Precision isotope shifts in ytterbium and implications for new physics

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16th Marcel Grossmann Meeting

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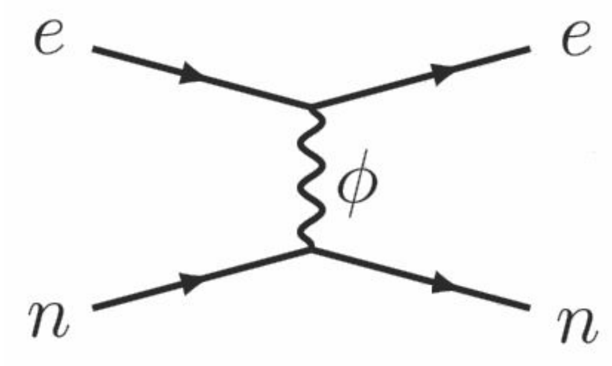
Search for light force mediator between electron and neutrons



Effective spin-independent potential

$$V_\phi(r) = -N\alpha_{\mathrm{NP}}\frac{e^{-m_\phi r}}{r}$$

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

y_e, y_n: effective charges

- 'Light': m_φ<100 MeV/c^2
- Could measure atomic transition & compare to theory.

  Problem: for interesting (heavy) atoms, theory not precise enough.

Search for light force mediator in isotope shifts of atomic spectra

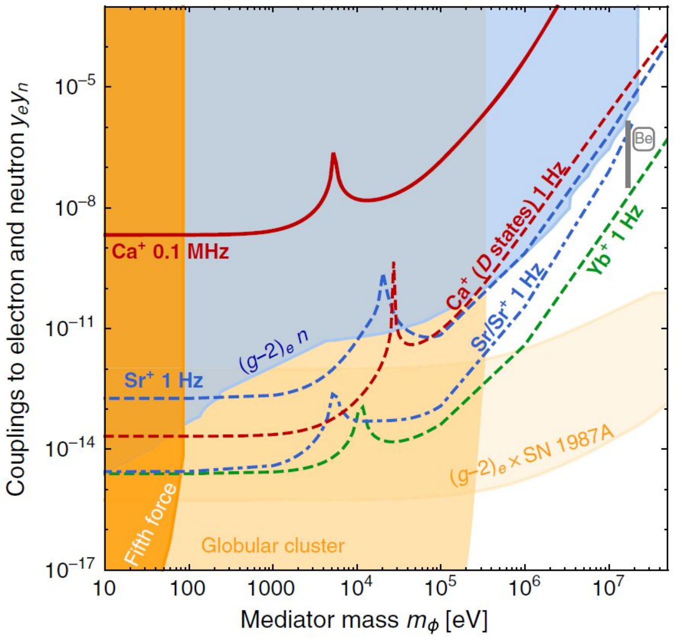
Probing New Long-Range Interactions by Isotope Shift Spectroscopy

Julian C. Berengut, Dmitry Budker, Cédric Delaunay, Victor V. Flambaum, Claudia Frugiuele, Elina Fuchs, Christophe Grojean, Roni Harnik, Roee Ozeri, Gilad Perez, and Yotam Soreq

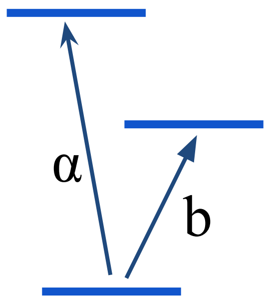
Phys. Rev. Lett. **120**, 091801 – Published 26 February 2018

Idea: Use Isotope Shift (IS) data from a pair of atomic transitions in a *King-plot analysis* to constrain new light bosons.

- Data-driven approach.
- Minimal input from theory.
- Need atoms with multiple isotopes and narrow transitions.



King-plot & its linearity



$$\nu_a^{ij} \equiv \nu_a^i - \nu_a^j = K_a \mu_{ij} + F_a \delta \langle r^2 \rangle_{ij}$$

Mass shift **Field shift**

K_α, F_α: transition- dependent, isotope independent parameters

$$\left.\begin{aligned} \delta\langle r^2\rangle_{ij} &\equiv \langle r^2\rangle_i - \langle r^2\rangle_j \\ \mu_{ij} &\equiv m_i^{-1} - m_j^{-1} \end{aligned}\right\}$$

Nuclear parameters (isotope-dependent)

Combine two transitions:

$$\boxed{\frac{\nu_a^{ij}}{\mu_{ij}}} = \frac{F_a}{F_b} \boxed{\frac{\nu_b^{ij}}{\mu_{ij}}} + \left(K_a - \frac{F_a}{F_b} K_b\right)$$

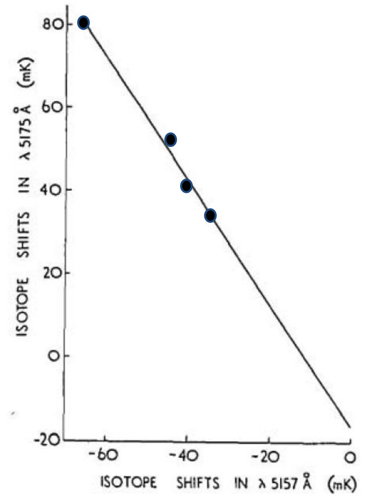


FIG. 1. A plot of the isotope shifts in λ5175 Å against the corresponding shifts in λ5157 Å. The relevant data are shown in Table II.

