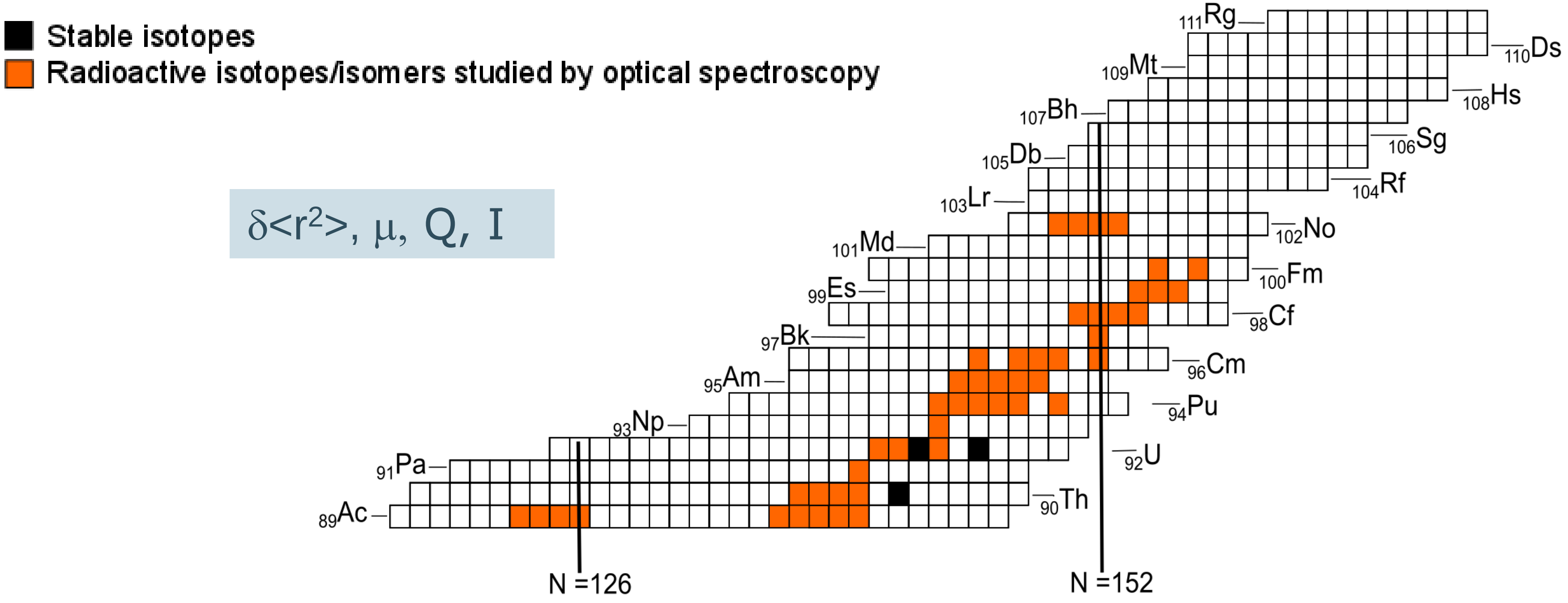
(Supersonic) Laser Ionization Spectroscopy of Heavy Elements

Rafael Ferrer
KU Leuven, Instituut voor Kern- en Stralingsfysica
Belgium

Outline

- Motivation for Laser Spectroscopy of Heavy Elements
- In-source laser spectroscopy of Ac isotopes
- The In-Gas Laser Ionization and Spectroscopy (IGLIS) technique
  - ➢ Off-line characterization studies
- Plans for IGLIS studies of exotic nuclei
- Summary & Outlook

Optical Spectroscopy Actinides



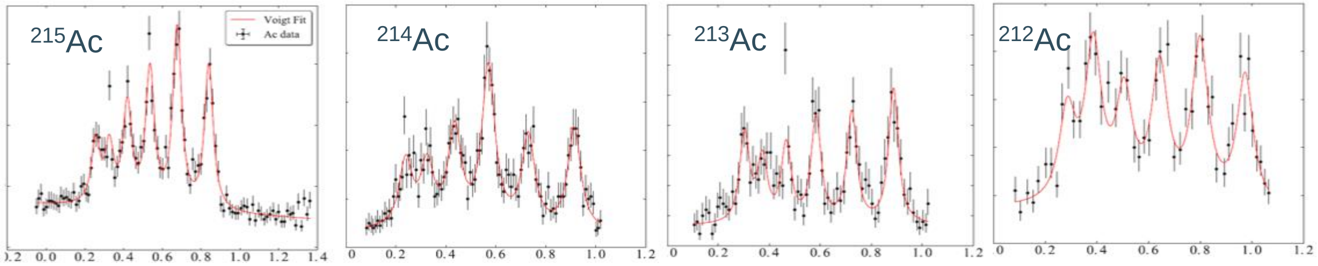
$\delta\langle r^2\rangle$, μ, Q, I

Challenges:

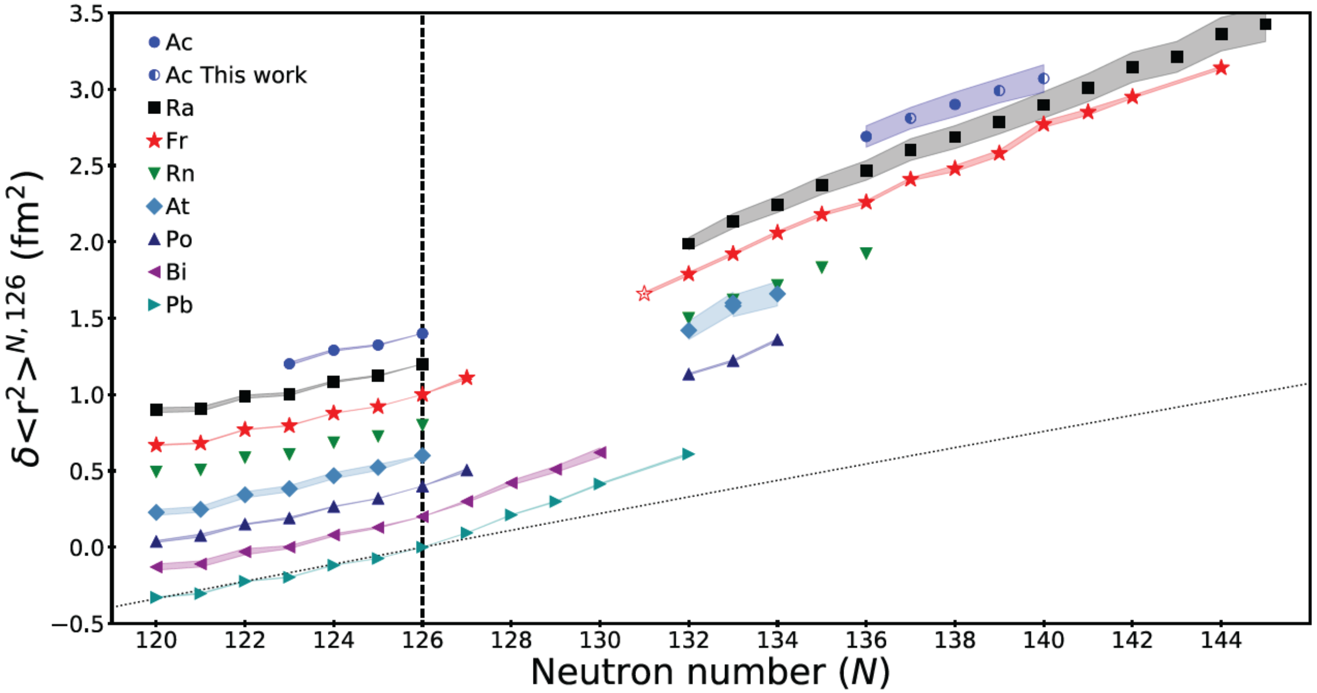
- Laser spectroscopy of fusion evaporation reaction products
- Low production rates of actinides call for a highly-sensitive and -efficient laser spectroscopy technique
- High spectral resolution required to resolve hyperfine structure

In-source Laser Spectroscopy of Ac

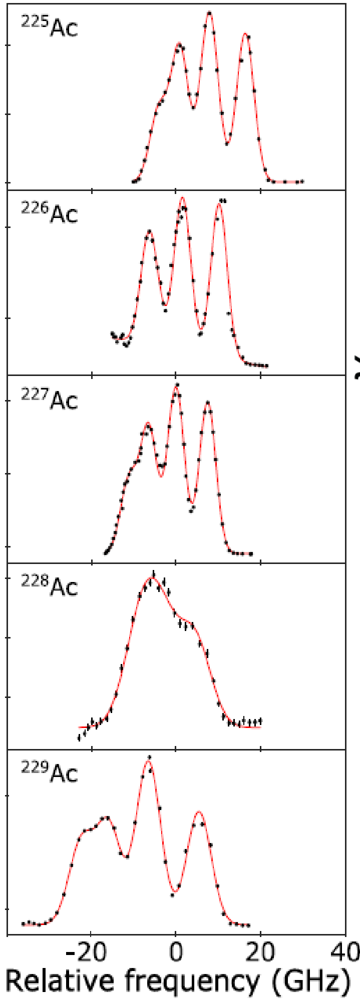
Gas cell (LISOL)



Relative freq. *100 (GHz)

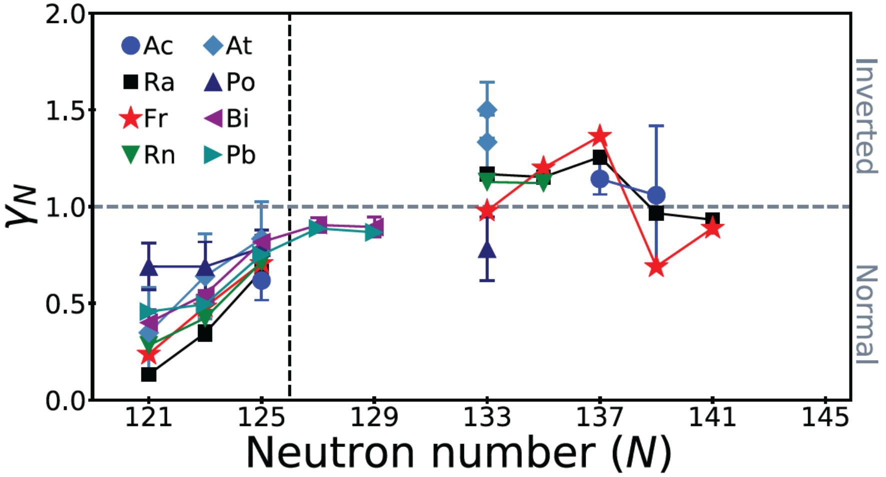


Hot Cavity (TRIUMF)



Staggering parameter odd N

$$\gamma_N = \frac{\delta\langle r^2\rangle^{N-1,N}}{\frac{1}{2}\delta\langle r^2\rangle^{N-1,N+1}}$$

