Shape and electromagnetic properties of the ^{229m}Th isomer

Nikolay Minkov

Institute of Nuclear Research and Nuclear Energy
Bulgarian Academy of Sciences, Sofia, Bulgaria
Research Group on Complex Deformed Atomic Nuclei

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Collaboration and Support

Collaborator: Adriana Pálffy

Max-Planck-Institut für Kernphysik
Heidelberg

and Friedrich-Alexander-Universität Erlangen-Nürnberg, Erlangen

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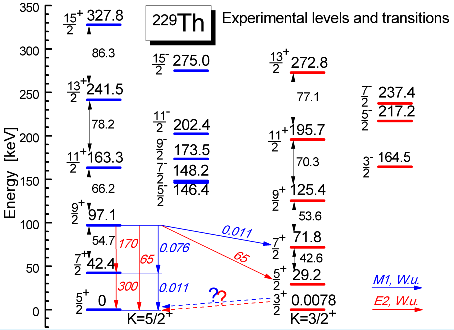
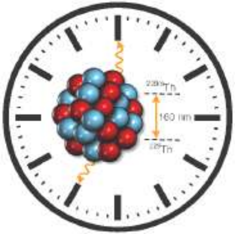
^{229}Th levels and transitions. ^{229m}Th isomer and nuclear clock.



Nuclear Clock?



$$E(^{229m}Th) = E_{IS}(\tfrac{3}{2}^{+}) \approx 8 \text{ eV}$$

$$\Leftrightarrow \lambda \sim 160 \text{ nm}, \ \Delta E/E \simeq 10^{-20}$$

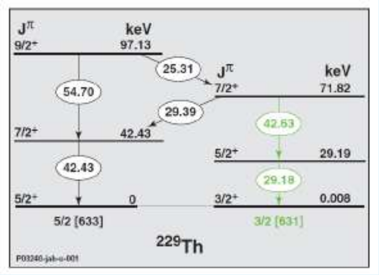
Advantages vs atomic clocks: better isolation from chem. environment; better frequency stability; higher accuracy: not lag behind / accelerate by more than a second in a period tens of times longer than the age of the Universe.

Possible applications: laser and plasma physics, metrology, geodesy, cosmology, gravitation waves, deep space navigation; ultra-precise chemical analysis etc.

https://en.wikipedia.org/wiki/Nuclear_clock

What do we need to create a ^{229m}Th clock?

Need of high precision ^{229m}Th $(3/2^{+})$ energy measurement

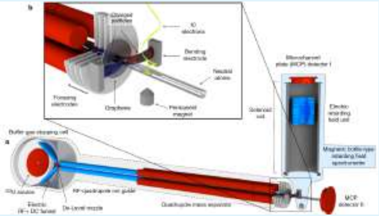


L. Kroger, C. Reich, NPA1976, $E_{IS} < 100$eV

D. Burke et al, PRC1990, NPA2008
R. Helmer, C. Reich, PRC1994, $E_{IS}\sim 3.5$eV

Micro-calorimetric methods:
B. Beck et al, PRL **98**, 142501 (2007);
LLNL-PROC-415170 (2009), $E_{IS} \sim 7.8$ eV

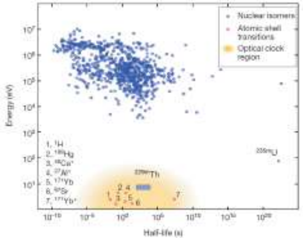
A. Yamaguchi et al, PRL **123**, 222501 (2019),
$E_{IS} = 8.30 \pm 0.92$ eV



Internal conversion electron (IC) spectroscopy:
$E_{IS} = 8.28 \pm 0.17$ eV
B. Seiferle et al, Nature **573**, 243 (2019).