W. H. King, JOSA, Vol. 53, 638 (1963)

Breaking the King-plot linearity

$$\nu_a^{ij} = K_a\mu_{ij} + F_a\delta\langle r^2\rangle + G_a^{(2)}\delta\langle r^2\rangle^2 + G_a^{(4)}\delta\langle r^4\rangle + \frac{a_{NP}}{a}D_a\Delta N$$

Mass shift

1st order Field Shift

Quadratic FS

Nuclear-deformation-dependent FS

New bosons

$$\frac{\nu_a^{ij}}{\mu_{ij}} = \frac{F_a}{F_b}\frac{\nu_b^{ij}}{\mu_{ij}} + \left(K_a - \frac{F_a}{F_b}K_b\right) \underbrace{+\left(G_a^{(2)} - \frac{F_a}{F_b}G_b^{(2)}\right)\frac{\delta\langle r^2\rangle^2}{\mu_{ij}} +\left(G_a^{(4)} - \frac{F_a}{F_b}G_b^{(4)}\right)\frac{\delta\langle r^4\rangle}{\mu_{ij}} +\frac{a_{NP}}{a}\left(D_a - \frac{F_a}{F_b}D_b\right)\frac{\Delta N}{\mu_{ij}}}_{\text{May cause deviations from straight line}}$$

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Phys. Rev. Lett. **120**, 091801 – Published 26 February 2018

- If no King-plot nonlinearity is observed, constrain new physics
- Can't discriminate subdominant nuclear effects from new physics
- Need at least four spin-zero isotopes of an element with narrow transitions (Sr,Yb, Ca ions, etc)

Most notable new-boson searches with King-plot analysis

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SYNOPSIS

PDF Version

Hints of Dark Bosons

September 15, 2020 • *Physics* 13, s115

A signal predicted for a type of dark matter appears in the spectra of ytterbium isotopes.

J. Hur/Massachusetts Institute of Technology

Improved Isotope-Shift-Based Bounds on Bosons beyond the Standard Model through Measurements of the $^2D_{3/2} - {}^2D_{5/2}$ Interval in Ca^+

Cyrille Solaro, Steffen Meyer, Karin Fisher, Julian C. Berengut, Elina Fuchs, and Michael Drewsen

Phys. Rev. Lett. 125, 123003 (2020)

Published September 15, 2020

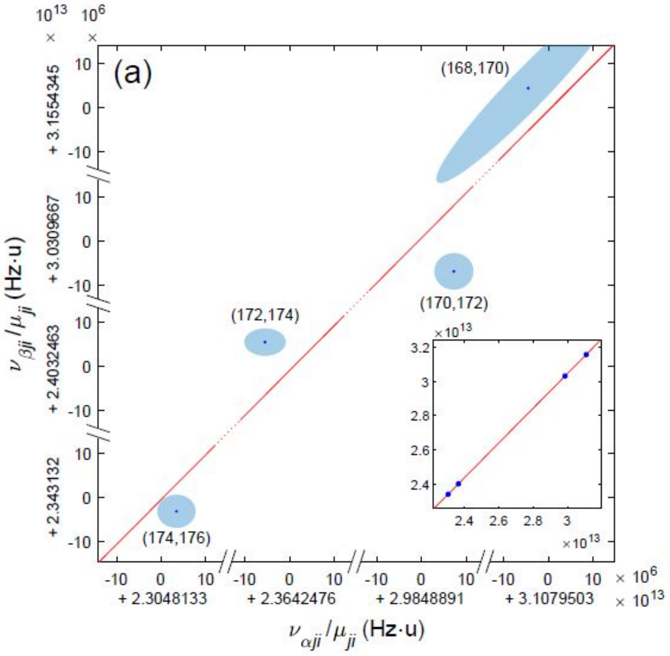
Evidence for Nonlinear Isotope Shift in Yb^+ Search for New Boson

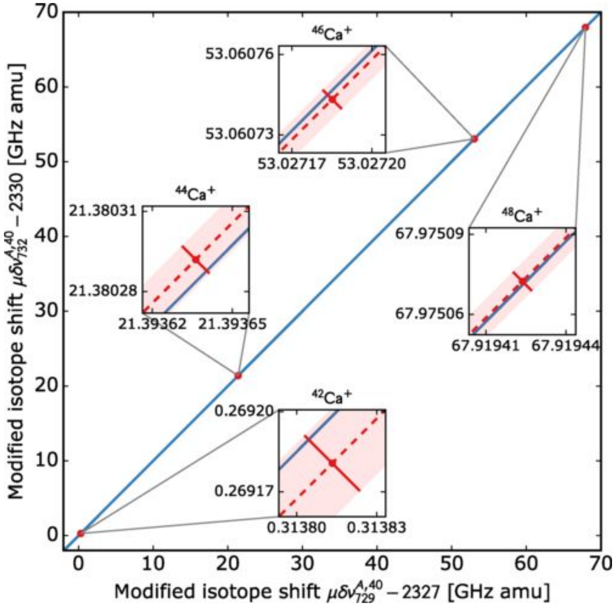
Ian Counts, Joonseok Hur, Diana P. L. Aude Craik, Honggi Jeon, Calvin Leung, Julian C. Berengut, Amy Geddes, Akio Kawasaki, Wonho Jhe, and Vladan Vuletić

Phys. Rev. Lett. 125, 123002 (2020)

Published September 15, 2020

Yb^+ & Ca^+ results and implications





Yb^+: 3σ deviation from linearity
(quadratic field shift ?)

