Th-229 Nuclear Clock

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Abstract:

Ultra-precise time keeping, and practical qubits have the potential to reveal new physics and enable unprecedented increases in computational capabilities, respectively. There is one potential nuclear transition that has an energy low enough (7.6 eV) that it could be directly excited by a laser at an approximate wavelength of 160 nm. By locking the laser frequency to the nuclear transition, one could create the world's most precise nuclear clock by 3 orders of magnitude compared to the current state of the art. This would create a new international time standard, enable general relativity experiments with unprecedented sensitivity, and enable an ultra-precise test of the constancy with time of the fundamental constants of nature. Direct coherent control of the nuclear transition would enable a long-decoherence-time quantum bit (qubit), which can then be engineered into a quantum computer. The fundamental discovery required to open these research paths is the discovery of the exact wavelength of the nuclear transition in Thorium-229.

White Paper:

The energy of the first excited state of the ^{229}Th nucleus is the lowest of all known isotopes, at a mere 7.6±0.5 eV [1-4] above the ground state; this transition energy corresponds to a wavelength of approximately 160 nm. The spin difference is 1 h-bar, and the excited state is meta-stable with a half-life as long as hours. This makes ^{229}Th the premier candidate for applying atomic spectroscopy techniques to a nuclear transition; ultraviolet-visible spectrometers would be used along with tabletop lasers and/or vacuum-ultraviolet (VUV) light sources to interrogate and to drive the transition between the two states of this nuclear doublet [5-14]. The ability to apply the arsenal of precision optical spectroscopy techniques (where frequencies/energies can be measured to a fractional precision of 10^{-15}) to the nuclear domain would be a breakthrough on par with the Nobel prize winning work of Mössbauer. Optical manipulation of the ^{229}Th nucleus could lead to unprecedented studies of the interplay between atomic and nuclear systems, provide a new frequency/time standard [15-16], be used as a qubit for quantum computing with extremely long decoherence times, improve the search for time-variation of fundamental constants by as much as six orders of magnitude [17-19], and demonstrate for the first time coherent control of a nucleus.

The low-lying nuclear level in ^{229}Th has attracted the attention of scientists all over the world and has been the subject of much experimental and theoretical interest. Other research groups around the world have performed challenging experiments to study the properties of this isomeric state, including performing collinear laser spectroscopy on ^{229}Th ions to study the hyperfine interaction, photon counting ^{229}Th atoms guided to a target using a radiofrequency ion guide and buffer gas technique, and bombarding the ^{229}Th atoms with intense x-ray beams from the Advanced Photon Source at Argonne National Laboratory. The ^{229m}Th half-life has never been measured, and calculations are unreliable, ranging from 10 μs to 5 hours. Recently, the neutral-atom half-life has been inferred from the internal-conversion (electron signal) decay of ^{229m}Th and found to be 7 μs [4]. While this is a positive step forward, the critical knowledge of the energy to a precision needed for laser excitation and the half-life of the ^{229m}Th nuclear state is still unknown.

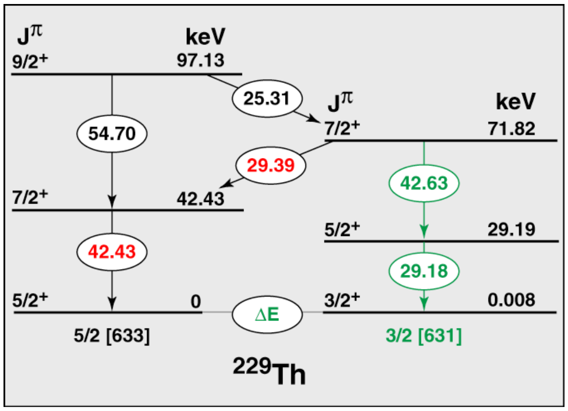

Figure 1. Thorium-229 decay scheme following alpha decay of Uranium-233.

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