Need of high-precision determination of ^{229m}Th lifetime

L. von der Wense, ..., P. Thirolf et al, Nature **533**, 47 (2016)



Lifetime needed 1) to unambiguously identify/characterize the ^{229m}Th decay; 2) to adjust conditions for the frequency stabilization (laser frequency comb and other methods)

$\Rightarrow$ need of high-precision determination of B(M1) and B(E2) rates for nuclear $3/2^+_{IS} \to 5/2^+_{GS}$ transitions

Decay detection and lifetime estimates:

L. von Wense, ..., P. Thirolf et al, Nature **533**, 47 (2016), τ(IC) (^{229m}Th^{2+}) $\gtrsim$ 60s
B. Seiferle et al, PRL **118**, 042501 (2017), τ(IC) (^{229m}Th) $= 7 \pm 1\mu$s

Magnetic moment measurement:

J. Thielking, ..., P. Thirolf et al, Nature **556**, 321 (2018), μ (^{229m}Th) $= -0.37(6)\mu_N$

Knowledge of the magnetic dipole moment needed 1) to reduce the ambiguity in the B(M1) and B(E2) transition rates determination; 2) to reveal details of the nuclear microscopic mechanism governing the ^{229m}Th isomer formation.

Quadrupole-octupole core plus particle model in ^{229}Th

N. Minkov and A. Pálffy, PRL **118**, 212501 (2017)

Hamiltonian, spectrum, E/M transition rates

$$H = H_{\text{quad-oct}} + H_{\text{s.p.}} + H_{\text{pair}} + H_{\text{Coriol}}$$

$$E_{nk}(I^\pi, K_b) = \epsilon_{\text{qp}}^{K_b} + \hbar\omega\left[2n+1+\sqrt{k^2 + b\widetilde{X}(I^\pi, K_b)}\right]$$

$$\widetilde{\Psi}^{\pi,\pi^b}_{nkIMK_b} = \frac{1}{\widetilde{N}_{I\pi K_b}}\left[\Psi^{\pi,\pi^b}_{nkIMK_b} + A\sum_{\nu\neq b} C^{I\pi}_{K_\nu K_b}\Psi^{\pi,\pi^b}_{nkIMK_\nu}\right]$$

$$\Psi^{\pi,\pi^b}_{nkIMK} = norm \cdot \Phi^{\pi\cdot\pi^b}_{nkI}\left[D^I_{M\,K}\mathcal{F}^{(\pi^b)}_{K} + \pi\cdot\pi^b(-1)^{I+K}D^I_{M\,-K}\mathcal{F}^{(\pi^b)}_{-K}\right]$$

$$B\begin{pmatrix}E\lambda\\ M1\end{pmatrix} = \frac{1}{2I_i+1}\left|\left\langle \widetilde{\Psi}^{\pi_f,\pi^{b_f}}_{n_f k_f I_f K_f}\middle\| \begin{matrix}\hat{Q}_\lambda\\ \hat{M}1\end{matrix} \middle\| \widetilde{\Psi}^{\pi_i,\pi^{b_i}}_{n_i k_i I_i K_i}\right\rangle\right|^2, \quad \lambda = 1,\ 2,\ 3$$

$$\hat{M}1 = \sqrt{\frac{3}{4\pi}}\mu_N\left[g_R(\hat{I}-\hat{j}) + g_s\,\hat{s} + g_l\,\hat{l}\right], \quad \hat{j} = \hat{l} + \hat{s}, \quad \mu_N = \frac{e\hbar}{2mc}$$

N. Minkov and A. Pálffy, PRL **122** 162502 (2019)

Magnetic dipole moment

$$\mu = \sqrt{\frac{4\pi}{3}}\langle\widetilde{\Psi}_{IIK_b}|\hat{M}1_z|\widetilde{\Psi}_{IIK_b}\rangle$$

Application to ^{229}Th with:

$g_s = q_s \cdot g_s^{free}$

spin gyromagnetic quenching (core polarization effect): $q_s = 0.6$

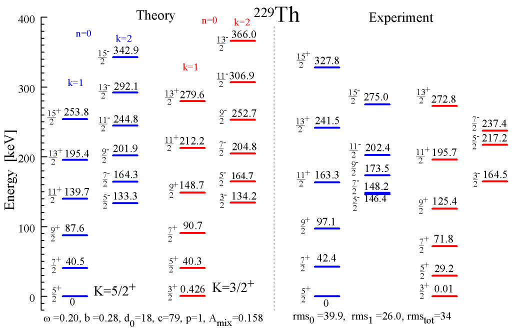
$g_R = q_R \cdot Z/A$

collective gyromagnetic quenching (pairing effect):

q_R=1.0, 0.8 (from exp. M1/E2), 0.7 (Nilsson), 0.6 (HF+BCS)