Ca^+: no evidence for nonlinearity

Similar sensitivity in constraining new physics in two works

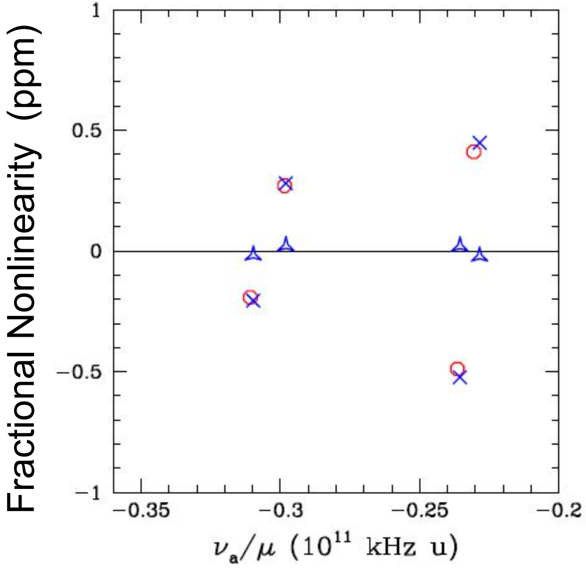
Effect of nuclear deformation on the observed Yb^+ nonlinearity

Nuclear deformation as a source of the nonlinearity of the King plot in the $\mathbf{Yb}^+$ ion

Saleh O. Allehabi, V. A. Dzuba, V. V. Flambaum, and A. V. Afanasjev
Phys. Rev. A **103**, L030801 – Published 3 March 2021

$$\frac{\nu_a^{ij}}{\mu_{ij}} = \frac{F_a}{F_b}\frac{\nu_b^{ij}}{\mu_{ij}} + \left(K_a - \frac{F_a}{F_b}K_b\right) + \left(G_a^{(2)} - \frac{F_a}{F_b}G_b^{(2)}\right)\frac{\delta\langle r^2\rangle^2}{\mu_{ij}} \boxed{+\left(G_a^{(4)} - \frac{F_a}{F_b}G_b^{(4)}\right)\frac{\delta\langle r^4\rangle}{\mu_{ij}}}$$

Main contributor to NL: influence of nuclear deformation on field shift



1. The deviations from linear King plot in experiment (solid
les) and theory. Theoretical deviations caused by nuclear
ation are shown as blue crosses, and those by QFS are shown
triangles. All theoretical numbers correspond to the FIT
model.

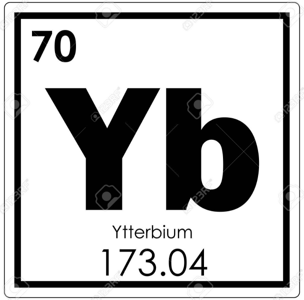
Account for known-physics NL with generalized King analysis

Generalized King linearity and new physics searches with isotope shifts

Julian C. Berengut, Cédric Delaunay, Amy Geddes, and Yotam Soreq
Phys. Rev. Research **2**, 043444 – Published 31 December 2020

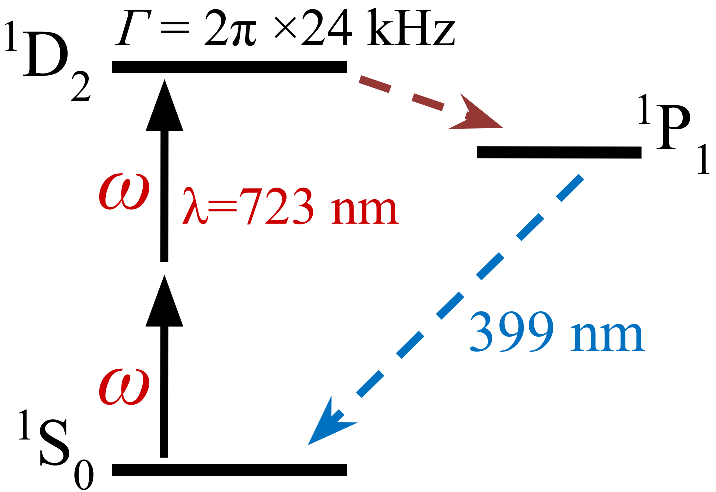
- Data-driven approach to account for subdominant nuclear effects
- Include more than two transitions in analysis
- With m transitions, m-2 subdominant nuclear contributions may be accounted for
- Can mix ions/neutrals

