Development of Vacuum Ultraviolet Laser Towards Th-229 Nuclear Clock

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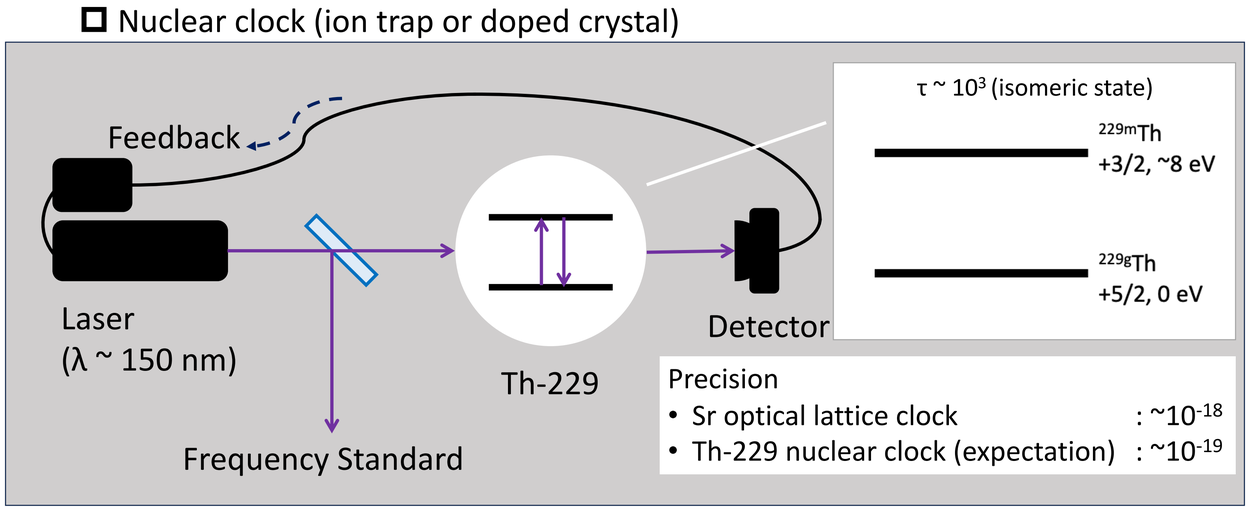
Abstraction

The Th-229 nucleus possesses the exceptionally low-energy first excited state (isomeric state) of approximately 8 eV, making it the only nucleus capable of being excited by lasers, and thus, it is expected to serve as a candidate for a nuclear clock. Last year, vacuum ultraviolet light with a wavelength of about 150 nm by the de-excitation from the isomeric state was observed for the first time, sparking research worldwide into laser excitation of the nucleus. Currently, our group is advancing research on the development of a vacuum ultraviolet laser for the direct excitation of the isomeric state, and in this presentation, we will discuss an overview of the laser development and its progress.

1. Th-229

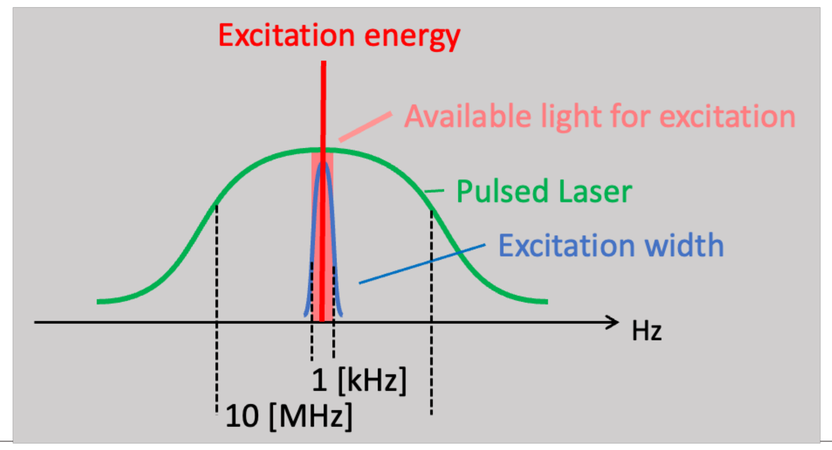
- The first nuclear excited state is the lowest among all nuclei
  - Typical energy: keV – MeV
  - Th-229: nuclear laser excitation is possible
- Application
  - Nuclear clock (ion trap or doped crystal)



