PROBING NEW PHYSICS WITH ATOMIC TRANSITIONS

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Workshop on New Physics at the Low-energy Precision Frontier
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Outline

• **Intro** | Light NP at the precision frontier

• Isotope shift and King linearity violation (KLV)
• Limitations of the original KLV method
• Generalized King plots

• **Summary/Outlook**
**Light New Physics**

- The SM *does not* completely describe Nature \( m_\nu, \eta_B, \Omega_{DM} \)
- The Higgs sector points to NP scales \( \sim \text{TeV} \) or (much) heavier, but *no experimental hint of it so far* (LHC, direct detection..)

- The motivation for light NP (below \( \sim \text{GeV} \)) is plenty:
  - Alternative solutions to the hierarchy problem? (like relaxion)
  - Axions
  - Light mediators for dark matter
  - ...

- If such NP couples significantly to *electrons/nucleons*, the *atom* is the natural place to search for it.
The Precision Atomic Frontier

• AMO techniques allow precision measurements of atomic frequency with ultra high precision

  • **Hydrogen lines:** \( \nu_{1S-2S} = 2\ 466\ 061\ 413\ 187\ 035(10)\ \text{Hz} \)
    \( u_\nu = 4.2 \times 10^{-15} \)  
    
    Parthey et al. (2011)

Combining with precise theory calculation, it allows to fix « fundamental » parameters like **Rydberg cste**

\[
R_\infty \equiv \alpha^2 m_e c / 2h = 3.289\ 841\ 960\ 355(19) \times 10^{15} \ \text{Hz}
\]

Mohr et al. [CODATA]
• AMO techniques allow precision measurements of atomic frequency with ultra high precision

• Optical clock transitions

$$\nu_{467\text{nm}} = 642\,121\,496\,772\,645.36(25) \text{ Hz}$$

$$u_{\nu} = 3.9 \times 10^{-16} \quad \text{Huntermann et al. (2014)}$$

clock \textbf{stability} in neutral Yb demonstrated at the $10^{-18}$ level \text{Huntermann et al. (2016)}
Probing New Physics in Atoms

• In principle these measurements are sensitive to tiny NP effects
• To probe them however requires equally fine theoretical control over standard EM contributions with either
  • **Precision calculation** of transition frequencies.
    Only available for simple atoms like H and He

  • **Combine transitions** into observables with reduced sensitivity to contributions with large theoretical uncertainty:
    → King linearity of isotope shifts

  Karshenboim et al. (2010)
Pachucki et al. (2017)
Probing new physics with King linearity
• Spectral lines are well measured, but theory is no match

• Frequencies are (mostly) set by the charge of the nucleus $Z$

• Hence dominant (uncalculable) contributions from EM cancel out in frequency differences between isotopes: $(\nu - \nu')/\nu \sim 10^{-6}$

• Spin-independent NP couples to the entire nucleus $A$ and thus is only mildly suppressed in isotope differences: $(A - A')/A \sim 0.1$

• Yet isotope shifts are also challenging to calculate…
Isotope Shift Theory

• Isotopes (same $Z$, different $A$) have the same atomic lines up to small nuclear effects:

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

• **Mass shift** (MS) due to change in the nuclear mass $\mu_{AA'} \equiv m_A^{-1} - m_{A'}^{-1}$ modifying the global atomic center-of-mass (normal MS) and the electron-electron repulsion terms (specific MS)

• **Field shift** (FS) due to change in the nuclear charge distribution $\sim$ size, which typically dominates for heavy elements
King Linearity

- Combining 2 transitions to eliminate the poorly known $\delta\langle r^2 \rangle$ yields a linear relation among modified IS, $m\nu_i^{AA'} \equiv \nu_i^{AA'}/\mu_{AA'}$:

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

$$\equiv F_2/F_1 \quad \equiv K_2 - F_{21}K_1$$

- Linearity follows from having only 2 independent nuclear parameters

- Values of $K, F, \delta\langle r^2 \rangle$ are not needed, only masses must be precisely known
Nonlinearities from New Physics

