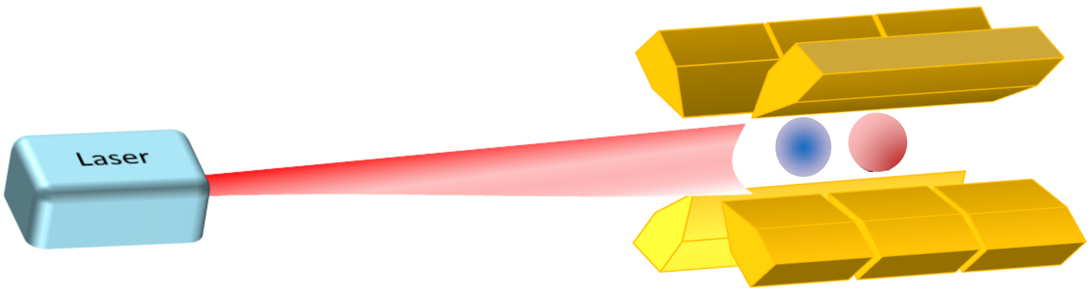
GGI 2018

Probing light new physics with Isotope shift spectroscopy



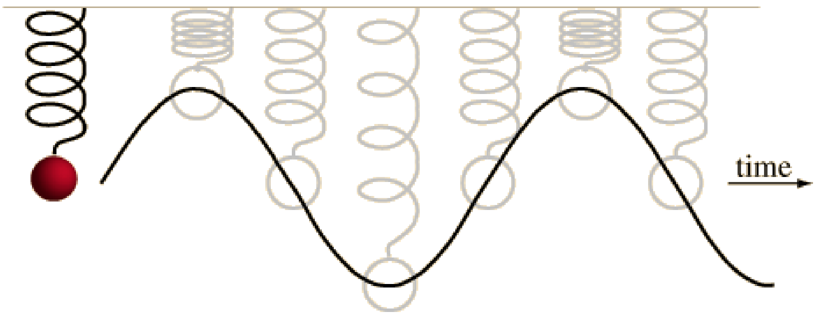
Roee Ozeri
Weizmann Institute of Science
Rehovot, Israel

Delaunay, RO, Perez and Soreq Phys. Rev. D 96, 093001 (2017)

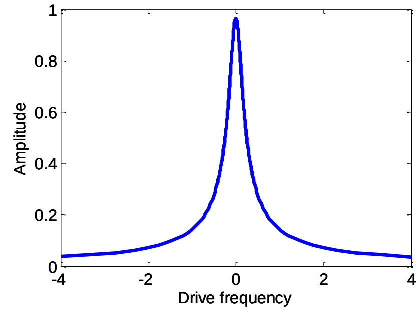
Berengut J. C.; Budker D.; Delaunay C.; Flambaum V. V.; Frugiuele C.; Fuchs E.; Grojean C.; Harnik R.; RO; Perez G.; Soreq Phys. Rev. Lett. 120, 091801 (2018)

Atomic Spectroscopy: the Naïve picture

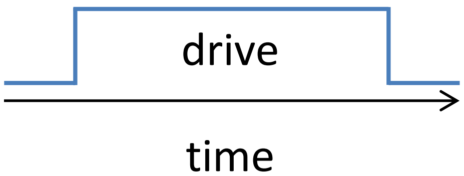
$$\ddot{x} + \gamma\dot{x} + \omega_0^2 x = F_0 \cos(\omega t - k_L x)$$

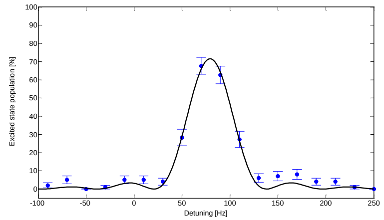


Steady-state response:

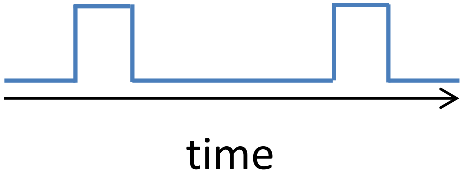


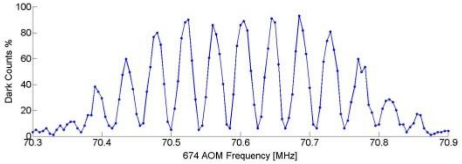
Rabi Spectroscopy:



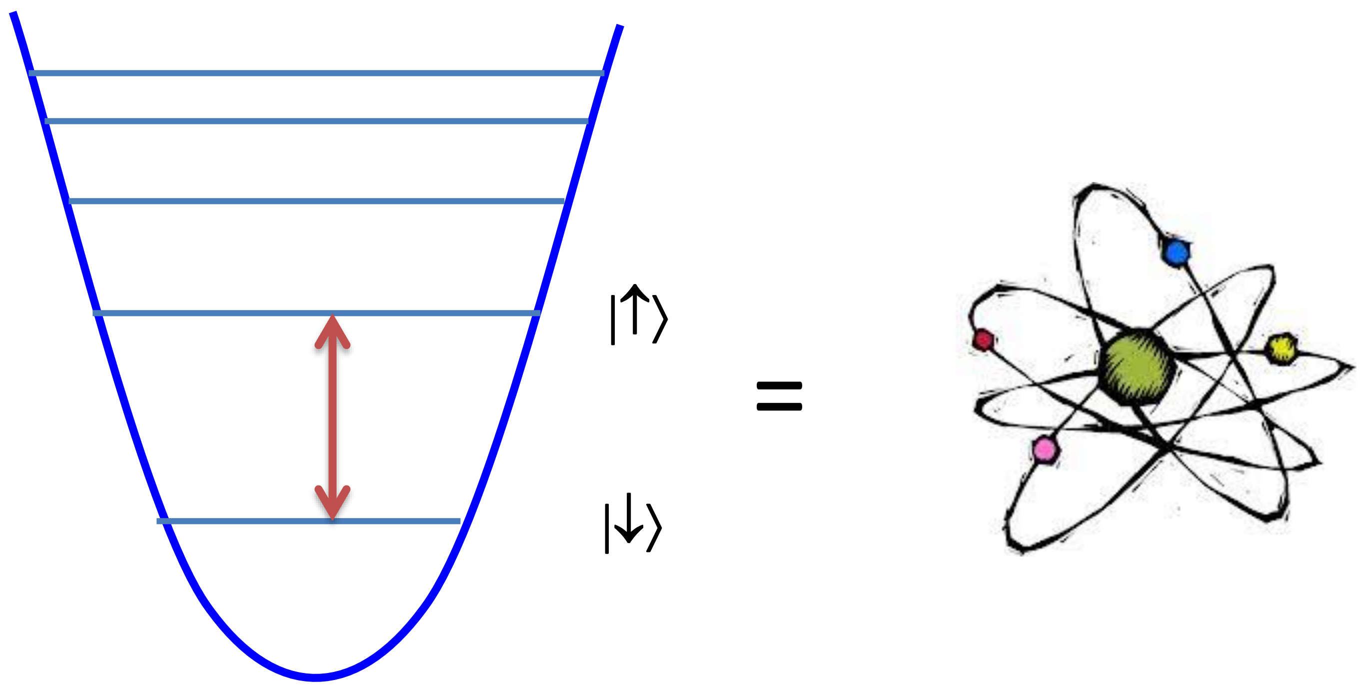


Ramsey Spectroscopy:



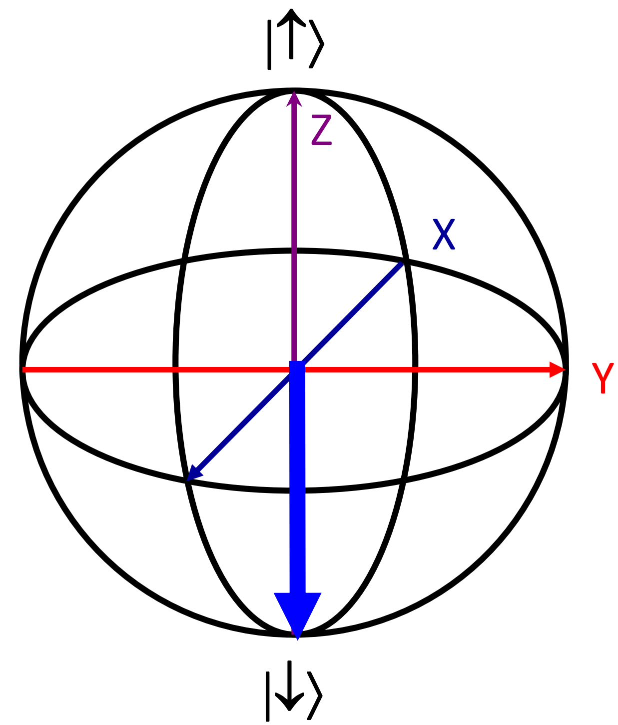


Atomic Spectroscopy



Quantum two-level system

The Bloch sphere



Ramsey Spectroscopy

1st Ramsey pulse

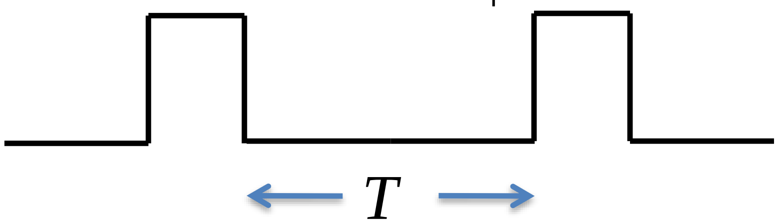
$\theta = \pi/2$

$\varphi = 0$

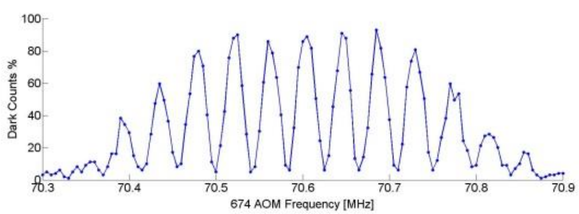
2nd Ramsey pulse

$\theta = \pi/2$

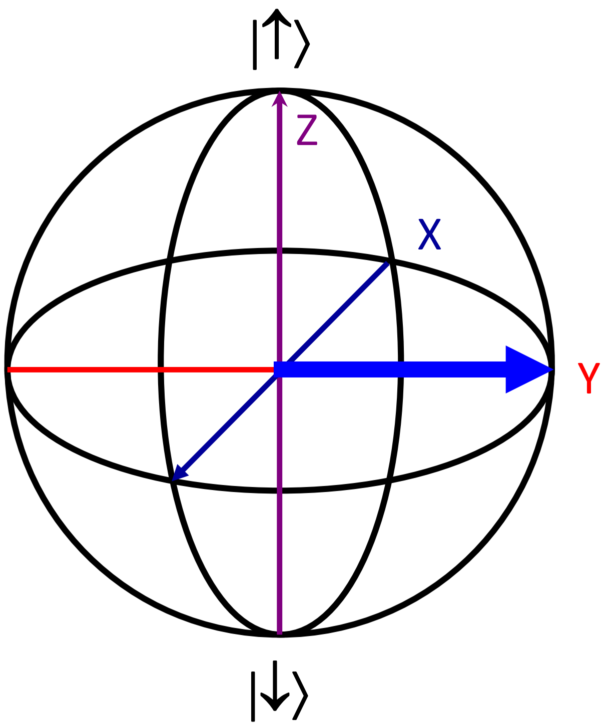
$\varphi = 0 \rightarrow 2\pi$



$$\phi = \int_0^T \xi dt$$

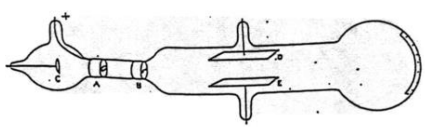


The Bloch sphere



Hand in hand with beam accelerators

Thomson and Rutherford
(Cambridge, 1897)



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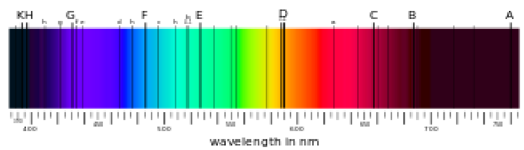
Ångstrom and Rydberg
(Upsala, Lund 1888)



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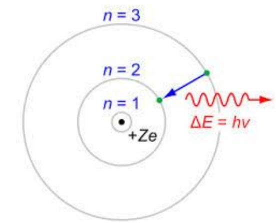
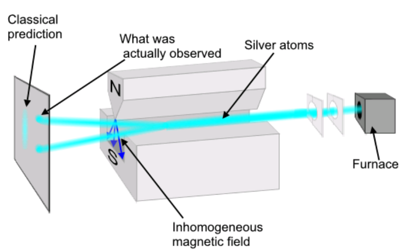
Bohr atom model
(Copenhagen, 1913)



Stern and Gerlach
(Frankfurt, 1922)



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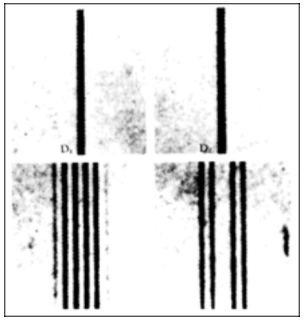
Zeeman
(Leiden, 1896)



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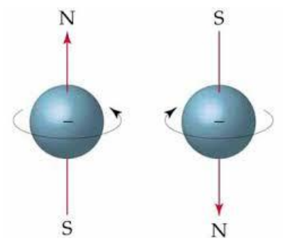
Uhlenbeck and Goudsmit
(Leiden, 1925)



Separate ways

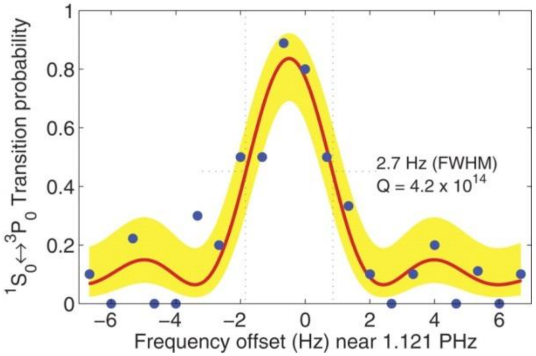
High Energy

Large Hadron Collider

13 TeV

Precision ~ 10^{-2}

High Precision



Aluminum-ion optical atomic clock

NIST, Boulder CO

Few eV

Precision ~ 10^{-18}

namical correction contributing <5% to the total shift). This can be measured directly by enclosing the atoms in a well-characterized blackbody environment and recording the clock shift as this temperature is systematically varied (this simultaneously decreases uncertainty in the BBR environment). The technical challenge lies in the control of temperature homogeneity over various functional areas of the vacuum chamber while accommodating sufficient optical access for a variety of atomic manipulations. One possible solution is to cool and trap atoms in a standard chamber and then transport them in a moving lattice (*34*) to a secondary chamber, where an ideal, well-defined blackbody environment is established (*16*). Such an approach avoids the complexity of cryogenic operation and can be generalized to other lattice clock species. These improvements can potentially improve the BBR-related uncertainty to far below 10^{-16}.

References and Notes

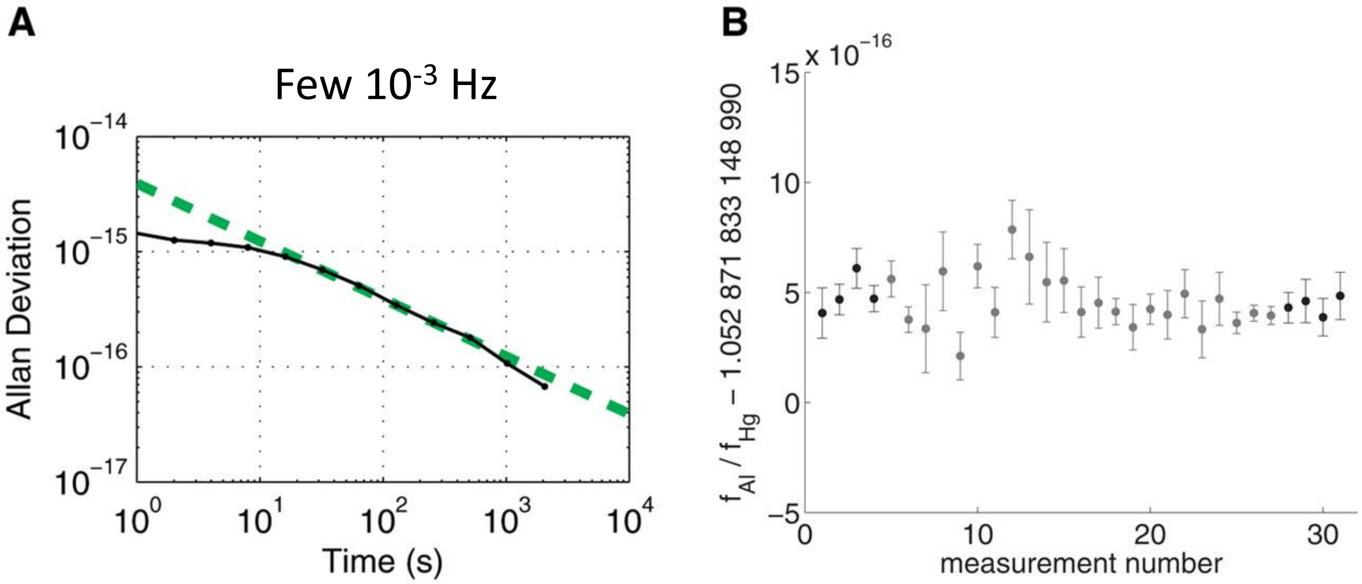
1. T. P. Heavner, S. R. Jefferts, E. A. Donley, J. H. Shirley, T. E. Parker, *Metrologia* **42**, 411 (2005).
2. S. Bize *et al.*, *J. Phys. B* **38**, S449 (2005).
3. L. Hollberg *et al.*, *J. Phys. B* **38**, S469 (2005).
4. M. M. Boyd *et al.*, *Science* **314**, 1430 (2006).
5. W. H. Oskay *et al.*, *Phys. Rev. Lett.* **97**, 020801 (2006).
6. H. S. Margolis *et al.*, *Science* **306**, 1355 (2004).
7. T. Schneider, E. Peik, C. Tamm, *Phys. Rev. Lett.* **94**, 230801 (2005).

The most accurate measurement of anything, ever.