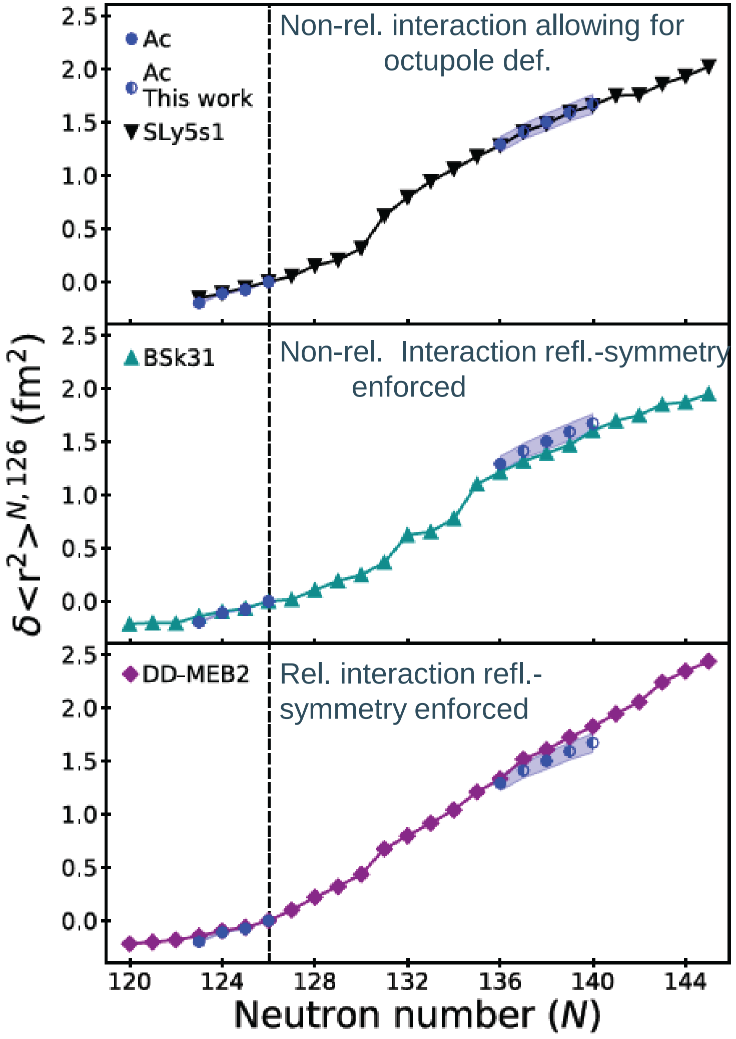


- An inversion OES ($\gamma_N > 1$), around N = 135, has been associated with reflection-asymmetric nuclear shapes
  → **Octupole deformation**

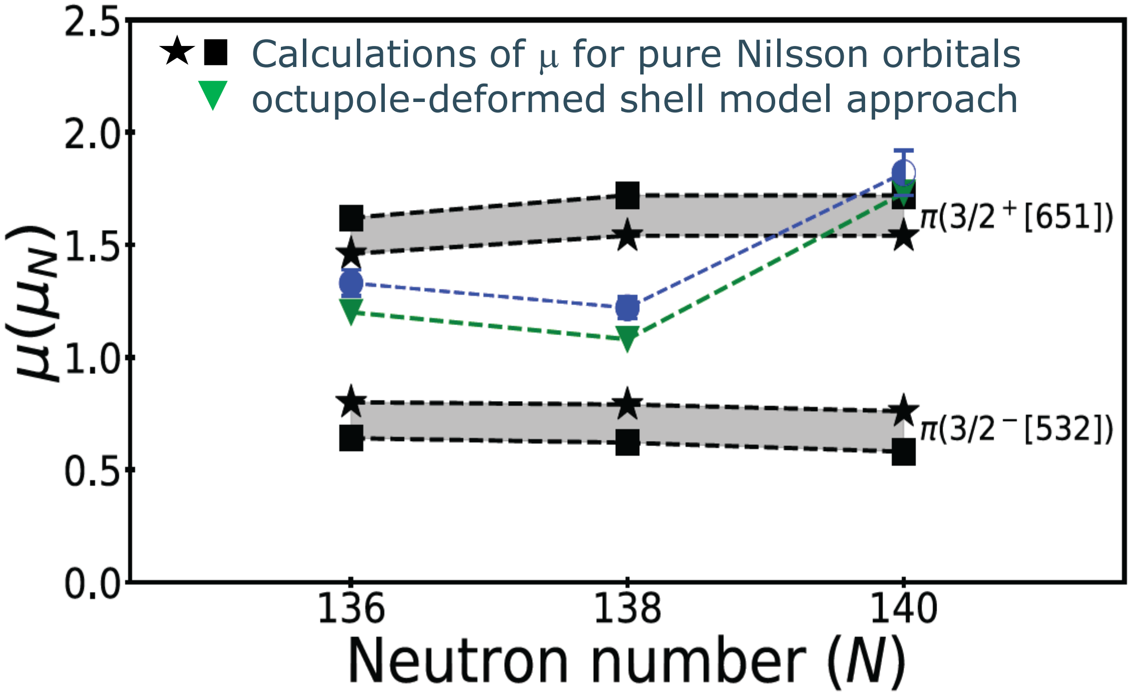
E. Verstraelen, A. Teigelhoefer, W. Ryssens et al. PRC (2019) Accepted

KU LEUVEN

In-source Laser Spectroscopy of Ac



- Three different EDFs calculations to describe charge radii of Ac
- Good agreement with experimental values for $^{225-229}$Ac when the octupole degree of freedom is taken into account
  - Comparison of μ values for the odd-mass Ac ●



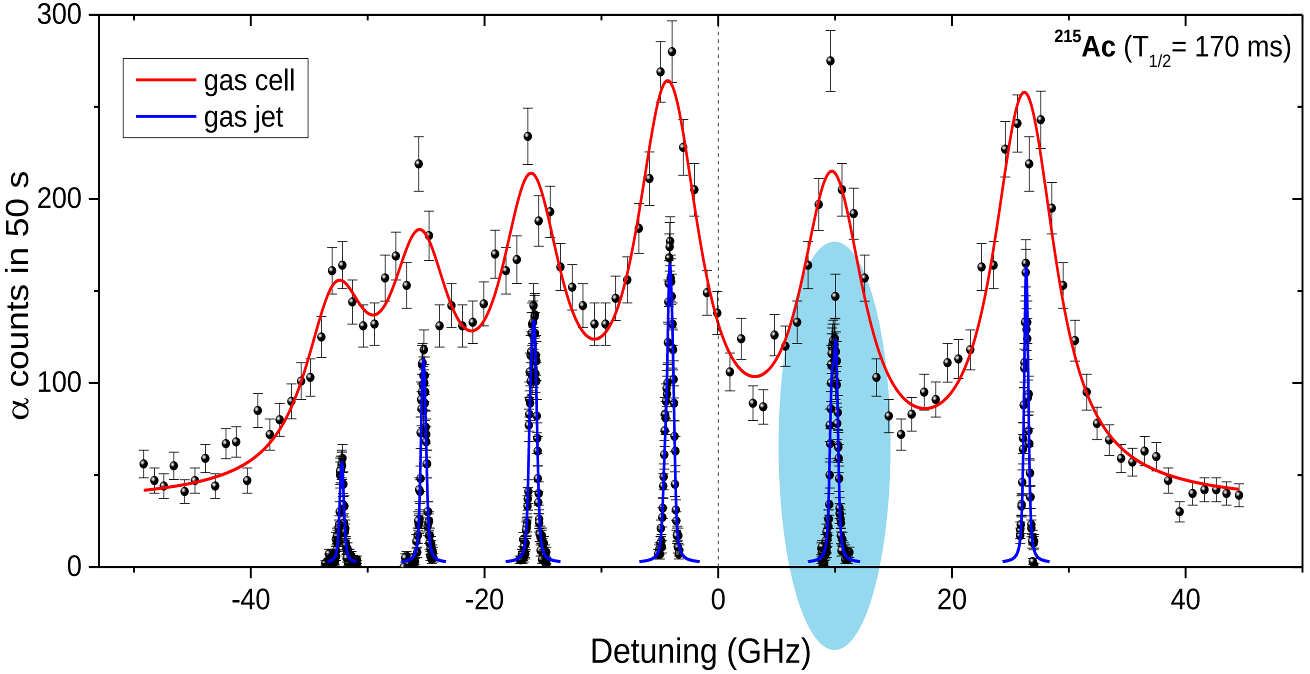
- Presence of octupole def. also supported by comparing μ of ^{226,228}Ac with predictions using the additivity rule

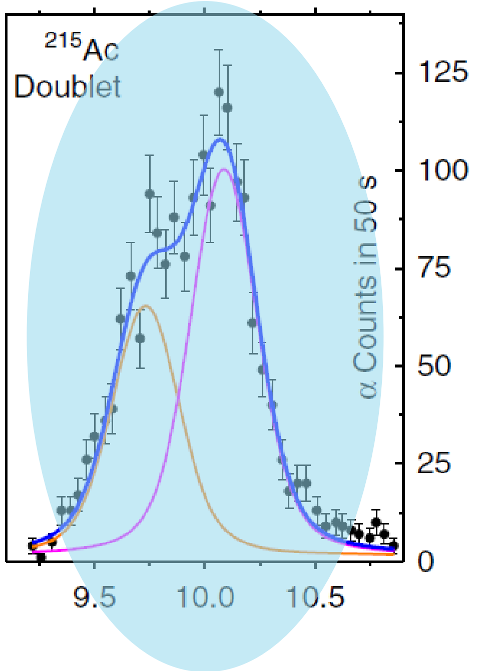
E. Verstraelen, A. Teigelhoefer, W. Ryssens et al. PRC (2019) Accepted
G. A. Leander and Y. S. Chen, Physical Review C 37, 2744 (1988)
G. Leander and R. Sheline, Nuclear Physics A 413, 375 (1984)

KU LEUVEN

In Gas Laser Ionization and Spectroscopy (IGLIS)

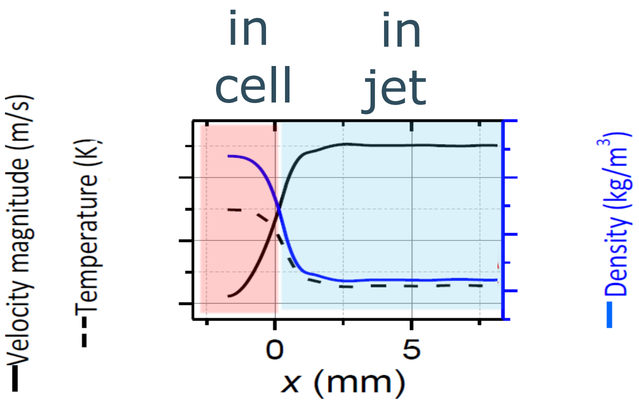
In-Cell vs In-Jet Spectroscopy





I & Q values for ^{214,215}Ac

$\mathcal{E}_{jet} \sim \mathcal{E}_{GC}$



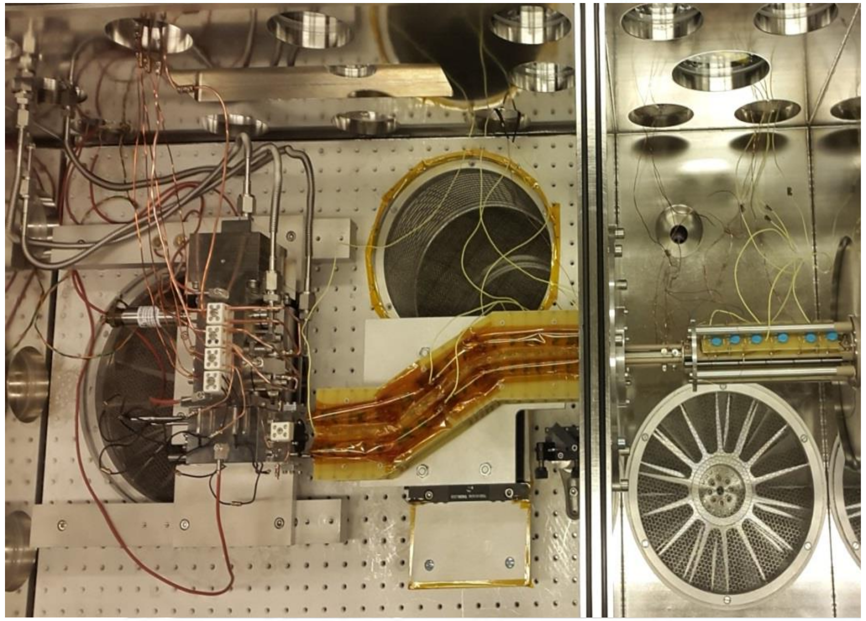
- collisions $\Delta\vartheta_\rho \sim \left(\frac{T_{jet}}{T_{293K}}\right)^{0.3} * \rho_{jet}$
- temperature $\Delta\vartheta_{Doppler} \sim \vartheta_0 \sqrt{T_{jet}/A}$

