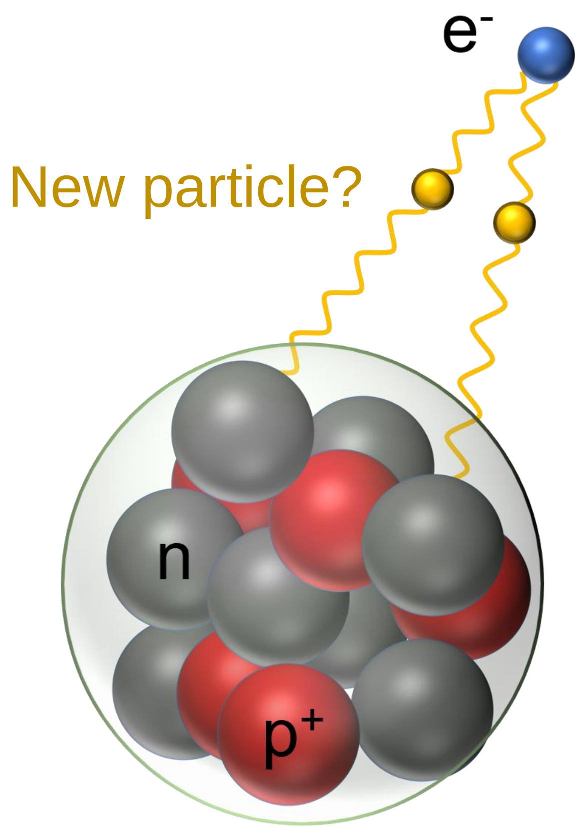
Insights into new physics and nuclear physics from precise isotope shift measurements

Taiki Ishiyama

Koki Ono, Tetsushi Takano, Ayaki Sunaga, Yosuke Takasu, Yasuhiro Yamamoto[1], Minoru Tanaka[2] and Yoshiro Takahashi

Quantum Optics Group, Kyoto. Univ.

NCTS, Taiwan[1], Osaka Univ.[2]



Outline

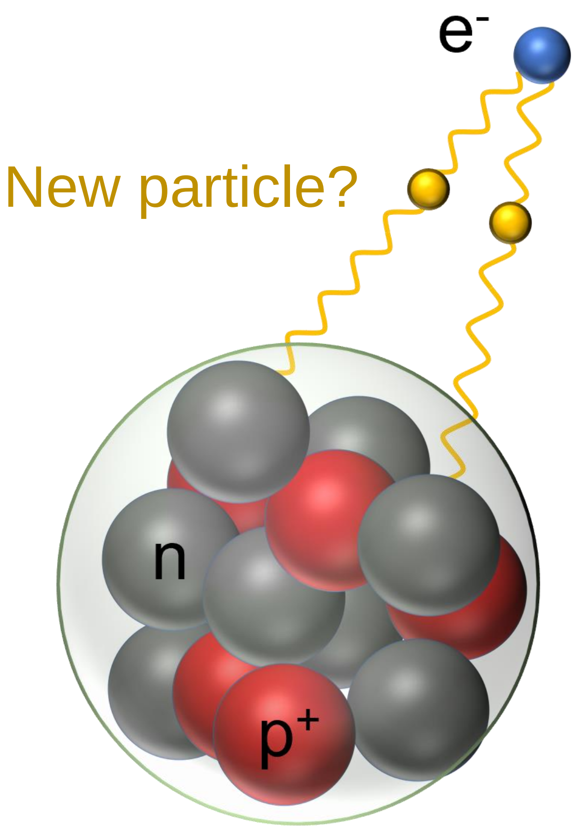
- Introduction
- Precise isotope shift measurement of 578 nm transition in neutral ytterbium (Yb)
- Summary

Background

- Standard model is one of the most successful physical theory, but also considered incomplete[1].
  e.g.) Dark matter, hierarchy problem, ...

- New Yukawa-type interaction has attracted much attention for a long time[2].

- Precise isotope shift measurement was proposed as a sensitive probe for this new physics[3,4].



Review: [1]PTEP 083C01 (2020)., [2]Rev. Mod. Phys. **90**, 025008 (2018).
Proposal: [3]PRD 96, 093001 (2017)., [4]Eur. Phys. J. C 77, 896 (2017)

Isotope shift

Isotope shift | Mass shift | Field shift

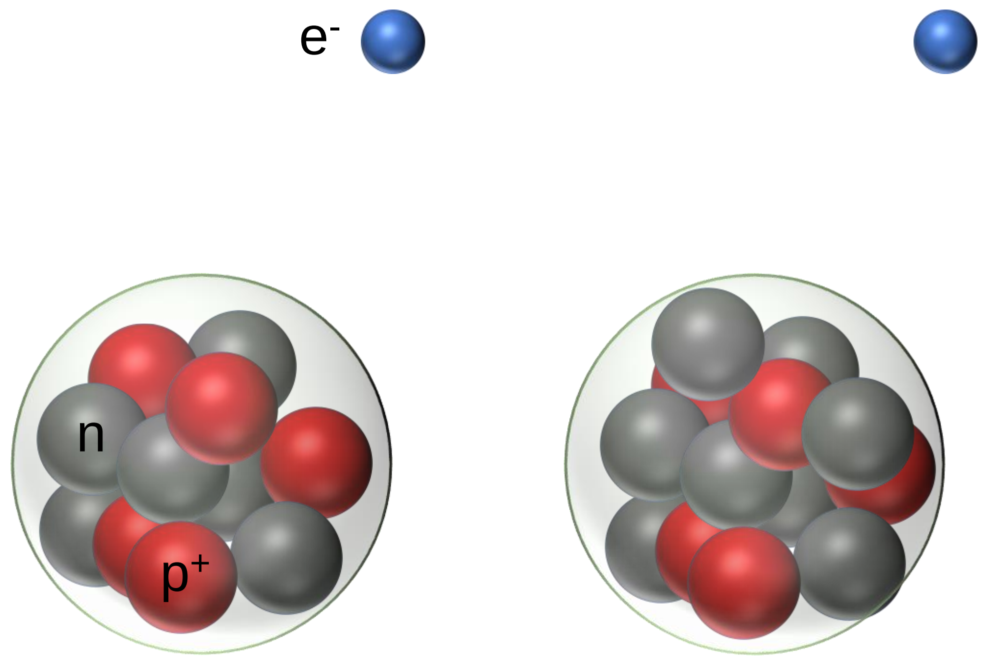
$$\delta\nu_i^{A,A_0} = K_i\,\delta\mu^{A,A_0} + F_i\,\delta\langle r^2\rangle^{A,A_0}$$

