The ^{229}Th Nuclear Clock Isomer: Half-life and Energy Determination in Several Different Crystals

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ISOLDE Workshop

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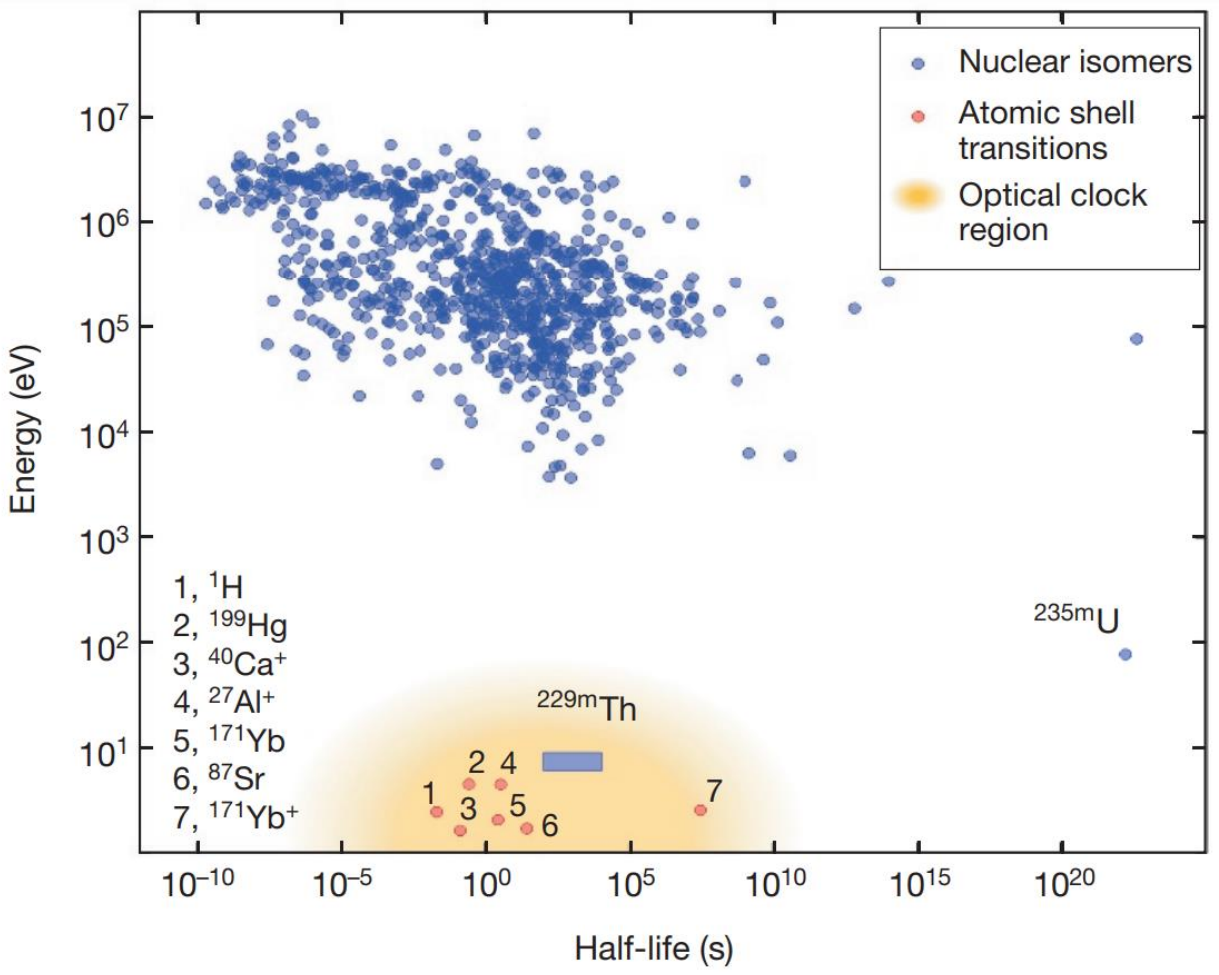
The ^{229}Th Isomer

- Low-lying isomer around 8 eV which is accessible to laser excitation (VUV lasers)
- The only known candidate for the development of a nuclear clock in the far-ultraviolet regime
- Energy is low enough to probe with a laser and has a long radiative lifetime
- Applications
  - Geodesy
  - Ultralight dark matter detection
  - Time-dependence of fundamental constants



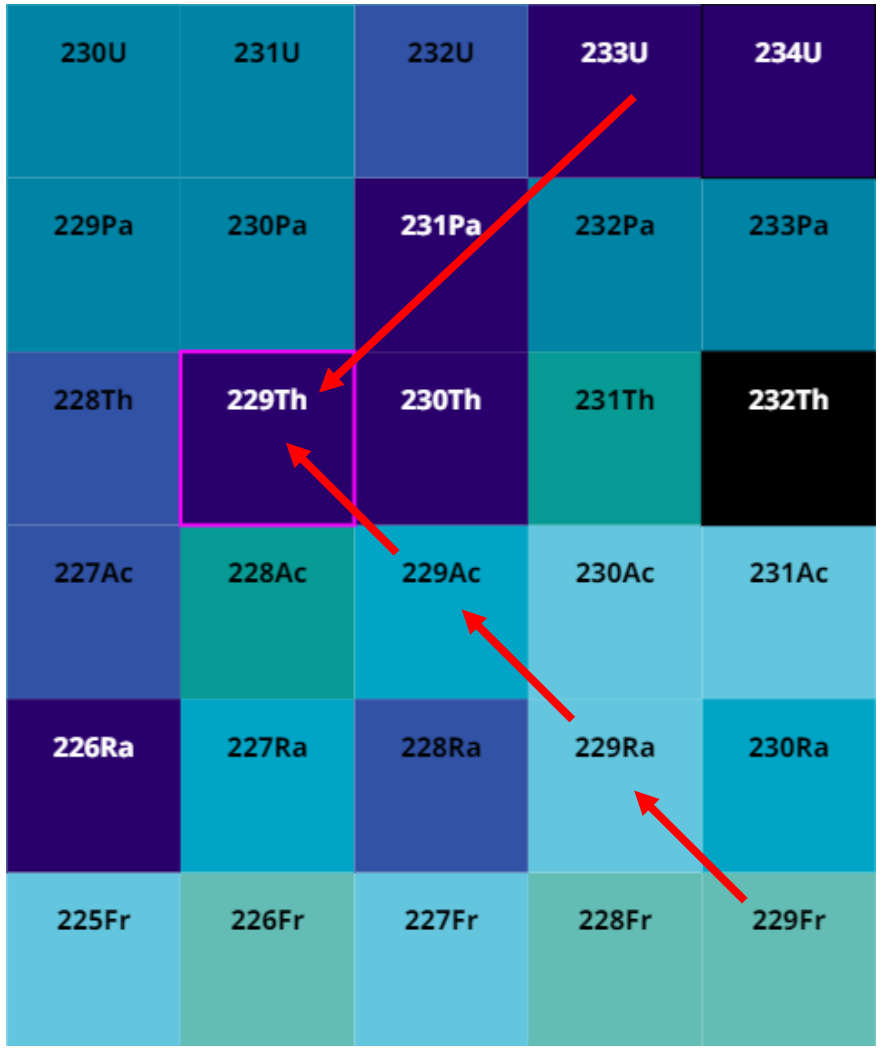
L. von der Wense *et. al.*, *Nature* **533**, 47-51 (**2016**).
P G Thirolf *et. al., J. Phys. B: At. Mol. Opt. Phys.* **52** 203001 (2019).

