Investigation of octupole deformation in neutron-rich actinium using high-resolution in-source laser spectroscopy

Proposal to the ISOLDE and Neutron Time-of-Flight Committee

P-556

Reinhard Heinke

on behalf of the P-556 collaboration

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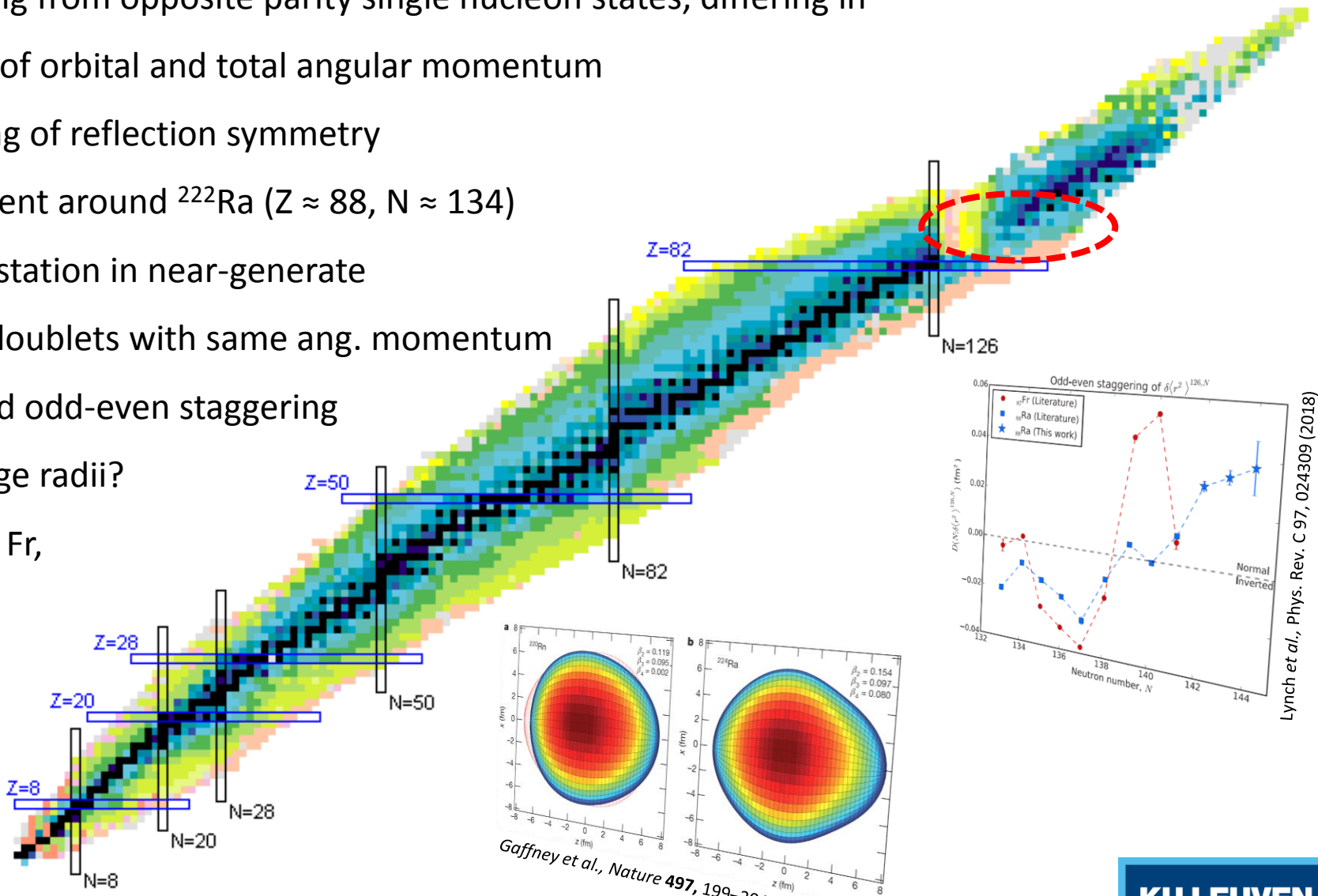
Octupole deformation in Ac region