- Electronic transition: i
- Mass number: A, A_0
- Factorization

  Electronic factor × Nuclear factor

  - $\delta\mu^{A,A_0} = 1/m_A - 1/m_{A'}$
  - $\delta\langle r^2\rangle^{A,A_0} = \langle r^2\rangle^{A} - \langle r^2\rangle^{A_0}$

    $\langle r^2\rangle$: Nuclear mean-square charge radii



Mass number: A_0 | A ($> A_0$)

Isotope shift and new physics

Isotope shift — Mass shift — Field shift

$$\delta\nu_i^{A,A_0} = K_i\,\delta\mu^{A,A_0} + F_i\,\delta\langle r^2\rangle^{A,A_0}$$

$$+\ \alpha_{NP}\,X_i\,(A - A_0)$$

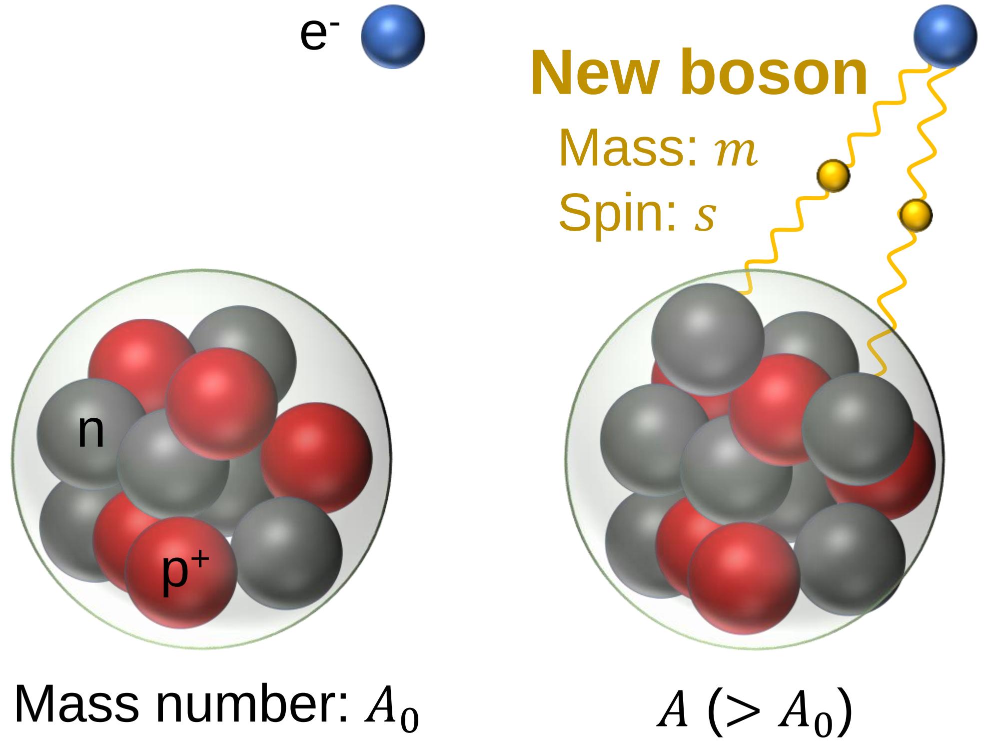
Particle shift

✓ New Yukawa-type interaction between electrons and neutrons[1]

$$V(r) = \alpha_{NP}\frac{\exp(-mcr/\hbar)}{r}$$

$$\alpha_{NP} = (-1)^{s+1}\frac{y_e y_n}{4\pi}$$

※ $y_{e(n)}$: coupling constants between new boson and e$^-$ (n)



[1] PRL **120**, 091801 (2018)

Isotope shifts can include the effect of a new particle.

King linearity

$$\delta\nu_i^{A,A_0} = K_i\, \delta\mu^{A,A_0} + F_i\, \delta\langle r^2\rangle^{A,A_0}$$

