MML FROM MATTER TO MATERIALS AND LIFE

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From the Atomic to the Nuclear Clock

The quest for an optical nuclear frequency standard, the 'nuclear clock'based on the elusive and uniquely low-energetic 'thorium isomer'229mTh, has increasingly triggered experimental and theoretical research activities in numerous groups worldwide in the last decade. Today's most precise timekeeping is based on optical atomic clocks. However, those could potentially be outperformed by a nuclear clock, based on a nuclear transition instead of an atomic shell transition. Only one nuclear state is known so far that could drive a nuclear clock: the 'Thorium Isomer 229mTh', i.e. the isomeric first excited state of 229Th, representing the lowest nuclear excitation so far reported. Such a nuclear clock promises intriguing applications in applied as well as fundamental physics, ranging from geodesy and seismology to the investigation of possible time variations of fundamental constants and the search for Dark Matter [1].
After years of nuclear-spectroscopy driven identification and characterization activities of 229mTh, the year 2024 witnessed seminal breakthroughs with first laser-driven excitations of the isomeric nuclear resonance in 229Th, both using intense broad-band [2,3] and VUV frequency-comb based narrow-band lasers [4], respectively. Hardly any physical observ-able experienced an improvement by 11 orders of magnitude within only 5 years, as it was reached for the excitation energy of the thorium isomer. Hence, the question is no longer 'Will there be a nuclear clock?', but rather 'Which types of nuclear clocks with which properties will be realized in the coming years?', driven by the requirements of a variety of fundamental and applied physics applications. While recent progress with opti-cal excitation of 229mTh was achieved via fluorescence detection in a solid-state approach using doped large-bandgap crystals and thin films [5], recently also laser-driven conver-sion-electron Mössbauer spectroscopy of the thorium isomer was demonstrated [6], while the complementary approach using individual laser-cooled trapped ions in vacuum is still under study.
The talk will review the status and perspectives of ongoing activities towards realizing a nuclear frequency standard based on the thorium isomer both in the solid-state and trapped 229mTh3+ ion approach, including experimental activities at GSI on highly charged 229Th ions.

[1] E. Peik et al., Quantum Sci. Technol. 6, 034002 (2021)
[2] J.Tiedau et al., Phys. Rev. Lett. 132, 182501 (2024)
[3] R. Elwell et al., Phys. Rev. Lett. 133, 013201 (2024)
[4] Ch. Zhang et al., Nature 633, 63-70 (2024)
[5] Ch. Zhang et al., Nature 636, 603 (2024)
[6] R. Elwell et al., arXiv:2506.03018 (accepted in Nature)

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