Populating the Isomer

- ^{233}U α-decay
  - Doping in CaF_2 crystal
  - Branching of 2%
- Disadvantages
  - 84 eV recoil energy
  - Strong radioluminescence background from α-decay

- ^{229}Ac β-decay approach
  - Branching >14%
  - Small recoil energy of 6 eV
- Disadvantages
  - Cherenkov background from β-decay

- Implant precursors into large bandgap crystals to measure the radiative decay of the isomer



NNDC Database, https://www.nndc.bnl.gov/nudat3/
Verlinde *et. al.*, *Phys. Rev. C* **100**, 024315 (**2019**).

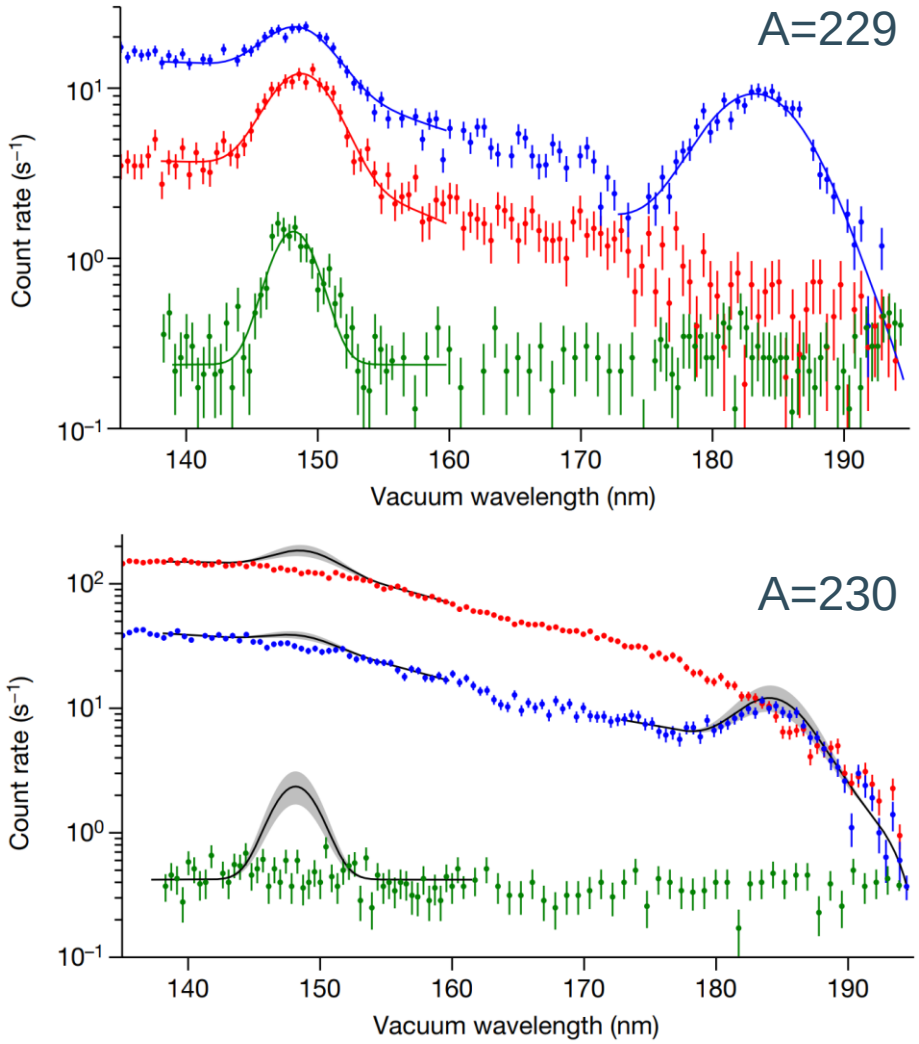
Previous Experiment-Radiative Decay Observation

- Radiative decay observed in three different crystals:
  - CaF_2 thick (5mm)
  - MgF_2 thick (5mm)
  - CaF_2 thin (50nm)

- Peaks can be observed due to:
  - Signal from ^{229m}Th
  - Crystal defect excitations

- The peak around 149 nm is present in A=229 but absent in A=230. This is a signature for ^{229m}Th

