773	0.136	5.652
		8^-	4.667	2.266	—	0.148	7.348
172	100	6^+	2.941	2.341	1.685	0.036	5.670
		8^-	3.723	2.130	2.006	0.062	7.338
174	102	6^+	2.073	2.282	1.549	0.074	5.676
		8^-	2.778	1.914	1.798	0.150	7.335
176	104	6^+	1.064	2.159	1.333	−0.029	5.697
		8^-	1.740	1.600	1.559	0.267	7.343
178	106	6^+	1.919	2.143	1.554	0.108	5.704
		8^-	1.141	1.352	1.147	0.311	7.349
180	108	6^+	3.739	2.190	1.703	0.167	5.697
		8^-	3.017	1.179	1.142	0.378	7.343
182	110	6^+	4.002	2.219	—	−2.051	5.757
		8^-	3.193	1.085	1.173	−1.880	7.378
184	112	6^+	4.042	2.258	—	−2.045	5.825
		8^-	3.214	1.031	1.272	−1.931	7.414
186	114	6^+					
		8^-	3.204	1.071	—	−2.028	7.455

A	N	E^{*n}_{th}	E^{*p}_{th}	E^*_{exp}	μ^n_{th}	μ^p_{th}
^{170}Gd	64	1.117	6.748	—	0.331	7.491
^{172}Dy	66	1.060	5.631	1.278	0.356	7.521
^{174}Er	68	1.020	4.331	1.112	0.334	7.571
^{176}Yb	70	1.031	3.015	1.050	0.359	7.422
^{178}Hf	72	1.141	1.351	1.147	0.311	7.349
^{180}W	74	1.308	2.532	1.529	0.256	7.354
^{182}Os	76	1.412	3.434	1.831	0.253	7.391
^{184}Pt	78	1.455	4.341	1.840	0.273	7.401
^{186}Hg	80	1.488	5.305	2.217	0.293	7.408
^{188}Pb	82	1.564	6.031	2.577	0.288	10.226

Data on magnetic moments can favour the n or p configuration

Two-quasiparticle isomers in heavy actinide and SH nuclei

N. MINKOV *et al.* PHYSICAL REVIEW C **105**, 044329 (2022)

Z \ N	138	140	142	144	146	148	150	152	154	156	
104								3.36			Rf
102							3.31	3.29			No
100						3.30	3.27		3.32	3.31	Fm
98							3.32	3.32	3.32		Cf
96					3.25	3.31	3.31	3.31			Cm
94			3.30	3.31	3.31	3.31	3.39	3.31			Pu
92	3.27	3.29	3.30	3.30	3.30	3.35	3.31				U
90	3.23	3.27	3.28	3.29	3.31						Th
88		3.21	3.25	3.29							Ra

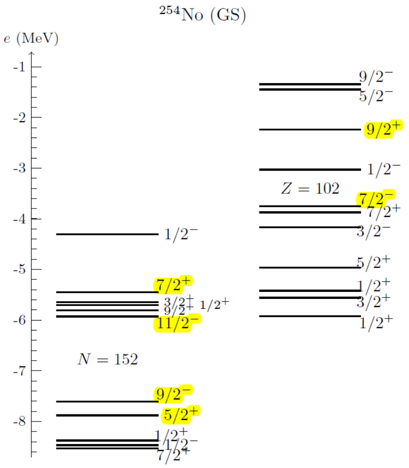
FIG. 1. Ratios $R_{4/2}$ outlining in the (N, Z) plane an area of good-rotor nuclei (with $R_{4/2} \geqslant 3.2$) within the actinide and transfermium region. The color code indicates the criteria under which the nuclei have been selected for this K-isomer study. The color coding is (yellow): nuclei with explicitly documented data on isomeric states [criteria (i) and (ii)]; (red): well-deformed nuclei with isomer-like excitations not explicitly adopted as K isomers [criterion (iii)]; (green): documented isomers in nuclei, assumed to be deformed, but with no data assessing the $R_{4/2}$ value [criterion (iii)].

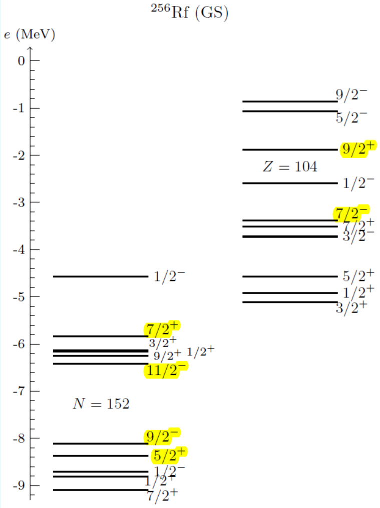
[N.M., L. Bonneau, P. Quentin, J. Bartel, H. Molique, D. Ivanova, PRC **105**, 044329 (2022)]

