

Atomic Parity Violation as a Light Z' Boson Probe

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What is Z'? Coupling Structure & Motivation

The effective coupling behind the Yukawa potential, and where it could come from

A Z' boson is a feebly-coupled neutral gauge boson, motivated for instance as a dark-matter mediator. It contributes to atomic parity violation through the same neutral-current channel as the SM Z boson.

Effective Coupling

$$\mathcal{L}_{\text{int}} = Z'_\mu \sum_{f=e,p,n} \bar{f} \gamma^\mu (g_f^V + \gamma_5 g_f^A) f$$

- Generates the electron–nucleon Yukawa potential:

$$V_{12}(r) = \frac{g_1^A g_2^V}{4\pi} \frac{e^{-m_{Z'} r}}{r} \gamma_5,$$

Motivating Scenarios

- Models with a **new U(1) gauge symmetry**
- Kinetic-mixing** dark photon — explains how dark matter could interact with ordinary matter
- Secluded/dark-sector** mediator — explains dark matter abundance in the early universe

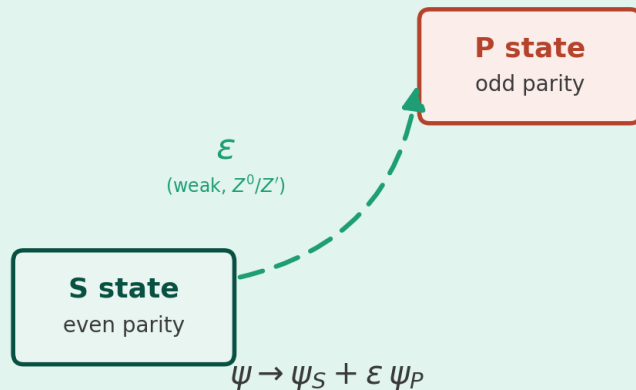
How Does Atomic Parity Violation Occur?

Pure electromagnetic eigenstates have definite parity. A parity-violating interaction forces them to mix, and a normally forbidden transition becomes weakly allowed.

Why It's Forbidden

- **Laporte's rule:** two states of the same parity (e.g. two s-states) connect by M1, but not by E1 — forbidden exactly
- **The weak neutral current** (SM Z, or a new Z') mixes in a tiny opposite-parity admixture
- This gives the transition a small, nonzero E1 amplitude A_{PV}

State Mixing



Atomic Parity Violation and a Light Z' Boson

Do we always need a bigger collider, or can answers be found on a laboratory bench?

If the Z' boson is light, it must have an extremely tiny coupling constant or else we would have found it already. The barrier to finding it isn't *energy*, it is *precision*.

Collider searches

- For $m_{Z'} \gtrsim \text{GeV}$: accessible by colliders, limited by collision energy
- For sub-eV to keV $m_{Z'}$: production rates and missing-energy signals become small compared to background

Atomic PNC

- Sensitive to the boson's Compton wavelength directly, no production required
- Z' enters as a Yukawa potential between electron and nucleus, mixing a small E1 amplitude into an otherwise forbidden transition

The two approaches probe different mass ranges of the same hypothetical particle; this talk concerns the low-mass end.

Why Light Atoms?

The Z'/SM ratio grows faster than $1/Z^2$ as the nuclear charge decreases

Heavy atoms (Cs, Fr, Ra⁺)

- Large PNC amplitudes
- Strong relativistic enhancement Z^2R for SM ($R \sim 10$)
- **Z'/SM ratio is suppressed**
- QED, Breit, neutron-skin corrections scale as $Z^2\alpha^2$ — limits interpretation



Light atoms (H, Rb, Sr⁺)

- Smaller absolute SM PNC
- R is smaller in Z^2R for light atoms
- **Z'/SM ratio grows faster than $1/Z^2$**
- Reduced QED, Breit, neutron-skin corrections — cleaner theory-experiment comparison

Going from Cs to Rb or Sr⁺ changes two things: a more favourable Z'/SM ratio while reducing several important Z -dependent corrections.