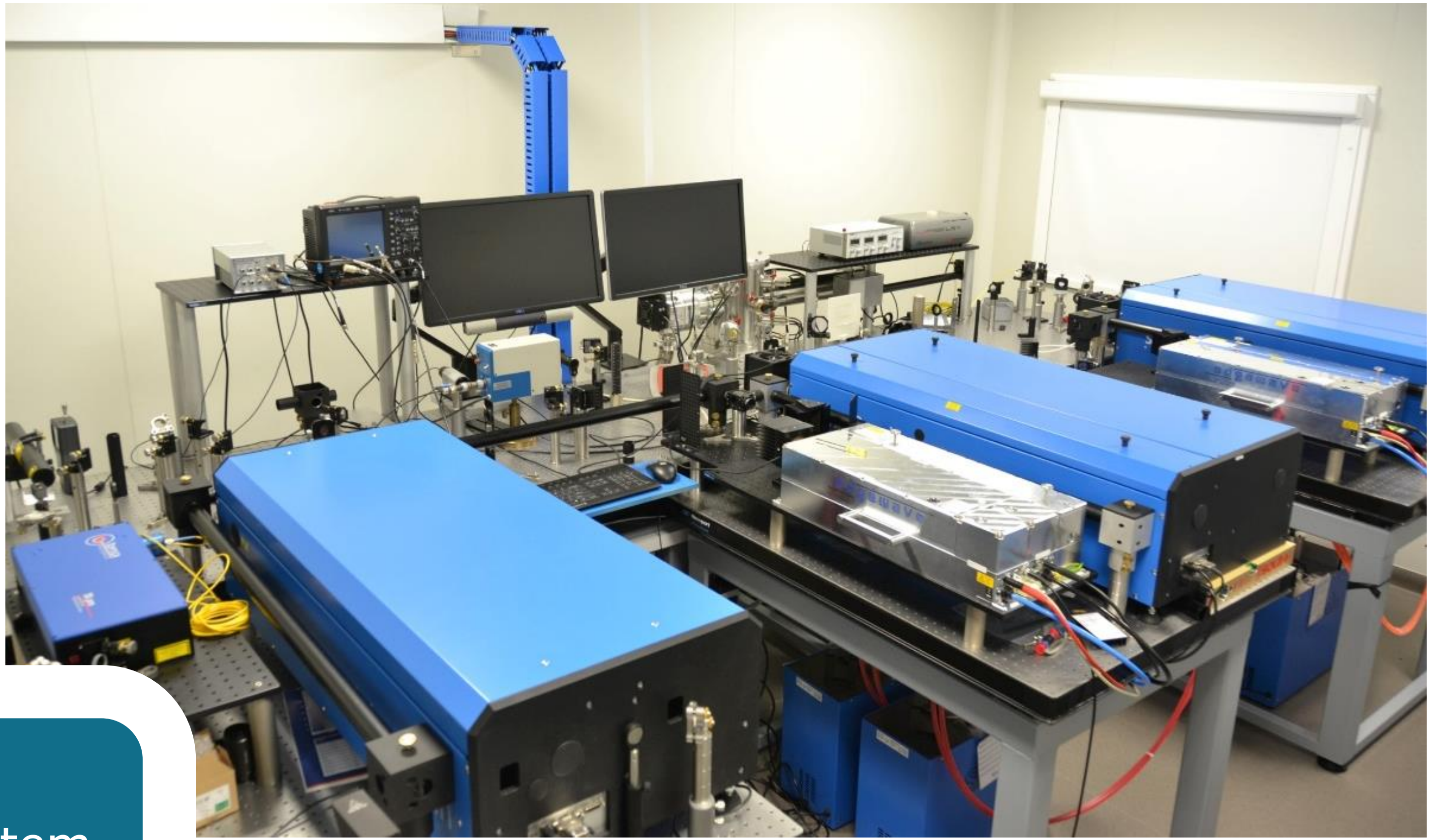
$$T_{jet} = \frac{T_0}{\left(1 + \frac{\gamma - 1}{2} M^2\right)},$$

Characterization/ optimization of IGLIS technique @ offline IGLIS laboratory

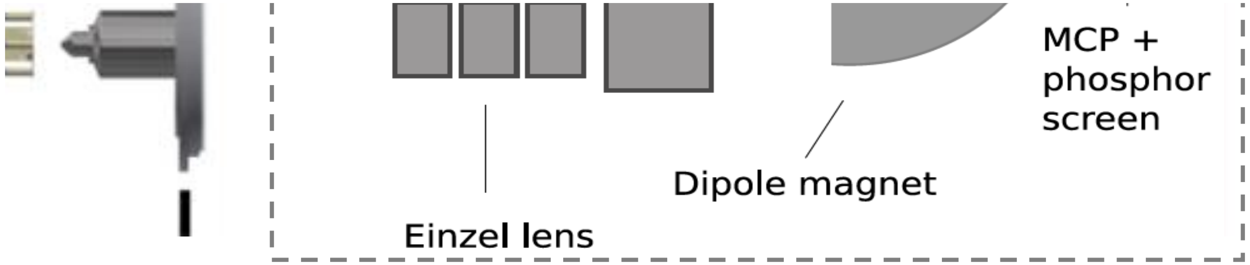
R. F. et al., Nat. Commun. 8 (2017) 14520

IGLIS laboratory @ KU Leuven (off-line studies)



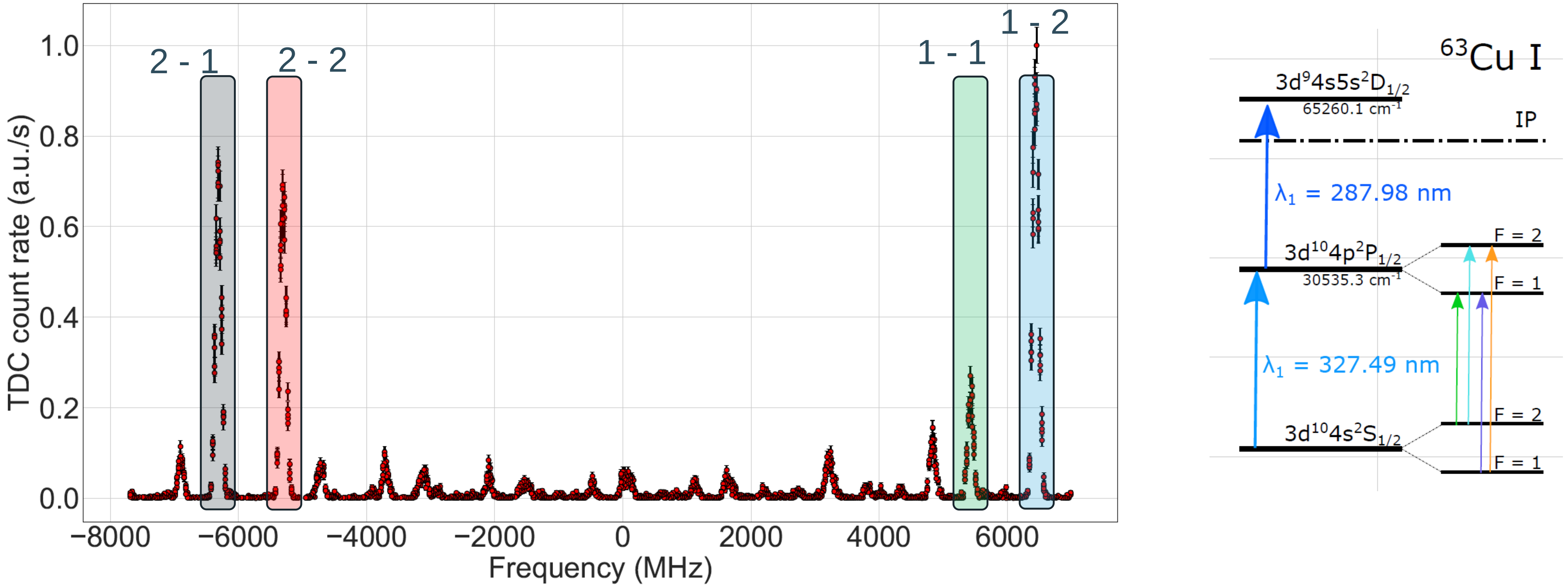


R&D on:
- High power high rep. dye laser system
- New gas cell designs
- RFQ Ion Guides
- Jet properties with CD nozzles



Laser Spectroscopy of Cu in Atomic Beam Unit

- Narrow-band pulse dye amplification results in multiple side-band formation in copper spectrum: sidebands = n*800 MHz



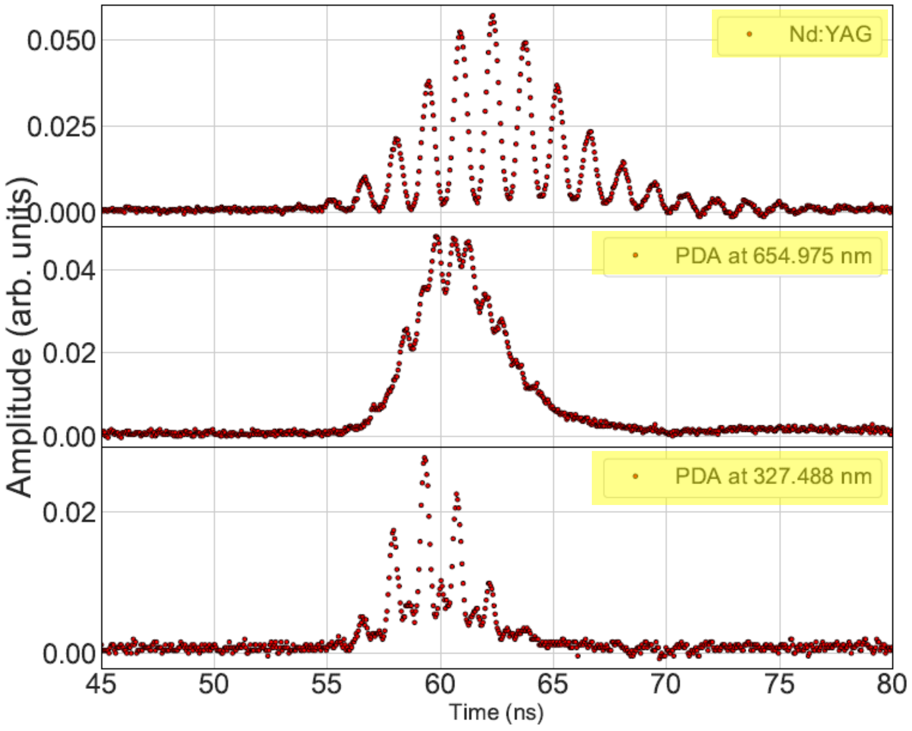
Fluctuations mode intensities in pump laser resonator are transferred to Pulsed Dye Amplifier (PDA) output

Multimode Pump Laser Waveforms

(INNOSLAB Edgewave 90 W @ 10 kHz)