- New Physics comes with its own independent nuclear/electronic parameters:

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

thus inducing nonlinearities (NL):

\[
m\nu_2^{AA'} = F_{21} m\nu_1^{AA'} + K_{21} + \alpha_{NP} X_{21} h_{AA'}
\]

with invariant measure: \( \vec{m}\mu = (1, 1, 1) \)

\[
NL = \det(\vec{m}\nu_1, \vec{m}\nu_2, \vec{m}\mu)
\]
Experimental Status

• Most accurate test of linearity to date is based on Ca\(^+\) IS data
  
  - Gebert et al. (2015)
  - Knollmann et al. (2019)

• It uses broad dipole transitions and is not very precise ~100kHz

• New tests (with Hz-10mHz accuracy) are in reach using Yb, Sr atoms

Significantly improved accuracy using entangled states
  
  Manovitz et al. 1906.05770 [atom–ph]
Bounding NP

• Solving King equation for the NP coupling gives:

$$\alpha_{\text{NP}} = \frac{\det(m\nu_1, m\nu_2, m\mu)}{\det[X_1 m\nu_2 - X_2 m\nu_1, \vec{h}, m\mu]}$$

$$= \epsilon_{ij} F_i X_j \times \det(m\delta\langle r^2 \rangle, \vec{h}, m\mu)$$

Electronic alignment → strong suppression for large $m_{\text{NP}}: X_i \propto F_i$

Nuclear alignment → suppression of $\delta m_A^{\text{max}}/m_A \sim \mathcal{O}(10)$ for NP coupling $\propto A$

NL in data

NL predicted by theory
New Physics Benchmark

- KLV is sensitive to new spin-independent interactions between electron and neutron (e-proton and e-e cancels out in the IS)

- For illustration we take a new boson \( \phi \) with \( y_e \) and \( y_n \) couplings

- \( \phi \)-exchange in the atom gives rise to a new force described by the non-relativistic Yukawa potential:

\[
V_\phi(r) = \frac{(-1)^{s+1}}{4\pi} y_e y_n (A - Z) \frac{\exp(-m_\phi r)}{r}
\]
• NP bound from linear \( \text{Ca}^+ \) data is not competitive with other laboratory constraints from He, \((g-2)_e\) or neutron scattering.

• Linear King plots in Yb or Sr transitions with state-of-the-art accuracy (\(~\text{Hz}\)) would provide strongest bound in the 100keV-20MeV range.
Going beyond King linearity
Limitations

• The KL bound is set only by the precision of IS measurements

• There are two important limitations to this method

  • Nuclear mass uncertainty

Linearity is defined in terms of modified IS

\[ m\nu_i = \nu_i / \mu \] which requires precise knowledge of nuclear masses

\[ u_{m\nu}^2 = u_\nu^2 + \left( \frac{m_A}{m_A - m_{A'}} \right)^2 u_m^2 \]

\( \sim 100 \)

For Yb \( \frac{m}{\delta m} u_m \sim \mathcal{O}(10^{-8}) \) while \( u_\nu \sim \mathcal{O}(10^{-9}) \) for Hz accuracy
Limitations

• The KL bound is set only by the precision of IS measurements

• There are two important limitations to this method:
  
  • Nonlinearities from nuclear effects

Linearity is broken by higher-order corrections

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

isotope dependent

For Yb case, quadratic FS is dominant with NL~10kHz
‘Massless’ King Linearity

- An alternative to better mass determination is to generalize the King relation by adding an extra transition to absorb the mass
- In the absence of NP there is a linear relation among $\nu_{1,2,3}$ that can be tested with spectroscopy only

$$\nu_{3AA'} = f_{3\alpha} \nu_{\alpha AA'}$$

with

$$X_{3\alpha} = f_{3\alpha}(K_{\alpha}) \gamma_{AA'}$$

$\alpha = 1, 2$

- As before NP breaks this relation
- The NP coupling can be extracted with 3 isotope pairs:

$$\alpha_{NP} = \frac{\det(\tilde{\nu}_1, \tilde{\nu}_2, \tilde{\nu}_3)}{\frac{1}{2} \epsilon_{ijk} \det(\tilde{\nu}_i, \tilde{\nu}_j, X_k \tilde{\gamma})} = \det(F, K, X) \times \det(\tilde{\gamma}^2, \tilde{\mu}, \tilde{\gamma})$$
Massless linearity in Yb

