KU LEUVEN

Study of the radiative decay of the low-energy isomer in ^{229}Th

P. Chhetri[1], S. Bara[1], K. Beeks[2], C. Bernerd[1,3], M. Block[4,5,6], A. Claessens[1], T.E. Cocolios[1], J.G. Correia[7], A.R.G. Costa[8], S. Cottenier[9], H. De Witte[1], R. Ferrer[1], S. Geldhof[10], N. Hosseini[2], F. Ivandikov[1], Yu. Koudriavtsev [1], U. Koester[11], S. Kraemer[1], M. Laatiaoui[5,6], R. Lica[3], G. Magchiels[8], J. Moens[8], I. Moore[12], L.M.C. Pereira[8], S. Raeder[4,5], M. Reponen[12], S. Rothe[3], A. de Roubin[1], T. Schumm[2], S. Sels[1], P.G. Thirolf[13], S.M. Tunhuma[8], P. Van Den Bergh[1], P. Van Duppen[1], A. Vantomme[8], R. Villarreal[8], U. Wahl[7]

Spokesperson: Premaditya Chhetri
Co-Spokesperson: Piet Van Duppen
Local contact: Cyril Bernerd

1Institute for Nuclear and Radiation Physics, KU Leuven, Belgium
2Institute of Atomic and Subatomic Physics, Vienna University of Technology, Austria
3ISOLDE-CERN, Switzerland
4GSI Helmholtzzentrum fur Schwerionenforschung, Germany
5Helmholtz-Institut Mainz, Germany
6Department Chemie, Standort TRIGA, Johannes Gutenberg Universitat Mainz, Germany
7Instituto Superior Tecnico, Universidade de Lisboa, Portugal
8Quantum Solid State Physics, KU Leuven, Belgium
9Center for Molecular Modelling, Ghent University, Belgium
10Grand Accelerateur National d'Ions Lourds, France
11Institut Laue-Langevin Grenoble, France
12Department of Physics, University of Jyvaskyla, Finland
13Ludwig-Maximilians-Universit¨at M¨unchen, Germany

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Towards the thorium nuclear clock-Current status

- Potential ultra-high precision frequency metrology
  - Sensitivity to variation of fundamental constants
  - Potential application

- Energy → 8.3 eV
  - Uncertainty ~ 0.17 eV (3 nm)
  - Large scanning range for potential laser excitation

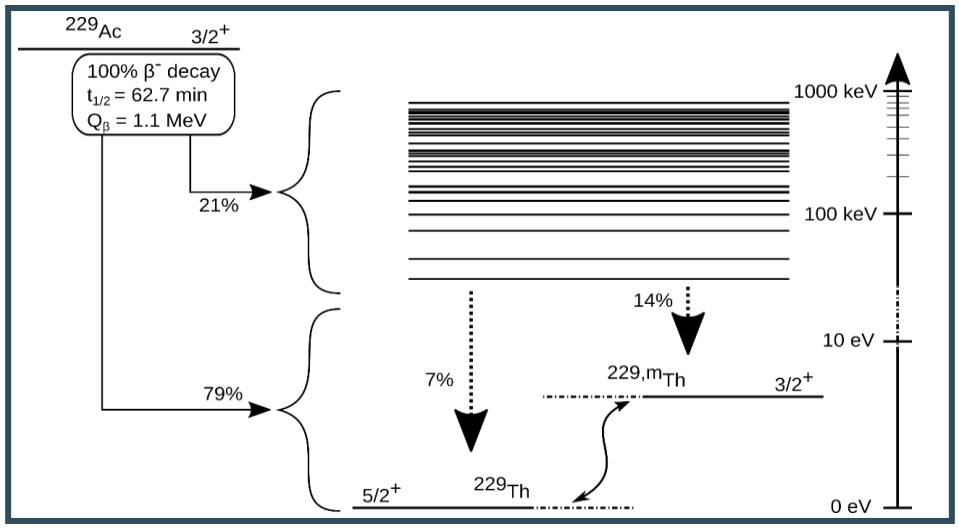
- Lifetime → 7μs (IC decay)