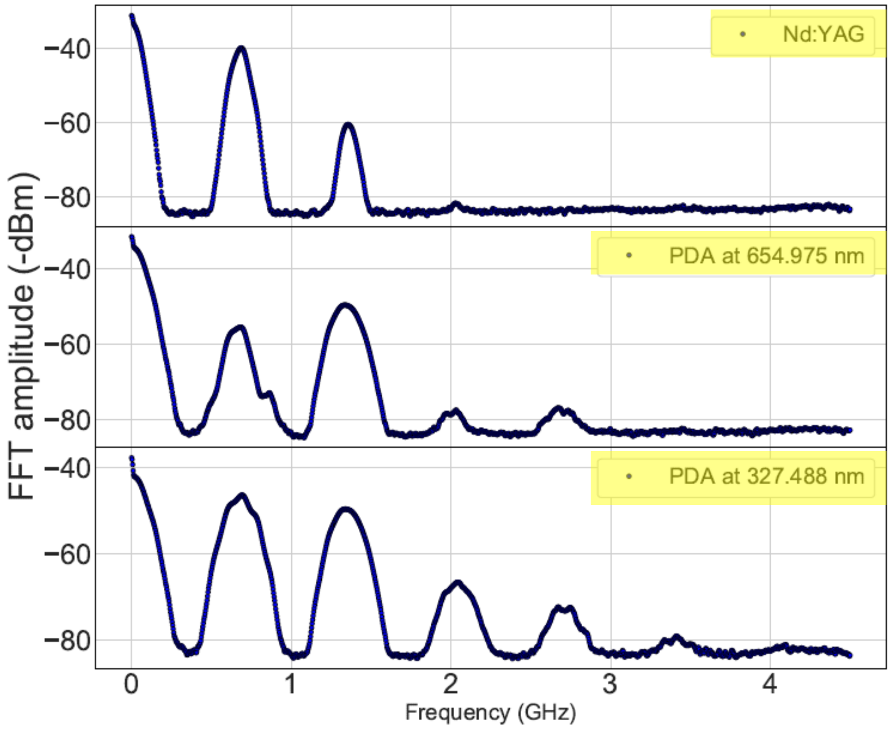
- Time profiles

Time modulation ~1.2 ns



- Frequency domain

Sideband formation harmonics 800 MHz

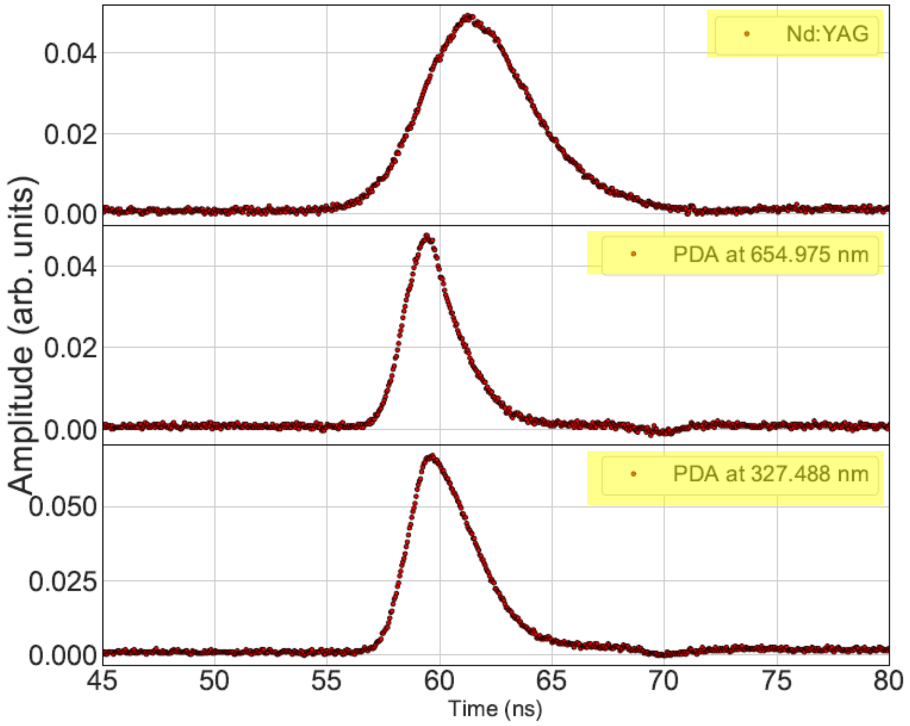


Single-Longitudinal-mode Pump Laser Waveforms

(INNOSLAB SLM Edgewave 40 W @ 10 kHz)

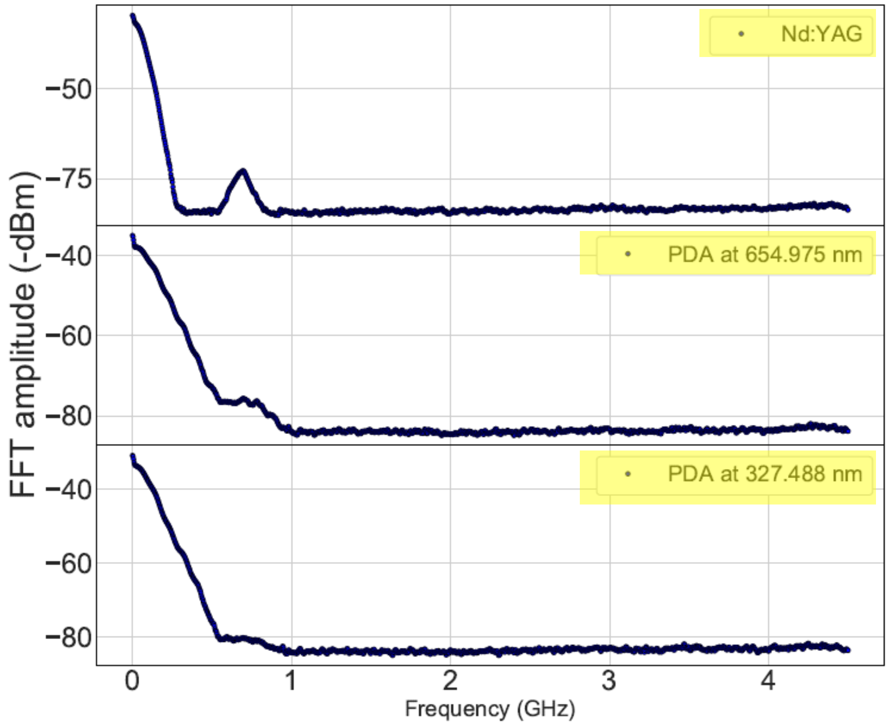
- Time profiles

Free of modulation



- Frequency domain

Side-band free spectrum



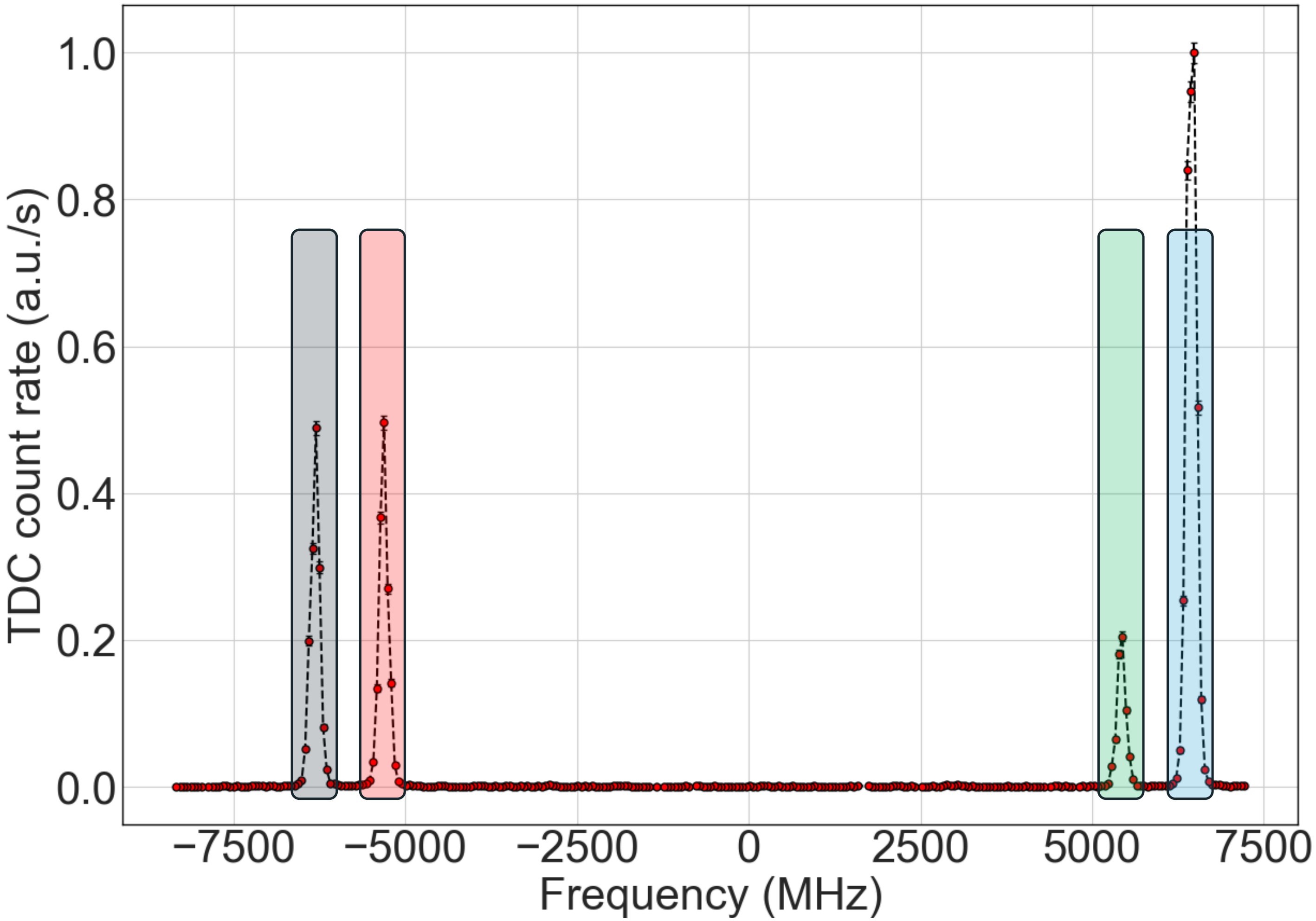
KU LEUVEN

Laser Spectroscopy of Cu in Atomic Beam Unit

Using Single-Longitudinal-Mode Pump Laser

- Single-mode operation
  - ABU spectroscopy results

New Laser for IGLIS
60 W @ 15 kHz
20 kHz max. rep. rate
8 ns pulses

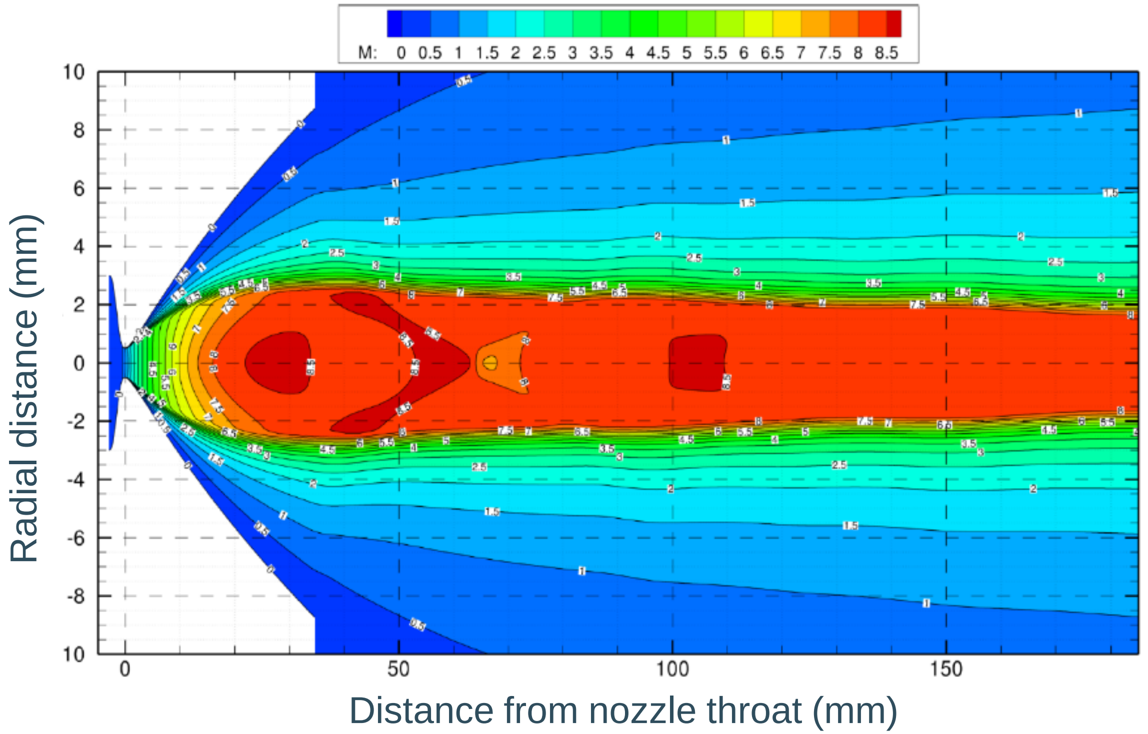


KU LEUVEN

High Mach-number Nozzle (M=8.5): Calculations & Manufacturing

New set of calculations

- nozzle contour from advanced simulation code by Aeronautics and Aerospace Department (*VKI)*

