Probing Variations of Fundamental Constants with Hyperfine Electronic Bridge Transitions in ^{229}Th

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1. Introduction: The fine-structure constant

$$\alpha = \frac{e^2}{4\pi\varepsilon_0\hbar c} \simeq \frac{1}{137.036}$$

The dimensionless strength of the electromagnetic interaction

Could α vary with time?

Some theories beyond the Standard Model predict a time-dependent α through its coupling to new dynamical fields.

One example: ultralight scalar dark matter coupled to photons.

The numerical value above is the low-energy value of α. Time variation remains unobserved.

D. Antypas et al., arXiv:2203.14915 (2022), Sec. II.A.

1. Introduction: Dark matter and varying α

$F_{\mu\nu}$: electromagnetic field-strength tensor

g_γ: scalar–photon coupling constant

A_μ: photon field; j^μ: charged-matter current

φ: ultralight scalar dark-matter field

m_φ: scalar dark-matter mass

α_0: α at φ=0; φ_0: oscillation amplitude

A linear coupling modifies the photon kinetic term:

$$\mathcal{L}_{\rm EM} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{g_\gamma\phi}{4}F_{\mu\nu}F^{\mu\nu} = -\frac{1}{4}(1-g_\gamma\phi)F_{\mu\nu}F^{\mu\nu}$$

Photon normalization changes its coupling to charged matter:

$$ej^\mu A_\mu = \underbrace{\frac{e}{\sqrt{1-g_\gamma\phi}}}_{e_{\rm eff}} j^\mu A_\mu^{\rm can} \quad\Longrightarrow\quad \alpha(t) = \frac{\alpha_0}{1-g_\gamma\phi(t)}$$

An oscillating dark-matter field produces an oscillating α:

$$\phi(t) \simeq \phi_0\cos(m_\phi t) \quad\Longrightarrow\quad \frac{\delta\alpha(t)}{\alpha_0} \simeq g_\gamma\phi_0\cos(m_\phi t)$$

Natural units: $\hbar$=c=1. Small coupling: $|g_\gamma\varphi|\ll 1$. No variation has been established.

D. Antypas et al., arXiv:2203.14915 (2022), Sec. II.A, Eqs. (3) and (5).

1. Introduction: Probing variations of α

Astrophysical observations

Compare astronomical spectra
to probe α over cosmic time.

Atomic clocks

Precise, repeatable measurements
of atomic and nuclear transitions.

Sensitivity of a transition frequency to α

$$\frac{\delta\nu}{\nu} = K_\alpha \frac{\delta\alpha}{\alpha}, \qquad K_\alpha = \frac{\partial \ln \nu}{\partial \ln \alpha}$$

The sensitivity factor measures an atomic clock's sensitivity to variations in α

Atomic clocks： Many optical transitions: $|K_\alpha| \sim 1$

The derivative is evaluated with other fundamental parameters held fixed.

P. Fadeev et al., Phys. Rev. A 102, 052833 (2020); D. Antypas et al., arXiv:2203.14915 (2022).

1. Introduction: Yb^+ clock tests of α variation

Two trapped Yb^+ ion clocks were compared via an optical frequency comb, tracking the E3/E2 frequency ratio over more than 4 years.

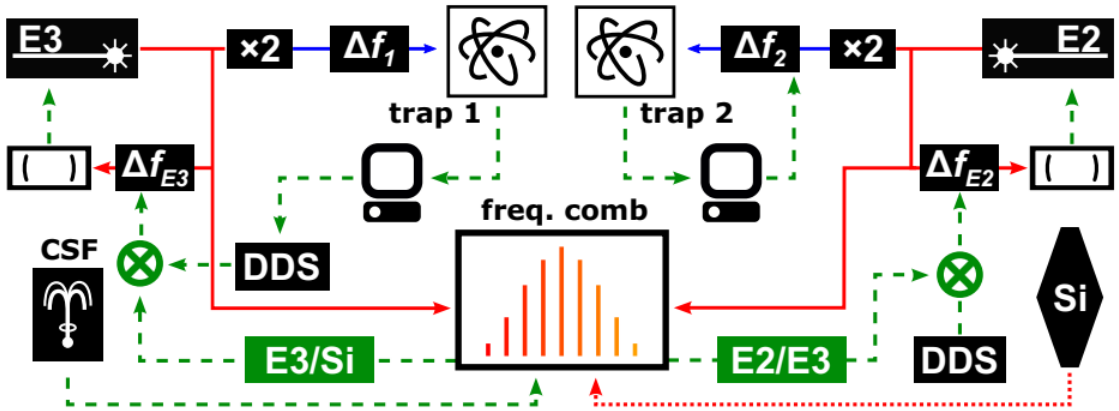
Yb^+ E3/E2 comparison at PTB (Germany)

E3: electric octupole transition

E2: electric quadrupole transition

Relative temporal variation rate of α:

$$\frac{\dot{\alpha}}{\alpha} = (1.0 \pm 1.1) \times 10^{-18}\ \mathrm{yr}^{-1}$$



Clock-comparison setup

R. Lange et al., Physical Review Letters 126, 011102 (2021).

No significant temporal drift of α was observed.