Three Systems

Each gives a different combination of theoretical and experimental advantages

H

Hydrogen

Z = 1

- Essentially exact analytic theory — low theoretical uncertainty
- Clean Z' -coupling extraction
- $2s-2p$, $3s-3p$, $4s-4p$ transitions
- The PNC amplitude itself is small

Rb

Rubidium

Z = 37

- Same electronic structure as Cs, fewer core electrons
- $5s-6s$ and $5s-4d_{3/2}$ transitions
- Reduced QED/Breit corrections relative to Cs
- Many-body calculation, benchmarked methods

Sr⁺

Strontium ion

Z = 38

- 4 stable isotopes (^{84}Sr , ^{86}Sr , ^{87}Sr , ^{88}Sr)
- Isotope-chain method cancels atomic-theory error
- Separate proton & neutron weak-charge extraction
- ^{87}Sr has nuclear spin — NSD access

Computational Method

Standard many-body methods, benchmarked against Cs, applied to Rb and Sr⁺

Relativistic Hartree-Fock → All-order correlation potential Σ → RPA (weak + E1 fields) → PNC amplitude

0.5%

benchmark accuracy in Cs
(Dzuba, Flambaum, Sushkov 1989–
present)

~1%

accuracy for Rb/Sr⁺
5s–6s PNC amplitudes

<5 %

accuracy for Rb/Sr⁺
5s–4d_{3/2} PNC amplitudes

This is the same many-body framework that achieves 0.5% theoretical accuracy in Cs. The best experimental accuracy 0.35% is from measurement of the 6s–7s PNC amplitude in Cs by Wood et al. (1997)

Calculated NSI PNC Amplitudes in Rb and Sr⁺

5s–6s and 5s–4d_{3/2} transitions in ⁸⁵Rb, ⁸⁷Rb and ⁸⁷Sr⁺

Calculated NSI Amplitudes in Rb and Sr⁺ (10⁻¹² iea₀)



The 5s–4d_{3/2} amplitude is about three times larger than 5s–6s.

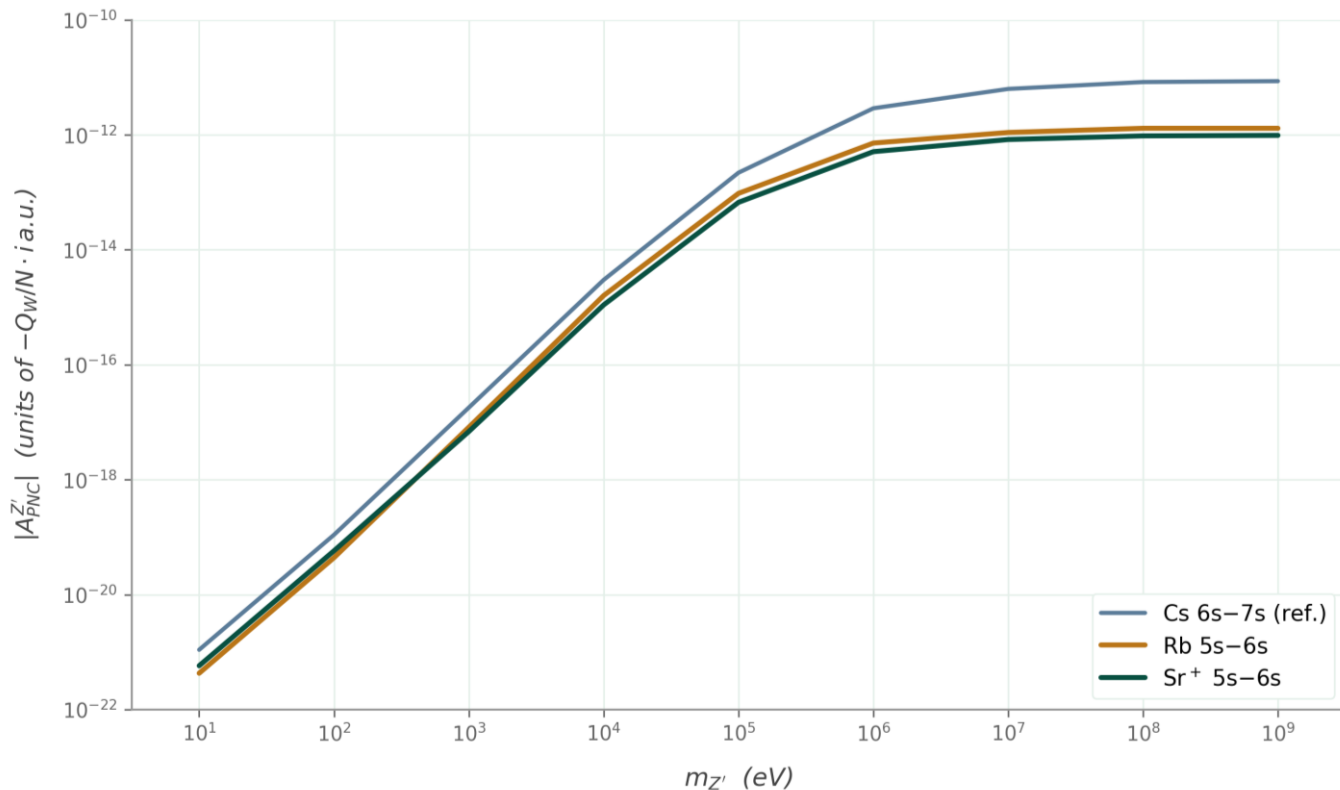
This transition is dominated by the n=5p_{1/2} intermediate state, so precise experimental data for the $\langle 5p_{1/2} | \mathbf{D} | 5d_{3/2} \rangle$ E1 transition matrix element can be used to improve the accuracy of the theoretical results.