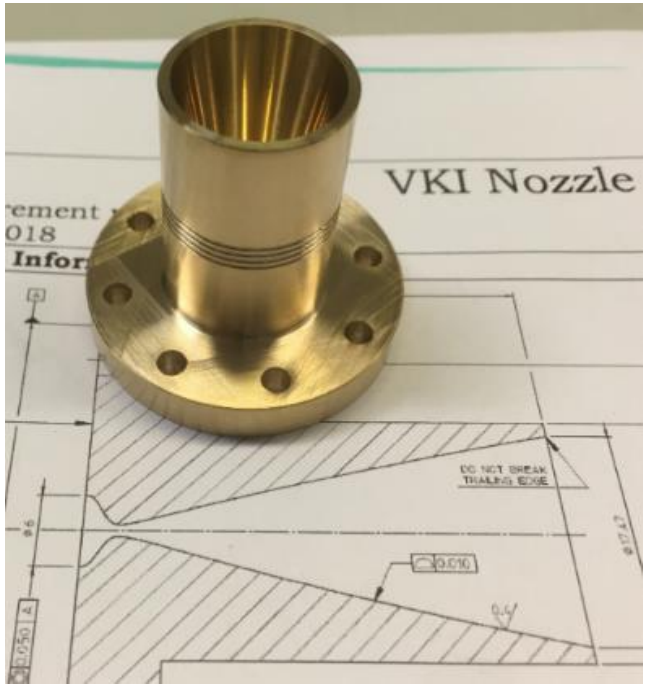


- Viscous corrections included

→ Simulations show developments of extremely thick boundary layers along nozzle walls

Precision machining

- precision inner contour ~ 5 μm
- surface finishing Ra= 0.1 μm



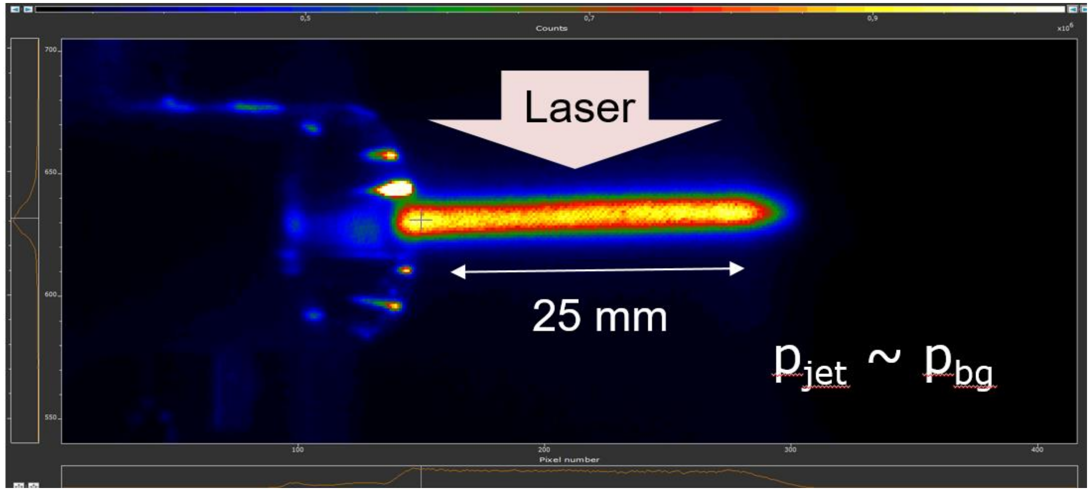
- Five pieces (two within specs)

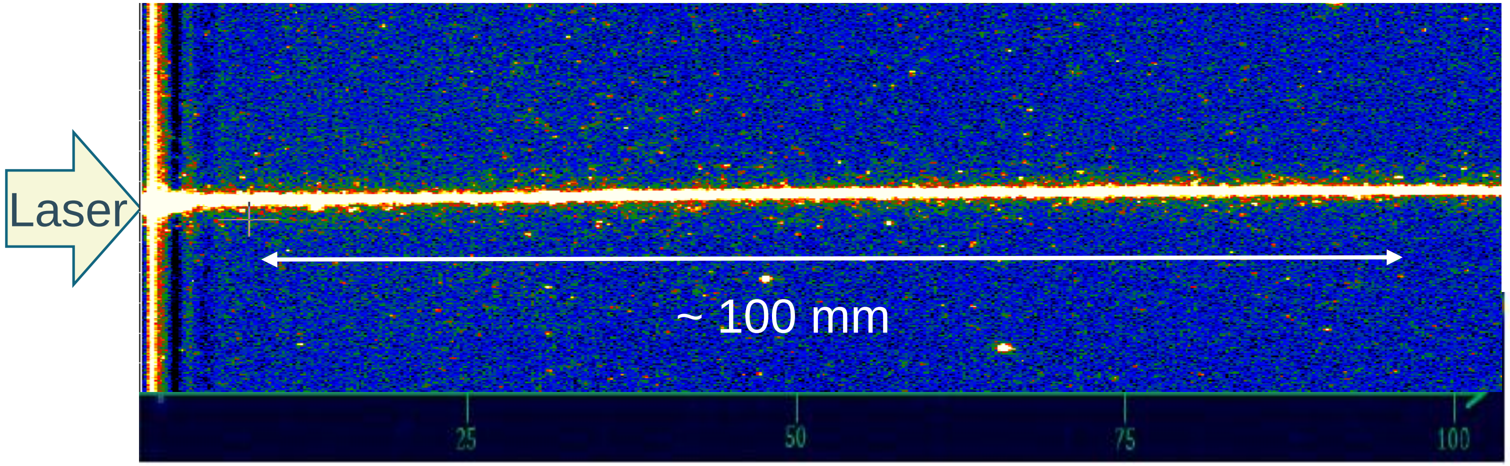
→ Check effect of contour imperfections in gas jet formation

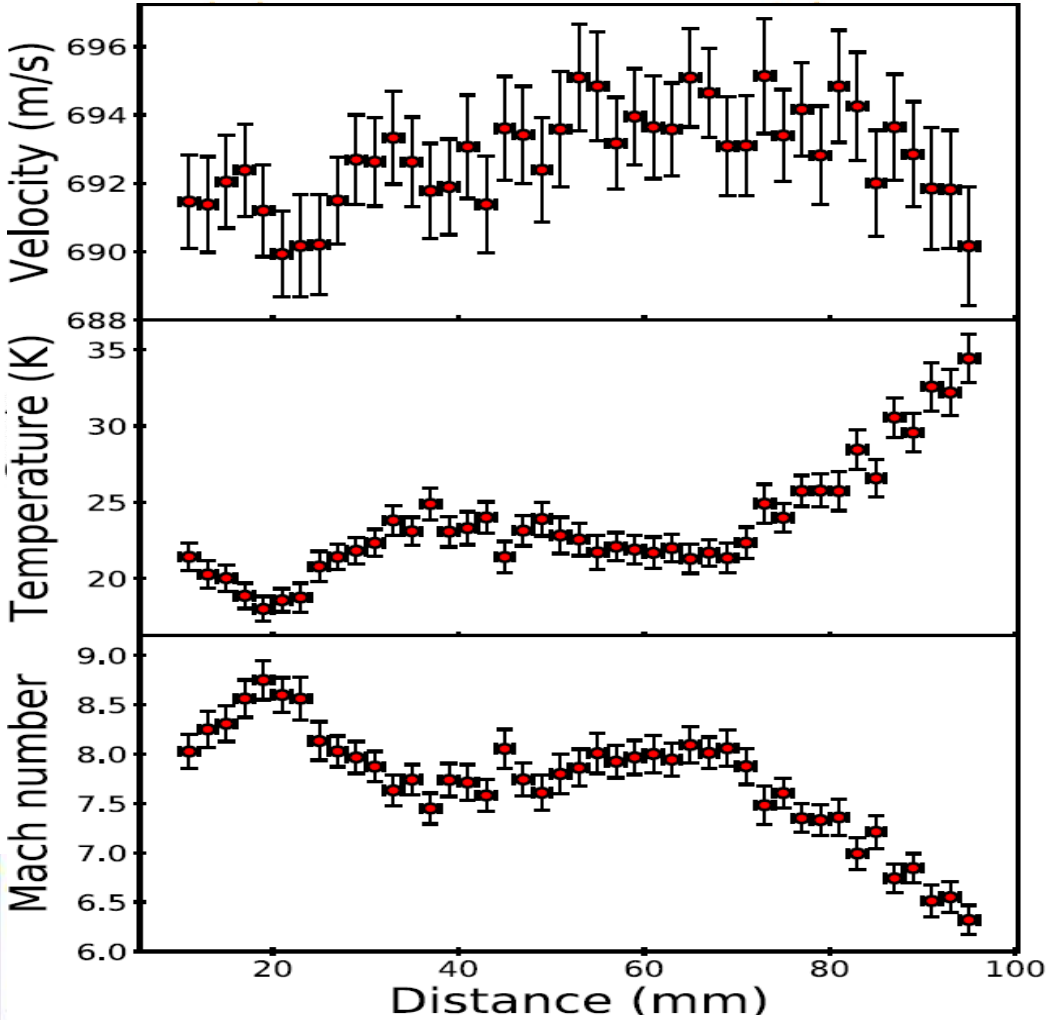
A. Zadvornaya et al. Phys. Rev. X 8, 041008 (2018)

KU LEUVEN

Characterization of local flow parameters:
Planar Laser Induced Fluorescence Spectroscopy