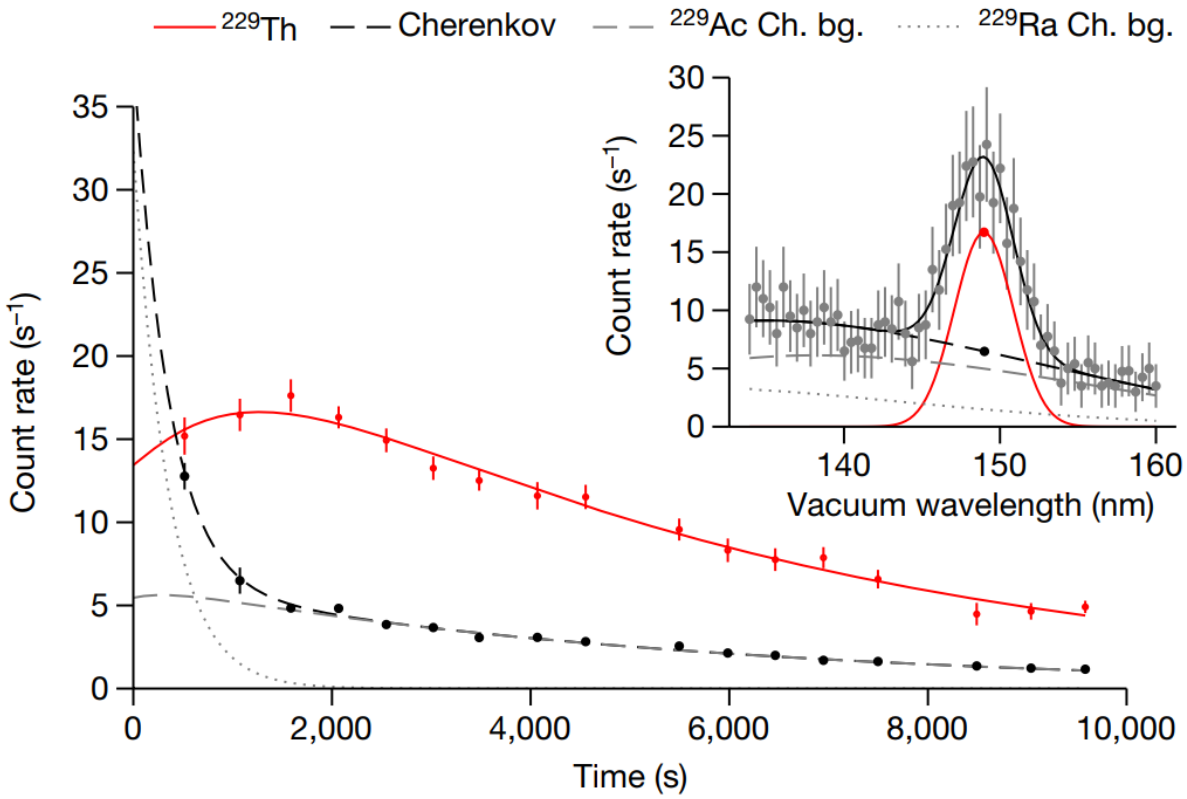
- The deduced isomer energy value was 8.338 +/- 0.024 eV (148.7 +/- 0.4 nm), whose uncertainty corresponds to 5.8 THz



S. Kraemer *et. al.*, *Nature* **617**, 706-710 (**2023**).

Previous Experiment-Radiative Decay Observation

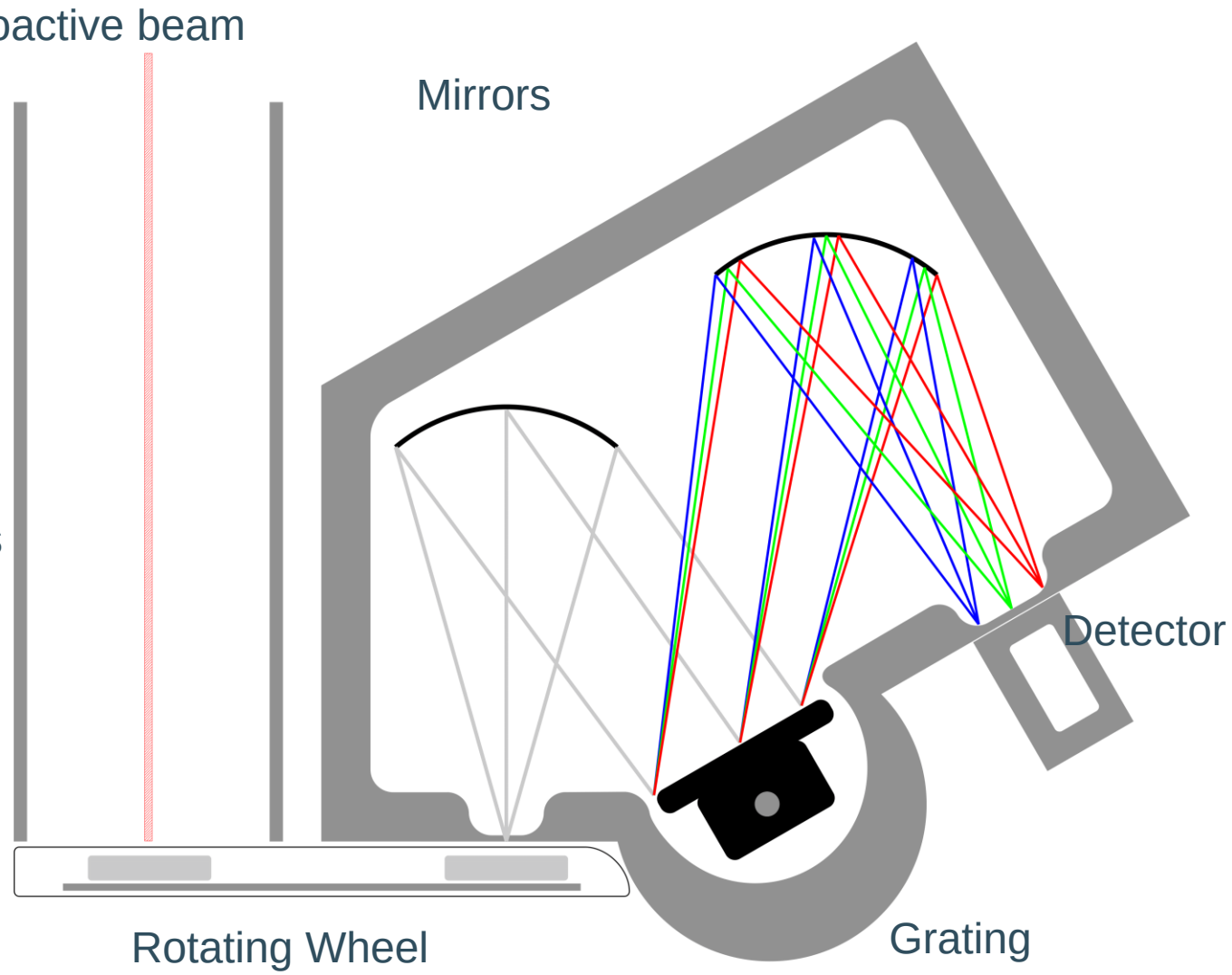
- Performing measurements in succession provides time behavior of the signal
- Determined the half-life of radiative decay in MgF_2 to be 670 +/- 102 s
- Half-life may be dependent on the chemical environment
- The most recent beamtime focused on improving the energy and half-life measurements, as well as testing some new crystals