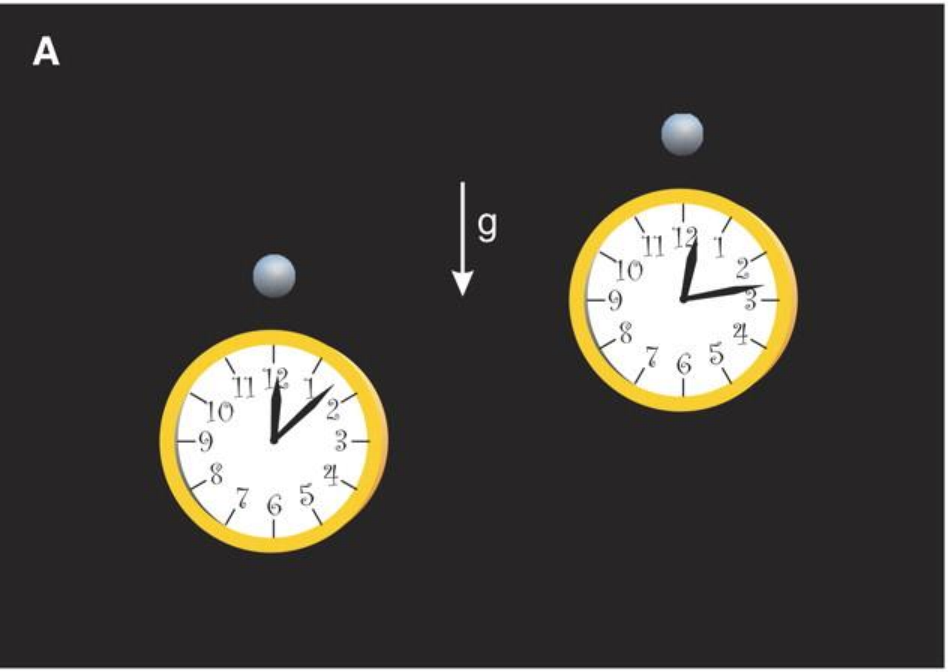
T. Rosenband,* D. B. Hume, P. O. Schmidt,† C. W. Chou, A. Brusch, L. Lorini,‡ W. H. Oskay,§ R. E. Drullinger, T. M. Fortier, J. E. Stalnaker,‖ S. A. Diddams, W. C. Swann, N. R. Newbury, W. M. Itano, D. J. Wineland, J. C. Bergquist

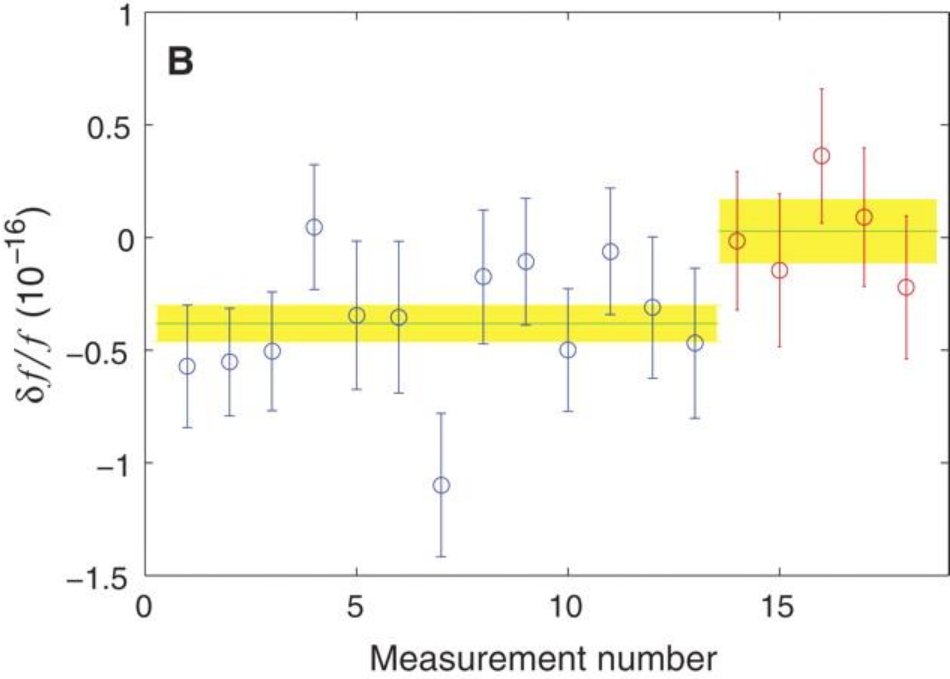
Time has always had a special status in physics because of its fundamental role in specifying the regularities of nature and because of the extraordinary precision with which it can be measured. This precision enables tests of fundamental physics and cosmology, as well as practical applications such as satellite navigation. Recently, a regime of operation for atomic clocks based on optical transitions has become possible, promising even higher performance. We report the frequency ratio of two optical atomic clocks with a fractional uncertainty of 5.2×10^{-17}. The ratio of aluminum and mercury single-ion optical clock frequencies ν_{Al^+}/ν_{Hg^+} is 1.052871833148990438(55), where the uncertainty comprises a statistical measurement uncertainty of 4.3×10^{-17}, and systematic uncertainties of 1.9×10^{-17} and 2.3×10^{-17} in the mercury and aluminum frequency standards, respectively. Repeated measurements during the past year yield a preliminary constraint on the temporal variation of the fine-structure constant α of $\dot{\alpha}/\alpha = (-1.6 \pm 2.3) \times 10^{-17}$/year.

Time is the physical coordinate over which humans have the least control, and yet it is the most accurately realized fundamental unit. Although any physical system that evolves predictably can serve as a time base, isolated atoms have long been recognized as near-ideal references for laboratory clocks, due to the abundance of identical copies, as well as their



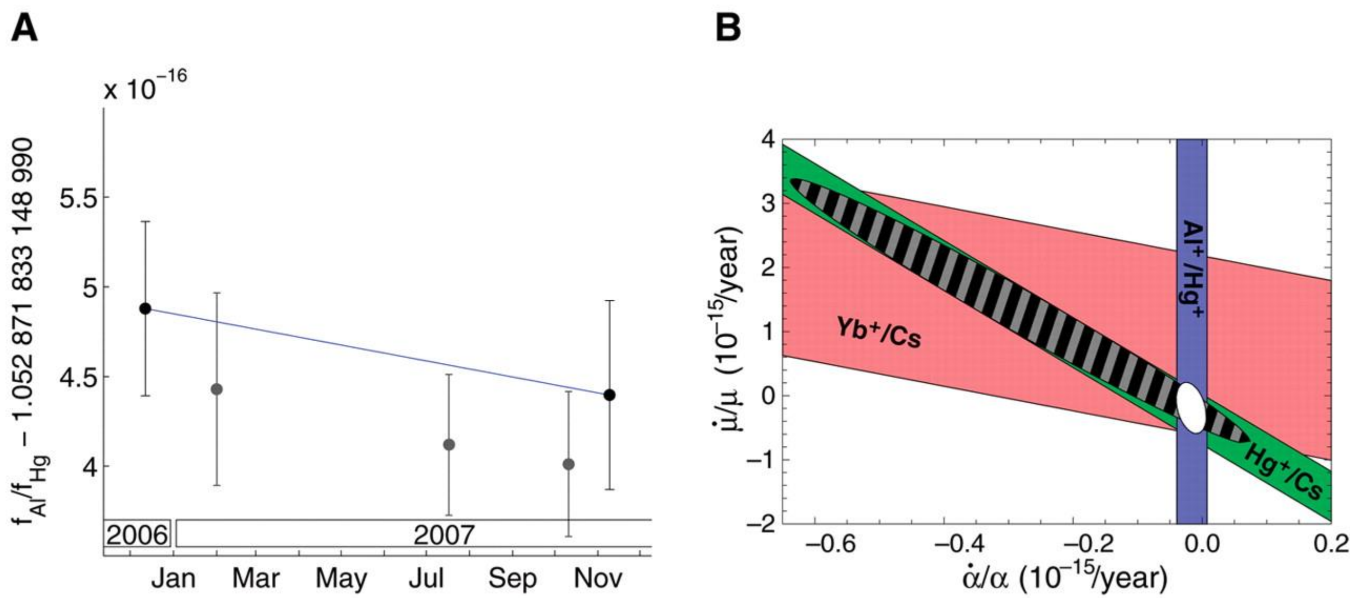
Gravitational red-shift@ 33 cm





Chou, Hume, Rosenband and Wineland, *Science,* **329**, 1630, (2010)

Time variation of fundamental constants



$$\dot{\alpha}/\alpha = (-1.6 \pm 2.3) \times 10^{-17}/\text{year}$$

Contrast with quasar absorption spectra:

- Observed $-0.543 \pm 0.116 \times 10^{-5}$ during the last 12 billion years
- $\dot{\propto}/\propto = \ -6.4 \pm 1.35 \times 10^{-16}$ / year

Rosenband *et. al., Science,* **319**, 1808, (2008)

Search for New Scalar or Vector Fields

- Search for physics Beyond the Standard Model highly motivated:

  - Flavor Mass Hierarchy problem
  - Strong CP problem
  - Neutrino oscillations
  - Matter vs. anti-matter asymmetry
  - Dark Matter

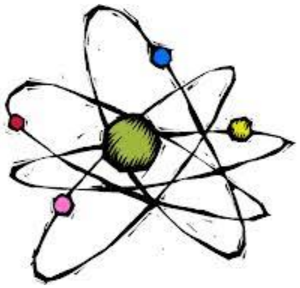
- Many theoretical solutions result in (pseudo) scalar or vector fields
  (axions/familons/ relaxions/ dark photons..)