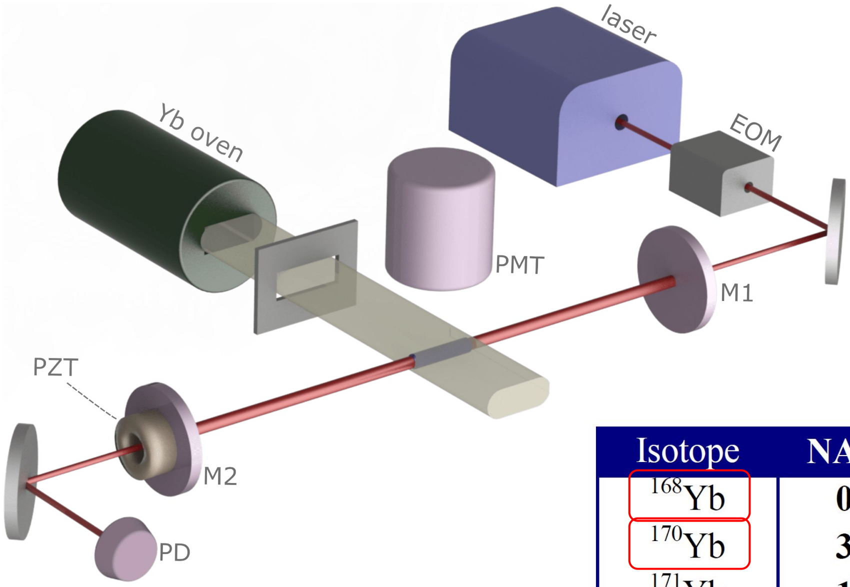
More IS data in the Yb system seem useful



- Use generalized King analysis by combining data with those in Yb^+, to account for nuclear effects.
- Validate the `3σ` observation in the Yb^+ experiment.
- Benchmark for nuclear calculations of the IS, since in comparing Yb^+/Yb data, the effects of nuclear contributions to the IS interaction is different.

Doppler-free spectroscopy on two-photon transition $^1S_0 \rightarrow {}^1D_2$





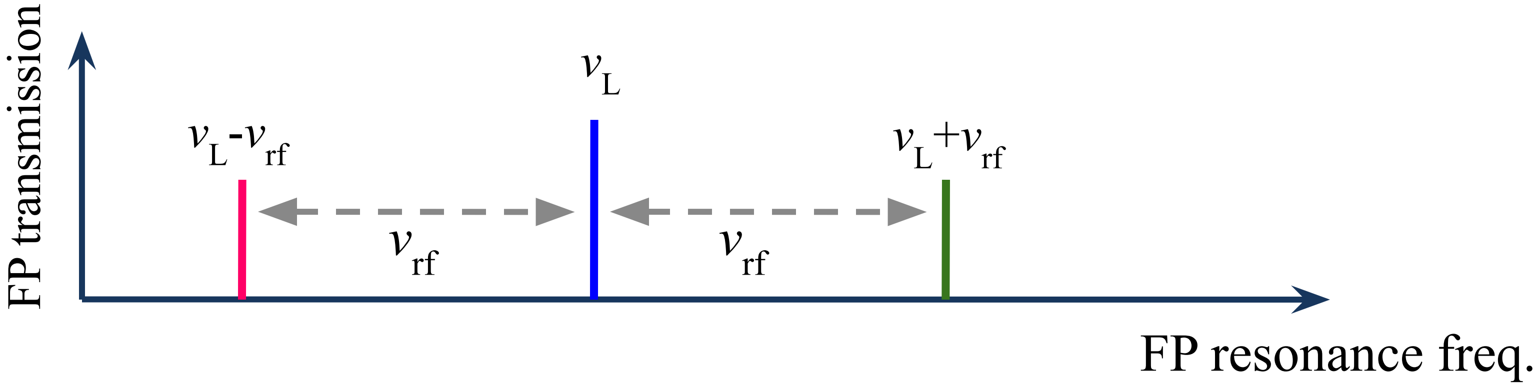
Isotope	NA (%)	I
^{168}Yb	0.13	0
^{170}Yb	3.04	0
^{171}Yb	14.3	1/2
^{172}Yb	21.8	0
^{173}Yb	16.1	5/2
^{174}Yb	31.8	0
^{176}Yb	12.8	0

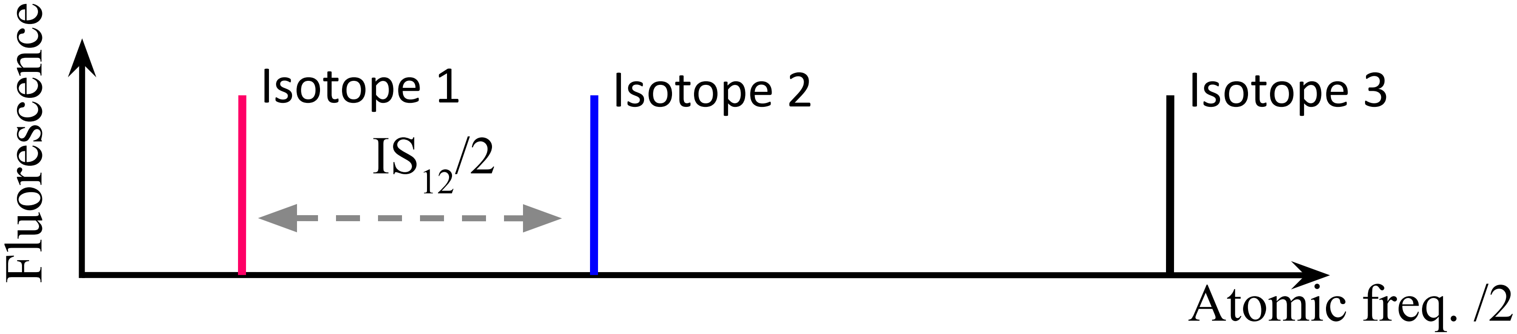
Measurement goal:

300 Hz accuracy in isotope shift, to match Yb^+ results

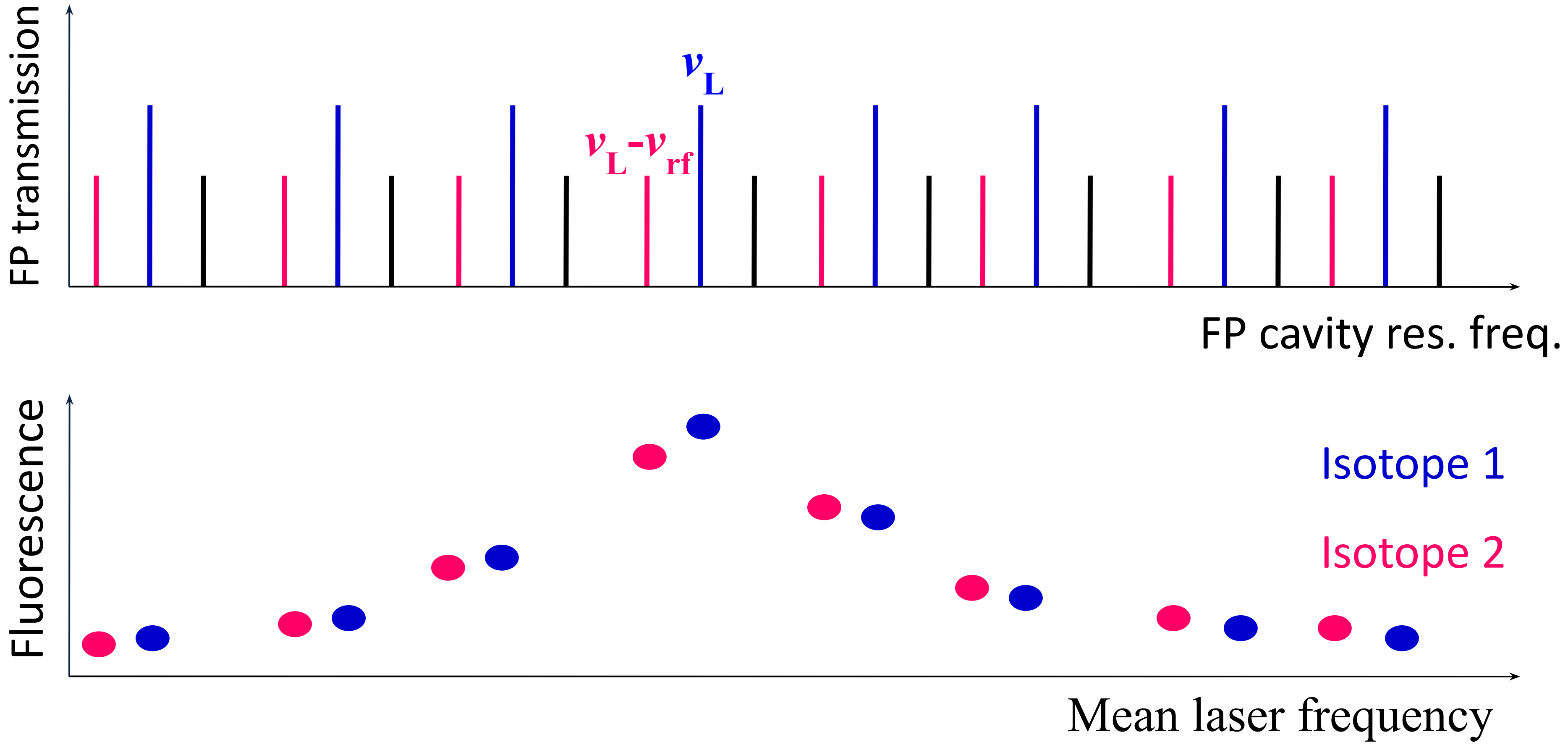
How to measure *difference* in optical frequencies ?