S. Kraemer *et. al.*, *Nature* **617**, 706-710 (**2023**).

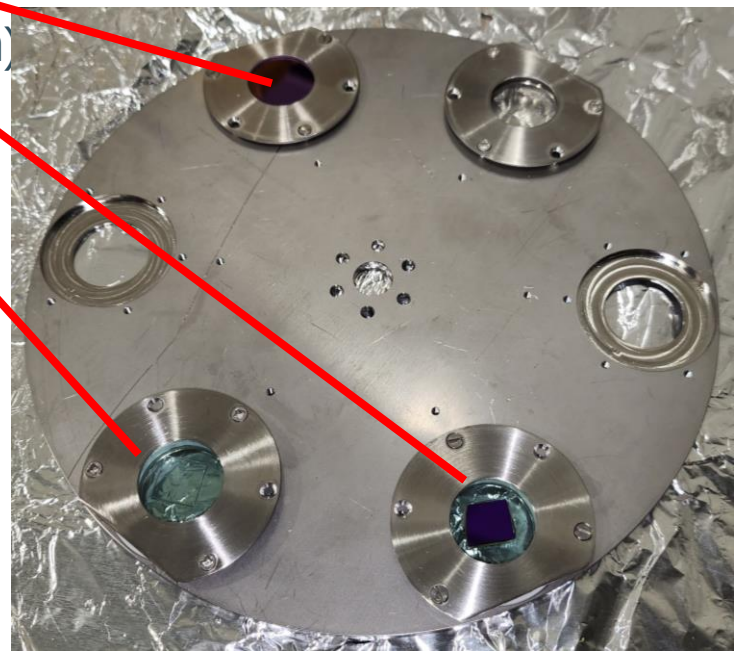
VUV Spectroscopy at ISOLDE

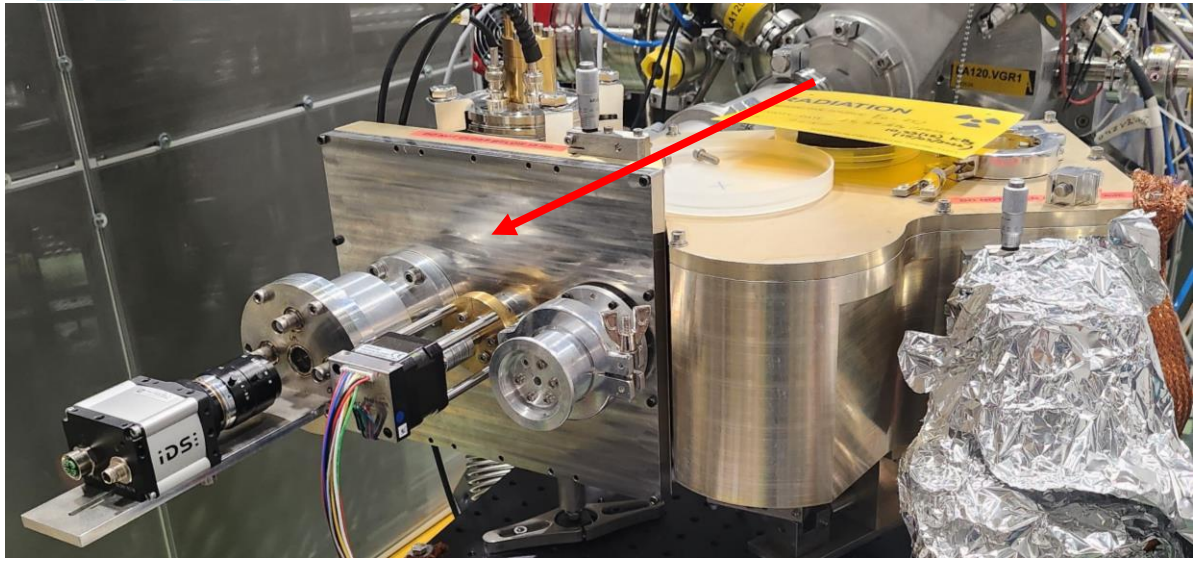
- Radioactive beam implanted onto crystals
- Crystals moved to the entrance of the spectrometer to observe the decay
- VUV photons travel from the crystal to a collimating mirror
- A diffraction grating separates the components of the light, which are then focused onto a PMT
- Rotating the grating effectively scans the wavelength range of the isomer

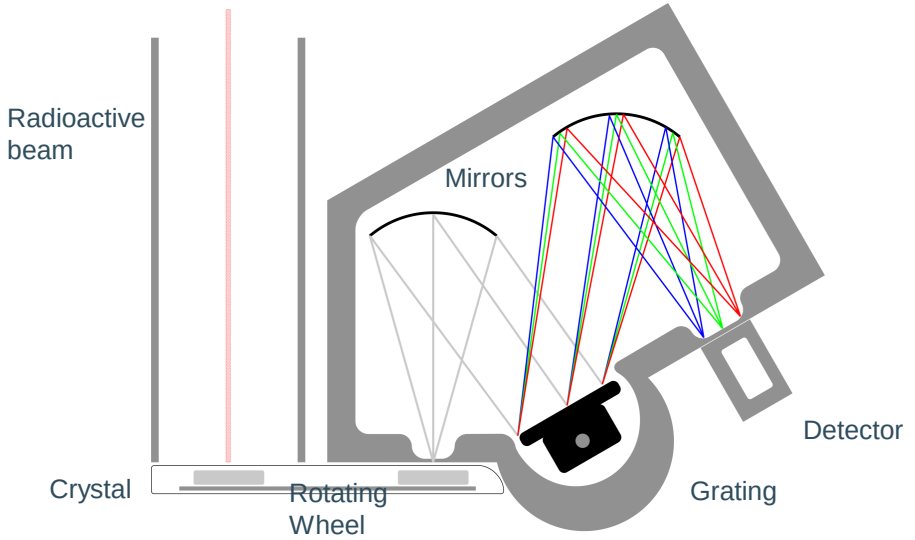


VUV Spectroscopy at ISOLDE

- Implanted on several different crystals:
  - MgF_2 (5mm bulk)
  - CaF_2 (50nm thin film and 5mm bulk)
  - SiO_2 (1mm)
  - AlN (1mm)
  - $LiSrAlF_6$ (1mm)