- Multitude of experimental searches

Graham *et. al.* Ann. Rev. Nuc. Part. Sci. 65, 485 (2015)

Safronova, Budker, et. al. Reviews of Modern Physics, 90, 025008 (2018)

NP detection through spectroscopy



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

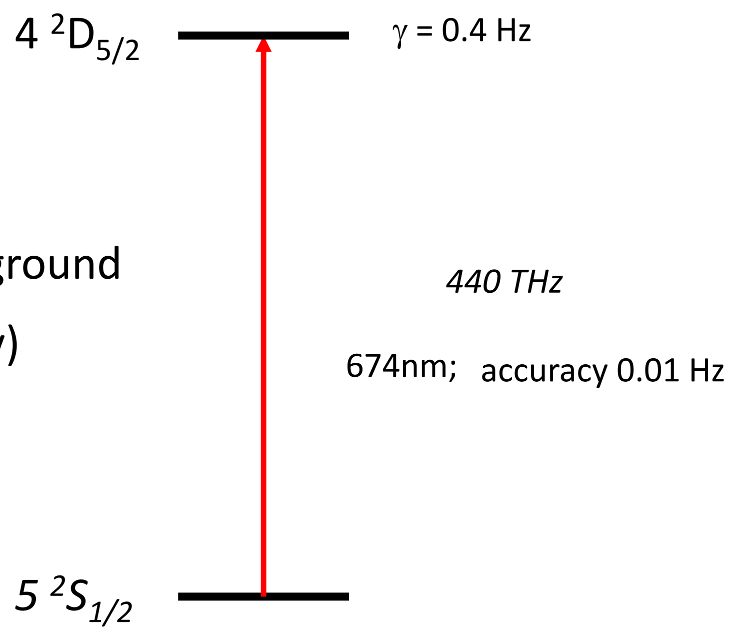
$$\alpha_{\rm NP} = (-1)^s y_e y_n / 4\pi$$

A new force between the electron and nucleus will modify the electronic spectrum in atoms

NP detection through spectroscopy

Now with numbers…

$$V_\phi(r) = -\alpha_{NP} A \frac{e^{-rm_\phi}}{r} \qquad \alpha_{\mathrm{NP}} = (-1)^s y_e y_n / 4\pi$$



- $y_e y_n \sim 10^{-6}$ ↔ *100 Hz*
- Can't differentiate this contribution from QED background

(calculate transition freq. with 10^{-13} accuracy)

Symmetry breaking in spectroscopy

- Parity symmetry: APV experiments
- Charge symmetry: Anti-hydrogen spectroscopy
- CP symmetry: electron EDM
- Lorenz symmetry: LLI experiments
- Time and space translation symmetry: Time variation of fundamental constants

Will not work with scalar, vector forces....
or anything else that respects all the symmetries QED respects

Isotope Shift Spectroscopy

$$V_\phi(r) = -\alpha_{NP}(A-Z)\frac{e^{-rm_\phi}}{r} \qquad \alpha_{\mathrm{NP}} = (-1)^s y_e y_n/4\pi$$

- $y_e y_n \sim 10^{-6}$ ↔ *100 Hz*

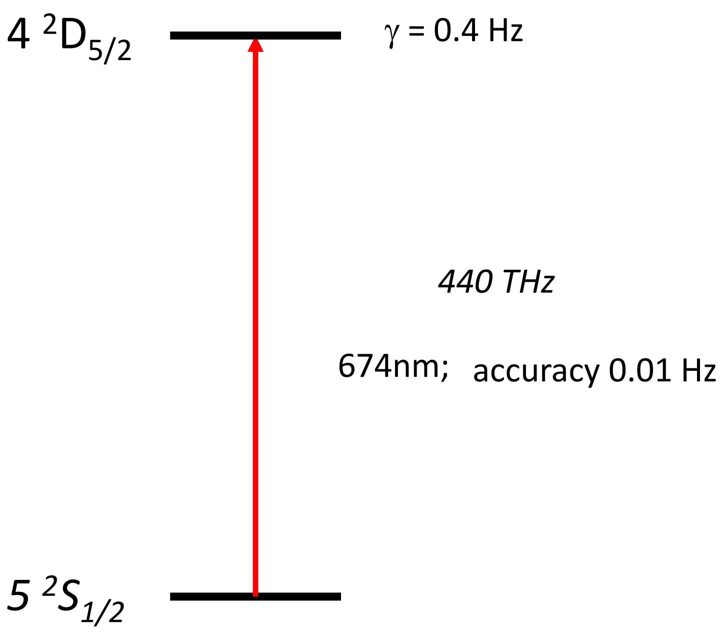
$^{86}\mathrm{Sr}^+ \longleftrightarrow {}^{88}\mathrm{Sr}^+$

New physics contribution to IS: *2 Hz*

(calculate IS with 10^{-8} accuracy)

$$\Delta\nu^{88,86}_{\mathrm{meas}} = 570.281(4)\ \mathrm{MHz}$$

$$\Delta\nu^{88,86}_{\mathrm{calc}} = 457(28)\ \mathrm{MHz}$$



Lybarger Jr., Berengut and Chiaverini Phys. Rev. A 83, 052509 (2011)

Isotope Shift Spectroscopy

A closer look

$$\mu_{AA'} \equiv m_A^{-1} - m_{A'}^{-1}$$

$$\nu_i^{AA'} = K_i \mu_{AA'} + F_i \delta \langle r^2 \rangle_{AA'} + \cdots$$

Mass shift

- Normal Mass shift(NMS): Change to electron reduced mass
- Specific Mass shift (SMS): Change to quasi-particle mass (many electrons)

Field shift

Due to the breaking of point-charge approximation for nucleus

- Factorization: separation of electronic and nuclear contributions

W. H. King "Isotope Shifts in Atomic Spectra" Springer (1984)

Isotope Shift Spectroscopy

A closer look

$$\mu_{AA'} \equiv m_A^{-1} - m_{A'}^{-1}$$

$$\nu_i^{AA'} = K_i \mu_{AA'} + F_i \delta\langle r^2 \rangle_{AA'} + \cdots$$

$$m\nu_i^{AA'} = \frac{\nu_i^{AA'}}{\mu_{AA'}} = K_i + F_i \frac{\delta\langle r^2 \rangle_{AA'}}{\mu_{AA'}}$$

- Factorization: separation of electronic and nuclear contributions

W. H. King “Isotope Shifts in Atomic Spectra” Springer (1984)

King Comparison

Two transitions

$$m\nu_1^{AA'} = \frac{\nu_1^{AA'}}{\mu_{AA'}} = K_1 + F_1 \frac{\delta\langle r^2\rangle_{AA'}}{\mu_{AA'}}$$

$$m\nu_2^{AA'} = \frac{\nu_2^{AA'}}{\mu_{AA'}} = K_2 + F_2 \frac{\delta\langle r^2\rangle_{AA'}}{\mu_{AA'}}$$

King's linear relation between normalized IS:

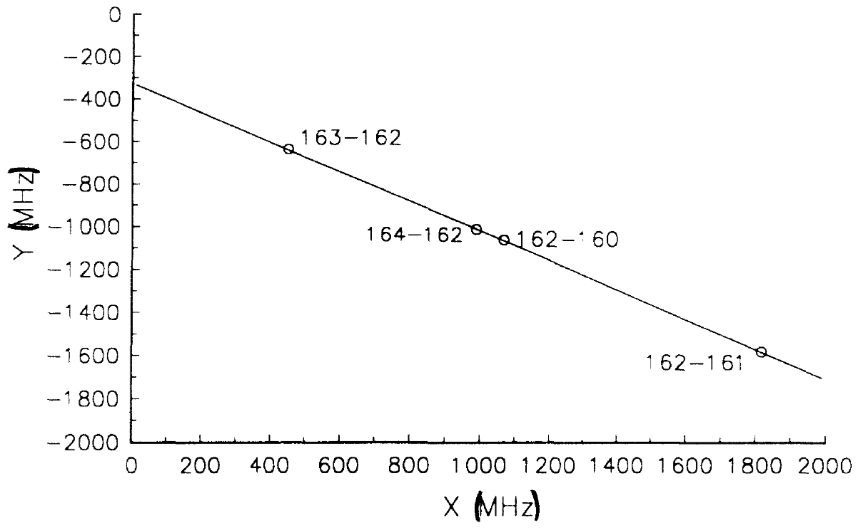
$$m\nu_2^{AA'} = K_{21} + F_{21} m\nu_1^{AA'}$$

$$F_{21} = \frac{F_2}{F_1} \qquad K_{21} \equiv K_2 - F_{21} K_1$$

W. H. King "Isotope Shifts in Atomic Spectra" Springer (1984)

King Plot

$$m\nu_2^{AA'} = K_{21} + F_{21} m\nu_1^{AA'}$$



Dy King plot. Budker et al 1994

King Linearity holds

PRL 115, 053003 (2015) PHYSICAL REVIEW LETTERS week ending 31 JULY 2015

Precision Isotope Shift Measurements in Calcium Ions Using Quantum Logic Detection Schemes

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[2]*School of Mathematics and Statistics, University of New South Wales, Sydney, New South Wales 2052, Australia*
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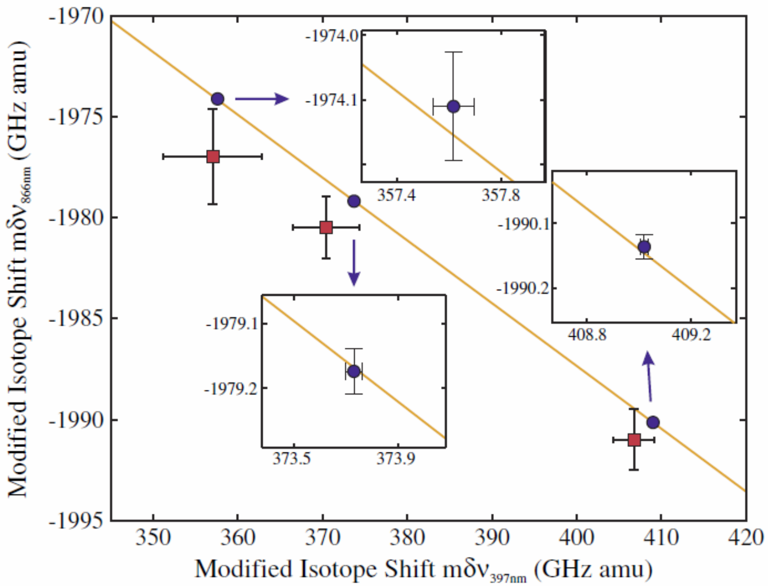
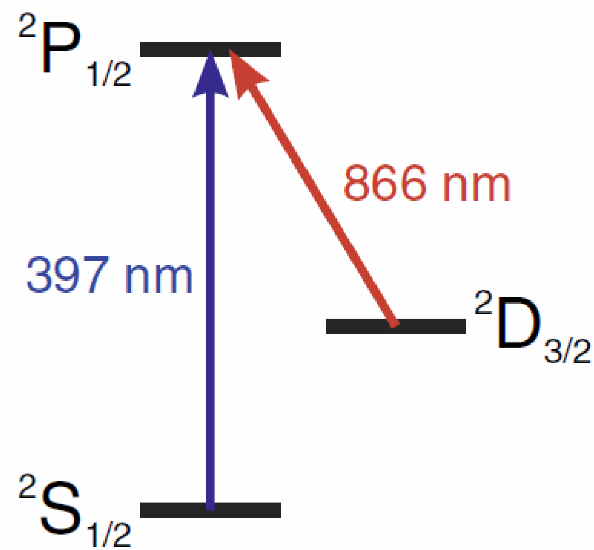
(Received 15 April 2015; published 29 July 2015)