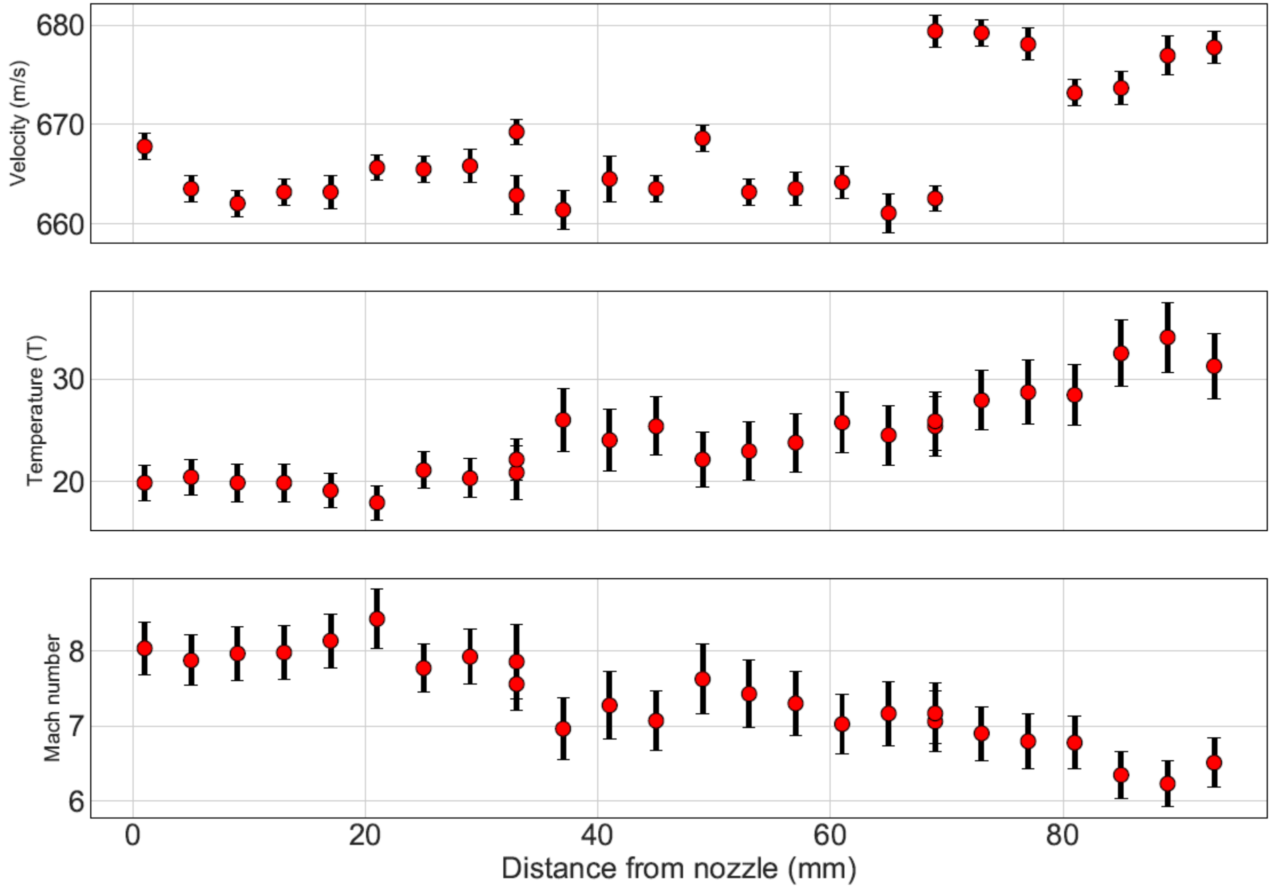


A. Zadvornaya et al. Phys. Rev. X 8, 041008 (2018)

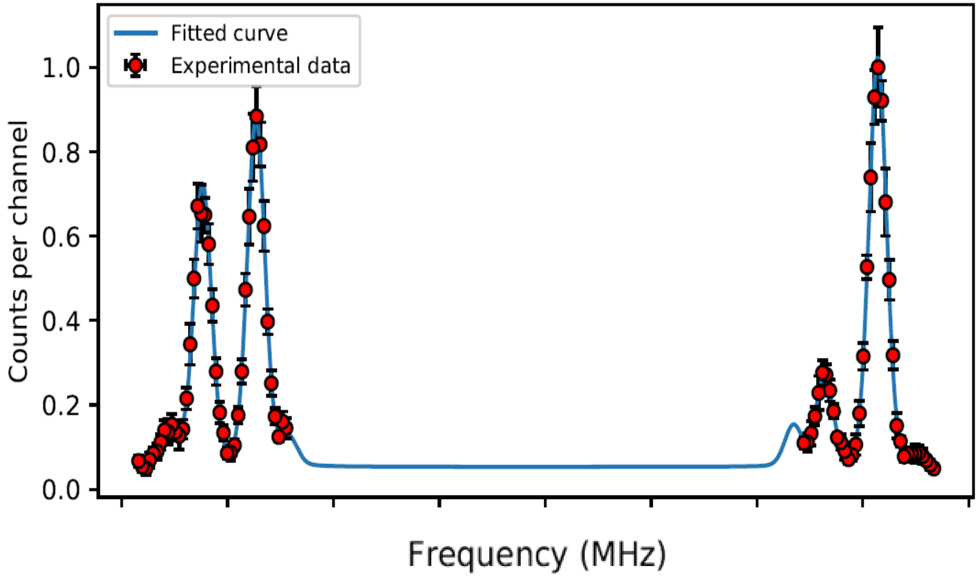
Characterization of local flow parameters:
Resonance Ionization Spectroscopy

- Geometrical scanning lasers to characterize jet parameters

300 times more efficient & ~ 5 times faster than PLIFS

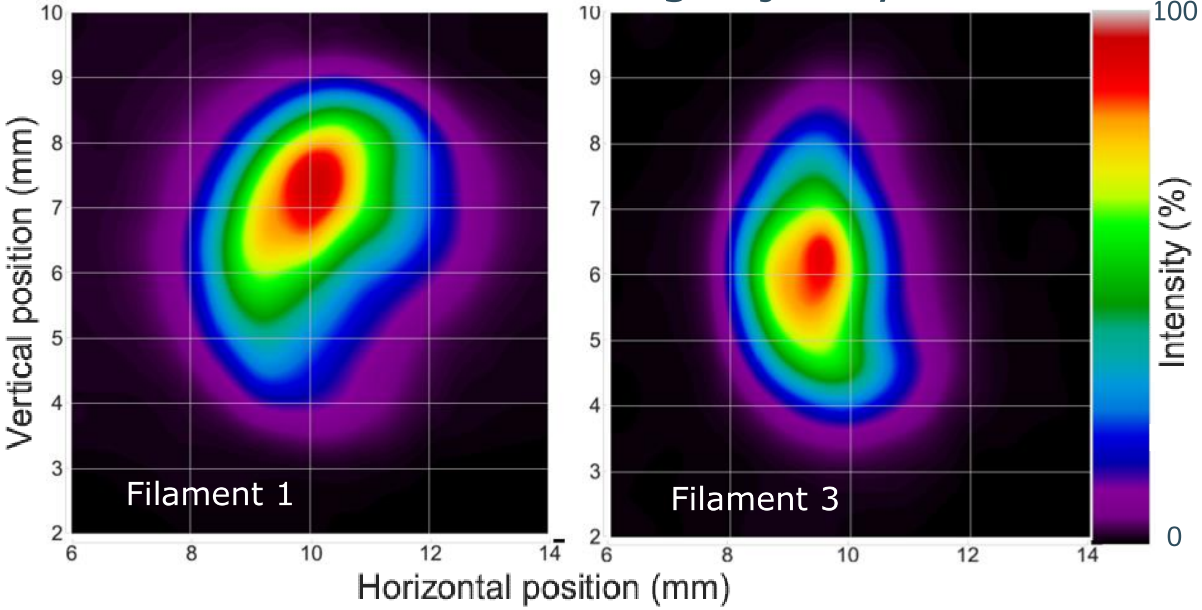


RIS on jet axis with 1st step collinear and 2nd step transverse ($P_{bg} \sim P_{jet}$)



High Mach-number Nozzle: results

- Calculations reproduce fairly well trend of RIS and PLIFS data
- Not well understood the observed offsets and sudden decrease of the experimental curves
- Radial cross-section gas jet by RIS



Cu flow lines do not travel on-center of the Ar jet?!

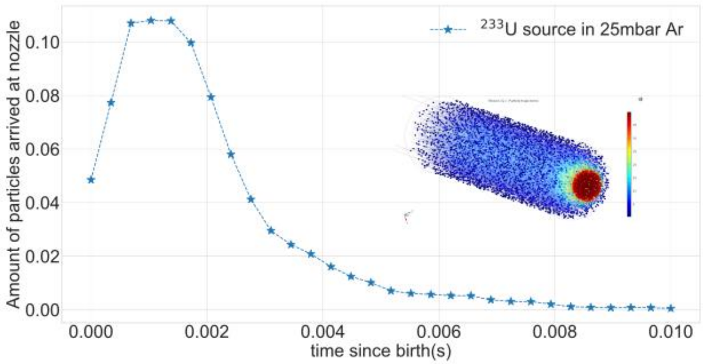
In-gas-jet laser ionization and spectroscopy of ^{229m}Th

Only one group has reported the production of a controlled ion beam of ^{229m}Th

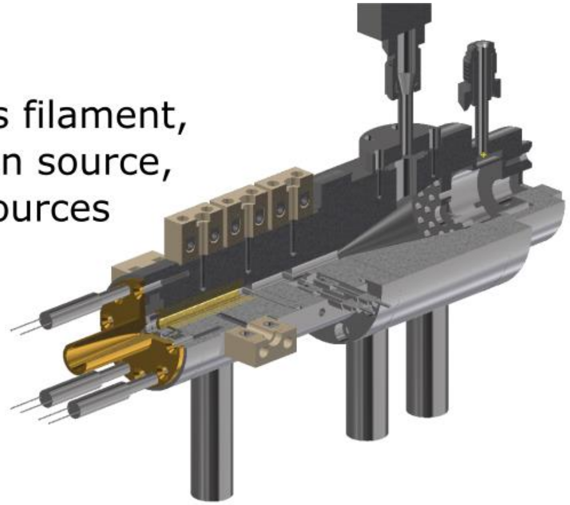
- Confirm nuclear structure (nuclear moments) and probe suspiciously absent $^{229m}Th^{1+}$
- Produce pure beams of ^{229m}Th

Fast gas cell

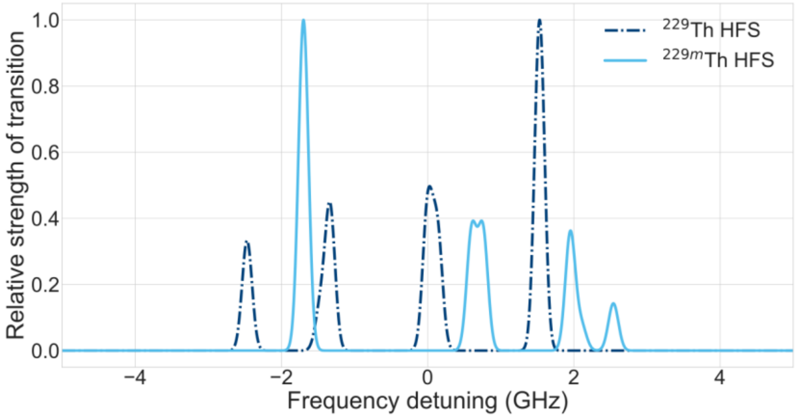
- ~1 ms extraction time



- Houses filament, ablation source, ^{233}U sources



- Expected FWHM ~ 160 MHz



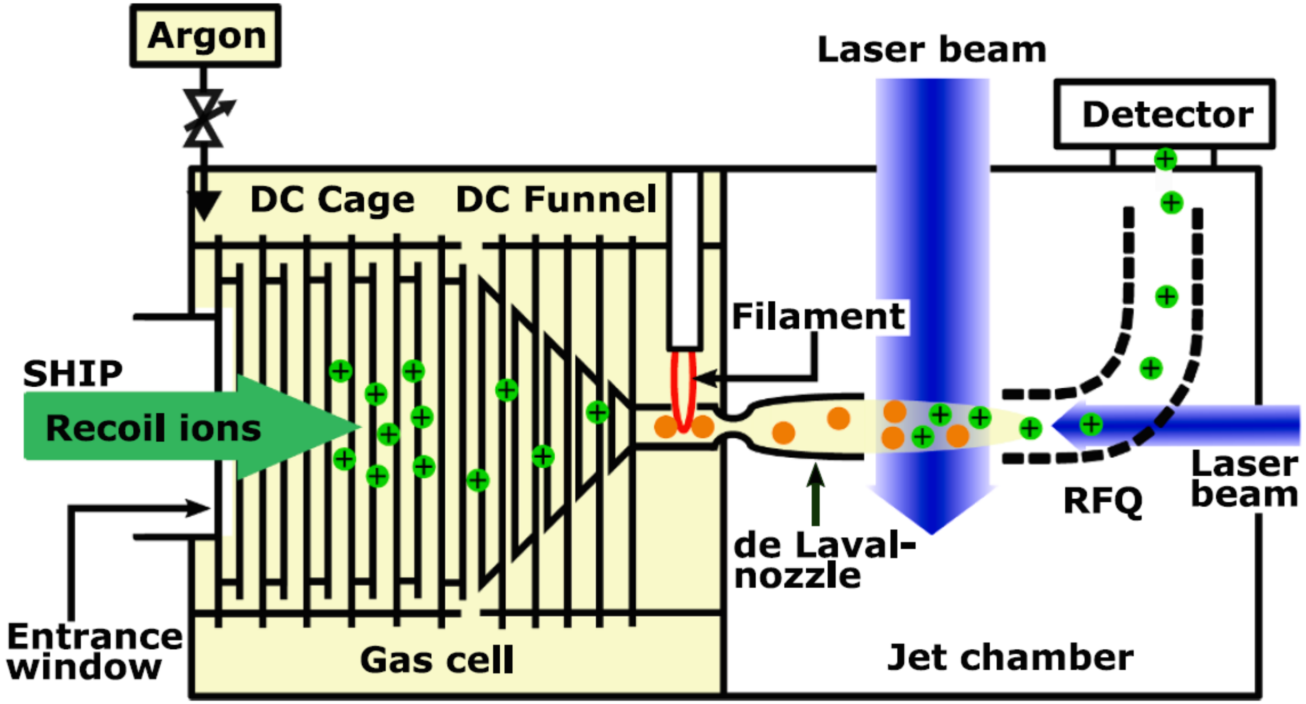
Goal: Determination of $E_{i.s.}$ by VUV spectrometry (149.7 ± 3.1 nm) using a 229Th-doped vacuum-ultraviolet-transparent crystal