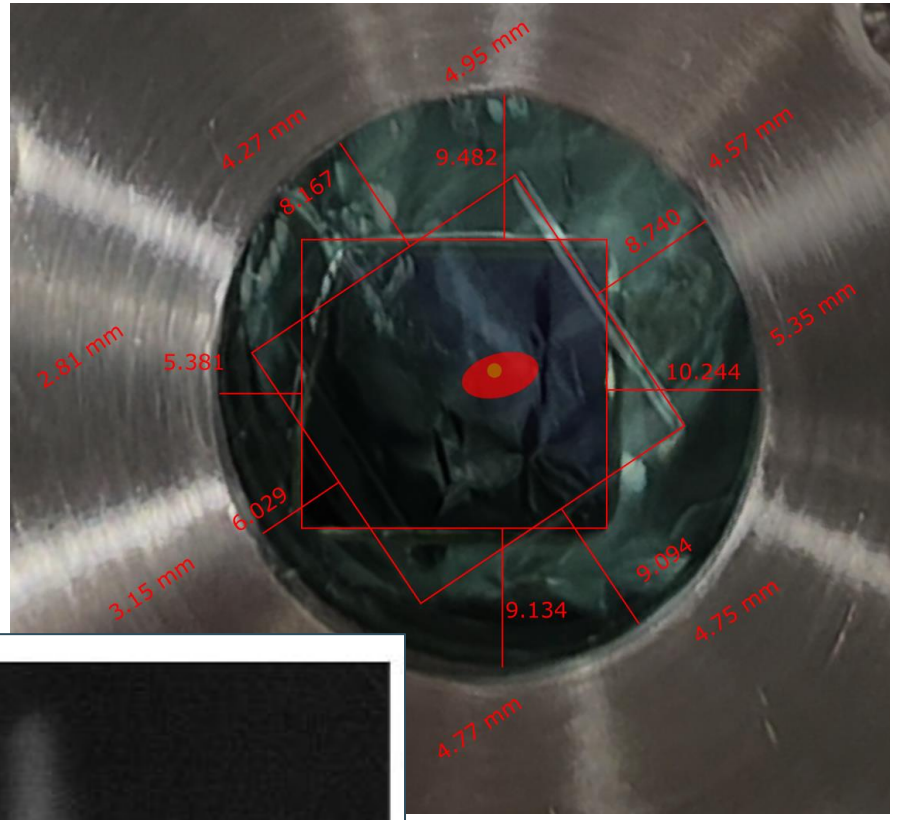


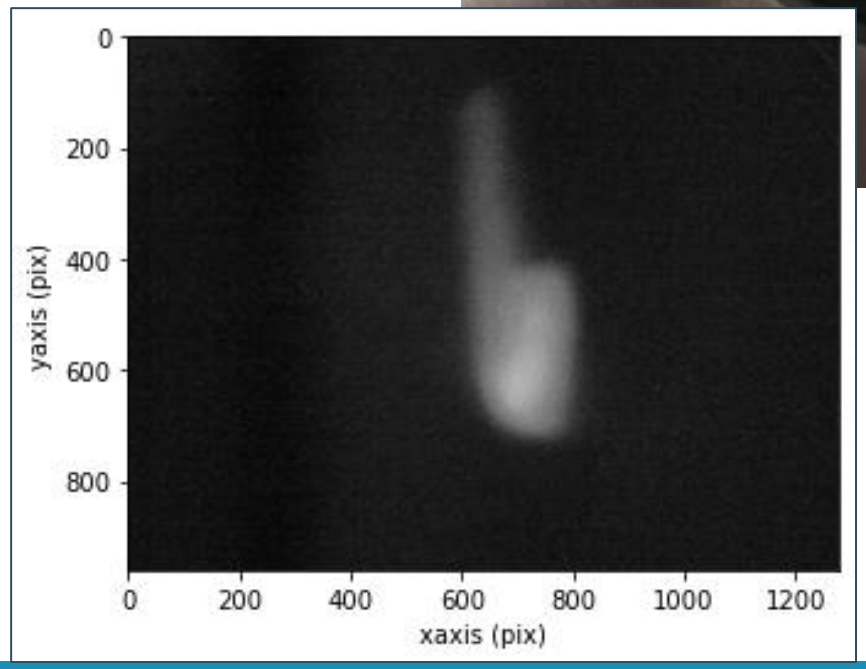




VUV Spectroscopy at ISOLDE

- Microchannel Plate detector used to measure the beam size and position
- 2mm x 3mm beam size
- ThCx target
- Higher rates compared to previous beamtime
  - Previous beamtime: ^{229}Ra ~10^{6} s^{-1}
  - Recent beamtime: ^{229}Ra ~10^{8} s^{-1}