Relative accuracy ~ $10^{-3} - 10^{-4}$





Nonlinear anomalies; e.g. Samarium; due to level degeneracies

New Physics and King linearity

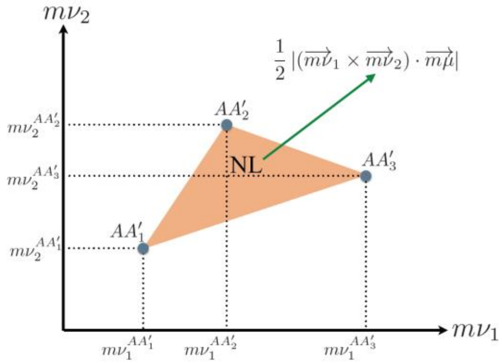
$$\nu_i^{AA'} = K_i \mu_{AA'} + F_i \delta\langle r^2 \rangle_{AA'} + \alpha_{\rm NP} X_i \gamma_{AA'}$$

Coupling Electronic Nuclear

New Physics is likely to break King linearity

Bounds on new physics

$$\mathrm{NL} = \frac{1}{2} |(\overrightarrow{m\nu}_1 \times \overrightarrow{m\nu}_2) \cdot \overrightarrow{m\mu}|$$



Estimate for new physics coupling:

$$\alpha_{\mathrm{NP}} = \frac{(\overrightarrow{m\nu}_1 \times \overrightarrow{m\nu}_2) \cdot \overrightarrow{m\mu}}{(\overrightarrow{m\mu} \times \vec{h}) \cdot (X_1 \overrightarrow{m\nu}_2 - X_2 \overrightarrow{m\nu}_1)}$$

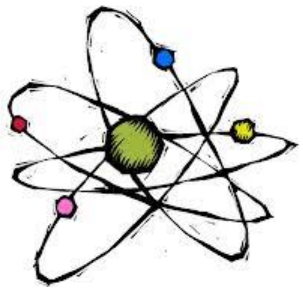
- $\overrightarrow{m\mu}$ $\overrightarrow{m\nu}$ measured

Minimal theory input:

- X expectation value (atomic structure calculations)
- $h_{AA'} \propto AA'$ (theory)

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

What do we need?



1. Two narrow optical transitions (optical clocks) with the same nucleus
2. Transitions between as different states as possible
3. At least four stable (even) isotopes without nuclear spin for three independent IS comparisons

Are King plots really linear?

- Higher order terms
- Nuclear polarizability
- Many-body effects

Ion	Z	A	A_1	A_2	A_3	Pair of transitions	Non-linearity (Hz)	$\frac{\alpha_{NP}}{\alpha}$			
								$m_\phi \to 0$	$m_\phi = 10^5$ eV	$m_\phi = 10^6$ eV	$m_\phi = 10^7$ eV
Ca^+	20	40	42	44	48	$3p^6 4s\ ^2S_{1/2} \to 3p^6 3d\ ^2D_{3/2}$	-3.0	5.6×10^{-12}	1.4×10^{-9}	-9.9×10^{-9}	-7.2×10^{-7}
						$3p^6 4s\ ^2S_{1/2} \to 3p^6 3d\ ^2D_{5/2}$					
Sr^+	38	84	86	88	90	$4p^6 5s\ ^2S_{1/2} \to 4p^6 4d\ ^2D_{3/2}$	-11.9	6.7×10^{-13}	5.5×10^{-11}	-7.4×10^{-10}	-3.8×10^{-8}
						$4p^6 5s\ ^2S_{1/2} \to 4p^6 4d\ ^2D_{5/2}$					
Ba^+	56	132	134	136	138	$5p^6 6s^1\ ^2S_{1/2} \to 5p^6 5d\ ^2D_{3/2}$	11.1	7.7×10^{-13}	3.9×10^{-11}	-3.4×10^{-8}	-3.3×10^{-7}
						$5p^6 6s^1\ ^2S_{1/2} \to 5p^6 5d\ ^2D_{5/2}$					
Yb^+	70	168	170	172	176	$4f^{14} 6s\ ^2S_{1/2} \to 4f^{13} 6s^2\ ^2F^o_{7/2}$	12190	-2.5×10^{-11}	2.4×10^{-9}	1.3×10^{-8}	3.2×10^{-7}
						$4f^{14} 6s\ ^2S_{1/2} \to 4f^{14} 5d\ ^2D_{3/2}$					
						$4f^{14} 6s\ ^2S_{1/2} \to 4f^{14} 5d\ ^2D_{3/2}$	-406	2.7×10^{-11}	2.2×10^{-9}	-1.7×10^{-8}	-3.9×10^{-7}
						$4f^{14} 6s\ ^2S_{1/2} \to 4f^{14} 5d\ ^2D_{5/2}$					
Hg^+	80	196	198	200	204	$5d^{10} 6s\ ^2S_{1/2} \to 5d^9 6s^2\ ^2D_{3/2}$	-2395	-1.8×10^{-10}	6.6×10^{-8}	-5.5×10^{-8}	-1.0×10^{-6}
						$5d^{10} 6s\ ^2S_{1/2} \to 5d^9 6s^2\ ^2D_{5/2}$					

- King linearity will provide solid bounds (baring cancelation)
- Observation of nonlinearity will require further investigations

Flambaum, Geddes, Viatkina Phys. Rev. A 97, 032510 (2018)

Current and projected bounds

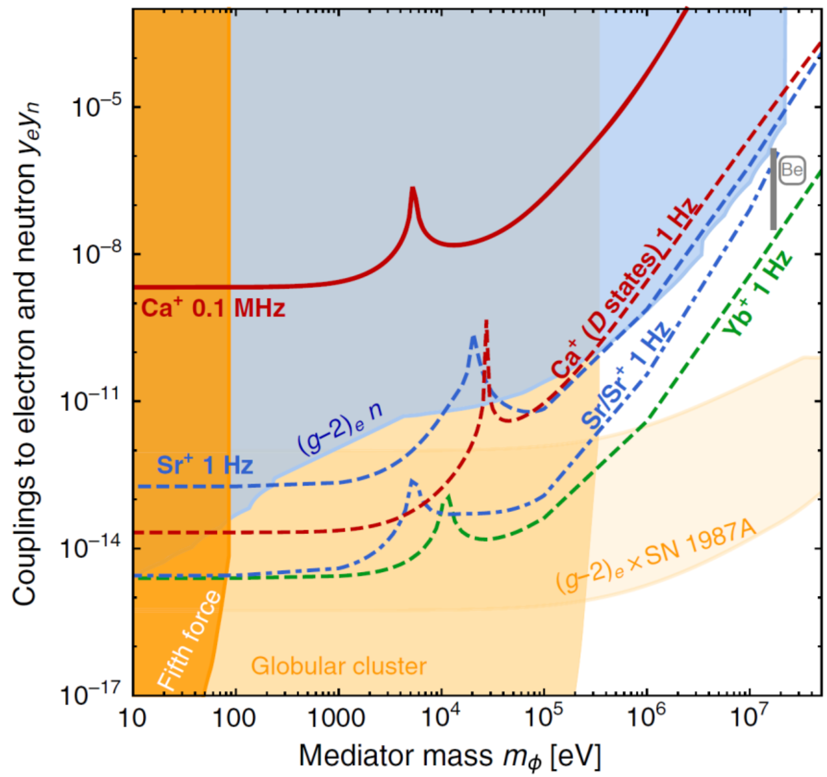
$$V_\phi(r) = -\alpha_{NP} A \frac{e^{-rm_\phi}}{r} \qquad \alpha_{\rm NP} = (-1)^s y_e y_n / 4\pi$$