$$E_{\text{PNC}}^{a \rightarrow b} = \sum_n \left[\frac{\langle a | \hat{W} | n \rangle \langle n | \mathbf{D} | b \rangle}{E_a - E_n} + \frac{\langle a | \mathbf{D} | n \rangle \langle n | \hat{W} | b \rangle}{E_b - E_n} \right]$$

Z'-Induced Parity Violation

Z'-Induced PNC amplitudes produced by a Yukawa potential:

$$V_{12}(r) = \frac{g_1^A g_2^V}{4\pi} \frac{e^{-m_{Z'} r}}{r} \gamma_5,$$



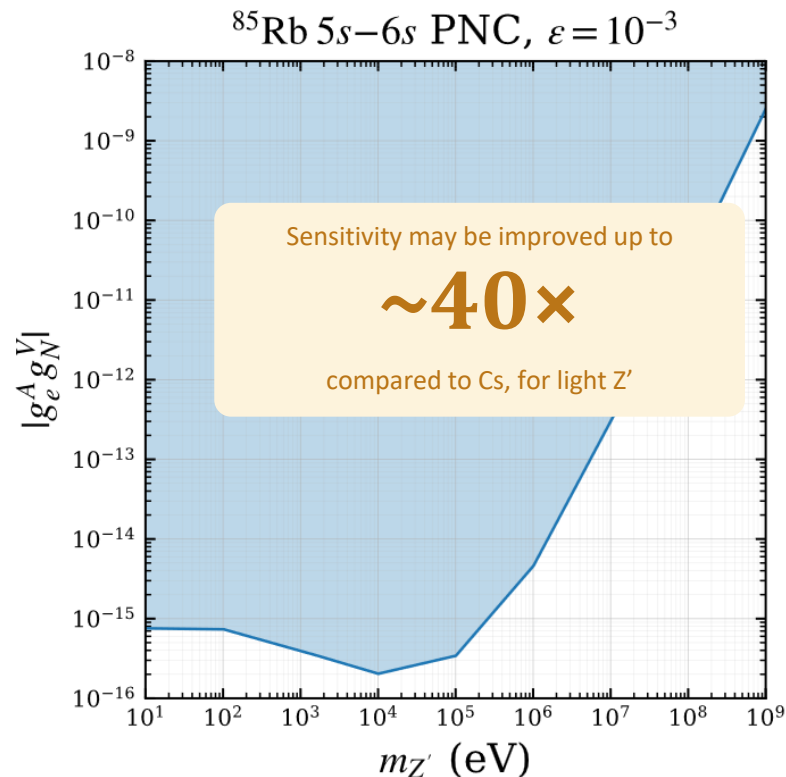
Projected Constraints on Z' Couplings

Assuming $\epsilon = 0.1\%$ accuracy. Corresponding to a 10x increase in the experimental and theoretical accuracy relative to Cs.