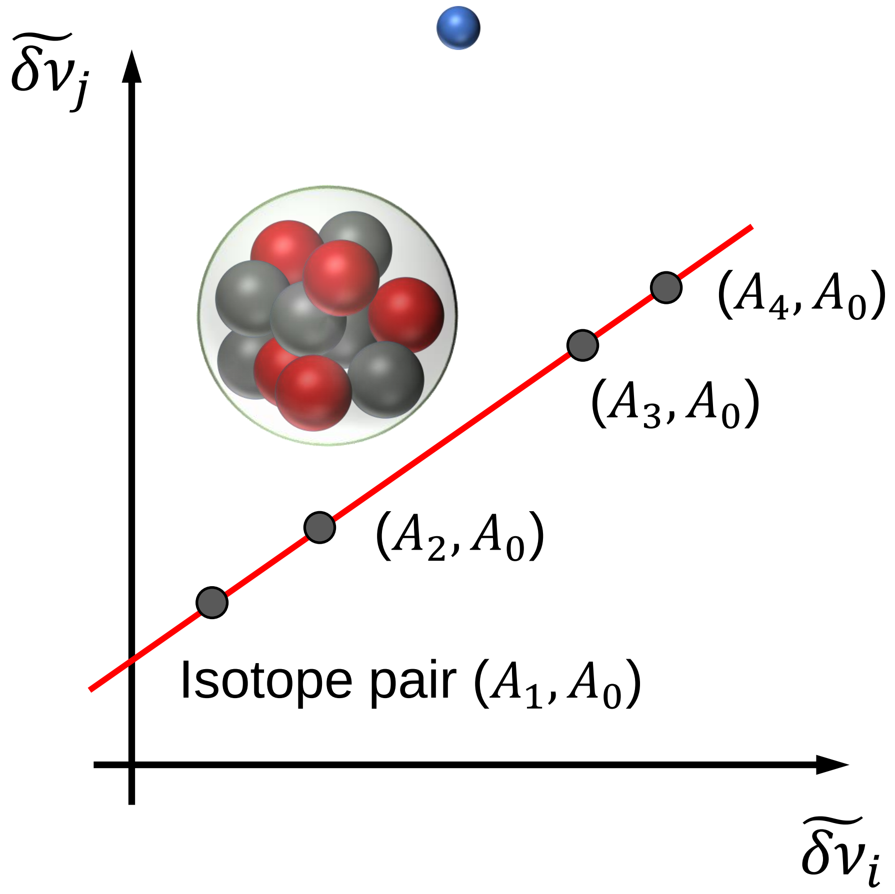
2 transition i, j

King linearity[1]

$$\widetilde{\delta\nu}_j^{A,A_0} = F_{ij} \times \widetilde{\delta\nu}_i^{A,A_0} + K_{ij}$$

$$\begin{cases} \widetilde{\delta\nu}^{A,A_0} = \dfrac{\delta\nu^{A,A_0}}{\delta\mu^{A,A_0}} \\ F_{ij} = \dfrac{F_j}{F_i} \quad K_{ij} = K_j - F_{ij}K_i \end{cases}$$

[1] W. H. King, J. Opt. Soc. Am. **53**, 638 (1968).



King linearity and new physics

$$\delta\nu_i^{A,A_0} = K_i\,\delta\mu^{A,A_0} + F_i\,\delta\langle r^2\rangle^{A,A_0}$$

2 transition i, j

~~King linearity~~

$$\widetilde{\delta\nu}_j^{A,A_0} = F_{ij} \times \widetilde{\delta\nu}_i^{A,A_0} + K_{ij}$$

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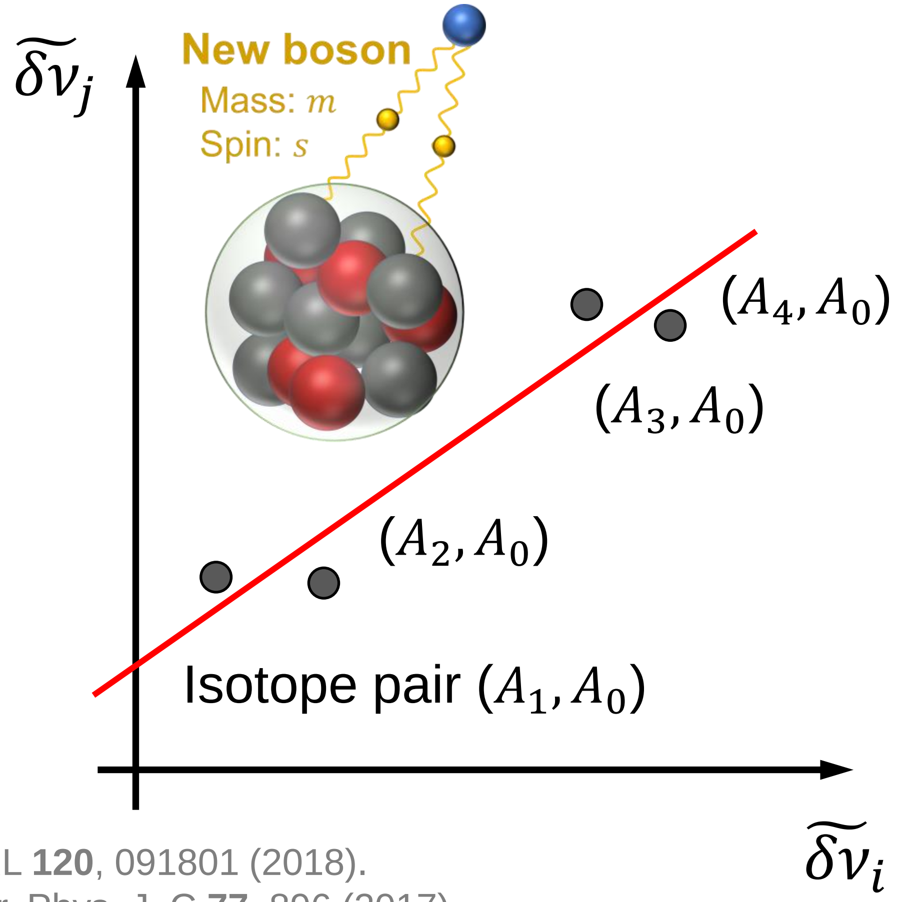


- The new particle violates King linearity[1].

→ We can probe the new particle via this linearity test with minimal theoretical input.