  - New physics search
    - Time variation of fine structure constant (α)
      higher sensitivity compared to atomic clocks
- Direct excitation to the isomeric state has not been successful .
  - Developing a laser for direct excitation to the isomeric state
  - Attempting direct excitation using the laser

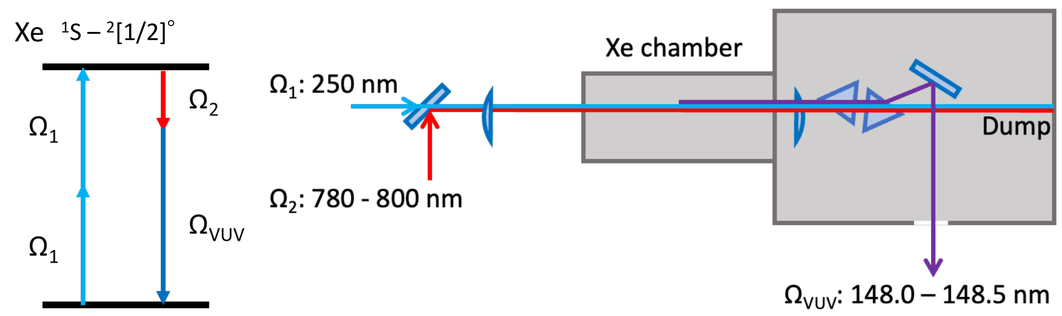
2. Laser Required for Excitation to Isomeric State

- Required laser power
  - The number of photons contained per Hz linewidth of the pulsed laser
    (pulse energy 10^{-1} [uJ], laser linewidth 10 [MHz])
    10^{-1} [uJ]/10 [MHz] = 7.5×10^{2} [photons/Hz pulse]
  - Th-229 doped crystal
    - Theoretical linewidth required for Th-229 excitation determined from the lifetime
      10 [mHz] → 7.5 [photons/pulse]
    - The linewidth used for excitation of nuclei in the crystal
      1 [kHz] → 7.5×10^{5} [/pulse]
    - Expected isomer yield → ~7.5×10^{5} [/pulse]
  - @SPring-8
    - The number of isomers produced in the SPring-8 experiment ~1.6×10^{5} [/set]
  - The power required to obtain Th-229 isomeric signal: ~10^{-1} [uJ]

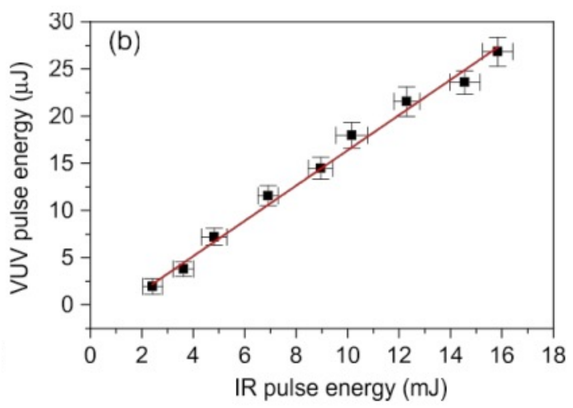


3. Setup

- Application
  - Four-wave mixing (FWM) $\Omega_{VUV} = \Omega_1 + \Omega_1 - \Omega_2$