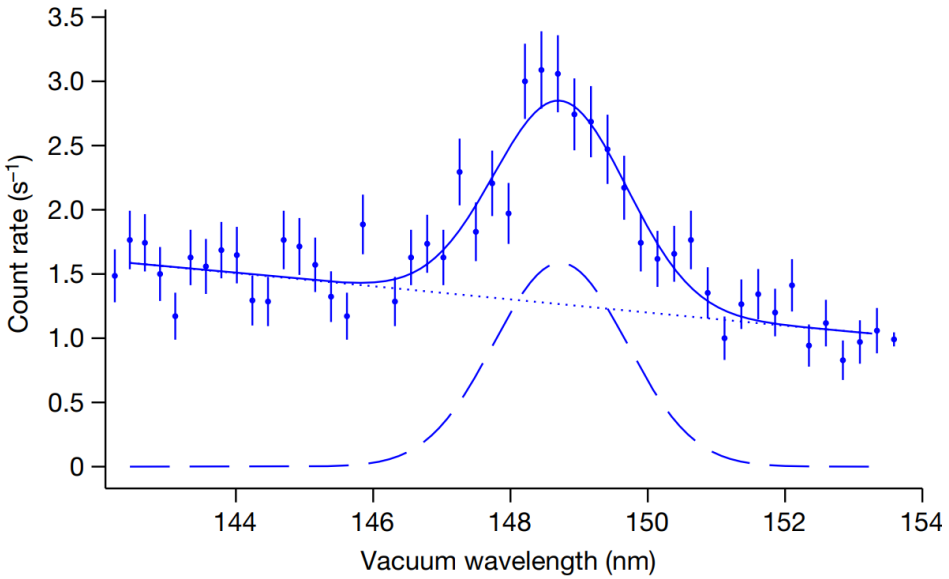


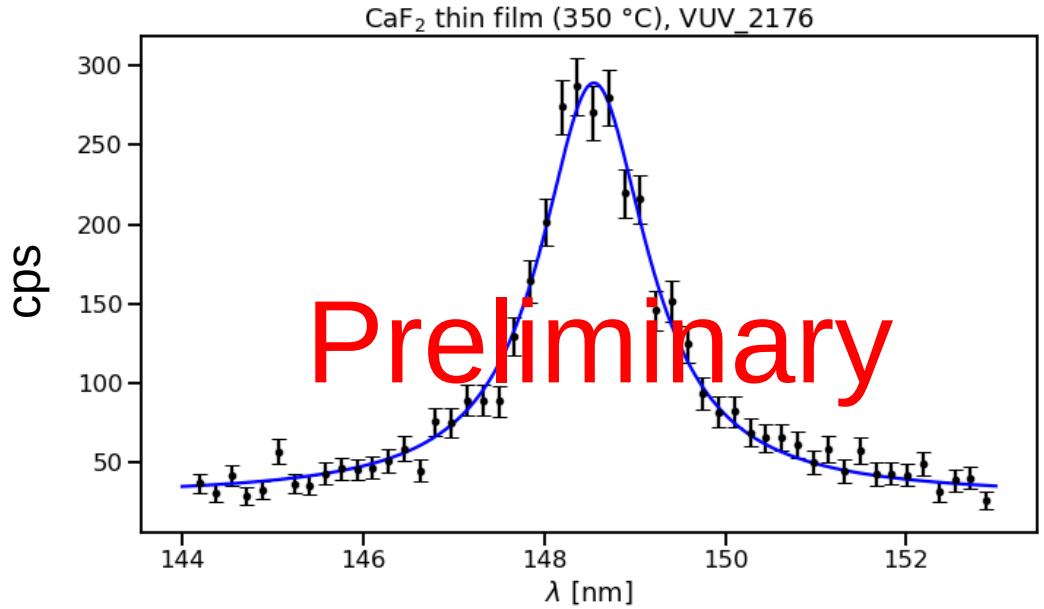


Experimental Results

- Measured energy in:
  - CaF_2
  - $LiSrAlF_6$
- 250 μm slit width
- Calibration measurements before and after each measurement
- Reduce uncertainty to <0.2 nm