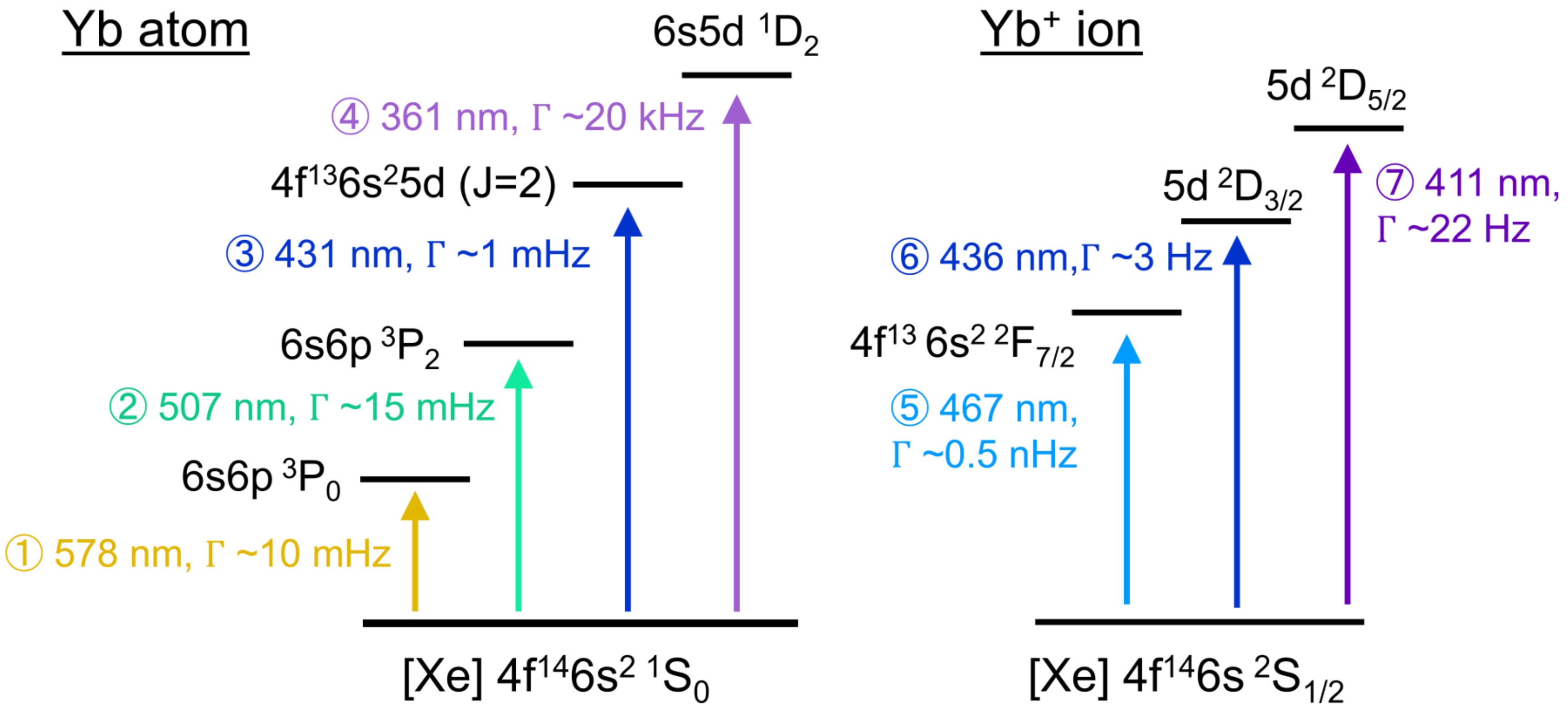
- This relationship can be generalized to higher dimension with additional transitions[2].

→ We can eliminate higher-order terms as well as $\delta\langle r^2\rangle$.

[1] PRL **120**, 091801 (2018).
[2] Eur. Phys. J. C **77**, 896 (2017).

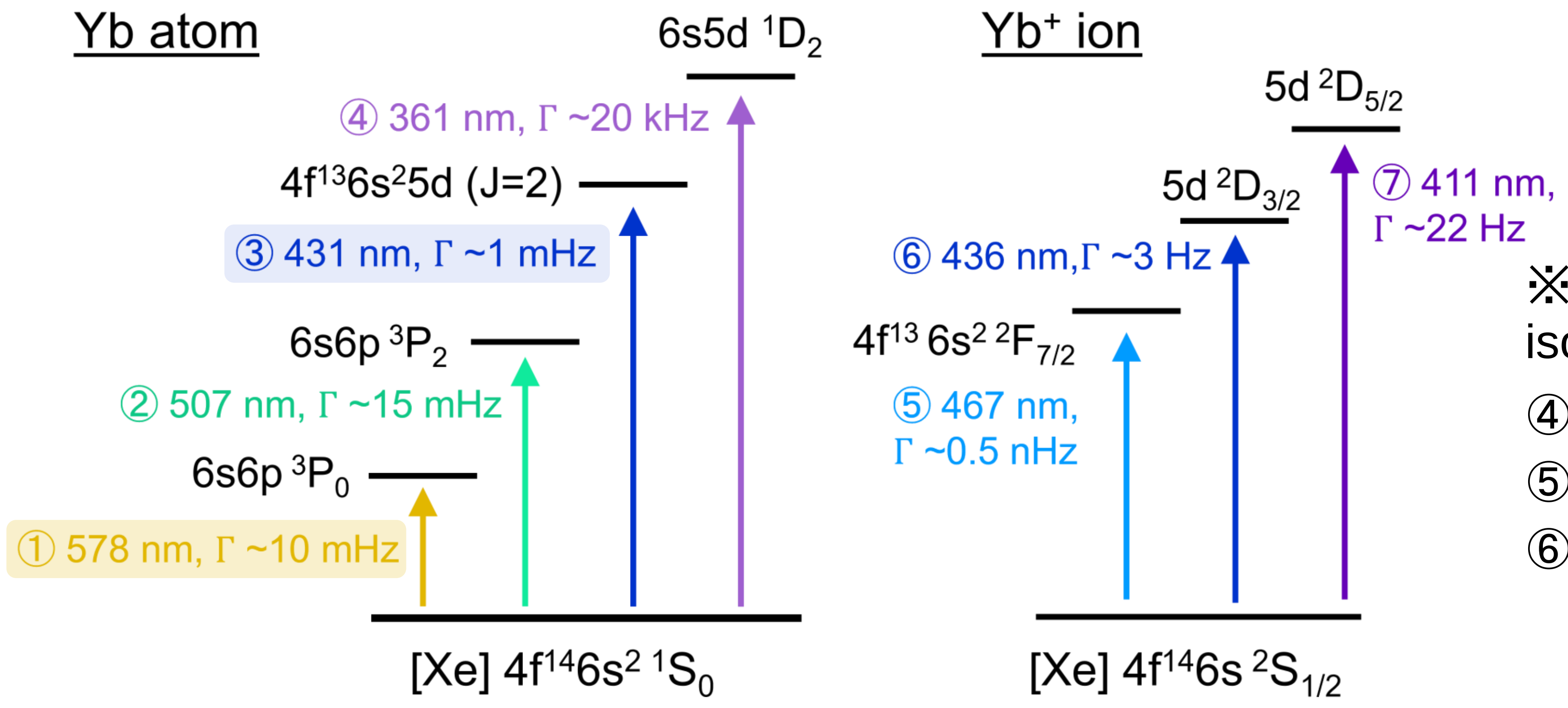
Ytterbium (Yb, Z=70)