→ Use multiple optical frequencies, precisely spaced

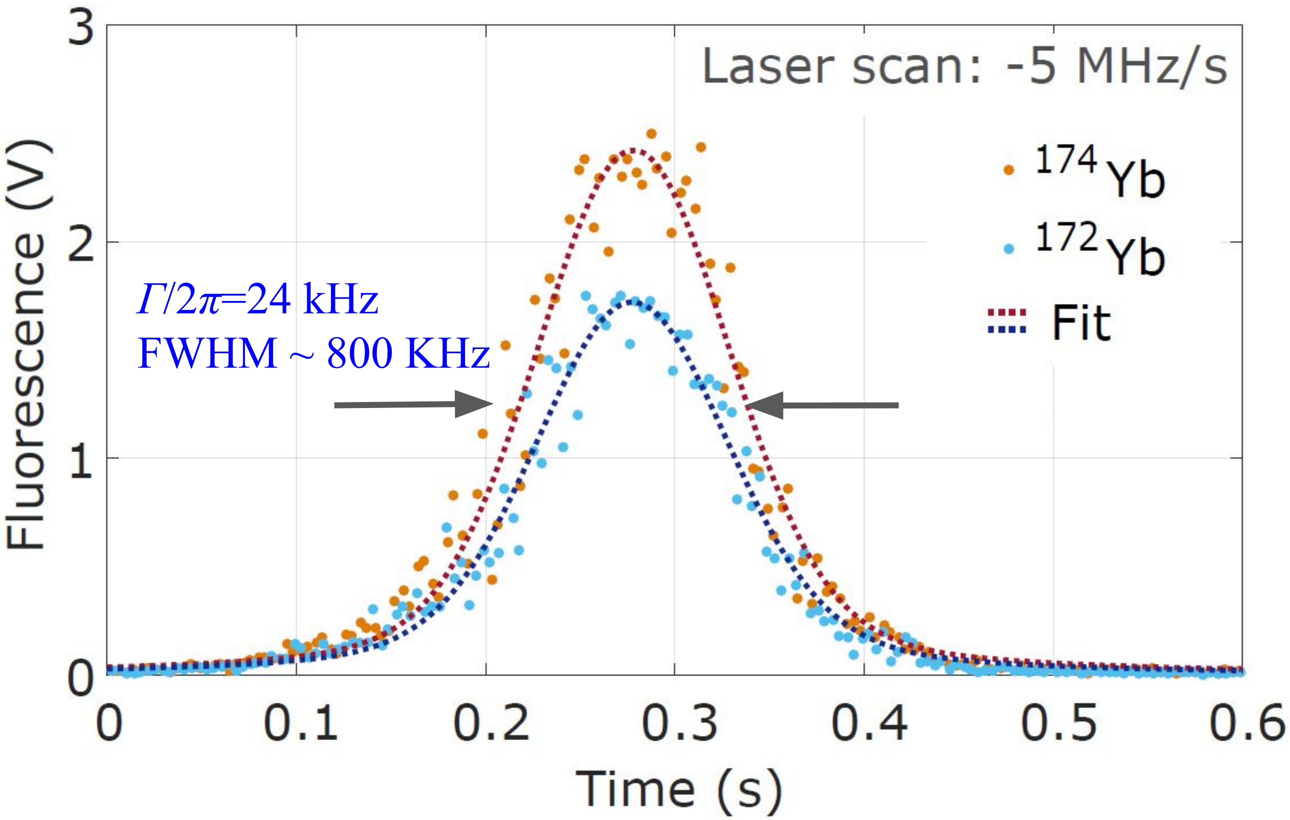




‘Simultaneous’ excitation of two isotopes

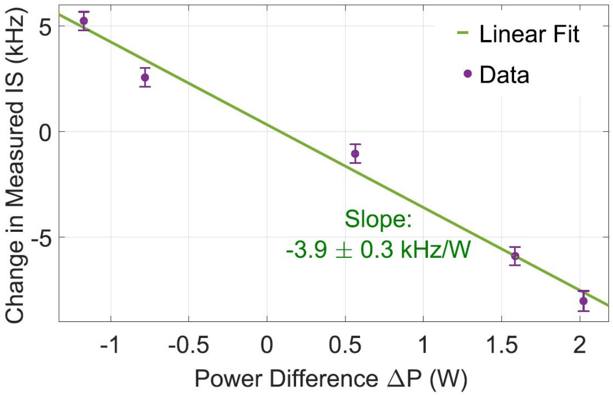


‘Simultaneous’ excitation of two isotopes

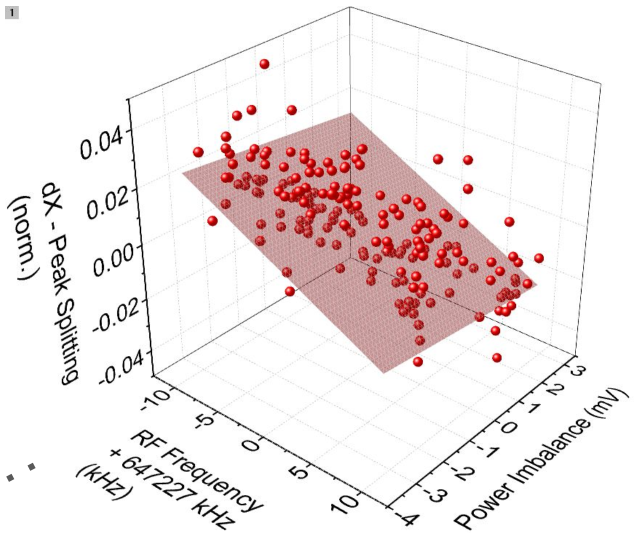


Main systematic 1: ac-Stark shifts

Differential ac-Stark shift



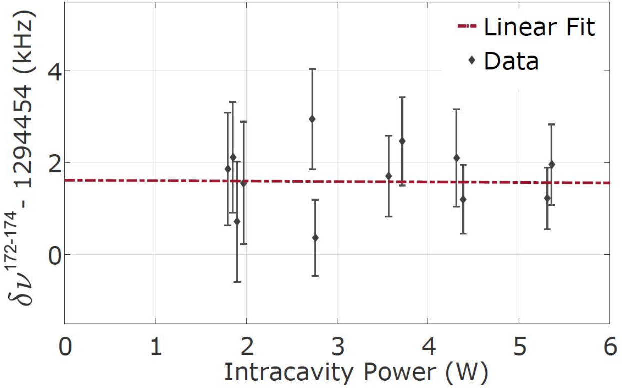
Incorporate residual ΔP in analysis



Fit: IS=a$\cdot$ ν_{rf} + b$\cdot$ΔP + c

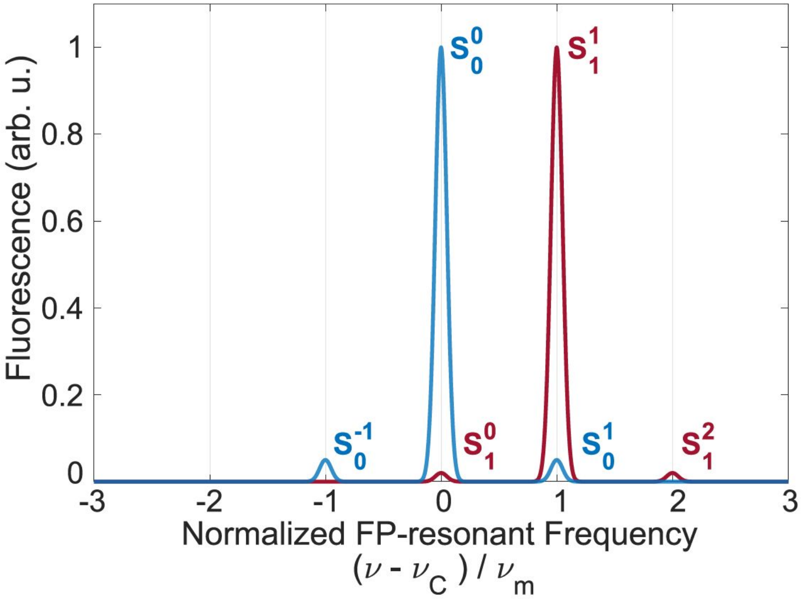
Zero-power extrapolation

Avoid `hidden` ac-stark contributions via extrapolating data to zero power

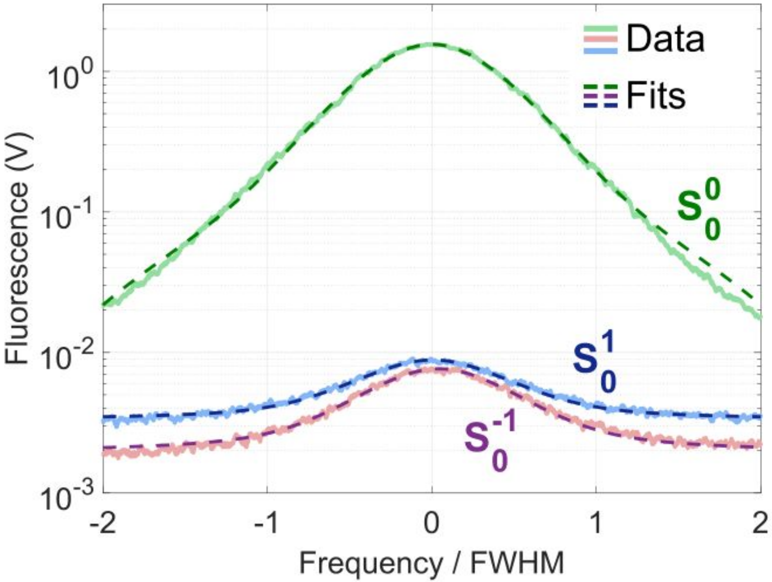


Main systematic 2: cavity spectral imperfections

`Crosstalk` in detection channels



Measured backgrounds



Mixed Yb/Yb$^+$ King plot and nonlinearity

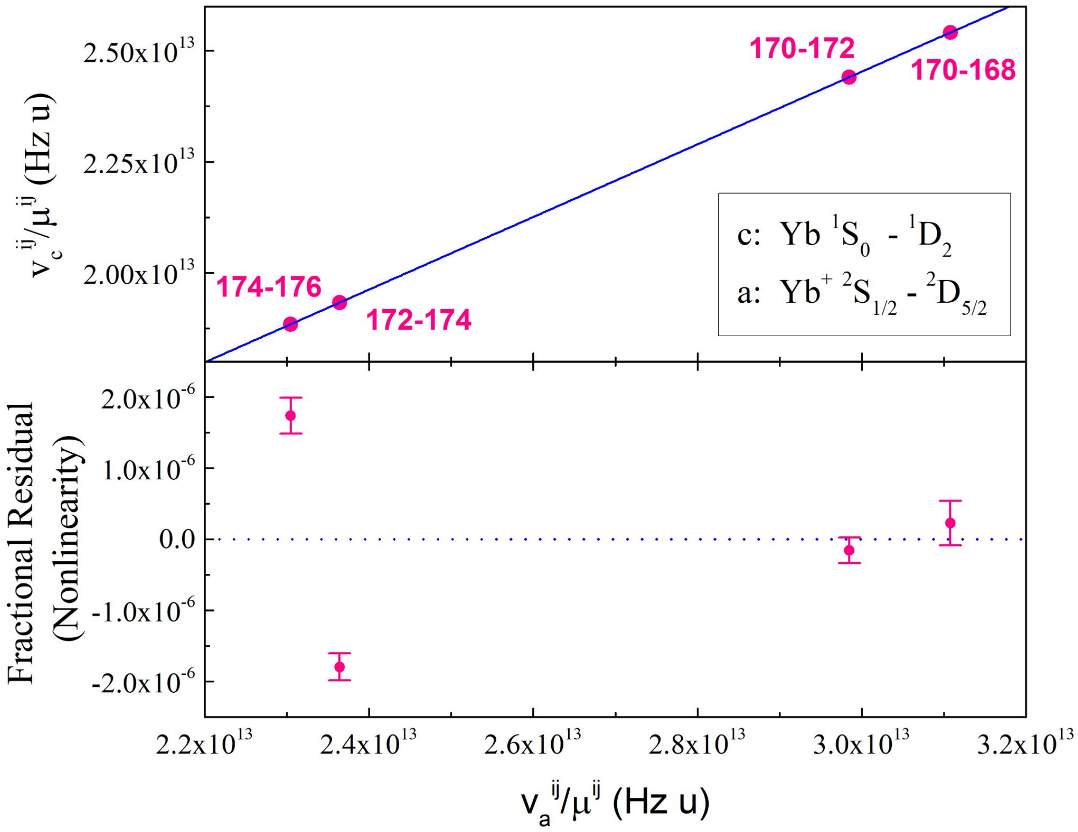