(1) Seiferle et al., Nature (London) 573, 243 (2019).
(2) Flambaum, PRL **97**, 9 (2006)
(3) Thirolf et al., Ann. Der Phys. 531, 1800381 (2019)

Population of the isomer-IS658

β −decay of 229Ac

- Feeding of isomer: 14% indirect between 0%-79% direct
- < 6eV recoil energy
  - ➢ Preservation of lattice position
- Radioluminescence: β −radiation
- $T_{1/2} = 62.7\ (5)$ mins
  - ➢ Time for manipulation of implanted sample



M. Verlinde et al., Physical Review C 100, 024315 (2019).

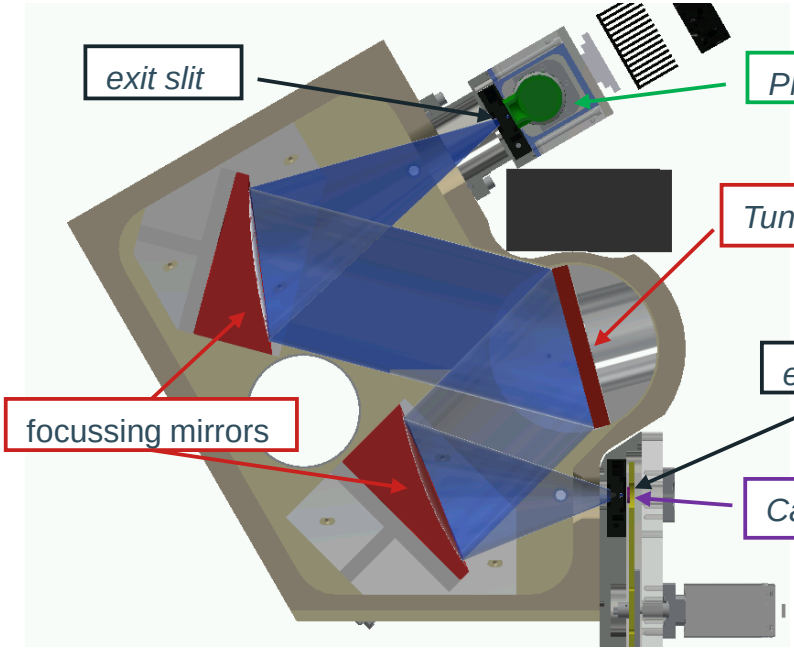
IS658-Beamtime 2021

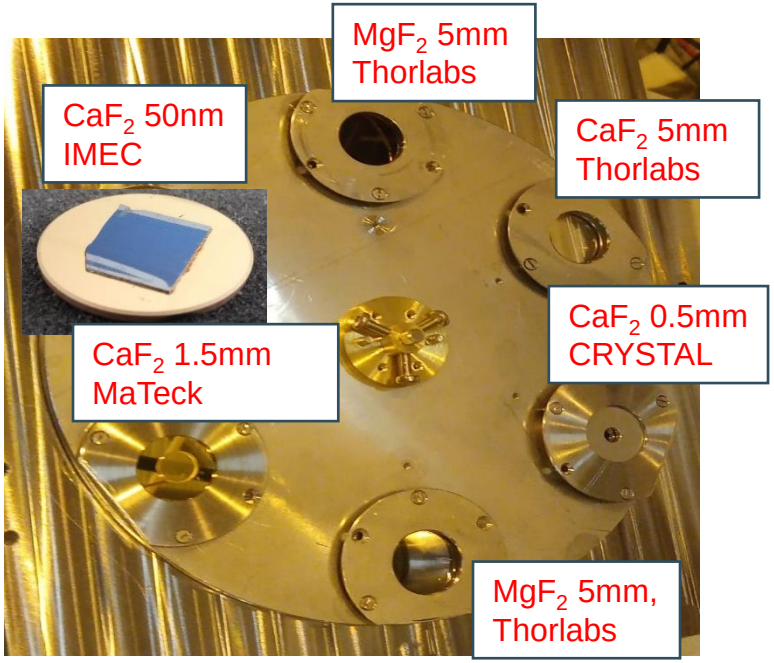
VUV spectroscopy

- 28 implantations into 5mm MgF_2, 5mm CaF_2, 50nm CaF_2
- Activity monitored using $LaBr_3$ and HPGe
- No laser ionized ^{229}Ac beam from ISOLDE
- Surface ionized A=229 and 230 beam from ISOLDE
- Production rate 10^6 ^{229}Ra pps and 10^5 ^{229}Fr pps