- ✓ 5 stable nuclear-spin-less isotopes: A=168, 170, 172, 174, 176
- ✓ A lot of ultra-narrow and narrow transitions



Yb is the most suitable element for King linearity test.

Our work



※ Systematic and precise isotope shift measurements

④ PRL **128**, 073001 (2022)

⑤ PRL **128**, 163201 (2022)

⑥,⑦ PRL **125**, 123002 (2020)

■ Precise isotope shift measurements of transition① (578 nm)

- New constraint on the new particle with other transitions' measurements.
- Insights into nuclear physics: $\delta\langle r^2 \rangle$ and odd-even staggering

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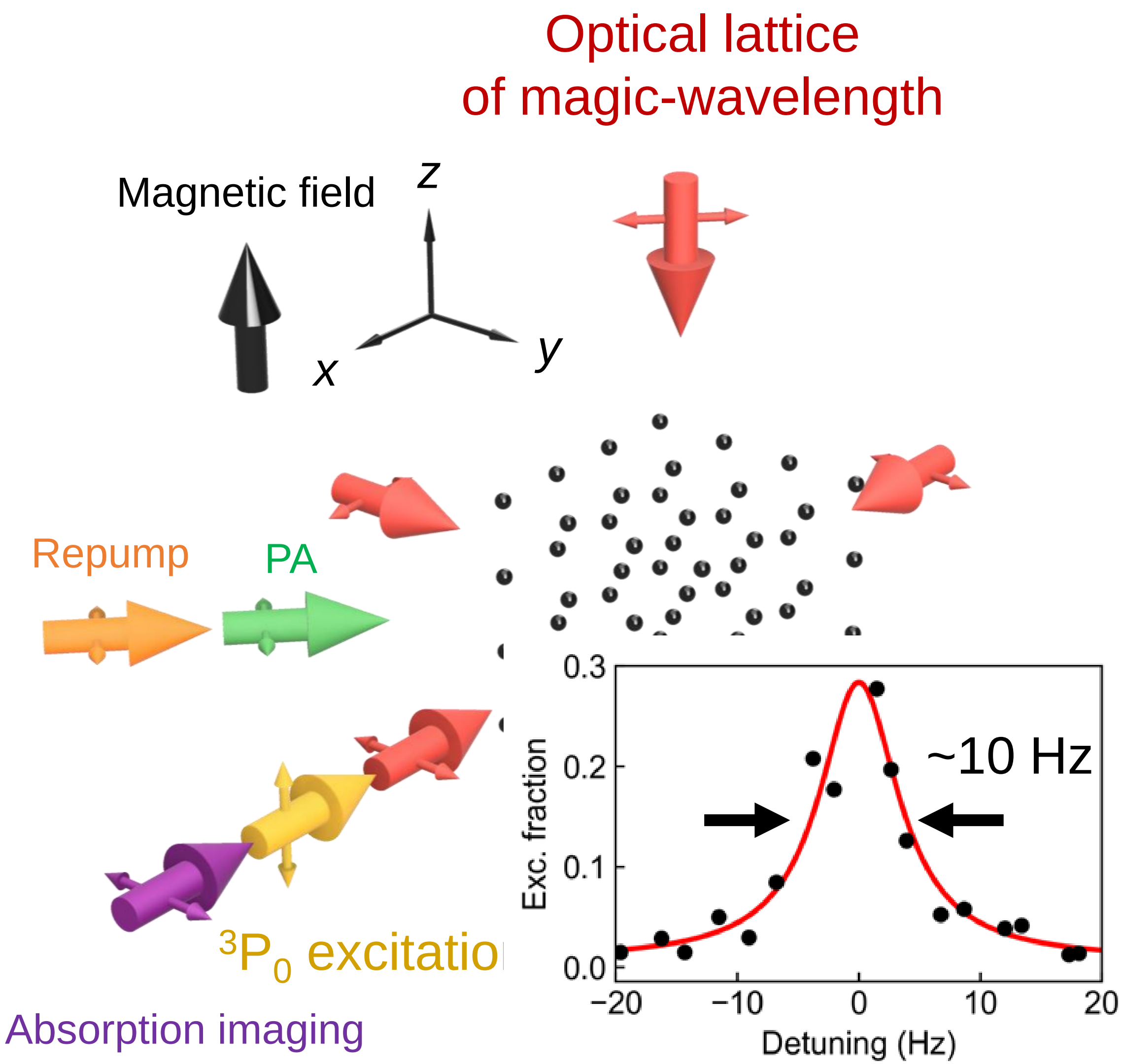
Precise isotope shift measurements

- Electronic transition
  $^1S_0 \leftrightarrow {}^3P_0$ (578 nm = 518 THz)

