Hyperfine anomaly in cesium:

From exotic atoms to improved searches for new physics

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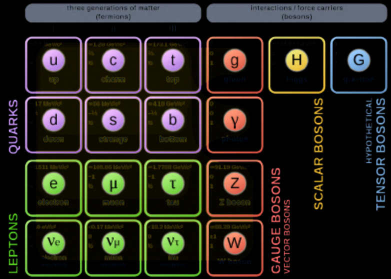
Sanamyan, BMR, Ginges, Phys. Rev. Lett. **130** 053001 (2023)

Roberts, Fairhall, Ginges, Phys. Rev. A. **107** 052812 (2023)
BMR, Ranclaud, Ginges, Phys. Rev. A. **105** 052802 (2022)
BMR, Ginges, Phys. Rev. A **104** 022823 (2021)
BMR, Ginges, Phys. Rev. Lett. **125** 063002 (2020)

DAMOP
7 June 2023

Current theory of the Universe

- **Standard Model + General Relativity**



Extraordinarily successful, however, several deep problems:

Matter–Anti-matter asymmetry

- The Big Bang should have created equal amounts of matter and antimatter.
- So why is there far more matter than antimatter in the universe?

Dark matter and dark energy

- Make up most ($\sim 95\%$) of the Universe – unexplained

Search for physics *beyond* the Standard Model

High-energy searches

- Other theories make *slightly* different predictions from SM+GR
- Dedicated experiment to test specific theories
- Targeted and precise: but narrow in scope
- Example: Large Hadron collider, CERN
- So far: no luck

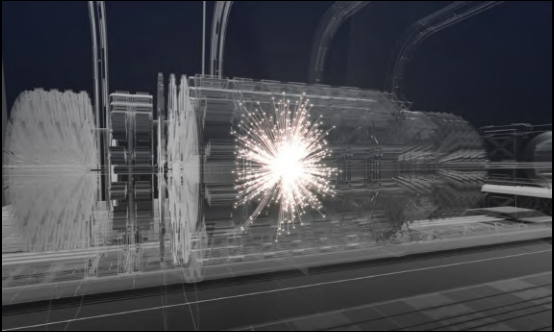


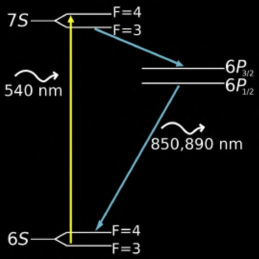
Image: CERN

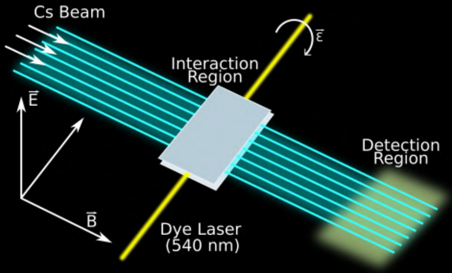
Low-energy searches

- Rely on precision
- Complementary

Low-energy atomic tests: parity violation

- Weak interaction: Z^0-boson
- Parity-forbidden E1 transition becomes allowed
- Tiny amplitude: $\propto Q_w$: weak charge
- Test of electroweak theory at low energy





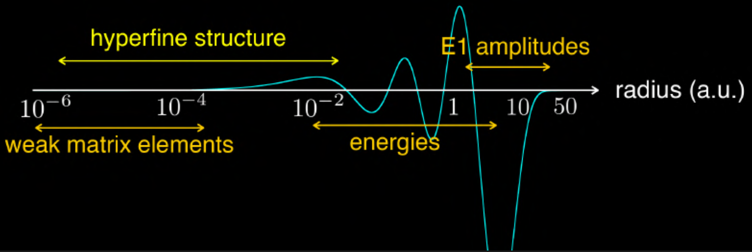
- Cs experiment: 0.35%

Wood, Bennett, Cho, Masterson, J. Roberts, Tanner, Wieman, Science **275**, 1759 (1997).