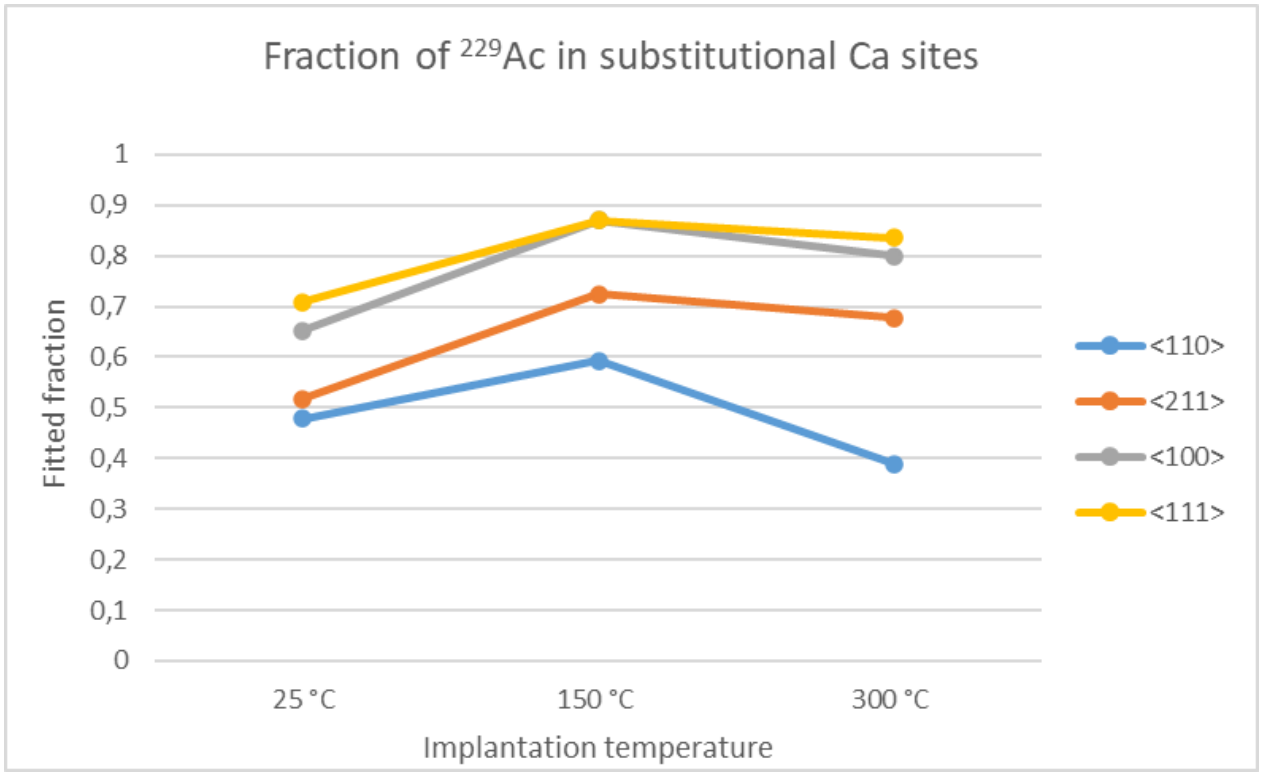
Emission channeling

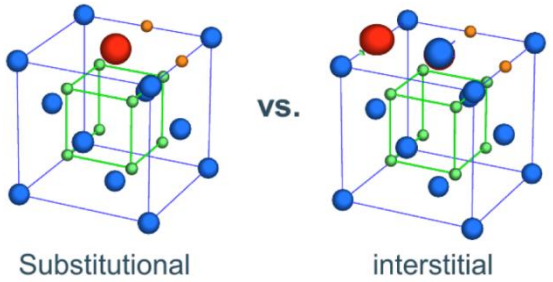
- Study of actinium and thorium lattice position in CaF_2