- Isotopes: all 7 stable isotopes
  Bosonic isotopes: A = 168, 170, 172, 174, 176
  Fermionic isotopes: A = 171, 173



Procedure

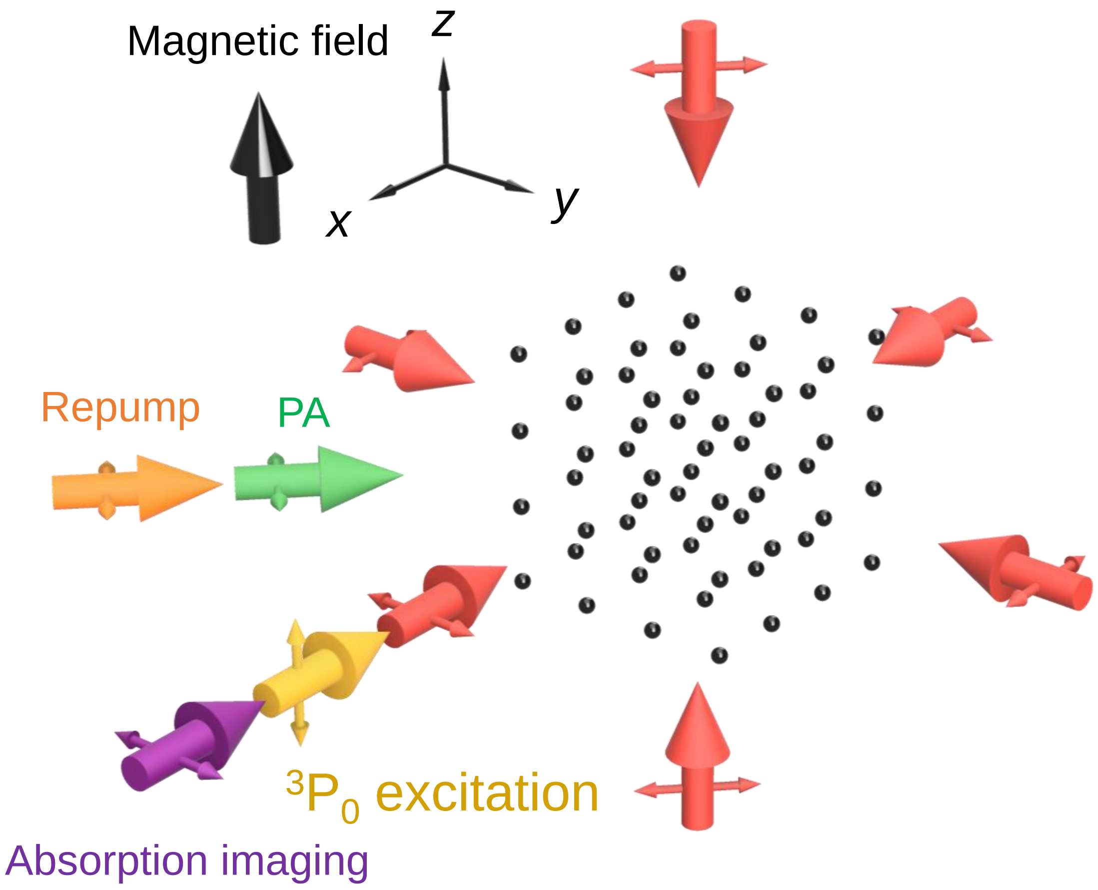
1. Cooling to O(100) nK
2. Trapping in an optical lattice of magic-wavelength
3. $^3P_0$ excitation
4. Observation
5. (alternate loading)

Precise isotope shift measurements

Result

(A, A’)	Isotope Shift (Hz)	Ref.
(168, 170)	1 358 484 476.2(2.2)	This work
(170, 174)	2 268 486 592.6(1.9)	This work
(172, 174)	992 714 586.6(2.1)	This work
(174, 176)	946 921 774.9(2.9)	This work
(173, 174)	551 536 104.9(2.3)	This work
(171, 174)	1 811 281 646.7(2.3)	This work
(171, 174)	1 811 281 645.8(0.9)	[1-2]

[1] F. Riehle *et al.*, Metrologia **55**, 188 (2018)
[2] N. Poli *et at.*, PRA **77**, 050501 (2008)