System / Transition	$ g_e^A g_N^V $ light Z'
$^{133}\text{Cs } 6s-7s \text{ (ref.)}$	3.1×10^{-14}
$^{85}\text{Rb } 5s-6s$	7.5×10^{-16}
$^{85}\text{Rb } 5s-4d_{3/2}$	9.2×10^{-16}
$^{87}\text{Sr}^+ 5s-6s$	4.1×10^{-16}
$^{87}\text{Sr}^+ 5s-4d_{3/2}$	1.9×10^{-16}

Low Mass Limits:

$$g_e^A g_N^V = \frac{G_F}{2\sqrt{2}} \frac{N}{A} \frac{A_{\text{PNC}}}{A_{\text{PNC}}^{Z'}} m_{Z'}^2 \epsilon, \quad m_{Z'} \ll 1/R_{\text{atom}}.$$



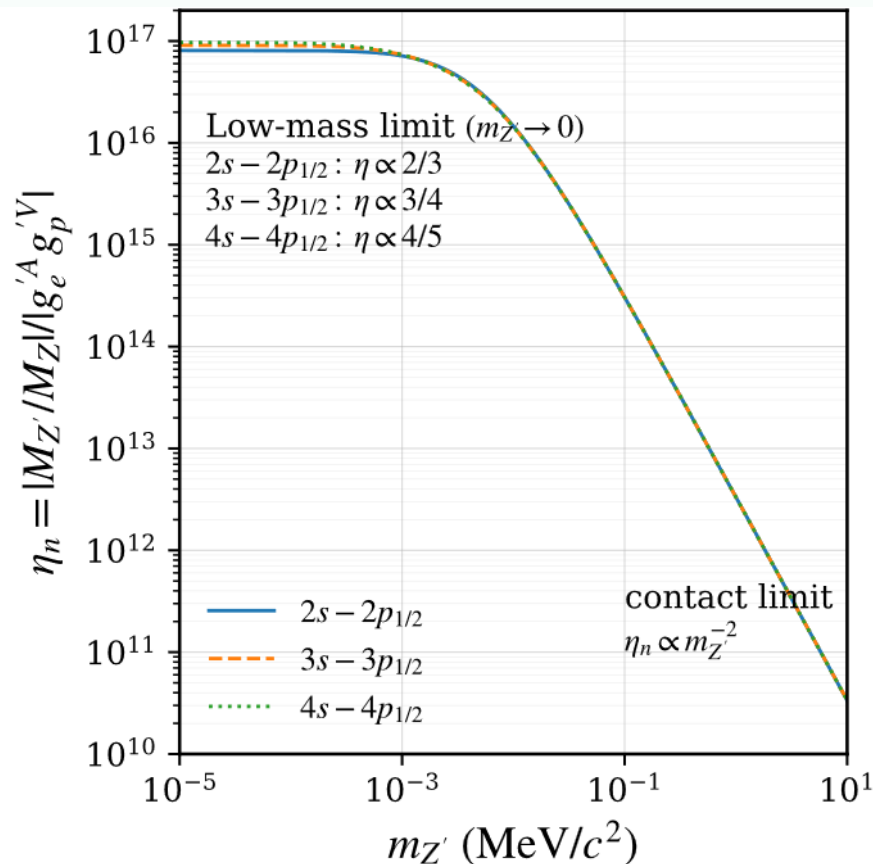
Hydrogen: Analytic Matrix Elements

- exact theory $\rightarrow$ clean interpretation of experimental results
- analytic dependence on $m_{Z'}$

NSI matrix element ratios:

$$\eta_n = |\mathcal{M}_n^{Z'} / \mathcal{M}_n^Z| / |g_{eA}' g_{pV}'|$$

$$\begin{aligned} \eta_2^{\text{point}}(\mu) &= \frac{2\sqrt{2}c}{3G_F Q_{Wp}} \frac{3\mu + 1}{(\mu + 1)^3}, & \text{where } \mu &= m_{Z'} c / (\alpha m_e) \\ \eta_3^{\text{point}}(\mu) &= \frac{6\sqrt{2}c}{G_F Q_{Wp}} \frac{81\mu^3 + 54\mu^2 + 30\mu + 4}{(3\mu + 2)^5}, \\ \eta_4^{\text{point}}(\mu) &= \frac{4\sqrt{2}c}{15G_F Q_{Wp}} \frac{960\mu^5 + 800\mu^4 + 640\mu^3 + 192\mu^2 + 42\mu + 3}{(2\mu + 1)^7}. \end{aligned}$$



Deuterium: a Special Case for NSD PNC

The relative sensitivity to the Z' spin-dependent amplitude is enhanced.