Results of IS658-Emission channelling





Preliminary results:

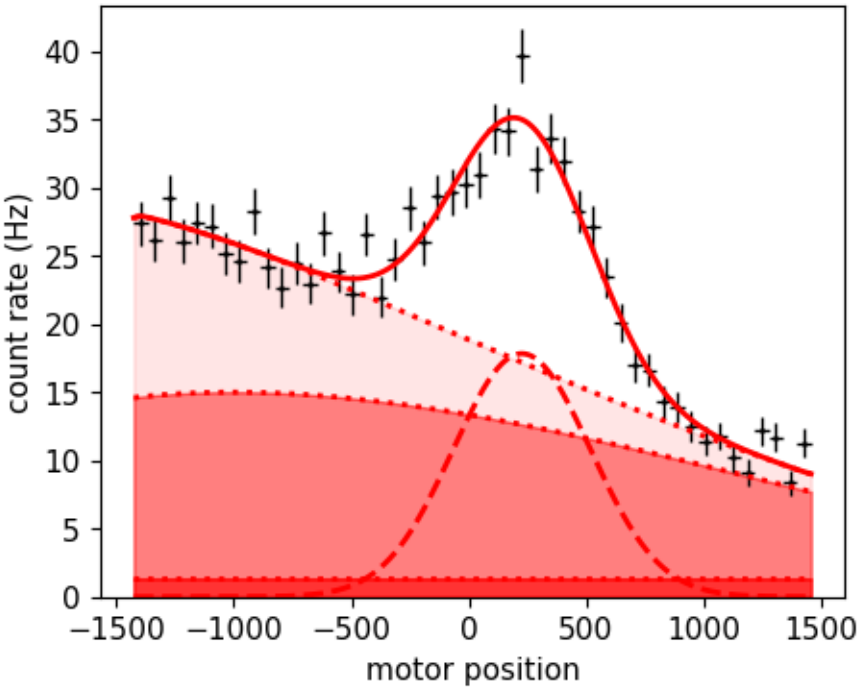
- Large fraction of ^{229}Ac occupies a favorable position in CaF_2
- Annealing increases the substitutional fraction

Data availability:

- ^{231}Ac decay chain data in CaF_2
- ^{229}Ac decay in MgF_2 feasibility test

Results of IS658-VUV spectroscopy: Identification

A = 229



CaF_2 thick crystal (5 mm)
MgF_2 thick crystal (5 mm)
CaF_2 thin crystal (50 nm)

Peaks can arise from:

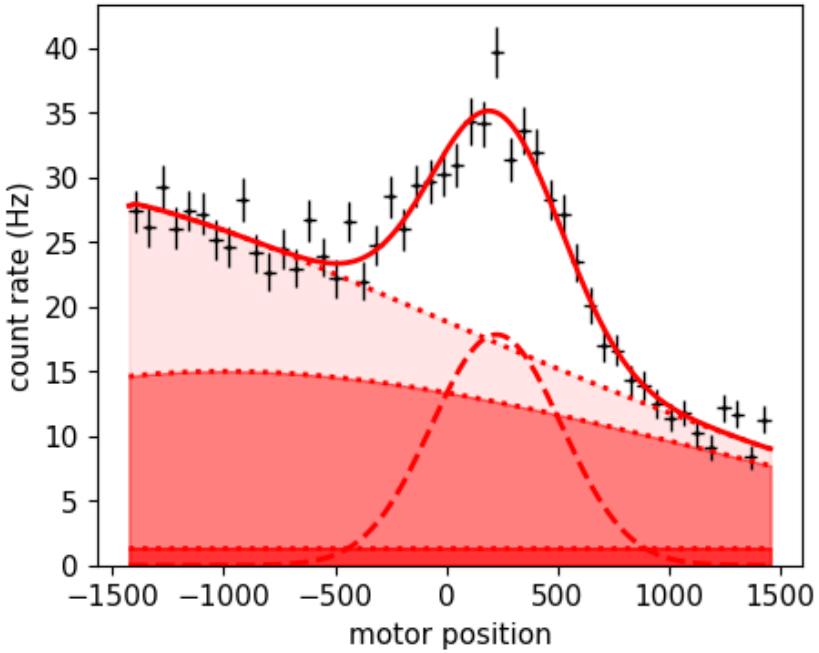
- **Signal of ^{229m}Th**
  - ⇒ Same for all crystals
  - ⇒ Present at A = 229
    Absent for A = 230
- **Crystal defect excitations**
  - ⇒ Present for crystal type only
  - ⇒ Present for both A=229 / A = 230