1. Introduction: The Th-229 nuclear clock

An exceptionally low-energy nuclear transition

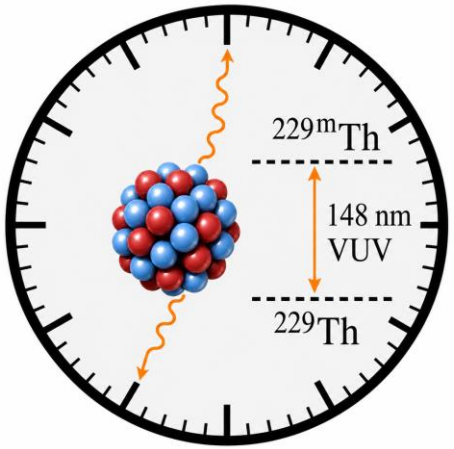
Ground state $5/2^+$ and isomer $3/2^+$

$E_n \approx 8.4$ eV; $\lambda \approx 148$ nm (vacuum ultraviolet)

A nuclear frequency reference

Stabilize a laser to the nuclear transition frequency.

A long radiative lifetime gives a narrow natural line.



Courtesy of Dr. Xiao Lu (陆晓)

Enhanced sensitivity to fundamental constants

The small transition energy amplifies its fractional response to changes in nuclear interactions.

Predicted $|K_\alpha| \sim 8000$

Challenge: vacuum-ultraviolet excitation and controlled isomer preparation/readout.

E. Peik and Chr. Tamm, Europhys. Lett. 61, 181 (2003); P. Fadeev et al., Phys. Rev. A 102, 052833 (2020).

2. Motivation: Coupling electrons and the nucleus

Conventional clock descriptions

Atomic clocks use electronic transitions.

Nuclear clocks use transitions between nuclear states.

These frequency references are often discussed separately.

What changes when the two transitions are coupled?

Transition frequency and accessibility

Sensitivity to variations of fundamental constants

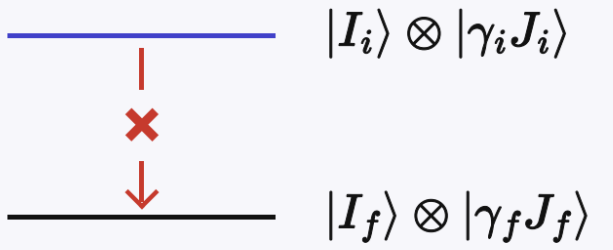
2. Mechanism: Hyperfine electronic bridge (HEB)

The hyperfine interaction couples electrons to nuclear electromagnetic moments.

It mixes electronic–nuclear configurations with the same total angular momentum F.

$I_i \neq I_f,\ \gamma_i J_i \neq \gamma_f J_f$: different initial and final electronic and nuclear states

Without hyperfine coupling

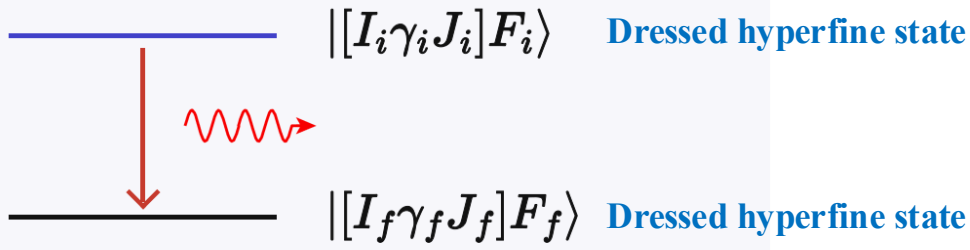


Simultaneous electron–nucleus transition: forbidden

Electronic and nuclear states are uncoupled

$H_{\mathrm{en}} \longrightarrow$ **hyperfine mixing**

With hyperfine coupling



Hyperfine electronic bridge transition: allowed

Electronic and nuclear states are coupled

Hyperfine electronic bridge: electron and nucleus undergo transitions simultaneously

Can this coupled transition retain nuclear sensitivity at a more accessible photon energy?

W. Wang, F. Zou, S. Fritzsche, and Y. Li, Physical Review Letters 133, 223001 (2024).

2. Dressed hyperfine state

Eigenstate of the coupled nuclear–electronic system.

$$H = H_{\mathrm{n}} + H_{\mathrm{e}} + H_{\mathrm{en}}$$

$$|[I\gamma J]FM\rangle = a|I, \gamma J; FM\rangle + \sum_t b_t |I_t, \gamma_t J_t; FM\rangle$$

A superposition of nuclear–electronic states.