^{229}Th: spectrum description and isomer lifetime prediction

N. Minkov and A. Pálffy, PRL **118**, 212501 (2017)



DSM: Ground-state and isomer s.p. orbitals GS(5/2[633]), IS(3/2[631])
Quadrupole and octupole deformations: $\beta_2 = 0.240$, $\beta_3 = 0.115$

⇒ Transition probabilities for the $3/2^+$-isomer decay in ^{229}Th predicted in the limits:

$B(E2)$=20–30 W.u. $B(M1)$=0.006–0.008 W.u.

⇒ **Predicted ^{229m}Th lifetime of approx. 10^4 sec.**

Magnetic moments in the $3/2^+_{\mathbf{IS}}$ and $5/2^+_{\mathbf{GS}}$ states of ^{229}Th

N. Minkov and A. Pálffy, PRL **122** 162502 (2019)

Theoretical magnetic moments (in μ_N) for different q_Rs compared to experiment

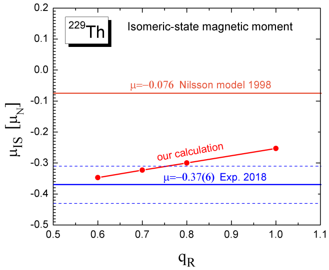
μ	q_R (our work)				other theories		laser spectroscopy			
	1.0	0.8	0.7	0.6	Th77	Th98	Exp74	Exp13	Exp18a	Exp18b
μ_{GS}	0.654	0.591	0.559	0.528	0.54	–	0.46(4)	0.360(7)	–	–
μ_{IS}	−0.253	−0.300	−0.323	−0.347	–	−0.076	–	–	[−0.3, −0.4]	−0.37(6)

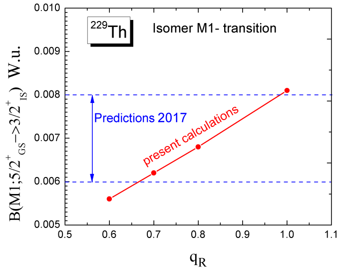
Th77: Modified Woods-Saxon Model, R. Chasman et al, RMP **49**, 833 (1977)
Th98: Nilsson Model, A. Dykhne and E. Tkalya, JETP Lett. **67**, 251 (1998)
Exp74: S. Gerstenkorn et al., J. Phys. **35**, 483 (1974)
Exp13: M. Safronova et al, PRA **88**, 060501(R) (2013)
Exp18a: R. Müller et al., PRA **98**, 020503(R) (2018)
Exp18b: J. Thielking,..., P.Thirolf, E.Peik, Nature **556**, 321 (2018)

Calculated $B(M1)$ rates (in W.u.) in dependence on q_R (and $\mu_{\mathbf{IS}}$, $\mu_{\mathbf{GS}}$)

Decay	q_R				Experiment [ENDSF]
	1.0	0.8	0.7	0.6	
$3/2^+_{\mathrm{ex}} \rightarrow 5/2^+_{\mathrm{yr}}$	0.0081	0.0068	0.0062	0.0056	–
$7/2^+_{\mathrm{yr}} \rightarrow 5/2^+_{\mathrm{yr}}$	0.0096	0.0043	0.0025	0.0011	0.0110 (40)
$9/2^+_{\mathrm{yr}} \rightarrow 7/2^+_{\mathrm{yr}}$	0.0185	0.0097	0.0065	0.0038	0.0076 (12)
$9/2^+_{\mathrm{yr}} \rightarrow 7/2^+_{\mathrm{ex}}$	0.0144	0.0147	0.0149	0.0151	0.0117 (14)

Magnetic moment and B(M1) rate in ^{229m}Th for different q_R values





Note 1: $\mu_{\text{IS}}^{\text{theo}}$ is obtained with model parameters adjusted (PRL2017) to energy levels and transition rates and not to $\mu_{\text{IS}}^{\text{exp}}$. Here only q_R is varied.