HFBCS description of K-isomer energies in actinides and SHs

Nucl.	N	K^π	2qp config., Refs.	μ (μ_N)	E^*_{HFBCS} (MeV)	E^*_{exp} (MeV)	$T^{\mathrm{exp}}_{1/2}$	Experiment Refs.
^{234}U	142	6^-	$(\frac{7}{2}^-, \frac{5}{2}^+)_n$ [12]	+0.23	1.582	1.421	33.5 (20) μs	[25,27] E*=1.481 MeV
		5^+	$(\frac{5}{2}^+, \frac{5}{2}^+)_n$ [29]	−0.02	2.425	1.553	2.20 (25) ns	[25,29] (BJP2019 Oct)
			$(\frac{7}{2}^+, \frac{3}{2}^+)_n$	+0.18	2.348			
^{236}U	144	4^-	$(\frac{7}{2}^-, \frac{1}{2}^+)_n$ [46]	+0.17	1.028	1.053	100 (4) ns	[25,27]
^{236}Pu	142	5^-	$(\frac{5}{2}^-, \frac{5}{2}^+)_p$ [47]	+4.23	1.138	1.186	1.2 (3) μs	[25,27]
		0^-	$(\frac{5}{2}^-, -\frac{5}{2}^+)_p$	0	1.289	1.312		[25]
^{238}Pu	144	5^-	$(\frac{5}{2}^-, \frac{5}{2}^+)_p$	+4.24	1.190			
		4^-	$(\frac{7}{2}^-, \frac{1}{2}^+)_n$ [29,48]	+0.23	1.033	1.083	8.5 (5) ns	[25]
^{240}Pu	146	3^+	$(\frac{5}{2}^+, \frac{1}{2}^+)_n$ [29]	−0.04	1.367	1.031	1.32 (15) ns	[25]
			$(\frac{7}{2}^+, -\frac{1}{2}^+)_n$	+0.30	1.245			
		5^-	$(\frac{5}{2}^-, \frac{5}{2}^+)_p$ [49]	+4.24	1.295	1.309	165 (10) ns	[25,27]
^{244}Pu	150	8^-	$(\frac{9}{2}^-, \frac{7}{2}^+)_n$ [28]	+0.28	1.219	1.216	1.75 (12) s	[25,28]
^{244}Cm	148	6^+	$(\frac{7}{2}^+, \frac{5}{2}^+)_n$ [29,50]	+0.12	1.042	1.040	34 (2) ms	[25,27]
^{246}Cm	150	8^-	$(\frac{9}{2}^-, \frac{7}{2}^+)_n$ [51,52]	+0.32	1.227	1.180	1.12 (24) s	[25,51,52]
^{248}Cm	152	8^-	$(\frac{9}{2}^-, \frac{7}{2}^+)_n$ [52]	−1.72	2.025	1.461	146 (18) μs	[52]
^{248}Cf	150	8^-	$(\frac{9}{2}^-, \frac{7}{2}^+)_n$ [30,51]	+0.31	1.276	1.261		[25]
^{248}Fm	148	6^+	$(\frac{5}{2}^+, \frac{7}{2}^+)_n$ [31]	+0.09	1.240	1.188	10.1 (6) ms	[31,53]
^{250}Fm	150	8^-	$(\frac{9}{2}^-, \frac{7}{2}^+)_n$ [26]	+0.32	1.374	1.199	1.92 (5) s	[26,27]
^{256}Fm	156	7^-	$(\frac{7}{2}^+, \frac{7}{2}^-)_p$ [12,54]	+6.31	1.312	1.426	70 (5) ms	[25,27]
^{252}No	150	8^-	$(\frac{9}{2}^-, \frac{7}{2}^+)_n$ [51,55]	+0.36	1.501	1.253	109 (3) ms	[25,27]
^{254}No	152	8^-	$(\frac{7}{2}^-, \frac{9}{2}^+)_p$ [29,56]	+7.31	1.914	1.297	263 (2) ms	[25,27]
			$(\frac{5}{2}^+, \frac{11}{2}^-)_n$	−1.65	2.209			
			$(\frac{9}{2}^-, \frac{7}{2}^+)_n$	−1.70	2.327			
		16^+	$(\frac{9}{2}^-, \frac{7}{2}^+)_n(\frac{7}{2}^-, \frac{9}{2}^+)_p$	+5.66	4.142	2.930	184 (2) μs	[25,27]
			$(\frac{5}{2}^+, \frac{11}{2}^-)_n(\frac{7}{2}^-, \frac{9}{2}^+)_p$	+5.71	3.892			
^{256}No	154	(5^-)	$(\frac{11}{2}^-, -\frac{1}{2}^+)_n$ [32]	+0.23	1.487	>1.089	$7.8^{+8.3}_{-2.6}$ μs	[32]
		(7^-)	$(\frac{11}{2}^-, \frac{3}{2}^+)_n$ [32]	+0.23	1.448			
^{254}Rf	150	(8^-)	$(\frac{9}{2}^-, \frac{7}{2}^+)_p$ [33]	+0.36	1.647		4.7(1) μs	[25,33,34]
^{256}Rf	152	(5^-)	$(\frac{1}{2}^-, \frac{9}{2}^+)_p$ [58]	+4.49	1.028	≈1.120	25(2) μs	[25,27]
		(8^-)	$(\frac{7}{2}^-, \frac{9}{2}^+)_p$ [58]	+7.33	1.748	≈1.400	17(2) μs	