L. von der Wense, et al. *Nature* 533, 47–51 (2016)
B. Seiferle et al. https://doi.org/10.1038/s41586-019-1533-4

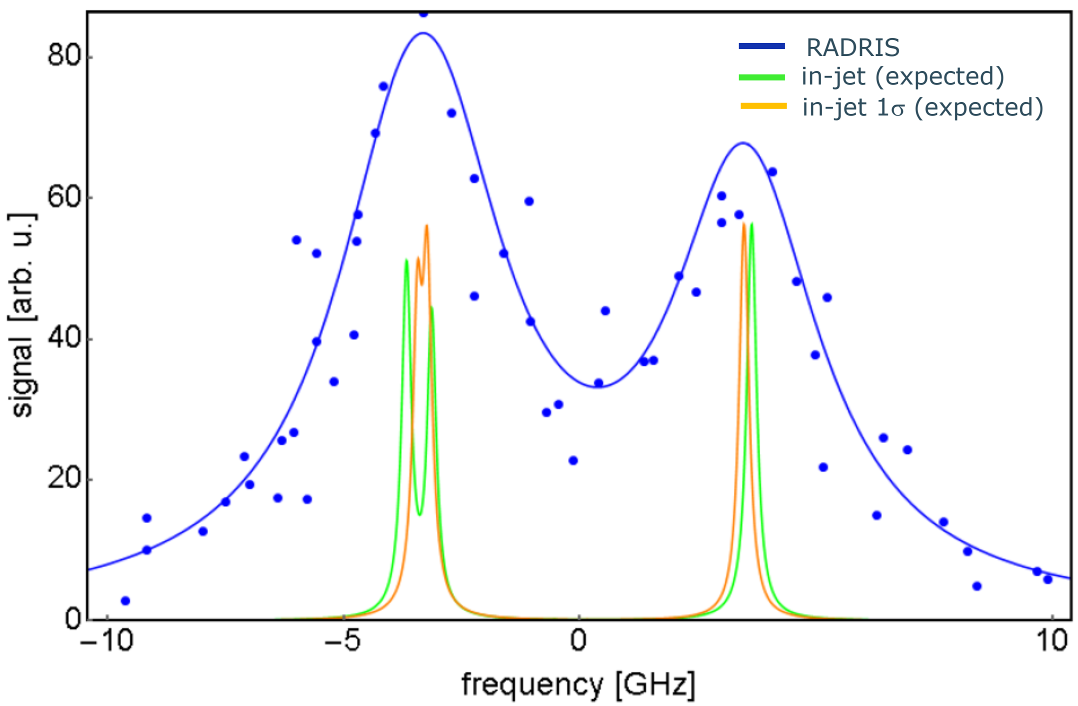
KU LEUVEN

In-gas-jet laser ionization and spectroscopy of ^{253,255}No

Combination of high-efficiency RADRIS with high resolution in-jet methods



HFS of ^{253}No

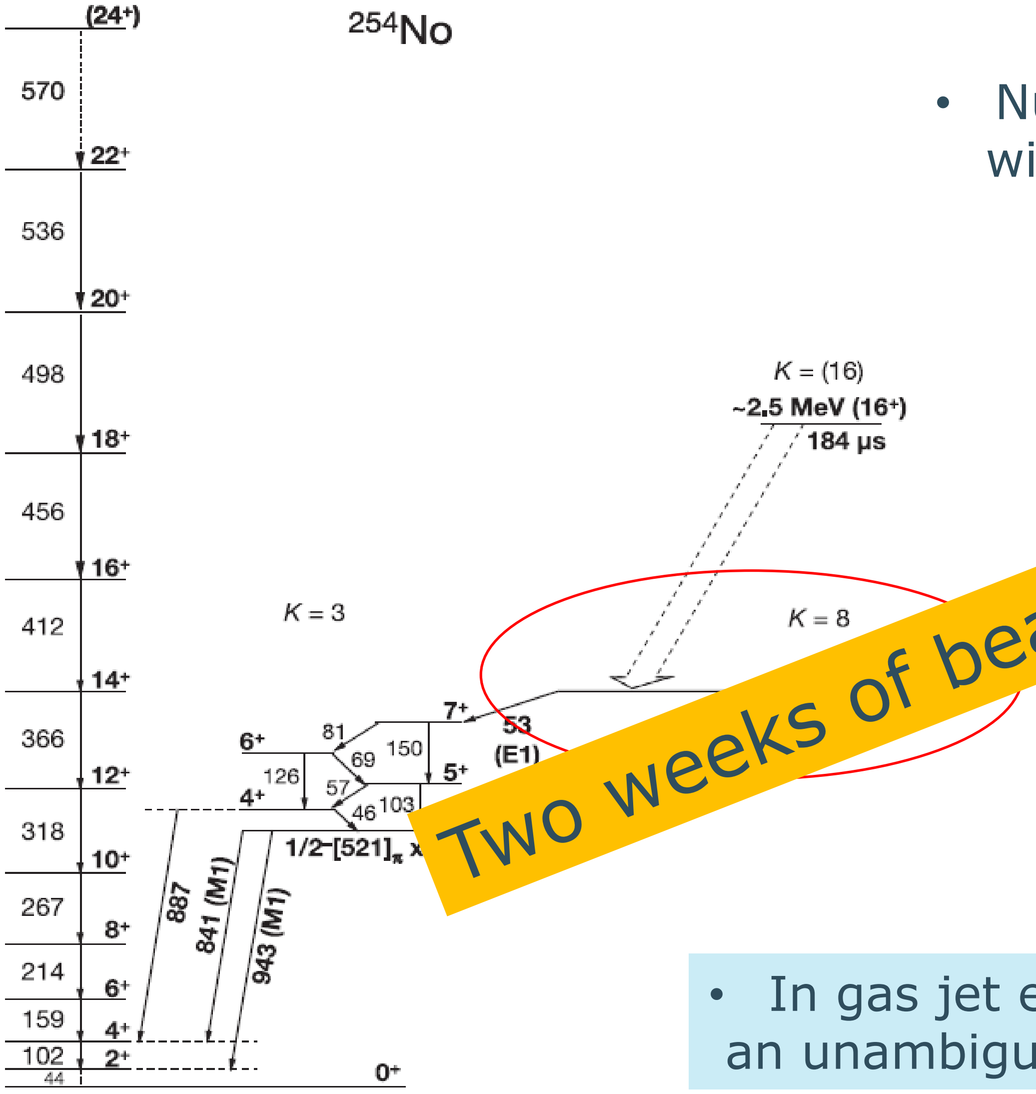


- Perform laser spectroscopy of the HFS of the isotopes ^{253,255}No with high resolution:
  Extracting deformation & assign Nilsson orbital→ validation nuclear models

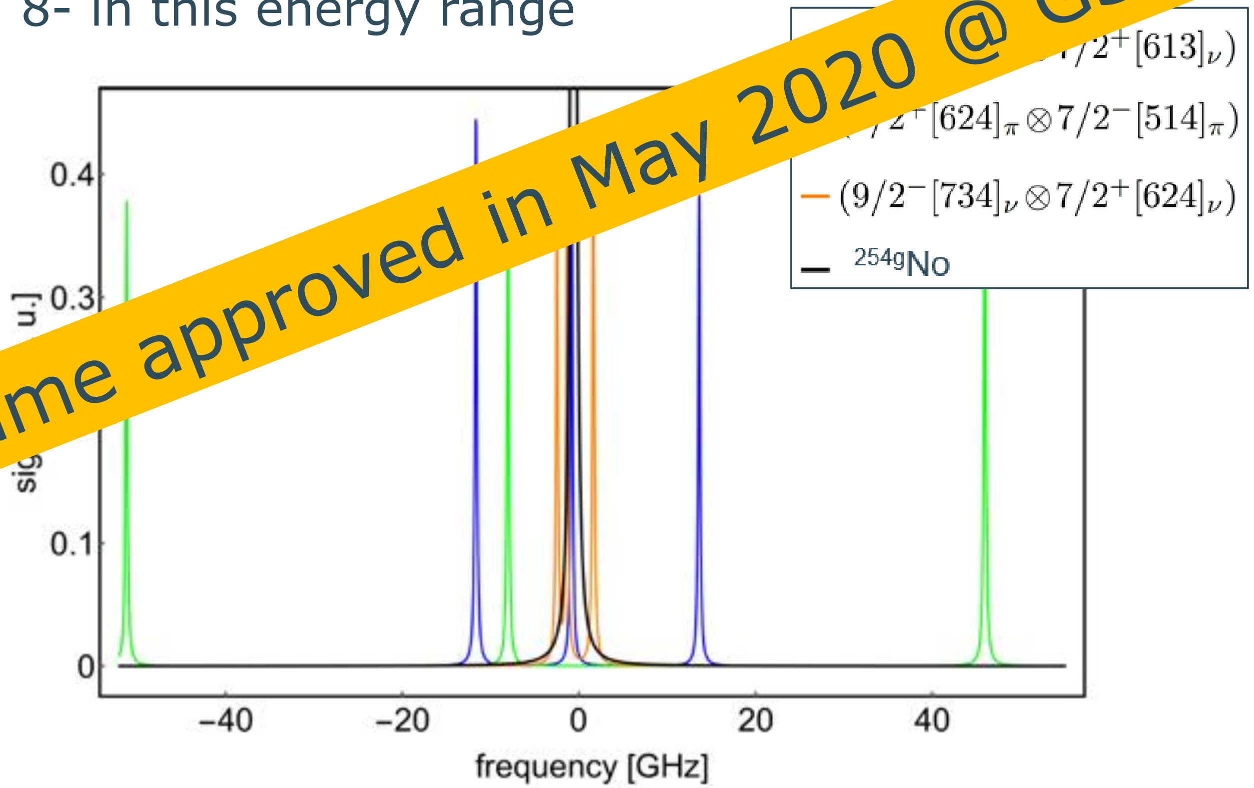
S. Raeder et al., NIM B (2019) In Press
M. Laatiaoui et al., Nature (London) 538, 495 (2016), S. Raeder et al. Phys.Rev.Lett. 120, 232503 (2018)

In-gas-jet laser ionization and spectroscopy of ^{254}No ($K^{\pi}=8^{-}$)

- Extend these measurements to the K = 8^{-} isomer in 254No



- Nuclear models calculate different configuration with spin 8- in this energy range