TABLE III: The deviations from the linearity of the King plot (in parts of 10^{-6}). Theoretical values are fitted to experiment by the contribution from a new boson (see Eqs. (7) and (8)).

Isotope pair	Yb II Expt.	Yb II Theory	Yb I Expt.	Yb I Theory
168 - 170	−0.1921	−0.2195	−0.2171	0.8619
170 - 172	0.2700	0.3079	0.1428	−0.1159
172 - 174	−0.4886	−0.4680	1.793	1.683
174 - 176	0.4106	0.3795	−1.732	−1.384

Calculations by V. Dzuba, V. Flambaum

- Yb accuracy in IS ~ 300 Hz (statistics limited).
- Nonlinearity few times greater than that in Yb$^+$ experiment
- Cause (theory): influence of nuclear deformation of Yb on the field shift

Next: Generalized King analysis (in progress)

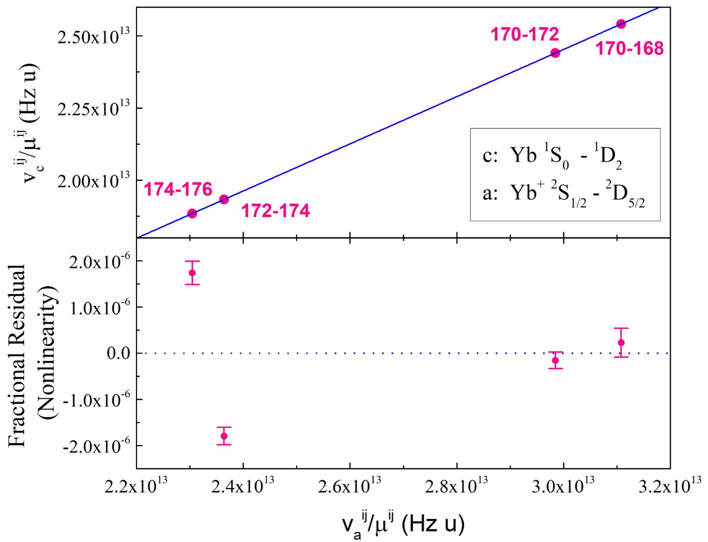
- Neutral Yb transition & two Yb^+ transitions used in GK analysis to separate new-physics contributions from known nuclear effects. (J. Berengut, with input from V. Dzuba, V. Flambaum).
- With three transitions, one known nuclear effect can be accounted for.
- **Preliminary** finding: the 3σ `hint` of new-physics in Yb^+ King Plot reduced to 2σ (to be confirmed).

Outlook

- Measurements on the Yb $^1S_0$-$^1D_2$ transition may be improved further (down to 10 Hz in IS).
- Interesting to measure narrow (180-kHz wide) transition $^1S_0$-$^3P_1$ in neutral Yb
- Other measurements underway in Yb^+ (S->F), Sr^+, Hg, HC ions, etc.
- Better than 1 Hz precision in IS expected in near future.

Summary

- Measured IS on a chain of five Yb isotopes in the ${}^1S_0$-${}^1D_2$ transition
- Large nonlinearity in Yb/Yb$^+$ King-plot comparison
- Likely due to influence of nuclear deformation on field shift
- Generalized King analysis will help check the interpretation of the Yb$^+$ data as new physics.



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