Accuracy across all scales

$$E_{\rm APV} = \boxed{Q_W} \frac{\boxed{\langle A|\boldsymbol{d}|n\rangle} \; \boxed{\langle n|h_{APV}|B\rangle}}{E_B - E_n} + c.c.$$

- Required experiment and theory
- Extract Q_W: nuclear weak charge



Highly accurate all-orders methods

- Require theory accuracy to rival experiment: Aim 0.1%
- Requires *all orders* methods

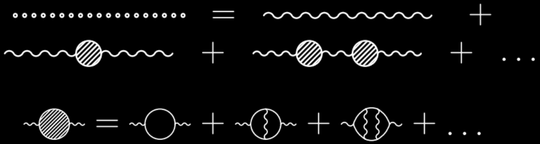
Coupled-cluster

- All-order in Coulomb
- finite in excitations

$$\Psi \sim (1 + \rho_{ma} a^\dagger_m a_a + \rho_{mnab} a^\dagger_m a^\dagger_n a_a a_b + \dots)\psi_0$$

Alternative: PTSCI

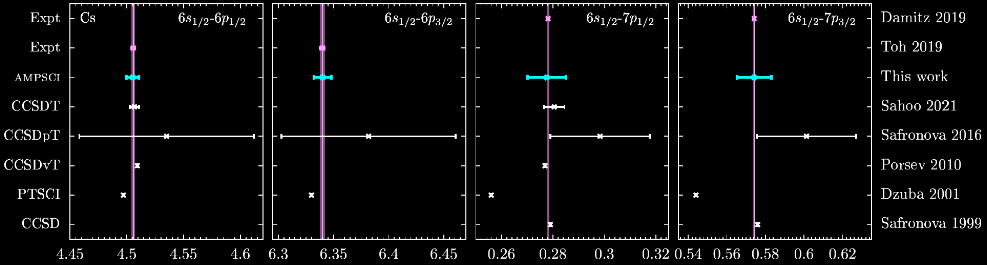
- Feynman Green's function approach
- (Dzuba, Flambaum, Sushkov method)
- All-orders in screening (+more)
- AMPSCI implementation: public soon



- Ensure accurate and reliable: How to test methods?

Electric dipole – large r test

- 50 transitions across K, Rb, Cs, Fr, Ca^+, Sr^+, Ba^+, Ra^+
- Theory at 0.1% for many cases
- Robust method for determining accuracy



- BMR, C. J. Fairhall, J. S. M. Ginges, Phys. Rev. A **107**, 052812 (2023).
[Poster: Thursday session!]

Hyperfine – low r test

- Hyperfine splitting: nuclear magnetic moment
- Hyperfine constant, A
- c.f. experiment: test low-r wavefunction...

$$A = \left(\frac{4\alpha}{3m_p I \mu_N}\right) \mu \int \mathrm{d}r\, f(r) g(r) \frac{F(r)}{r^2}$$

Problem:

- Depends on nuclear magnetisation distribution
- $F(r) = 1$ for pointlike nucleus

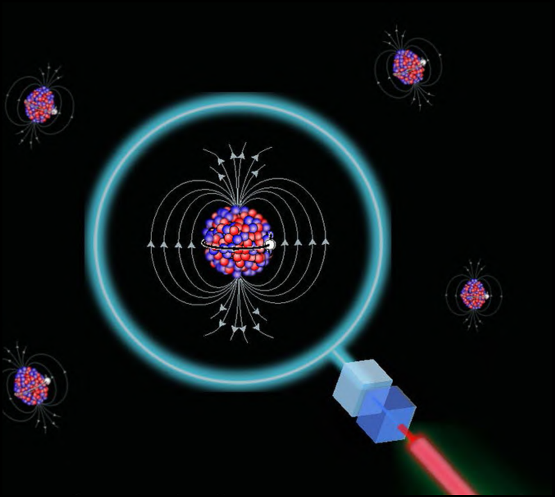
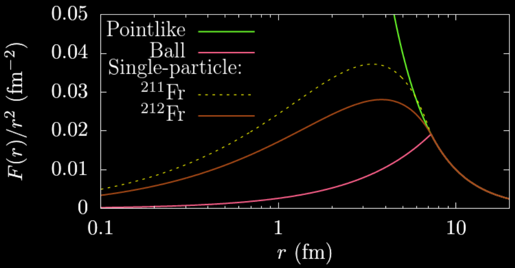


Image: Adam Vernon, news.mit.edu

Nuclear structure: Bohr-Weisskopf effect + hyperfine anomaly

Nuclear Magnetisation Distribution

- Bohr-Weisskopf
- Uniform ball: overestimates by ∼2x
- Simple "single-particle" model: better
- 0.5 – 5% shift in hyperfine constant A!
- Huge for atomic theory 0.1 – 0.5%