Massless limit:

$$m_\phi \lesssim (1+n_e)/a_0$$

$$V_\phi \propto 1/r$$

Renormalization of Coulomb interaction



Heavy mass limit:

$$m_\phi \gtrsim 1/r_N$$

$$V_\phi \propto \delta(r)/(m_\phi^2 r^2)$$

Inseparable from other nuclear effects: loss of sensitivity

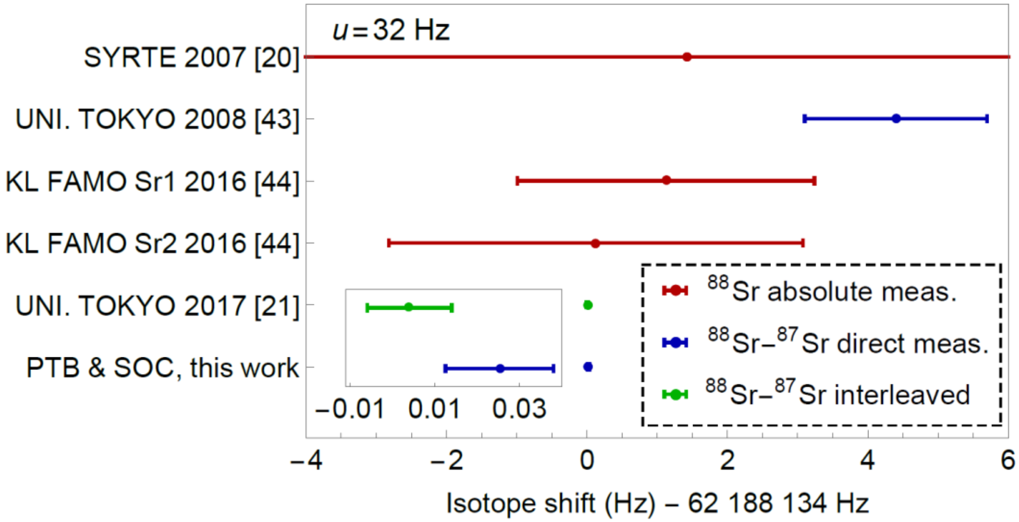
Intermediate regime

$$(1+n_e)/a_0 \lesssim m_\phi \lesssim 1/r_N$$

$$V_\phi \propto e^{-m_\phi r}/r$$

Recent accurate IS measurements

Comparison between two lattice clocks $^{88}\mathrm{Sr}–^{87}\mathrm{Sr}$



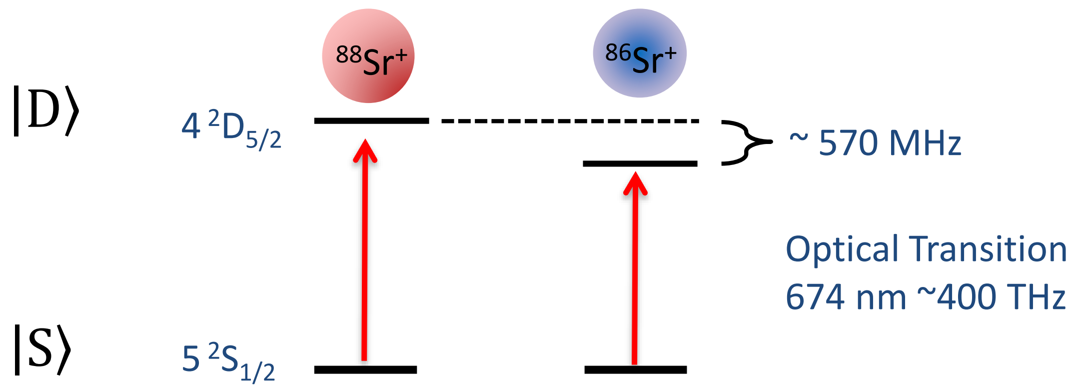
Uncertainty: $12\ \mathrm{mHz}$ 3.0×10^{-17}

Takano, Mizushima and Katori arXiv:1706.02905 (2017)

Origlia *et. al.* arXiv:1803.03157 (2018)v

IS measurement in a Decoherence-Free Subspace

The optical Quadruple transition in Sr+



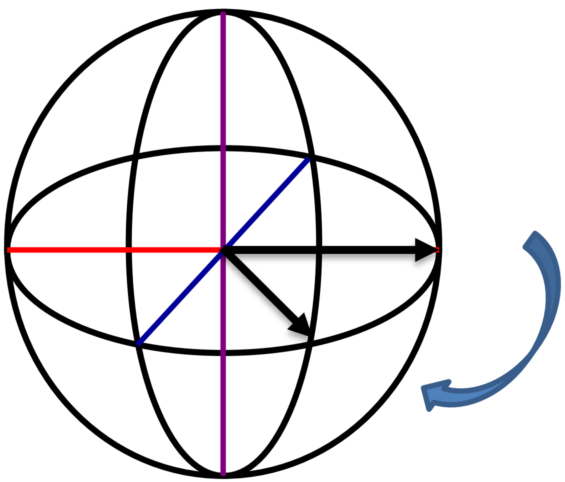
Measuring the Isotope shift in decoherence free subspace

