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Effects of New Physics in Nuclei and Atoms

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Abstract

The isomeric transition in ^{229}Th - recently laser-excited by multiple groups - opens a path to a nuclear clock with accuracy competitive with, and potentially exceeding, the best optical atomic clocks. The nuclear clock can be realised using different charge states - Th^{+}, Th^{2+}, Th^{3+}, and Th^{4+} - each exhibiting distinct frequency shifts due to electron-nucleus interactions. In effect, these represent different clocks, each with unique properties and precision limits.

The surrounding electrons strongly mediate excitation and decay via the electronic-bridge mechanism and can modify both transition probability and lifetime by orders of magnitude. Nucleus is very small and sealed inside atom, making it insensitive to external perturbations. A ”stretched-state” scheme suppresses leading-order electron-nucleus entanglement and mitigates key systematic effects.

The ^{229}Th transition is exceptionally sensitive to physics beyond the Standard Model: spatial/temporal variation of fundamental constants (α, quark masses, Λ_{QCD}), ultralight dark-matter couplings to gluons and nucleons, and violations of Lorentz invariance and Einstein’s equivalence principle. Four orders enhancement factors relative to electronic transitions, together with frequency-ratio networks linking nuclear and atomic references, enable stringent constraints.

Measurements of nuclear moments that violate parity (P) and time-reversal invariance (T) provide critical tests of unification theories predicting CP violation and the matter-antimatter asymmetry observed in the Universe (baryogenesis). These T,P-violating moments include the electric dipole moment (EDM), Schiff moment, magnetic quadrupole moment, and octupole moment. T,P-violating nuclear moments are primarily generated by T,P-violating nuclear forces, with smaller contributions arising from the proton and neutron EDMs. These moments exhibit collective enhancement in deformed nuclei. For example, the Schiff moment is enhanced by factors of 100-1000 in nuclei with octupole deformation, while the magnetic quadrupole moment is significantly enhanced in quadrupole-deformed nuclei. The interaction of electrons with T,P-violating nuclear moments results in atomic and molecular EDMs, which are directly measurable. Additionally, the nuclear anapole moment (a parity-violating magnetic moment) has been experimentally observed in ^{133}Cs.

Oscillating T,P-violating nuclear moments can be induced through interactions with oscillating axion dark matter field, making their measurement a promising method for dark matter detection.