

DOCTORAL DISSERTATION ABSTRACT

Scientific discipline: Physical Sciences

Title of the doctoral dissertation: Towards High-Precision Spectroscopy of Alkaline, Alkaline-Earth-Like, and Antimatter Atomic Systems

Doctoral dissertation abstract:

In my thesis, I describe how I use high-precision optical spectroscopy on two complementary platforms, neutral mercury (Hg) atoms and positronium (Ps), to turn minute physical effects into measurable frequency shifts that both support next-generation timekeeping and test fundamental physics in a clean, controlled way. Hg, a heavy many-electron atom, offers an ultra-narrow clock transition with exceptionally low sensitivity to environmental perturbations and direct relevance for optical atomic clocks; Ps, a purely leptonic, nucleus-free system, provides a uniquely clear testbed for bound-state quantum electrodynamics and matter–antimatter symmetry. Treating these systems side-by-side lets me link practical metrology with incisive tests of theory within one coherent programme.

I aimed to build, stabilise and characterise the instruments required to interrogate these systems at state-of-the-art precision, and to make the measurements traceable to the SI second. At the National Laboratory FAMO in Toruń, I developed a room-temperature ultra-stable optical cavity, integrated fibre-noise-cancelled optical links, and implemented optical power amplification and frequency quadrupling, all to probe the $^1S_0 - ^3P_0$ transition in Hg near 265.6 nm. I built repumping laser systems, including custom extended-cavity diode lasers operating at 404.7 nm and 546.1 nm with a digital frequency stabilisation loop. Finally, because the existing scientific chamber constrained the implementation of an optical lattice operating at the magic wavelength, I designed a new main chamber and an in-vacuum lattice-cavity assembly to enable efficient coupling and mirror mounting. Collectively, these steps take the laboratory to the threshold of Hg clock-transition spectroscopy with traceable accuracy and controlled systematics.

In parallel at CERN, within the AEGIS collaboration, we progressed positronium towards precision spectroscopy. Based on the success of the first experimental demonstrations of laser cooling of Ps, I designed a Doppler-free, cavity-enhanced two-photon spectroscopy system for the $1^3S_1 - 2^3S_1$ transition. Effectively, it operates at 486 nm, and includes referencing to an optical frequency comb and a power-enhancement cavity. The detection is based on a digital frequency lock, and the estimated uncertainty budget suggests the possibility of achieving sub-100 kHz accuracy. Wherever possible, I transferred metrology-grade techniques matured on the Hg laser system—comb referencing, cavity stabilisation, fibre-noise cancellation and rigorous stability analysis—to the antimatter platform to ensure SI traceability and to approach state-of-the-art accuracy.

I find that the Hg platform I constructed with the help of my colleagues delivers the optical stability, referencing and UV power needed for the $^1S_0 - ^3P_0$ transition spectroscopy. In Ps, the introduction of laser cooling and the planned cavity-enhanced, comb-referenced spectrometer establishes a clear route to higher-accuracy measurements of the $1^3S_1 - 2^3S_1$ interval in a nucleus-free

atom.