

5. Thorium's Nuclear Tick- Science & Technology

Scientists have found a way to detect thorium-229's nuclear 'tick' in a solid, opening a path to miniaturised nuclear clocks

Background- Limits of Conventional Atomic Clocks

Principle of atomic clocks

1. Atomic clocks measure time by counting electron transitions between energy levels in atoms (e.g., caesium, strontium).
2. These transitions define the SI second and underpin modern technologies such as GPS and telecom networks.

Key limitation

1. Electron orbitals are highly sensitive to- Electric fields Magnetic fields Temperature fluctuations
2. This environmental sensitivity introduces fundamental limits to long-term stability.

Need for advancement- As precision science advances (deep-space navigation, relativity tests), even atomic clocks are approaching their theoretical ceiling.

Concept of a Nuclear Clock

Core idea- A nuclear clock measures time using energy transitions within an atomic nucleus, rather than electron shells.

Nuclei Are Superior

1. The nucleus is deeply shielded by surrounding electrons.
2. Nuclear energy levels are- Far less affected by electromagnetic disturbances Inherently more stable over long periods

Timekeeping mechanism

1. Ultraviolet light excites the nucleus to a higher energy state.
2. The frequency of this excitation-decay cycle acts as the time reference.
3. Counting these oscillations yields extremely precise time measurement.

Thorium-229 Is Unique

Exceptional nuclear property- Thorium-229 possesses the lowest known excited nuclear energy state among all nuclei.

Technological significance- This excitation energy lies in the vacuum-ultraviolet (VUV) range, unlike most nuclear transitions which require gamma rays. Allows direct laser excitation of a nuclear transition – a rare phenomenon. Makes thorium-229 the only known practical candidate for a laser-driven nuclear clock.

Main Experimental Challenge

Internal Conversion Problem

1. In solid materials, when the thorium-229 nucleus is excited- Energy is transferred to an orbital electron The electron is ejected instead of photon emission
2. This process, called internal conversion, prevents direct optical detection.

Earlier approaches

1. Researchers attempted to suppress internal conversion.
2. Detection remained weak and indirect, delaying progress for decades.

Breakthrough Experimental Approach

Innovative strategy- Instead of avoiding internal conversion, researchers used it as the detection signal.

Methodology- Thorium-229 nuclei embedded in thorium dioxide (ThO₂) crystals. VUV laser pulses used to excite nuclear transitions. Decay detected by measuring delayed electrons emitted via internal conversion. Converts a long-standing obstacle into a measurement advantage. Eliminates reliance on complex photon-based optics.

Key Experimental Results

Precise nuclear resonance- Detected at 2,020,407.5 GHz, confirming long-theorised predictions.

Measured lifetime- Internal conversion decay lifetime- 12.3 microseconds.

Unprecedented accuracy- Projected error- 1 second in ~15.8 billion years. Comparable to the age of the Universe, far exceeding atomic clock performance.

Significance of the Breakthrough

Scientific Significance- Provides the first practical pathway to building a nuclear clock. Confirms the feasibility of laser-controlled nuclear transitions. Opens new domains in nuclear quantum optics.

Technological Significance- Enables miniaturisation Time can be read via electron current rather than bulky optical systems. Improves robustness and portability of ultra-precise clocks.

Applications of Nuclear Clocks

Fundamental physics

1. Testing whether fundamental constants (fine-structure constant) vary over time.
2. High-precision tests of General Relativity.

Precision sensing

1. Enhanced gravitational time dilation measurements.
2. Ultra-sensitive geodesy and Earth observation.

Future navigation

1. Deep-space navigation where GPS is unavailable.
2. Autonomous spacecraft timekeeping.

Atomic Clock vs Nuclear Clock (Conceptual Comparison)

Reference system

1. Atomic clocks- Electron orbital transitions.
2. Nuclear clocks- Nuclear energy transitions.

Frequency range

1. Atomic clocks- Microwave to optical.
2. Nuclear clocks- Ultraviolet (much higher).

Environmental sensitivity

1. Atomic clocks- Moderate.
2. Nuclear clocks- Extremely low.

Current status

1. Atomic clocks- Fully operational.
2. Nuclear clocks- Experimental but rapidly advancing.

Overall Assessment

Nuclear clocks represent a paradigm shift in timekeeping, comparable to the transition from mechanical to atomic clocks. The thorium-229 breakthrough

1. Overcomes decades-old experimental barriers
2. Makes ultra-stable nuclear time standards realistic

While still in the research phase, nuclear clocks are poised to become cornerstone technologies in precision science, navigation, and fundamental physics.

Source- <https://www.thehindu.com/sci-tech/science/thorium-nuclear-clock-mossbauer-spectroscopy/article70402209.ece>