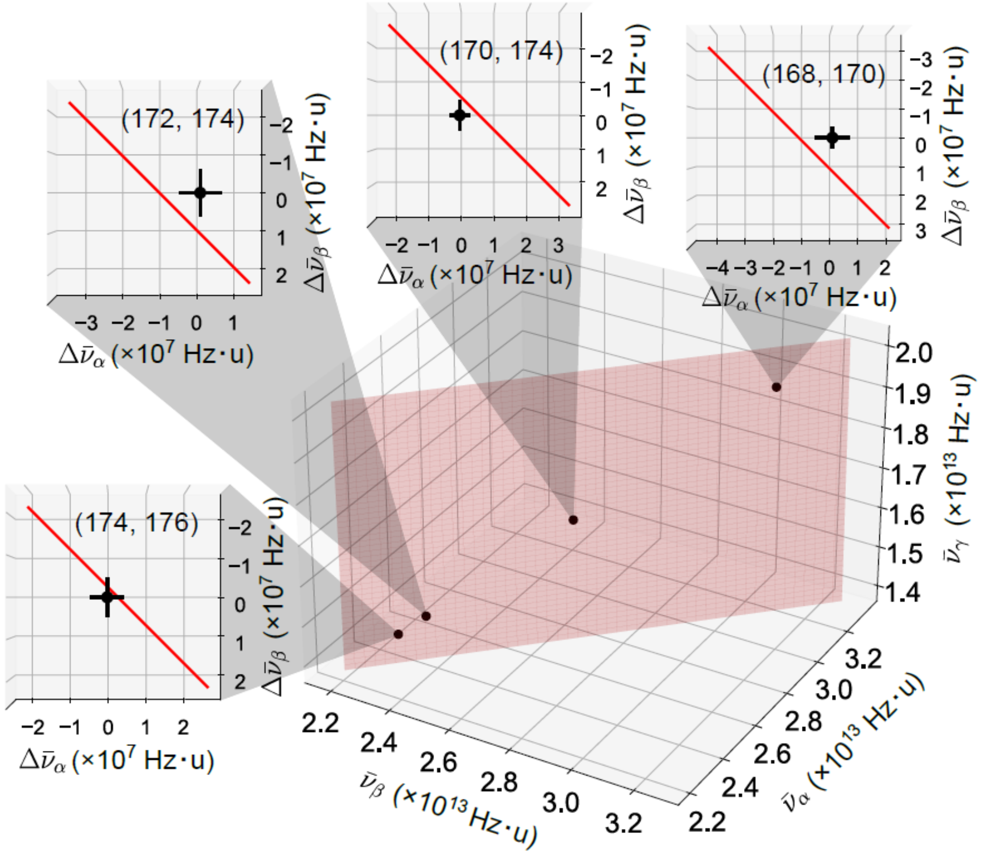


The uncertainty of our measurements is a few Hz ($\sim 10^{-9}$).

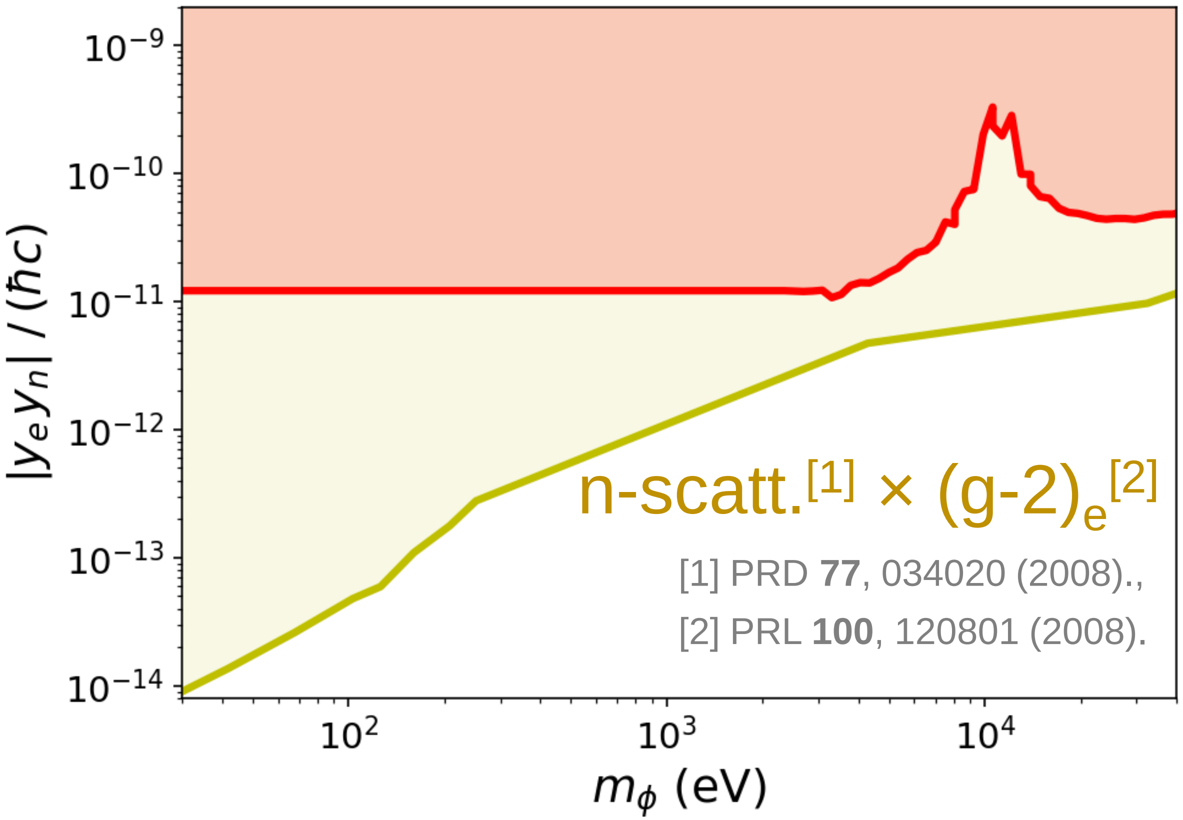
Constraint on the new physics

King linearity test

e.g.) 411 nm, 436 nm and 578 nm transitions



Constraint obtained by isotope shift measurements of Yb



Our constraint is getting close to the most stringent terrestrial bound.

Insights into nuclear physics: $\delta\langle r^2\rangle$

Isotope shift — Mass shift — Field shift

$$\delta\nu_i^{A,A_0} \sim K_i\,\delta\mu^{A,A_0} + F_i\,\delta\langle r^2\rangle^{A,A_0}$$

$$\Rightarrow \delta\langle r^2\rangle^{A,A_0} = \frac{\delta\nu_i^{A,A_0} - K_i\delta\mu^{A,A_0}}{F_i}$$

- $\delta\mu^{A,A_0} = 1/m_A - 1/m_{A'}$ [1]
- Electronic factors[2]
  - $K_i = -288(75)\ \mathrm{GHz/fm^2}$
  - $F_i = -10.848(21)\ \mathrm{GHz \cdot u}$
- Higher-order field shift: -5.9%[3] (not included in the above equation)

Isotope A	$\delta\langle r^2\rangle^{A,176} = \delta\langle r^2\rangle^{A} - \delta\langle r^2\rangle^{176}$		
	578 nm	556 nm[2]	Database[4]
168	**-0.456(2)**	-0.455(2)	-0.5406(3)
170	**-0.321(2)**	-0.320(2)	-0.3845(1)
171	**-0.275(1)**	-0.274(1)	-0.3273(1)
172	**-0.194(1)**	-0.193(1)	-0.2366(1)
173	**-0.1496(8)**	-0.1493(7)	-0.1810(1)
174	**-0.0946(5)**	-0.0944(5)	-0.1159(1)

※ Uncertainties of “578 nm” and “556 nm” are limited by theoretical uncertainties of the electronic factor K.