  - Needed IR pulse energy



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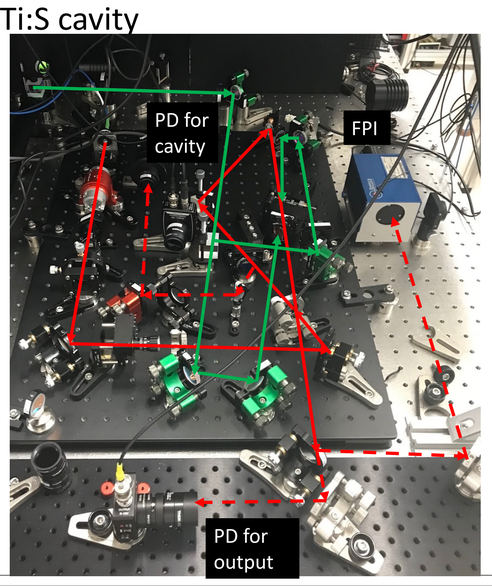
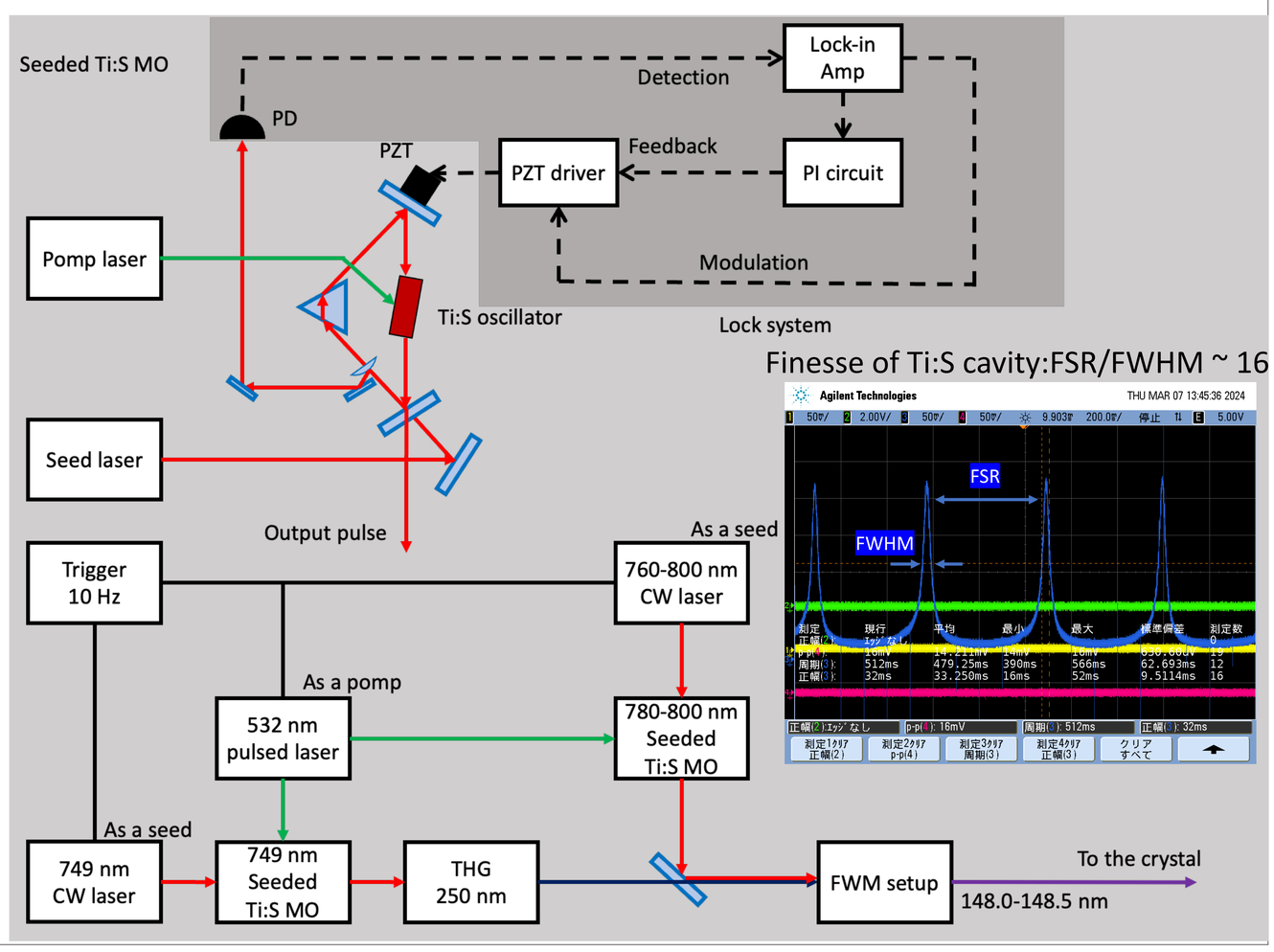
~1 mJ IR pulsed laser should be developed