- Pear shaped intrinsic nuclear configurations
- Resulting from opposite parity single nucleon states, differing in 3 units of orbital and total angular momentum
- Breaking of reflection symmetry
- Prominent around ^{222}Ra (Z ≈ 88, N ≈ 134)
- Manifestation in near-generate parity doublets with same ang. momentum
- Inverted odd-even staggering of charge radii? (Po, At, Fr, Rn, Ra)



Gaffney et al., Nature **497**, 199–204 (2013)

Lynch *et al.*, Phys. Rev. C 97, 024309 (2018)

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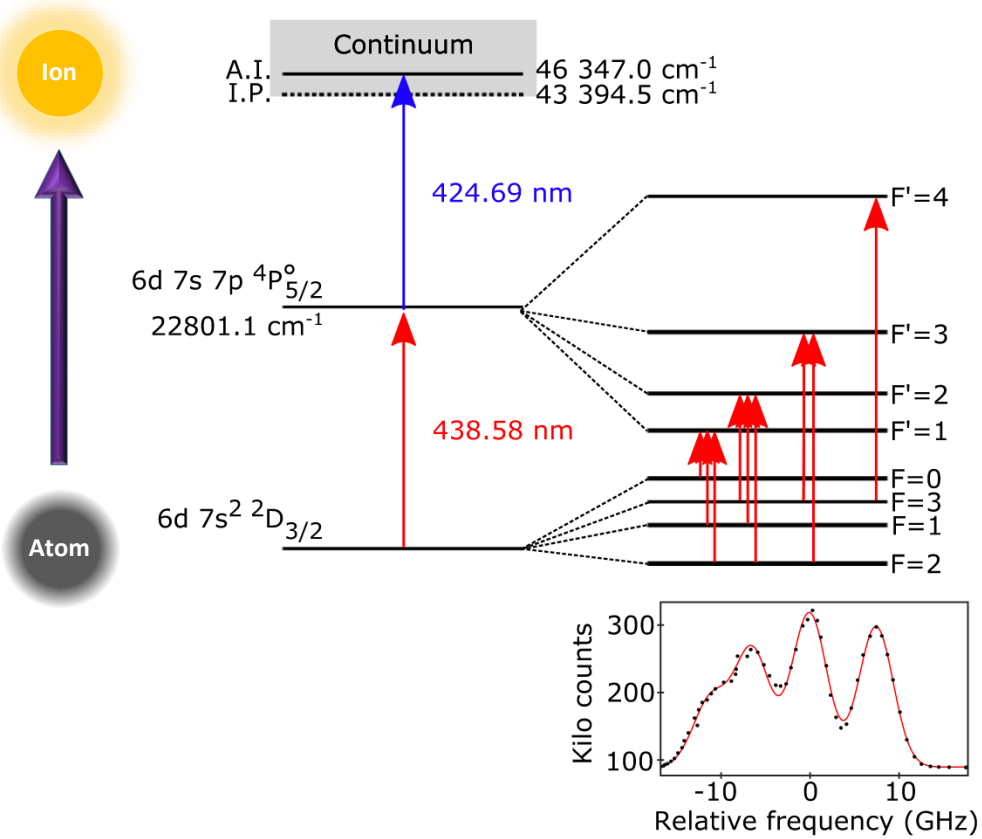
Nuclear shape investigations by laser spectroscopy

Ac laser ionization scheme

(used at LISOL, TRIUMF, ISOLDE, JGU, …)



- Isotope shift:
  Evolution of center frequency with changing N

$$\delta\nu_{A,A'} = \nu_{A'} - \nu_A =$$

$$(\mathrm{K_{NMS}} + \mathrm{K_{SMS}})\frac{m_A - m_{A'}}{m_A \cdot m_{A'}} + \mathrm{F_{FS}}\,\delta\langle r^2\rangle_{A,A'}$$

- Hyperfine structure:
  Spin, magnetic dipole moment, electric quadrupole moment

$$A = \frac{\mu_I B_J}{IJ} \qquad B = eQ_s\left\langle\frac{\partial^2 V_e}{\partial z^2}\right\rangle_{r=0}$$

Fig. from Verstraelen et al.,
Phys. Rev. **C** 100, 044321 (2019)