$$\psi(T) = |D^{88}S^{86}\rangle + e^{i2\pi\Delta v_{IS}T}|S^{88}D^{86}\rangle$$

IS measurement in a Decoherence-Free Subspace

Δv_{IS}

$|D^{88}S^{86}\rangle$



$$\psi_{init} = |D^{88}S^{86}\rangle + |S^{88}D^{86}\rangle$$

$|S^{88}D^{86}\rangle$

$$\psi(T) = |D^{88}S^{86}\rangle + e^{i2\pi\Delta v_{IS}T}|S^{88}D^{86}\rangle$$

- Zeeman shifts
- Quadrupole shifts
- BBR
- 2^{nd} order Doppler

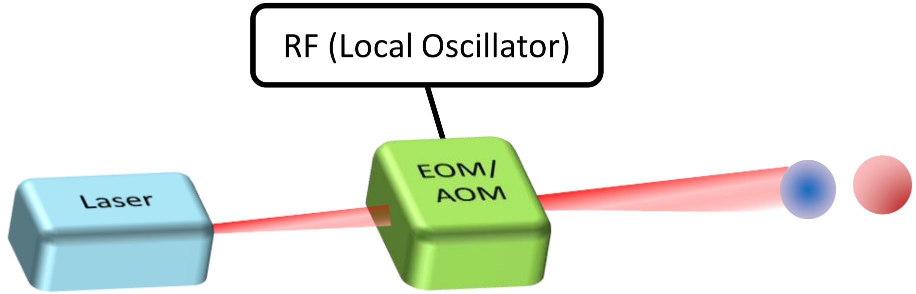
→ Canceled up to gradients

IS measurement in a Decoherence-Free Subspace

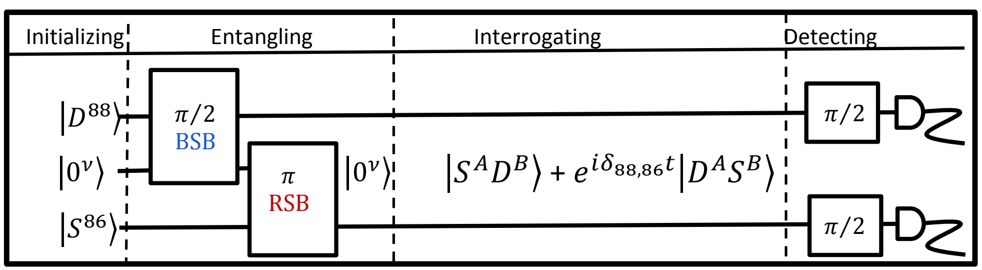
Preliminary

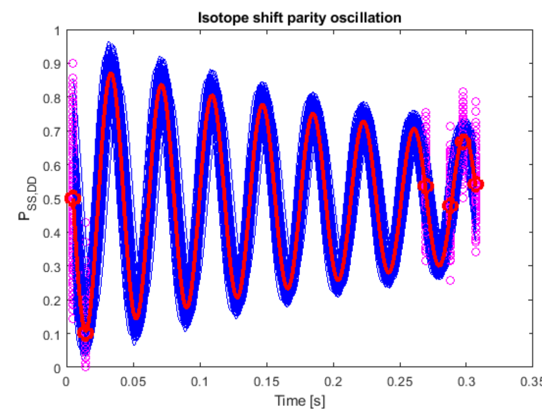
Nitzan Akerman

Tom Manovitz

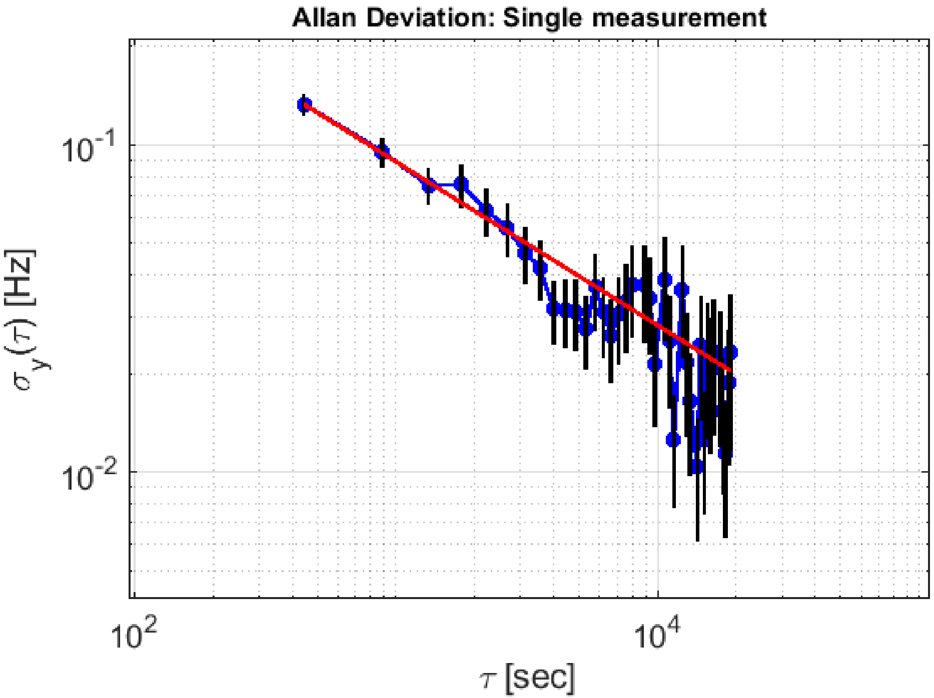


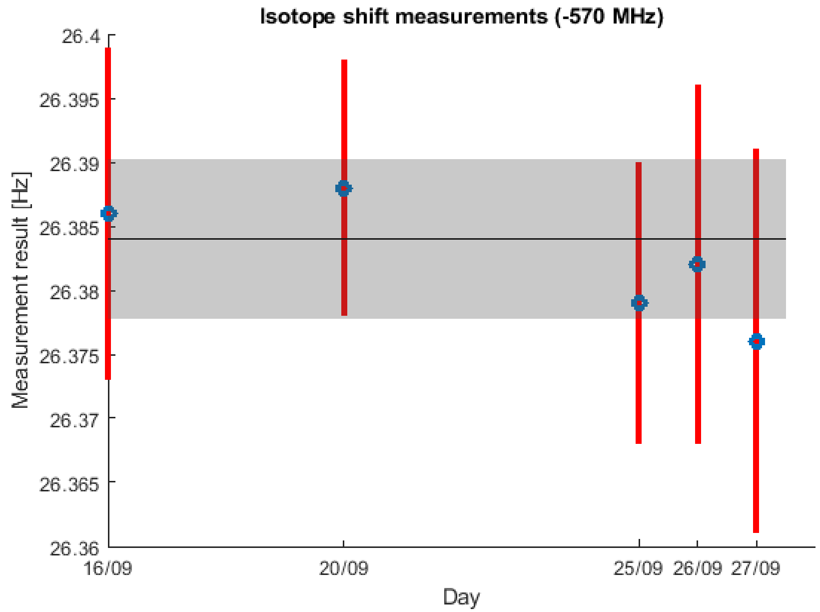
$Parity = P_{SS} + P_{DD} - (P_{DS} + P_{SD})$





IS measurement in a Decoherence-Free Subspace





$$\psi(T) = |D^{88}S^{86}\rangle + e^{i2\pi\Delta\nu_{IS}T}|S^{88}D^{86}\rangle$$

Preliminary

- IS clock
- MW clock (~ 570.281 MHz) with optical clock systematics (e.g. 2nd – order Doppler)
- Statistical uncertainty < 10 mHz

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Elina Fuchs
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Available postdoc positions

ISRAEL SCIENCE FOUNDATION
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erc European Research Council
MINERVA STIFTUNG Gesellschaft für die Forschung m.b.H.

Geometric Interpretation

$$m\nu_i^{AA'} = \frac{\nu_i^{AA'}}{\mu_{AA'}} = K_i + F_i \frac{\delta\langle r^2\rangle_{AA'}}{\mu_{AA'}}$$

$$\overrightarrow{m\nu}_i = K_i \overrightarrow{m\mu} + F_i \overrightarrow{m\delta\langle r^2\rangle}$$

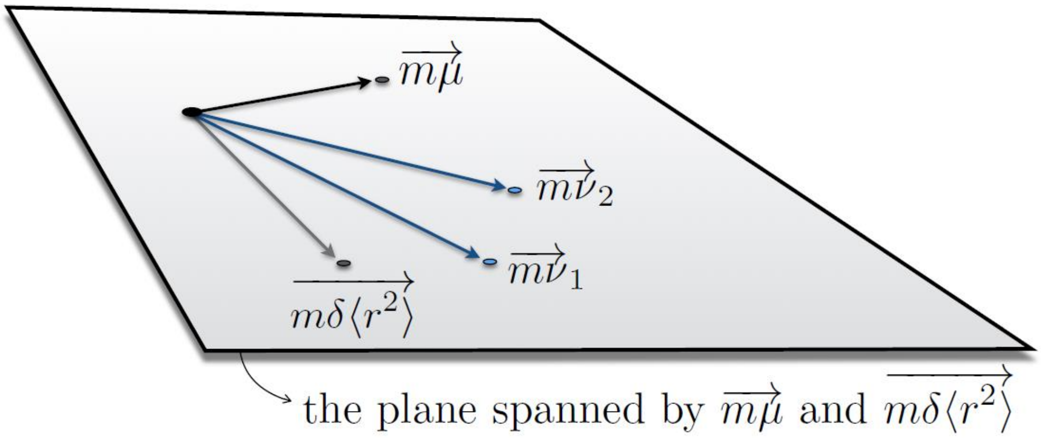
$$\overrightarrow{m\nu}_i \equiv \left(m\nu_i^{AA'_1}, m\nu_i^{AA'_2}, m\nu_i^{AA'_3}\right)$$

$$\overrightarrow{m\mu} \equiv (1, 1, 1)$$

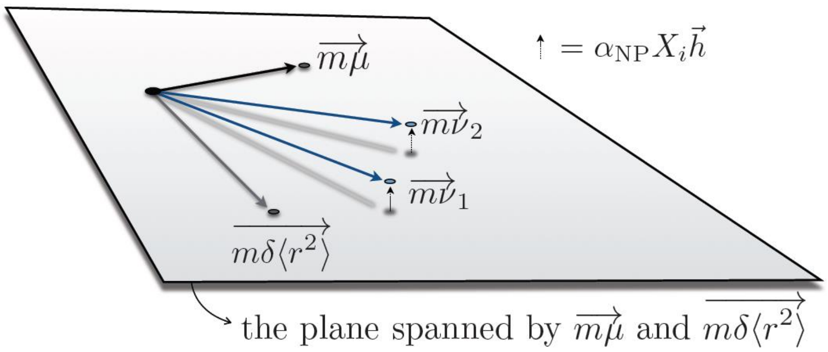
$$\overrightarrow{m\delta\langle r^2\rangle} \equiv \left(\langle r^2\rangle_{AA'_1}/\mu_{AA'_1}, \langle r^2\rangle_{AA'_2}/\mu_{AA'_2}, \langle r^2\rangle_{AA'_3}/\mu_{AA'_3}\right)$$

Geometric Interpretation

King linearity = co-planarity of $\overrightarrow{m\nu}_{1,2}$

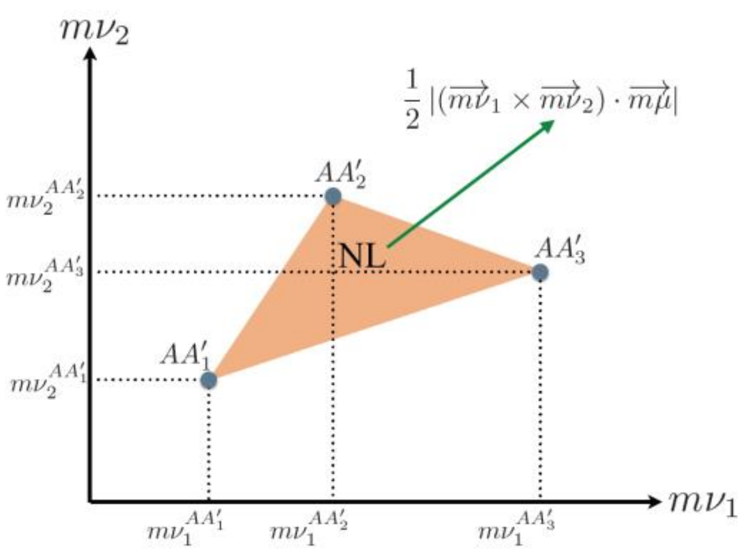


Geometric Interpretation

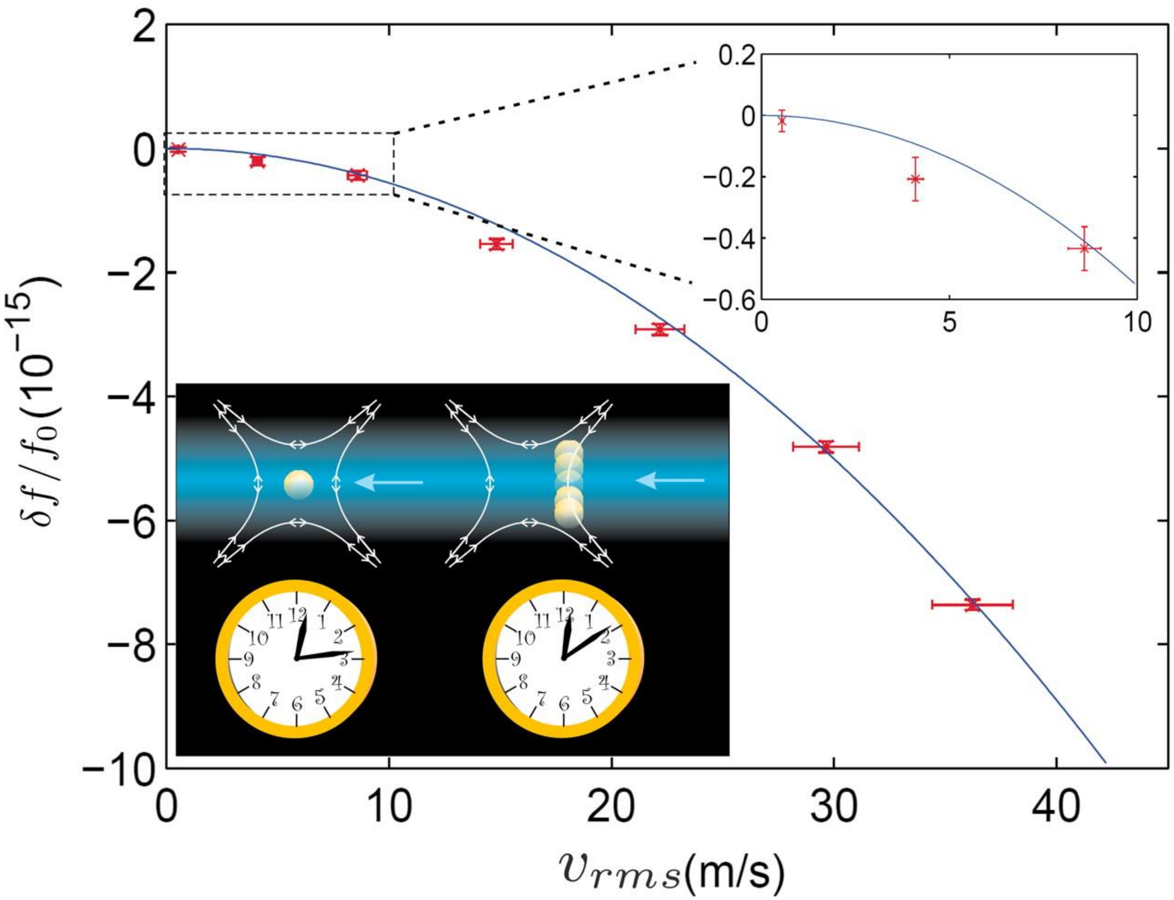


Nonlinearity:

$$\mathrm{NL} = \frac{1}{2}\left|(\overrightarrow{m\nu}_1 \times \overrightarrow{m\nu}_2)\cdot\overrightarrow{m\mu}\right|$$