One leading configuration with small hyperfine admixtures.

For an isolated ion, total angular momentum F and parity are conserved.

W. Wang, F. Zou, S. Fritzsche, and Y. Li, Physical Review Letters 133, 223001 (2024).
W. Wang, S. Fritzsche, and Y. Li, Physical Review A 112, 022811 (2025).

3. Enhanced sensitivity of the HEB transition

$$K_\alpha^{\mathrm{HEB}} \simeq \frac{\Delta E_{\mathrm{C}}}{E_{\mathrm{HEB}}}\left[1-\sum_t\left(|b_{i,t}|^2+|b_{f,t}|^2\right)\right]$$

$$\frac{K_\alpha^{\mathrm{HEB}}}{K_\alpha^{\mathrm{nuc}}} \simeq \frac{E_{\mathrm{n}}}{E_{\mathrm{HEB}}} \qquad \text{(weak mixing)}$$

ΔE_C: nuclear Coulomb-energy difference between the isomer and ground state.

E_{HEB}: transition energy of the coupled electron–nucleus system.

E_{n}: bare nuclear transition energy (≈8.4 eV for Th-229).

$E_{\mathrm{HEB}} < E_{\mathrm{n}}$ enhances $|K_\alpha|$ for small hyperfine admixtures.

W. Wang, S. Fritzsche, and Y. Li, Phys. Rev. A 112, 022811 (2025).

3. Results: HEB transition in Th-229 (40+)

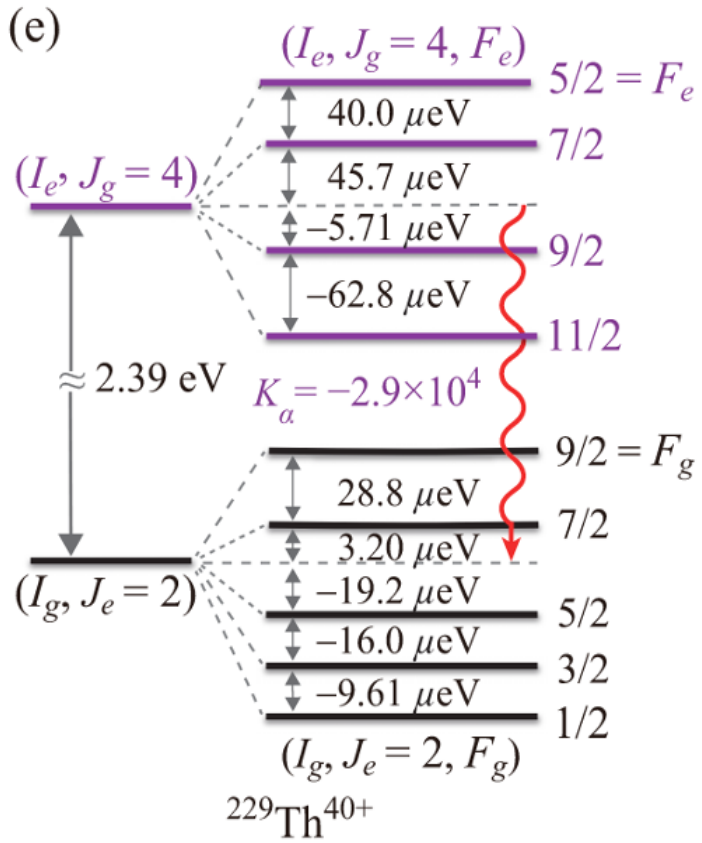
Visible-light HEB transition (≈ 519 nm)

Ion	E_{HEB}	K_α	Enhancement
$^{229}\mathrm{Th}^{40+}$	2.39 eV	-2.9×10^4	3.5 times

Nuclear isomer → ground state; electronic $J = 4 \rightarrow 2$.

Sensitivity to α variation: 3.5 times that of the bare nuclear transition.

A new route to combine highly charged ions with nuclear clocks, with enhanced sensitivity to new physics.



$^{229}\mathrm{Th}^{40+}$ level scheme

W. Wang, S. Fritzsche, and Y. Li, Phys. Rev. A 112, 022811 (2025).

4. Summary and Outlook

Summary:

Hyperfine mixing enables HEB transitions between dressed nuclear–electronic states.

In Th-229 (40+), the predicted HEB transition lies in the visible spectrum:
2.39 eV (approximately 519 nm).

Its sensitivity to α variation is 3.5 times that of the bare nuclear transition.

Outlook:

Extend the HEB framework to probe variations of strong-interaction parameters.

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Thank you!