Previous Experiment

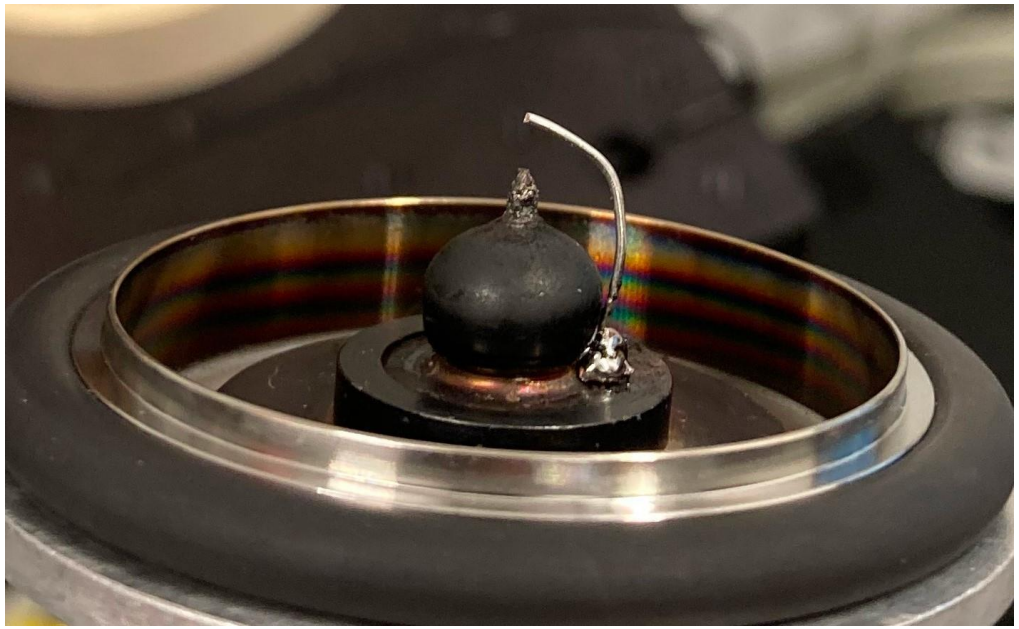


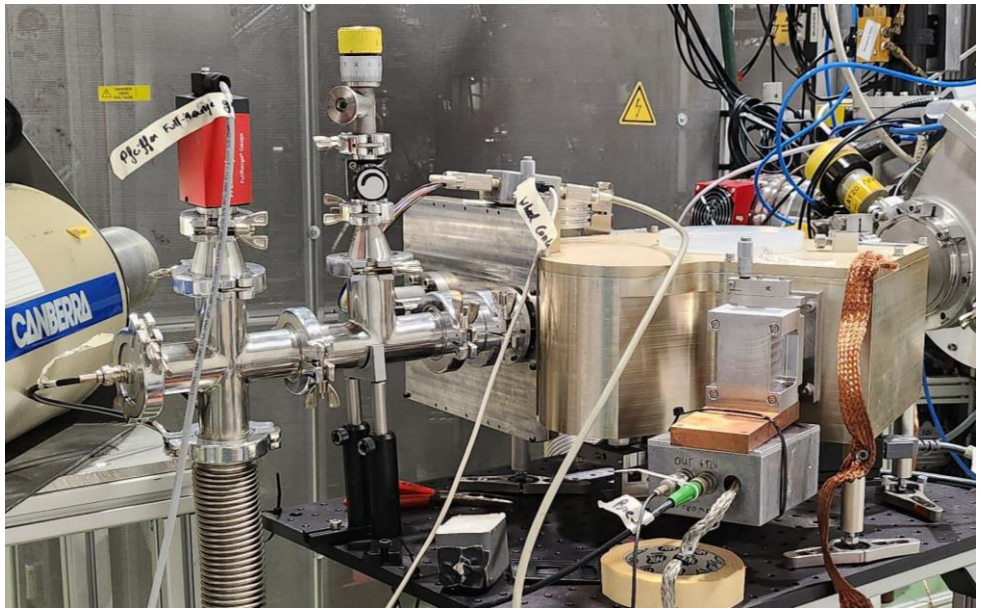


S. Kraemer *et. al.*, *Nature* **617**, 706-710 (**2023**).

Calibration Measurements

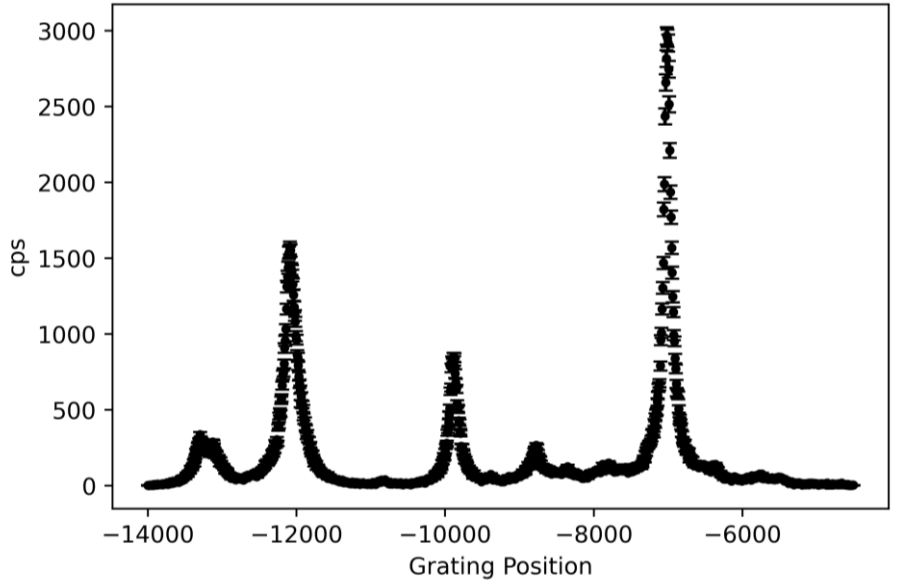
- Plasma source used to calibration our data
- Allows us to convert from motor position to wavelength

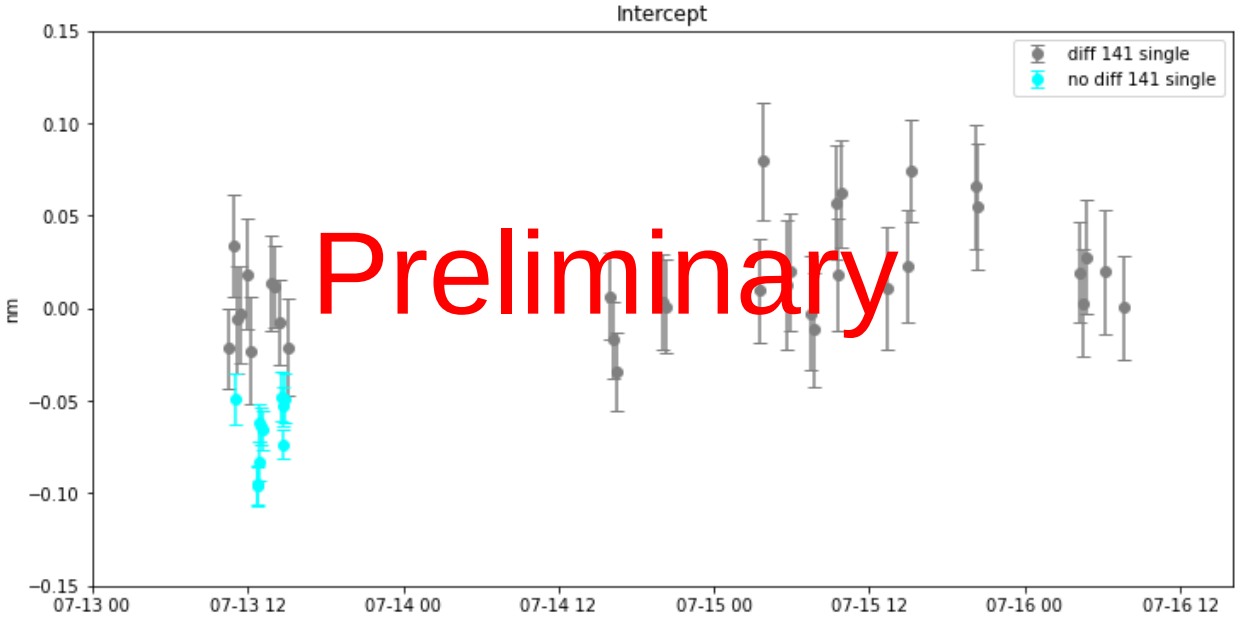


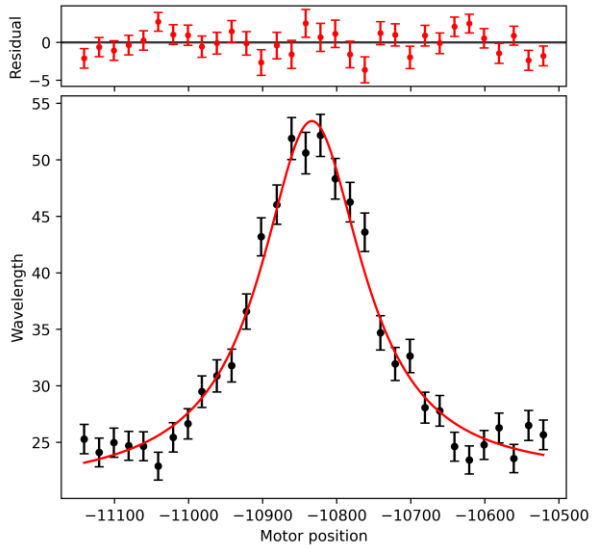


Calibration Measurements

- Scatter of calibration measurements ~0.12 nm with diffuser
- Offline measurement campaign in progress