In the Standard Model, $\kappa_n \approx -\kappa_p$, so the deuterium NSD coupling $\kappa_d \approx 0$.

The SM NSD PNC amplitude in deuterium nearly vanishes.

This gives deuterium a large relative enhancement to the NSD Z' contribution and new physics.

NSD matrix element ratios:

$$\eta_2^{\text{SD}}(\mu) = \frac{\sqrt{2}c}{9G_F\kappa_p} \frac{9\mu^2 + 4\mu + 1}{(\mu + 1)^4},$$

$$\eta_3^{\text{SD}}(\mu) = \frac{\sqrt{2}c}{G_F\kappa_p} \frac{729\mu^4 + 324\mu^3 + 342\mu^2 + 72\mu + 8}{(3\mu + 2)^6},$$

$$\eta_4^{\text{SD}}(\mu) = \frac{2\sqrt{2}c}{45G_F\kappa_p} \frac{5760\mu^6 + 2560\mu^5 + 4000\mu^4 + 1024\mu^3 + 396\mu^2 + 48\mu + 3}{(2\mu + 1)^8}.$$

NSI in deuterium:

Deuterium weak charge $Q_W \approx 0.91$ is dominated by the neutron (its coefficient is $\sim 14\times$ the proton's) — a clean, simple system for probing the neutron weak charge specifically.

Summary

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1

Light atoms are disproportionately sensitive to a low-mass Z'

The Z'/SM ratio grows faster than $1/Z^2$ as the nuclear charge decreases, since the relativistic enhancement that boosts the SM signal in heavy atoms does not carry over to the Yukawa regime.

2

Sr^+ and Rb improve projected Z' constraints over Cs by up to 40×

Sr^+ additionally offers an isotope chain with one spin-bearing isotope, giving access to both NSI and NSD amplitudes and to the proton and neutron weak charges separately.

3

Rubidium shares Cs's electronic structure with smaller theoretical corrections

The lower nuclear charge reduces QED, Breit, and neutron-skin uncertainties.

4

Hydrogen provides an exact analytic benchmark

Closed-form matrix elements exist for arbitrary Z' mass, useful as a cross-check on the many-body Rb and Sr^+ calculations even without a direct measurement.

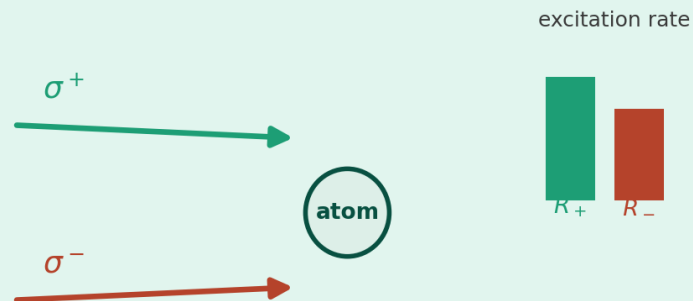
Thank you.

How to Measure Atomic Parity Violation?

How it's Measured

- Apply a Stark field E , inducing an ordinary E1 amplitude A_{Stark} in the same transition
- $W_{\pm} = |\pm A_{Stark} + A_{PV}|^2 \approx A_{Stark}^2 \pm 2A_{Stark}A_{PV}$
- $Asymmetry = (W^+ - W^-)/(W^+ + W^-) \sim A_{PV}/A_{Stark}$
- **Stark-interference technique** (Bouchiat & Bouchiat)

Observing the Effect



$$Asymmetry = \frac{R_+ - R_-}{R_+ + R_-} \propto Q_W$$