※ “Database” does not include uncertainties of electronic factors.

[1] Chin. Phys. C **45**, 3 (2021). [2] PRA **104**, 022806 (2021).
[3] Num. Data and Funct. Relat. in Science and Tech., Springer (2004). [4] At. Data Nucl. Data Tables **99**, 69 (2013).

Insights into nuclear physics: $\delta\langle r^2\rangle$

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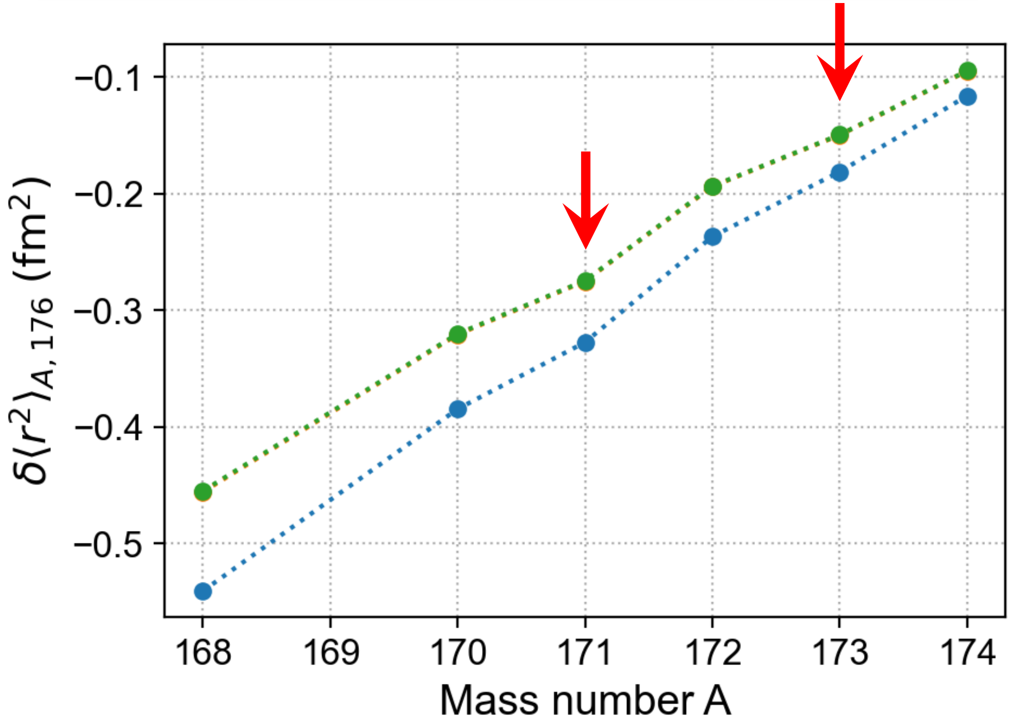


※ "578 nm" and "556 nm" are overlapped.

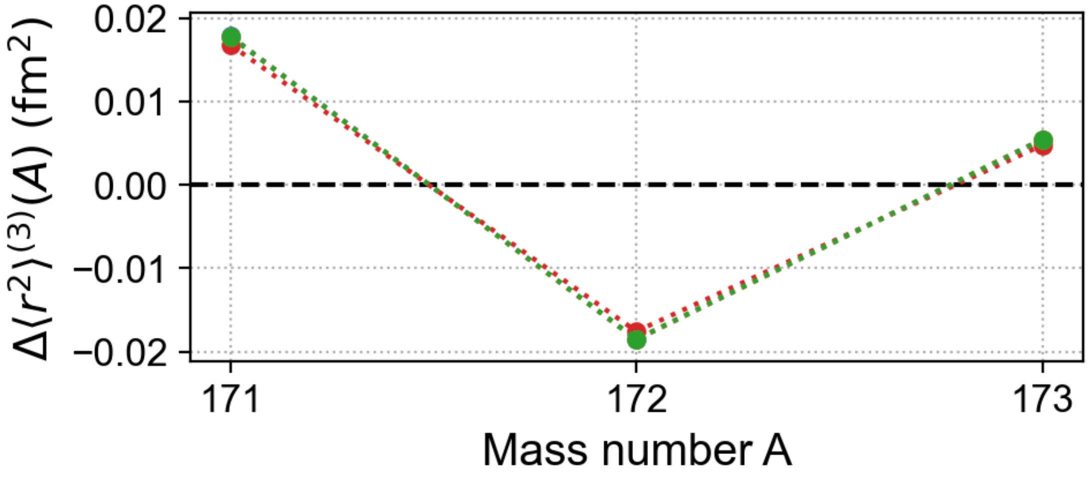
Odd-even staggering (OES) in $\delta\langle r^2\rangle$[1-2]

Odd neutron-number (N) isotope has a smaller charge radius $\langle r^2\rangle$ than the average of its two even-N neighbors.

- K (Z=19): [1] Nat. Phys. **17**, 439–443 (2021).
- Hg (Z=80): [2] PRL **126**, 032502 (2021).

OES parameter

$$\Delta\langle r^2\rangle^{(3)}(A) = \frac{1}{2}\left[\langle r^2(A-1)\rangle + \langle r^2(A+1)\rangle - 2\langle r^2(A)\rangle\right]$$



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✓ Precise isotope shift measurements of 578 nm transition in neutral Yb

- New constraint on a coupling constant of the new particle
- $\delta\langle r^2\rangle$ and odd-even staggering