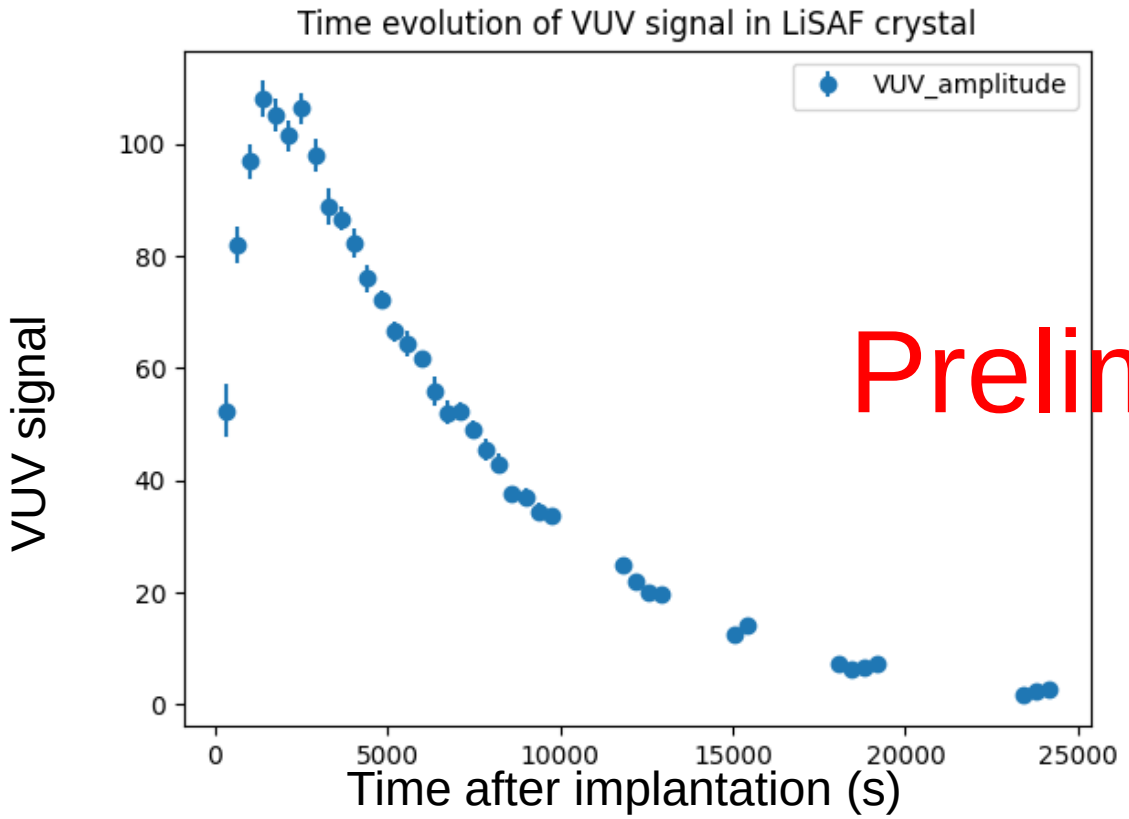


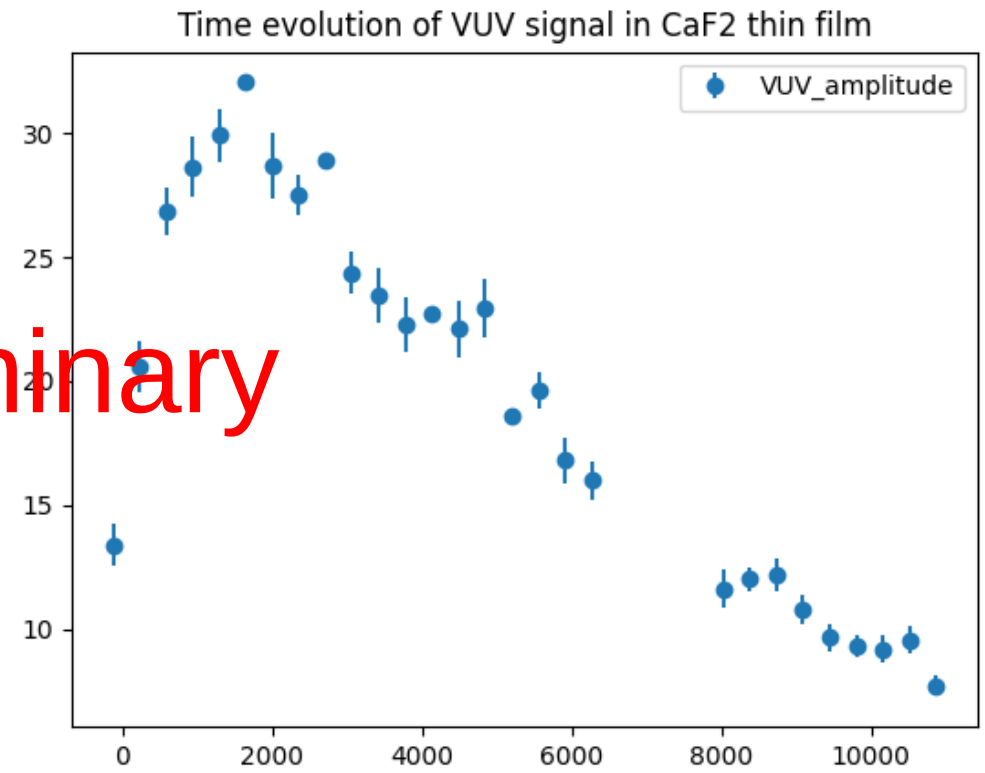




Experimental Results

- Measured lifetime in CaF_2 (thin film and bulk), $LiSrAlF_6$,MgF_2
- Shorter implantation time





Preliminary

Summary

- The previous experiment (IS-658) resulting in the observation of the ^{229m}Th radiative decay
  - Improved energy determination by a factor of 7
  - First determination of radiative half-life in MgF_2 crystal
- Most recent beamtime at ISOLDE (IS-715)
  - Isomer energy measured with a higher precision
  - Half-life of the isomer measured in more crystals
- Data analysis is ongoing
- A step forward in the development of the nuclear clock
- Upgrading the system for faster detection time (poster from Yens Elskens)
  - Allows for more precise measurement of the isomer's half-life
  - Annealing

Acknowledgements

The IS-715 Collaboration

M. Athanasakis, M. Au, S. Bara, M. Bartokos, K. Beeks, P. Chhetri, K. Chrysalidis, A. Claessens, J.G. Correia, Y. Elskens, R. Ferrer, R. Heinke, F. Ivandikov, U. Köster, S. Kraemer, M. Laatiaoui, R. Lica, G. Magchiels, J. Moens, D. Moritz, I. Morawetz, L.M.C. Pereira, S.V. Pineda, S. Raeder, S. Rothe, A. de Roubin, F. Schaden, K. Scharl, T. Schumm, S. Stegeman, P.G. Thirolf, P. Van Duppen, A. Vantomme, R. Villarreal, U. Wahl