  - Ti:S cavity



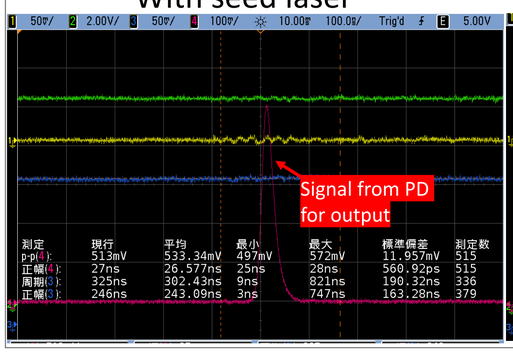
- Schematic view



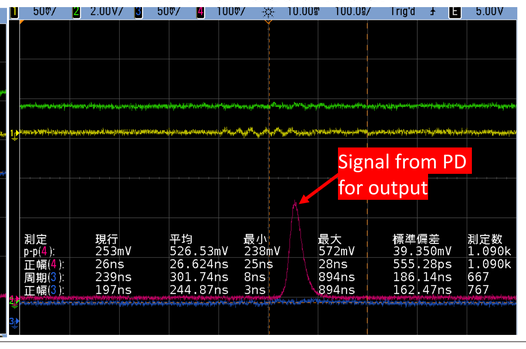
4. IR pulsed laser with Ti:S

- IR pulsed laser was successfully generated

With seed laser



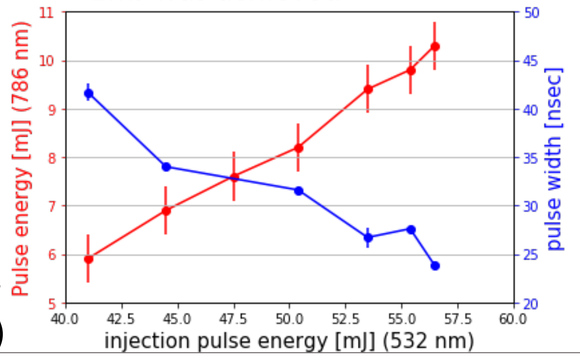
Without seed laser



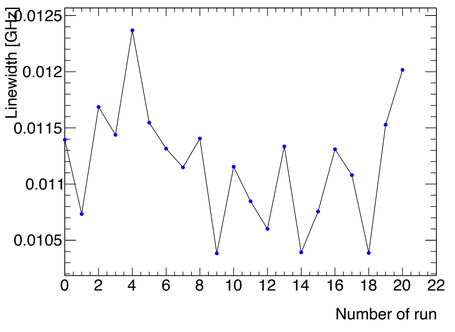
1ch: Signal from PD in FPI
2ch: Voltage of PZT in FPI
3ch: Signal from PD for cavity
4ch: Signal from PD for output pulse

  - Without seed
    →Pulse height becomes lower
    (Absence of induced emission)

- Performance evaluation
  ~1mJ was achieved



- Linewidth
  ~11.5 MHz



5. Summary and Prospect

- We are currently working on the development of the isomeric level excitation laser and have developed an IR pulse laser intended to be integrated into the VUV laser system.
- We are going to construct the UV laser with THG system for four-wave mixing.