$N = 152$ deformed shell gap issue





[N.M., L. Bonneau, P. Quentin, J. Bartel, H. Molique, D. Ivanova, PRC **105**, 044329 (2022)]

HFBCS description of K-isomer radii and quadrupole moments

Nucleus	State	r_c (fm)		Q_c (b)	
		Theory	Expt. [41]	Theory	Expt. [42]
^{234}U	GS	5.902	5.8291 *52*	10.08	10.35 *10*
	$(6^-)_n$	5.901		10.14	
^{236}U	GS	5.916	5.8431 *38*	10.36	10.80 *9*
	$(4^-)_n$	5.917		10.55	
	$(4^-)_p$	5.910		10.14	
^{236}Pu	GS	5.932		10.85	
	$(5^-)_p$	5.936		11.17	
^{238}Pu	GS	5.945	5.8535 *378*	11.10	11.26 *9*
	$(4^-)_n$	5.946		11.21	
	$(5^-)_p$	5.948		11.39	
^{240}Pu	GS	5.958	5.8701 *379*	11.28	11.44 *9*
	$(5^-)_p$	5.960		11.54	
^{244}Pu	GS	5.980	5.8948 *382*	11.35	11.73 *9*
	$(8^-)_n$	5.980		11.50	
^{244}Cm	GS	5.998	5.8429 *181*	12.02	12.14 *8*
	$(6^+)_n$	5.999		12.16	
^{246}Cm	GS	6.008	5.8562 *184*	12.01	12.26 *8*
	$(8^-)_n$	6.008		12.12	
^{248}Cm	GS	6.018	5.8687 *193*	11.99	12.28 *8*
	$(8^-)_n$	6.014		11.72	

HFBCS description of ^{270}Ds K-isomer: test calculations

$E^{\rm exp}_{\rm isomer} = 1.348(66)$ MeV, $T^{\rm exp}_{1/2} = 3.9(+13, -8)$ ms ??, $K^\pi = (10^-)$
F. Kondev, G. Dracoulis, T. Kibedi, ADNDT **103-104**, 50 (2015);
D. Ackermann et al., GSI Sci. Rep. 2011, p.208 (2011) [^{266}Hs]

$E^{\rm exp}_{\rm isomer} = 1.13$ MeV, $T^{\rm exp}_{1/2} = 6.0(+82, -22)$ ms, $K^\pi =$?
S. Garg et al., ADNDT **150**, 101546 (2023); S. Hofmann et al., EPJA **10** 5 (2001); D. Ackermann, C. Theisen, Phys. Scr. **92**, 083002 (2017)

Configuration	$E^{\rm HFBCS}_{\rm isomer}$ (MeV) / Skyrme force					
	SIII$_{(s1)}$	SIII$_{(s2)}$	SkM$^*_{(s1)}$	SLy4$_{(s1)}$	SLy4$_{(s2)}$	SLyIII$_{(s1)}$
$9^-\{n\frac{7}{2}^+[613], n\frac{11}{2}^-[725]\}$	1.946	2.402	2.635	1.079	1.343	1.920
$10^-\{n\frac{9}{2}^+[615], n\frac{11}{2}^-[725]\}$	2.593	2.985	1.668	0.547	0.823	2.461

BCS pairing constants sets
s1: $G_n = 15.8$ MeV, $G_p = 14.2$ MeV (overall adjusted in actinides)
s2: $G_n = 17.0$ MeV, $G_p = 16.0$ MeV

Reflection symmetry conserved

Concluding remarks

- DSM and TCSM approaches: Influence of octupole deformation on the formation of 2qp K-isomeric states in heavy and SH nuclei and their magnetic moments; Enhanced 1qp isomer decay resulting from Coriolis K-mixing.
- Skyrme HFBCS in Hf isotopes and $N = 106$ isotones: Good reproduction of the $K^\pi = 6^+$ and $K^\pi = 8^-$ isomer energies and magnetic moments, identified mixing of p and n configurations; Reproduced systematic behaviour of isomer energies.
- Skyrme HFBCS in heavy actinides and SHs: Overall good reproduction of 2qp isomer energies and GS radii and quadrupole moments; Skyrme SIII and $N = 152$ deformed shell gap; SLy4 in ^{270}Ds; Possible readjustment of the Skyrme force including very heavy and SH nuclei.
- Further work: Tests of Skyrme interactions on multi-q.p. isomers; Odd-mass and odd-odd heavy and SH nuclei; Exploring the octupole mode.

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