Clear narrow peak around ~ 150 nm only present in A = 229, where isomer is expected.

Absent for A = 230

⇒ **^{229m}Th signature**

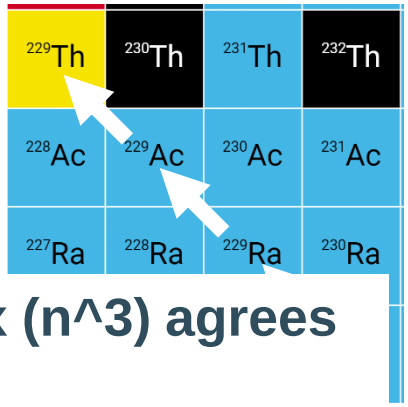
Results of IS658-VUV spectroscopy: Identification – Excitation energy of ^{229m}Th isomer



- Energy for A= 229 peak around 150 nm within 0.07 nm for all crystals
- Uncertainty in energy~0.4 nm (dominated by systematic uncertainties)
  - Radioactive source distribution
  - Hysteresis of the spectrometer
  - Crystal position compared to the calibration source
- **New calibration procedure and small slit: systematics down to 0.1 nm (aim of the current proposal)**

(1) B. Seiferle et.al. Nature 573**,** 243 (2019)
(2) T. Sikorsky et.al. Phys. Rev.Lett **125,** 142503 (2020)

Lifetime of radiative decay in MgF_2 crystal host



Lifetime of 10 mins→Corrected for the refractive index (n^3) agrees with predictions

(1) E.V. Tkalya et.al. Phys. Rev. C **92**, 054324 (2015)

Aim of this proposal

- **Precise energy measurement**:
  - Slit size of <0.5*mm* to reduce systematic uncertainty → higher production rates
  - Better calibration procedure
  - < 0.1*nm* accuracy to bridge the gap to laser excitation
- **Precise measurement of the lifetime** (<10% uncertainty):
  - Shorter implantation cycles ~30 mins → higher production rates
  - Lifetime dependency on the refractive index of the crystal
  - disentangle the branching ratio from the efficiency
- **Ratio of VUV photons to implanted ions**:
  - Check if substitutional position gives rise to radiative decay
- **Emission Channeling**:
  - Quantification and optimization of the substitutional incorporation of Ac/Th in CaF2 *thin film* and MgF_2
- **Alternative crystals** (bandgap<isomer energy) (CdF_2, PbF_2, AlI, MgO):
  - VUV spectroscopy
  - Emission channeling measurements if VUV signal observed

Beamtime Request

- Optimization and extraction ^{229}Ac

  3 shifts (laser ionization of ^{229}Ac)

- VUV spectroscopy

  Precise measurements of the isomer's energy and lifetime in CaF_2 and MgF_2 and measurements on alternative crystals CdF_2 and PbF_2

  25 shifts (>25 implantation of 30 mins - 2h spread over several days)

- Emission channeling measurements:

  Quantization and optimization of the substitutional incorporation of Ac/Th in CaF_2 thin film, MgF_2 and other crystals from which we see a VUV photon signal

  15 shifts (multiple collections of 2 h spread over several days)

Total number of shift : 28