Search for BSM Boson via Precision Atomic Studies

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Precision isotope shift (IS) spectroscopy is a sensitive probe of physics beyond the Standard Model (BSM), where nonlinearities (NLs) in King's plots can signal new interactions. We present a relativistic many-body analysis of higher-order NL effects in low-lying transitions of Ca^+, focusing on constraints on a hypothetical electron–neutron interaction mediated by a BSM boson. The corresponding potential is (in atomic units) [1]

$$V_{PS} = (-1)^{s+1}\alpha_{NP}\, c\, \frac{e^{-m_\phi r/c}}{r}, \tag{1}$$

with $\alpha_{NP} = (-1)^{s+1}\frac{y_e y_n}{4\pi c}$.

In standard IS theory, an atomic transition is dominated by the mass shift (MS) and field shift (FS), which factorize into isotope- and transition-dependent parts, leading to a linear relation between differential isotope shifts of two transitions known as the King's plot relation. Deviations from this linearity can arise from both BSM boson exchange and SM effects; therefore, unambiguous identification of BSM signals requires precise control of all SM-induced NLs. A generalized form of the King's plot equation that incorporates nonlinear contributions is given by [4, 5]

$$\begin{aligned}\delta\nu_a^{AA'} \;\simeq\; & \left[K_{ab}\mu^{AA'} + F_{ab}\delta\nu_b^{AA'}\right] + G^{(4)}_{ab}\delta\langle r^4\rangle_{AA'} + \left(G^{(2)}_{ab} + F^{(2)}_{ab}\right)\left(\delta\langle r^2\rangle^2\right)^{AA'} \\ & + K^{(2)}_{ab}\tilde{\mu}^{AA'} + (A - A')D_{ab}\alpha_{NP}.\end{aligned} \tag{2}$$

Here, $G^{(2)}$, $G^{(4)}$, $F^{(2)}$, and $K^{(2)}$ characterize higher-order SM contributions to the NL, while D represents the BSM contribution. To assess their interplay, we determine bounds on α_{NP} in two cases: Case I, neglecting SM-induced NLs, and Case II, including them explicitly. We find that accounting for SM NLs significantly relaxes the constraint on the electron–neutron coupling, from $\alpha_{NP} < 7.9 \times 10^{-11}$ in Case I to $\alpha_{NP} < 5.9 \times 10^{-10}$ in Case II, underscoring the importance of properly incorporating SM nonlinearities in precision isotope-shift analyses.

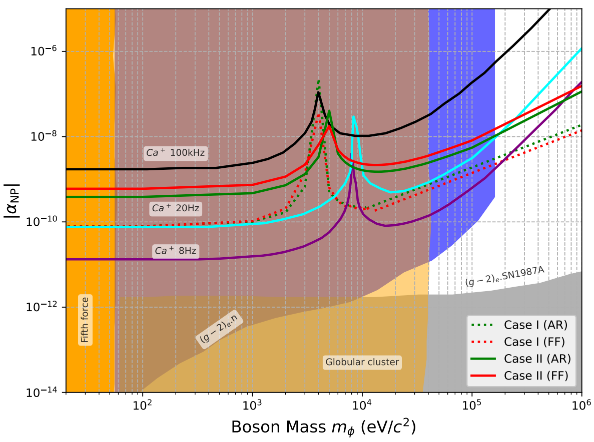

Figure 1: Demonstrating α_{NP} variation with m_ϕ [6].

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