Note 2: Surprisingly good agreement with $\mu^{\text{exp}}_{\text{IS}} = -0.37(6)\ \mu_N$ is found.

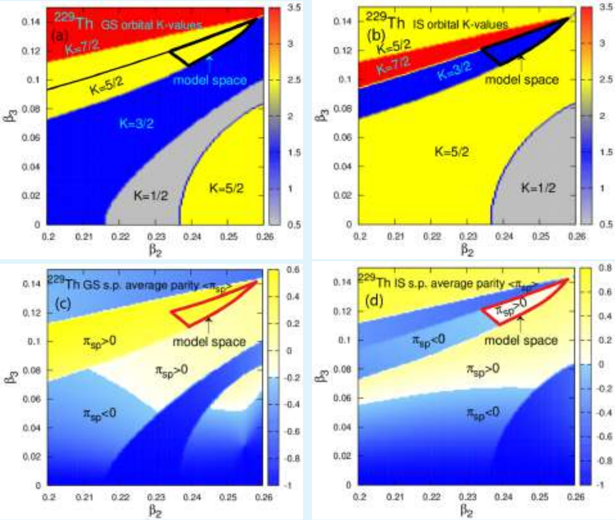
Note 3: The best agreeing $\mu_{\text{IS}}^{\text{theo}} = -0.347\ \mu_N$ value suggests a smaller $\text{B(M1)}_{\text{IS}} = 0.0056$ W.u. compared to PRL2017 pointing on **^{229m}Th lifetime possibly larger than 10^4 sec.**

⇒ Needs to study additional dependencies which may constraint the isomer decay rates and lifetime suggesting further more precise determination of ^{229m}Th nuclear clock characteristics.

Further understanding of the ^{229m}Th isomer formation mechanism and properties

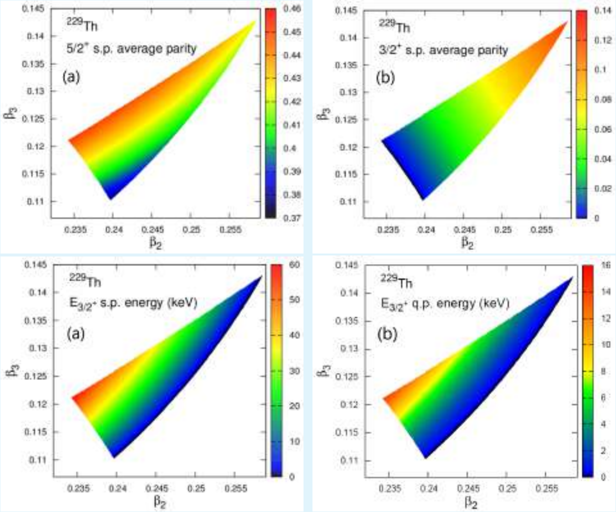
- How does the shape dynamics determine the emergence of such a nuclear structure phenomenon as the tiny energy difference between the IS and the GS?
- What is the degree of arbitrariness in the choice of parameters providing the model predictions?
- In which limits the model predictions for the transition rates and magnetic moments vary and could they be further constrained?
- Is ^{229m}Th a unique phenomenon appearing by chance, or the considered dynamical mechanism could provide the presence of similar not yet observed phenomena in other nuclei?

