

Nuclear-atomic overlap for the isotope thorium-229

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The dense spectral line structure of neutral thorium (Th I) as seen in a hollow cathode lamp observed with an echelle spectrograph. This is a double spectrum in which the visible spectrum is cut into horizontal strips to expand the wavelength range. Credit: Observatoire de Haute-Provence, France.

More than 99.9% of the mass of any atom is concentrated into a quadrillionth of its volume, the part occupied by the nucleus. Unimaginably small, dense and energetic, atomic nuclei are governed by laws quite distinct from those that regulate atomic electrons, which constitute the outer part of atoms and which are immediately responsible for light, chemistry and thus life. Yet there are sporadic regions of

contact between these disparate realms. JQI Adjunct Fellow Marianna Safronova and her collaborators (1) have been exploring one area of nuclear-atomic overlap for the isotope thorium-229. This isotope is a candidate for a new type of atomic clock and quantum information processor.

A ticking time bomb

The quantum states of [atomic nuclei](#) are usually separated in energy by thousands or millions of electron volts (eV), compared to the few-electron-volt energy range characteristic of atomic electrons. This is reflected in the "megatons of TNT" scale for nuclear vs. chemical explosions, and the radiation associated with jumps between nuclear quantum states lying in the x-ray or gamma-ray regions of the spectrum, in contrast to the optical realm of electronic transitions.

By some strange accident of nuclear physics, there is one nucleus, thorium-229, which possesses a nuclear excited state (isomer) that lies just a few eV above the ground state. That is, for Th-229 there exists a nuclear transition that looks more like an atomic transition. This isomer has not yet been detected directly, but the state is known to have a lifetime of about six hours. This may not sound like much—not even a full season of "Downton Abbey"—but the lifetime of the "clock" state of the recently-announced world's most accurate clock state is about two minutes (1). The lifetime of the clock state is a key factor in the performance of atomic clocks—the longer, the better—and the tiny size of nuclear isomers suggests that they may be far less susceptible than electronic clock states to stray fields, blackbody radiation, and other environmental effects that degrade accuracy and stability.

Solitary confinement

Indeed, the remarkable isolation of the isomers is reflected in the poor state of knowledge of their properties. The work of Safronova et al. has resulted in a new determination of the magnetic and electric moments of the thorium-229 nuclear ground state. This work shows that previous measurements, which were most demanding, were in error by up to 25%.

There are thousands of spectral lines in the visible spectrum of thorium – indeed, the spectrum is so dense that thorium lamps are often used as wavelength calibration standards for solar and stellar astronomy.

To reduce the complexity of this system, Safronova et al. treated the much simpler spectrum of the ion Th^{3+} (Th IV), an ion with only one electron outside a closed shell. This ion had previously been laser-cooled and trapped by Campbell et al. (3). The wavelengths of its emission lines depend weakly upon the magnetic moment and the electric quadrupole moment of the nucleus, a phenomenon commonly called "hyperfine structure". By performing precise, first principles calculations of [electronic states](#) of thorium, Safronova et al. were able to extract the values of the nuclear magnetic and electric moments from the experimentally-measured wavelengths.

Accurate knowledge of this data is critical to building an "electronic bridge" (4) that would facilitate laser control of nuclear states. Proposals for such a bridge involve engineering the intrinsic coupling between electrons and nuclei so that laser control of electronic states can be extended to nuclear states.

- See more at: jqj.umd.edu/news/solitary-conf...sthash.Vw8hqT28.dpuf

More information: M. S. Safronova, U. I. Safronova, A. G. Radnaev, C. J. Campbell, and A. Kuzmich, "Magnetic dipole and electric quadrupole moments of the ^{229}Th nucleus", *Phys. Rev. A* 88, 060501(R) (2013)

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