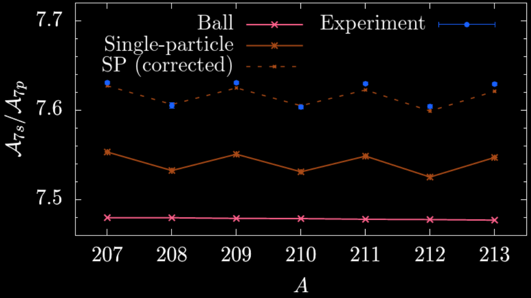
Nuclear Charge Distribution

- Breit-Rosenthall: Well understood

Gives hyperfine anomaly

- Non-linear differences across isotopes

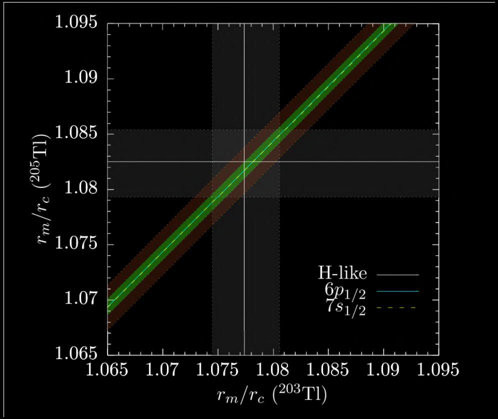
Improved nuclear modelling: Fr μ



- Recover odd-even staggering
  - Great test of *relative* Bohr-Weisskopf effect
- Test in H-like systems: Bi, Pb
  - Good test of *absolute* BW effect (but: different nucleus)
- Extract μ(Fr) with 0.5% accuracy
  - 2% shift compared to old values!
  - Huge c.f. atomic theory accuracy

- BMR and J. S. M. Ginges, Phys. Rev. Lett. **125**, 063002 (2020).

Extract nuclear magnetic radius for Tl



- H-like hyperfine constants A
  - Individual r_m, low accuracy
- Neutral hyperfine anomaly
  - Ratio of r_m^1/r_m^2 high accuracy
- Combine: very precise magnetic radius

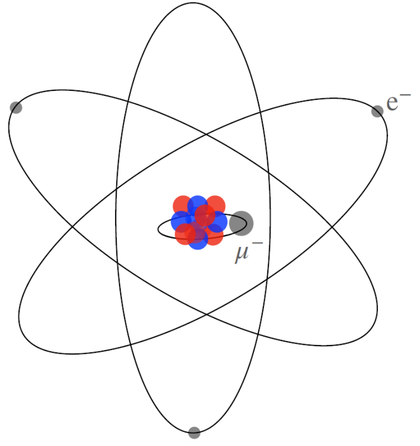
- BMR, Ranclaud, Ginges, Phys. Rev. A **105**, 052802 (2022).

What about Cs? muonic atoms!

Muonic atoms

- $m_\mu \approx 200\, m_e$: times heavier
- Wavefunction *inside* nucleus
- Bohr-Weisskopf effect: huge
- Exceptionally sensitive to finite nuclear effects
- Extract directly from historitcal data
- Atomic theory: one-particle system only

$$A^\mu_{\rm Expt} = A^\mu_0 (1 + \epsilon_{\rm BW}) + A^\mu_{\rm QED}$$



- W. Y. Lee, ..., C. S. Wu, *et al.*, Phys. Rev. Lett. **23**, 648 (1969)

Remove nuclear uncertainty

PHYSICAL REVIEW LETTERS **130,** 053001 (2023)

Empirical Determination of the Bohr-Weisskopf Effect in Cesium and Improved Tests of Precision Atomic Theory in Searches for New Physics

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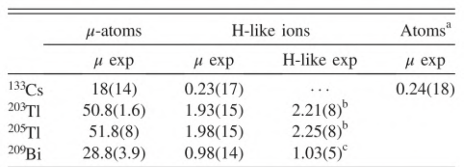

	μ-atoms	H-like ions		Atoms[a]
	μ exp	μ exp	H-like exp	μ exp
^{133}Cs	18(14)	0.23(17)	⋯	0.24(18)
^{203}Tl	50.8(1.6)	1.93(15)	2.21(8)[b]	
^{205}Tl	51.8(8)	1.98(15)	2.25(8)[b]	
^{209}Bi	28.8(3.9)	0.98(14)	1.03(5)[c]	

- Screening effect: from H-like to neutral [BMR, Ranclaud, Ginges, PRA **105**, 052802 (2022)]
- Shifts previous theoretical A for Cs by 0.5%
- Allows test at atomic theory at 0.2%
- Crucial for Atomic Parity Violation

Upcoming postdoc position – UQ, Brisbane

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