^{229}Th GS and IS K-values in the DSM (β_2, β_3) space



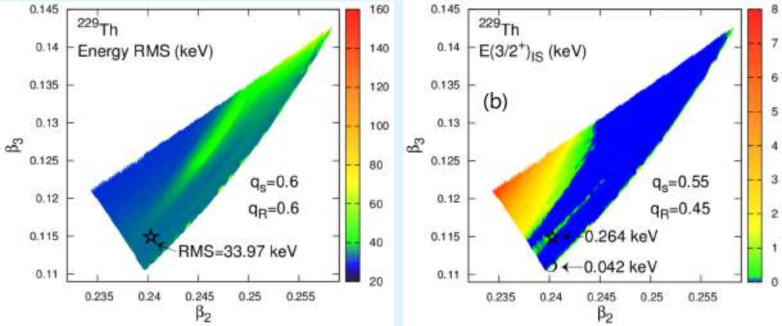
N. Minkov and A. Pálffy, PRC **103**, 014313 (2021)

GS and IS average parity and IS s.p.&q.p. energy in the DSM (β_2, β_3) space

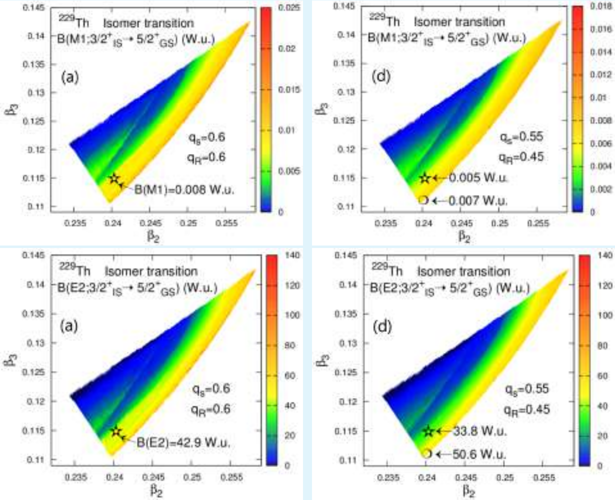


Model fits in the (β_2, β_3) space: Energy RMS and IS energy.

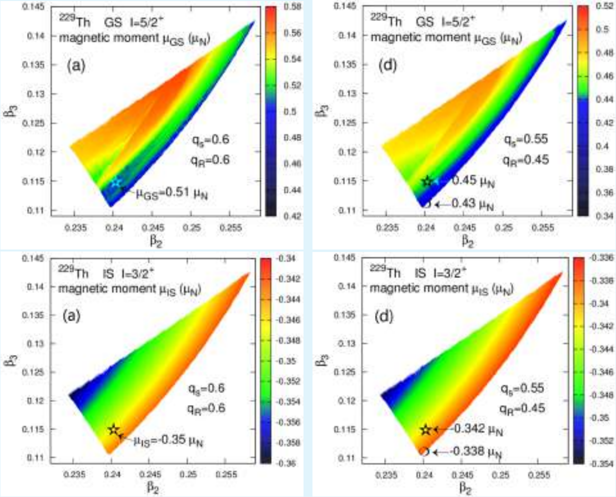
Full model fits (CQOM and Coriolis strength) to the energy, transition rates and magnetic moments over a net in the DSM (β_2, β_3) space



Model fits in the (β_2, β_3) space: B(M1) and B(E2) IS decay rates.



Model fits in the (β_2, β_3) space: GS and IS magnetic moments.



Concluding remarks

- CQOM+DSM+BCS model analysis: The ^{229}Th isomer can be formed in rather limited QO deformation space $0.235 \leq \beta_2 \leq 0.255$ and $0.11 \leq \beta_3 \leq 0.14$. Crucial role of the nonzero octupole deformation.
- Model description and predictions: → Smooth behaviour of the model determined quantities – energy, B(M1) and B(E2) transition rates and magnetic moments within the model deformation space. Rather constrained arbitrariness in the obtained descriptions and predictions.
- Slight update of model predictions: IS $B(M1) \sim 0.005$ W.u., $B(E2) \sim 30 - 50$ W.u., $\mu_{\text{GS}} \sim 0.43 - 0.48\ \mu_N$, $\mu_{\text{IS}} \sim (-0.35) - (-0.34)\ \mu_N$ (firmly within exp. uncertainty limits).
- Model mechanism: the fine interplay between nuclear collective and intrinsic degrees of freedom may be a plausible reason for the isomer formation. The same dynamical mechanism may govern also in other nuclei the formation of excitations close to the border of atomic physics energy scale.