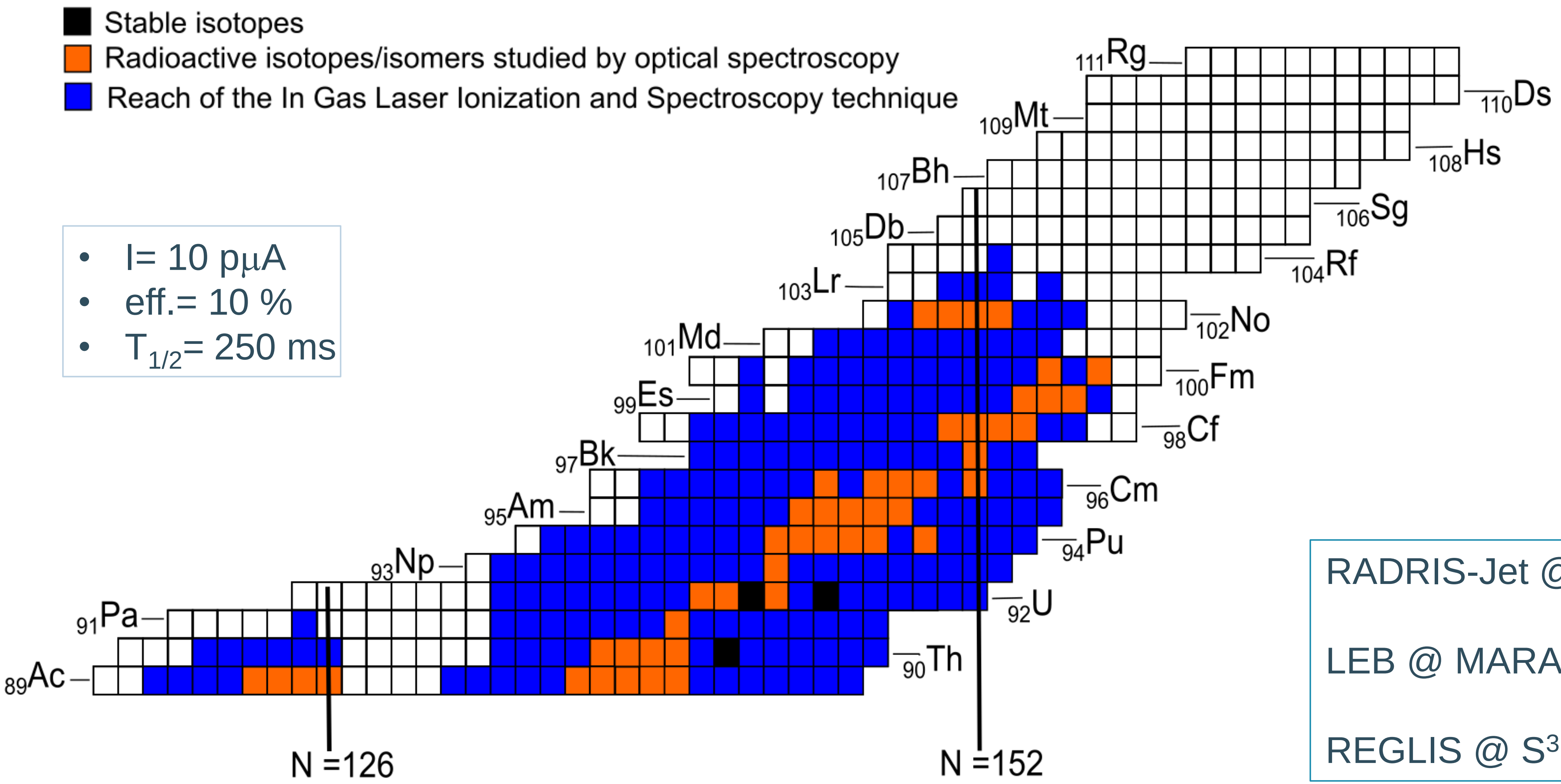


Two weeks of beam time approved in May 2020 @ GSI

- In gas jet experiments will provide μ with a high precision enabling an unambiguous nucleon configuration assignment of the isomer

R.-D. Herzberg, et al., Nature, 442(7105) 896, 2006

Outlook: Reach of IGLIS on Actinides



- I= 10 pμA
- eff.= 10 %
- $T_{1/2}$= 250 ms

RADRIS-Jet @SHIP (GSI)

LEB @ MARA (JYFL)

REGLIS @ S^3 (GANIL)

Summary

- $\delta<r^2>$ of Ac isotopes (heaviest isotopic chain crossing N=126 shell closure) have been obtained:

  - Good description by DFT of the experimental $\delta<r^2>$ for $^{225-229}$Ac only obtained when octupole deformation is taken into account

  - Presence of octupole deformation in $^{225-229}$Ac is further supported by comparison of obtained μ values with different calculations

- Optimization/characterization of IGLIS technique to study products of fusion evaporation reaction is ongoing at KU Leuven

- Comparison RIS & PLIFS shows that the former can be also used to characterize local flow parameters → Higher efficiency and faster

- IGLIS combines good efficiency and spectral resolution and is well suited for the study of heavy elements → ^{229m}Th@KU Leuven, ^{253,254m,255}No@GSI, REGLIS@S^3……

Acknowledgments

KU Leuven

K. Dockx, M. Huyse, S. Kraemer, Yu. Kudryavtsev, V. Manea, M. Nabuurs, P. Van den Bergh, D. Reynaerts, J. Romans, P. Van Duppen, M. Verlinde, E. Verstraelen

Collaborators

S. Raeder[1,2], H. Backe[4], M. Block[1,2,4], B. Cheal[5], P. Chhetri[1,6], Ch. Droese[1,7], A. Drouart[8], Ch. E. Duellmann[1,2,4], X. Flechard[8], S. Franchoo[9], F. Giacoppo[1,2], S. Goetz[1,2], F. P. Heberger[1,2], O. Kaleja[1,4,10], J. Kallunkathariyil[8], J. Khuyagbaatar[1,2], T. Kron[2], P. Kunz[11], M. Laatiaoui[3], W. Lauth[4], N. Lecesne[12], A.K. Mistry[1,2], T. Murboeck[1], H. Savajols[12], F. Schneider[2,4], B. Sulignano[8], Ch. Theisen[8], M. Vandebrouck[8], Th. Walther[6], A. Yakushev[1,2]

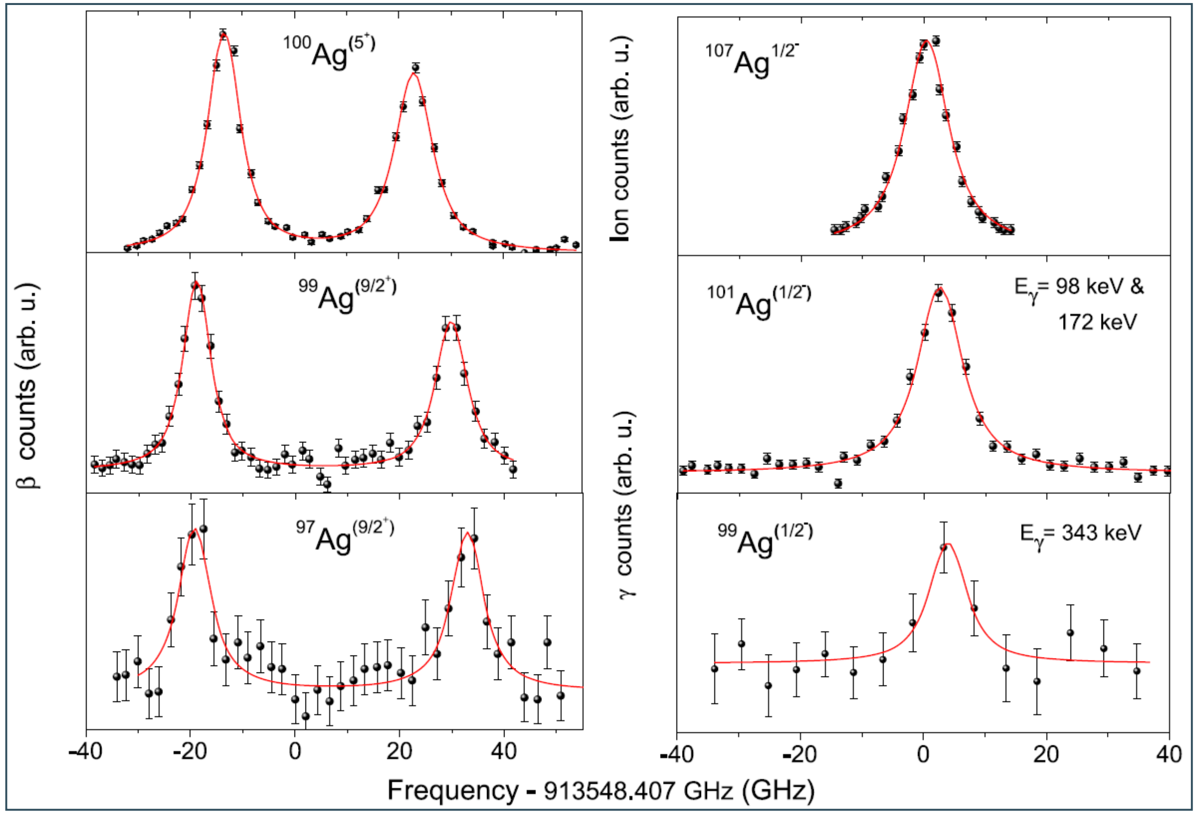
[1]GSI Helmholtzzentrum fuer Schwerionenforschung, 64291 Darmstadt, Germany | [2]Helmholtz Institut Mainz, 55128 Mainz, Germany | [4]Johannes Gutenberg-Universitaet, 55099 Mainz, Germany | [5]University of Liverpool| [6]TU Darmstadt | [7]Ernst-Moritz-Arndt-Universitaet 17487 Greifswald, Germany | [8]CEA Saclay | [9]INP Orsay | [10]Max-Planck-Institut fuer Kernphysik, 69117 Heidelberg, Germany | 11TRIUMF| 12GANIL

In-Gas-Cell Laser Spectroscopy of Ag

$^{92}Mo(^{14}N - 130\ MeV, 2pxn)^{104-x}Ag$

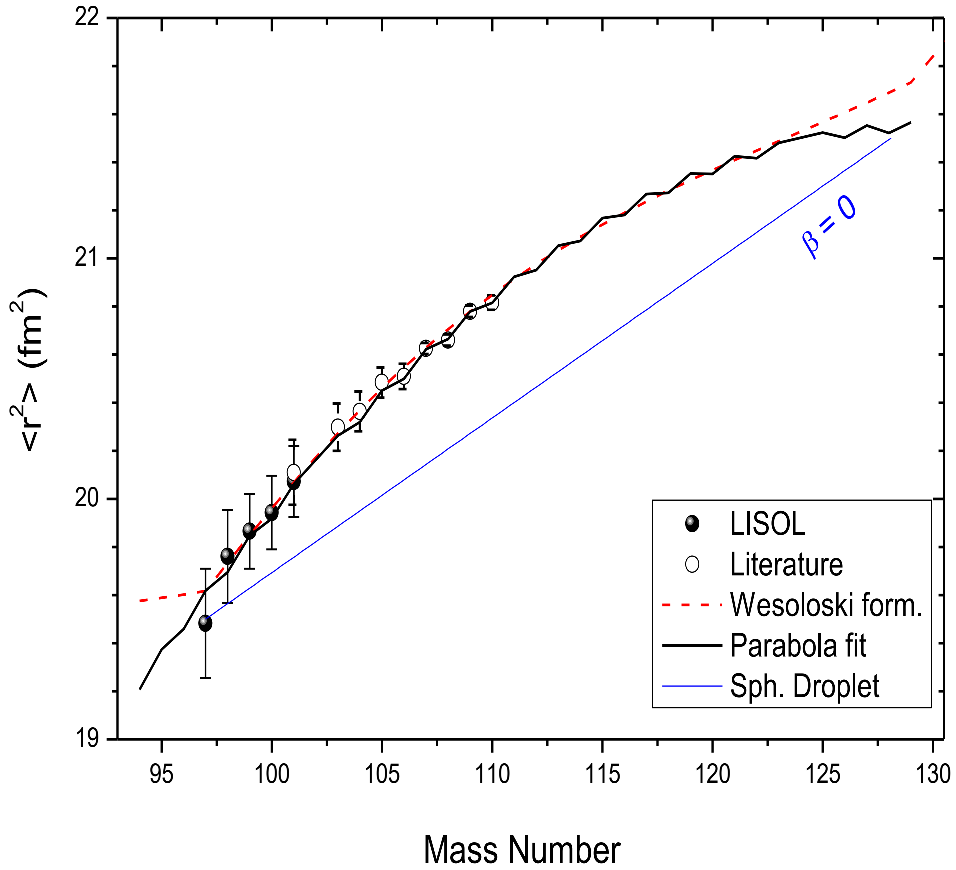
$^{64,nat}Zn(^{36}Ar - 125\ MeV, pxn)^{101-x}Ag$

R. F. et al., PLB 728 (2014) 191



count rates: ^{101}Ag=2.3 pps , ^{97}Ag=0.9 pps
ε_{total}~2 %

- Mean charge radii show parabolic trend as in isotope chains of Cd, In, and Sn
- LISOL results show a trend towards spherical nuclear shape as predicted by droplet model



U. Dinger et al. NPA, 503 (1989) 331
W. Fischer et al. Z. Phys. A, 274 (1975) 79