- Using known narrow transitions, assuming 10mHz accuracy:
  1) \((4f^{14}\ 6s\)^{2S_{1/2}} \rightarrow (4f^{14}\ 5d)^{2D_{5/2}}\)
  2) \((4f^{14}\ 6s\)^{2S_{1/2}} \rightarrow (4f^{13}\ 6s^2)^{2F_{7/2}}\)
  3) \((4f^{14}\ 6s^2)^{1S_{0}} \rightarrow (4f^{14}\ 6s6p)^{3P_{0}}\)

- Sensitivity to NP is recovered w/out precise mass determination
Overcoming Nonlinearities

• NP can still be probed *without* theory calculation of NLs
• The idea is to *use extra transitions* (and isotopes) to absorb the nuclear parameters sourcing the nonlinearities

• Consider one *higher-order correction* dominates (like $FS^2$):
  (generalization to any number of independent nuclear parameters is straightforward)

\[ \nu_i^{AA'} = K_i \mu_{AA'} + F_i \delta \langle r^2 \rangle_{AA'} + G_i \lambda_{AA'} \]

• Modified IS of 3 transitions are linearly related:

\[ m\nu_3^{AA'} = f_{3\alpha} m\nu_{\alpha}^{AA'} + [K_3 - f_{3\alpha} K_{\alpha}] \]

\[ \alpha = 1, 2 \]
Generalized King Plots

• mLS data for 4 isotope pairs are on a plane

→ King coplanarity

• Again NP breaks this prediction

\[ m\nu_3^{AA'} = f_{3\alpha} m\nu_\alpha^{AA'} + [K_3 - f_{3\alpha} K_\alpha] \]
\[ + \alpha_{NP} [X_3 - f_{3\alpha} X_\alpha] h_{AA'} \]

• Invariant measure of breaking is the volume of the pyramid

\[ NL_3 = \det(\vec{m}\nu_1, \vec{m}\nu_2, \vec{m}\nu_3, \vec{m}\mu) \]
NP coupling

• The NP coupling can be extracted using only spectroscopy, without knowledge of $K$, $F$, $\delta\langle r^2 \rangle$ and $G$, $\lambda$:

$$\alpha_{NP} = \frac{\text{det}(m\nu_1, m\nu_2, m\nu_3, m\mu)}{\frac{1}{2} \epsilon_{ijk} \text{det}(m\nu_i, m\nu_j, X_k \vec{h}, m\mu)}$$

$$= \epsilon_{ijk} F_i G_j X_k \times \text{det}(m\delta\langle r^2 \rangle, m\lambda, \vec{h}, m\mu)$$

Electronic alignment

Nuclear alignment

volume in data

volume predicted by theory
Generalized King in Yb

• Using known narrow transitions, $A = 168, 170, 172, 174, 176$ isotopes, assuming 10mHz accuracy:

1) $(4f^{14} 6s)^2S_{1/2} \rightarrow (4f^{14} 5d)^2D_{5/2}$
2) $(4f^{14} 6s)^2S_{1/2} \rightarrow (4f^{13} 6s^2)^2F_{7/2}$
3) $(4f^{14} 6s^2)^1S_0 \rightarrow (4f^{14} 6s6p)^3P_0$

• Sensitivity to NP is recovered without calculating NLs
Summary
Take Home

• Atomic clock transitions are measured with ultra high precision
• Theory calculations are very challenging, with only rough results
• High sensitivity to new forces below ~GeV can still be achieved by combining different measurements (isotope shifts)
• The simplest probe of NP looks for violation of linearity between IS of 2 transitions drawn on a so-called King plot.
• This method is (will soon be) limited by mass uncertainties and/or nonlinearities from nuclear physics
• We propose generalizations entirely based on spectroscopy