The twins paradox at running speed



Chou, Hume, Rosenband and Wineland, *Science,* **329**, 1630, (2010)

Precision mass measurements: 10^{-10}

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The most precise atomic mass measurements in Penning traps

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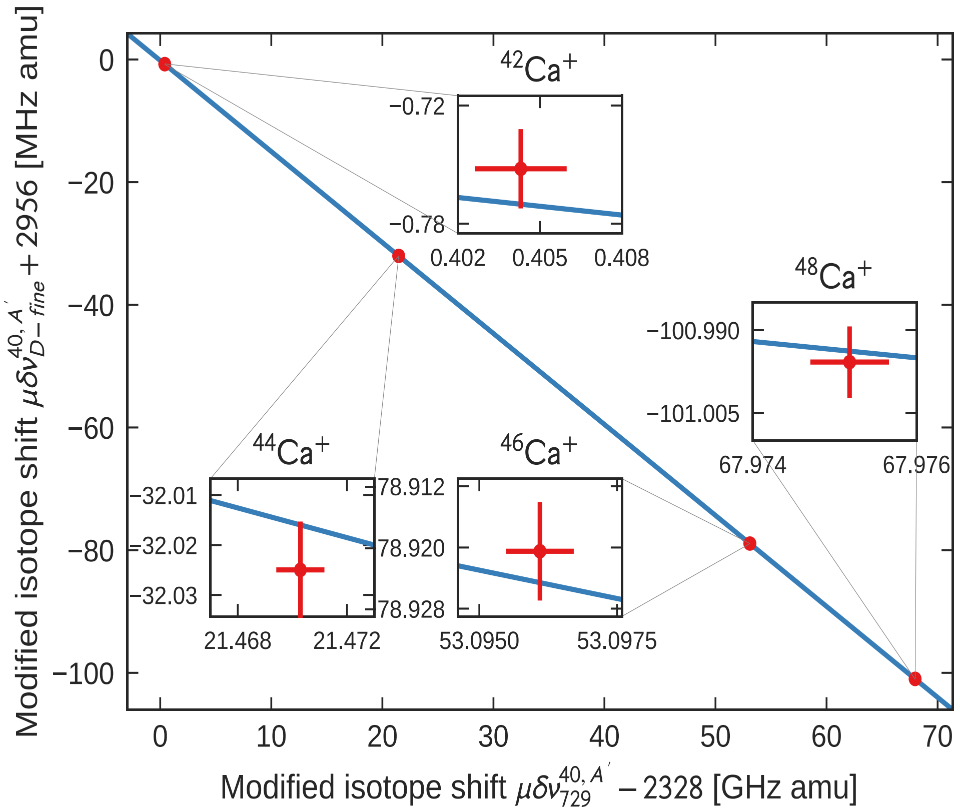
Table 10
Atomic masses of the most abundant isotopes of strontium and ytterbium measured at FSU [109].

Atom	FSU mass (u)	σ_m/m (ppt)
^{86}Sr	85.909 260 730 9(91)	105
^{87}Sr	86.908 877 497 0(91)	105
^{88}Sr	87.905 612 257 1(97)	110
^{170}Yb	169.934 767 241(18)	105
^{171}Yb	170.936 331 514(19)	110
^{172}Yb	171.936 386 655(18)	105
^{173}Yb	172.938 216 213(18)	105
^{174}Yb	173.938 867 539(18)	105
^{176}Yb	175.942 574 702(22)	125

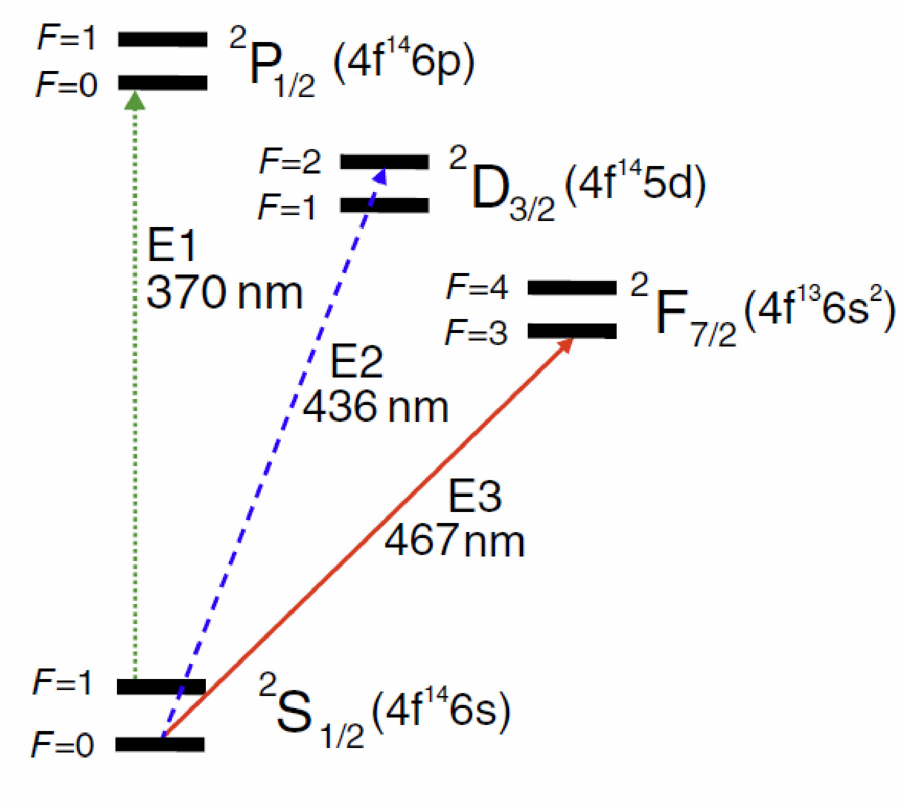
King Linearity holds

Relative accuracy ~ $10^{-3} – 10^{-4}$



Nonlinear anomalies; e.g. Samarium; due to level degeneracies

Yb^+ ion-clock



New Journal of Physics
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Absolute frequency measurement of the $^2S_{1/2}$–$^2F_{7/2}$ electric octupole transition in a single ion of $^{171}Yb^+$ with 10^{-15} fractional uncertainty

S A King[1,2,3], R M Godun[1], S A Webster[1], H S Margolis[1], L A M Johnson[1], K Szymaniec[1], P E G Baird[2] and P Gill[1,2]
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Selected for a Viewpoint in *Physics*
PRL 113, 210802 (2014) PHYSICAL REVIEW LETTERS week ending 21 NOVEMBER 2014

Improved Limit on a Temporal Variation of m_p/m_e from Comparisons of Yb^+ and Cs Atomic Clocks

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(Received 16 July 2014; published 17 November 2014)

Accurate measurements of different transition frequencies between atomic levels of the electronic and hyperfine structure over time are used to investigate temporal variations of the fine structure constant α and the proton-to-electron mass ratio μ. We measure the frequency of the $^2S_{1/2} \to {}^2F_{7/2}$ electric octupole ($E3$) transition in $^{171}Yb^+$ against two caesium fountain clocks as $f(E3) = 642\,121\,496\,772\,645.36$ Hz with an improved fractional uncertainty of 3.9×10^{-16}. This transition frequency shows a strong sensitivity to changes of α. Together with a number of previous and recent measurements of the $^2S_{1/2} \to {}^2D_{3/2}$ electric quadrupole transition in $^{171}Yb^+$ and with data from other elements, a least-squares analysis yields $(1/\alpha)(d\alpha/dt) = -0.20(20) \times 10^{-16}$/yr and $(1/\mu)(d\mu/dt) = -0.5(1.6) \times 10^{-16}$/yr, confirming a previous limit on $d\alpha/dt$ and providing the most stringent limit on $d\mu/dt$ from laboratory experiments.

Fundamental and New Physics Searches

- Parity violation: nuclear electroweak neutral charge
- Search for electron electric-dipole moment: SUSY breaker
- Search for time variations of fundamental constants
- Measurement of the electron anomalous g-factor: validity of QED
- Tests of CPT: Spectroscopy of anti-matter
- Rydberg constant and Proton charge radius: Spectroscopy in Hydrogen or Muonic Hydrogen
- Dark matter searches
- Axion searches
- Search for violation of Lorenz invariance