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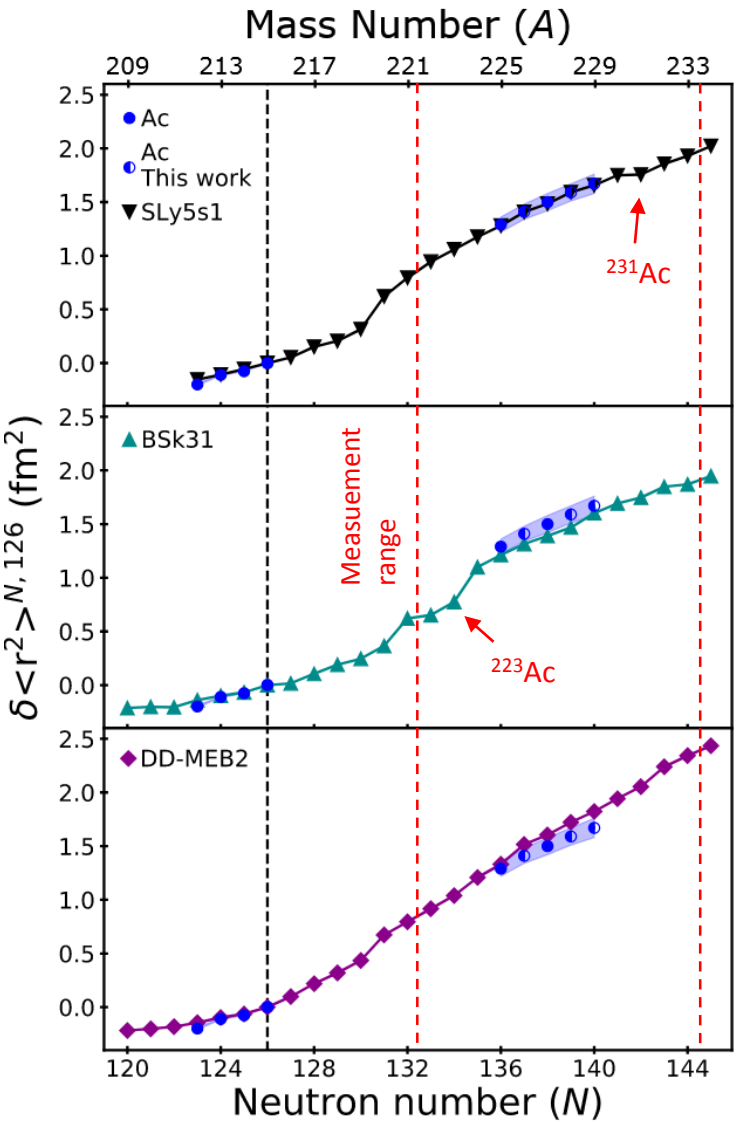
Changes in mean-square charge radii

State-of-the-art EDF calculations in comparison to laser spectroscopy data



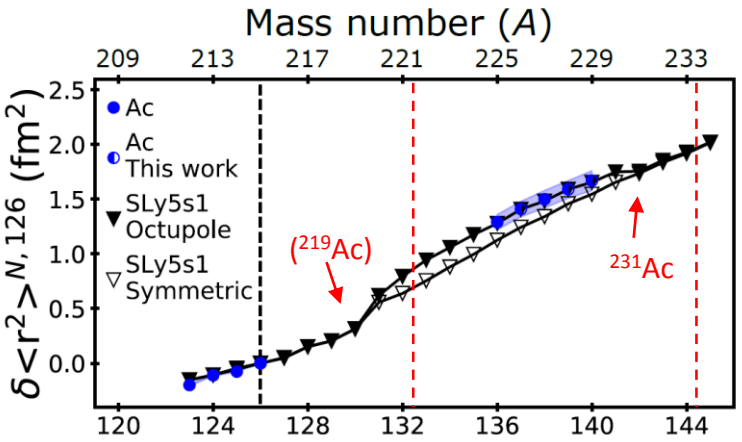


Fig. from Verstraelen et al., Phys. Rev. **C** 100, 044321 (2019)

- Data below N = 126 described equally well
- Neutron-rich data as benchmark cases
- Incorporation of reflection-asymmetry as key parameter
- Measurement of $\delta\langle r^2\rangle$ to pin down behavior
- Evaluation of odd-even staggering
- Strong support from theory

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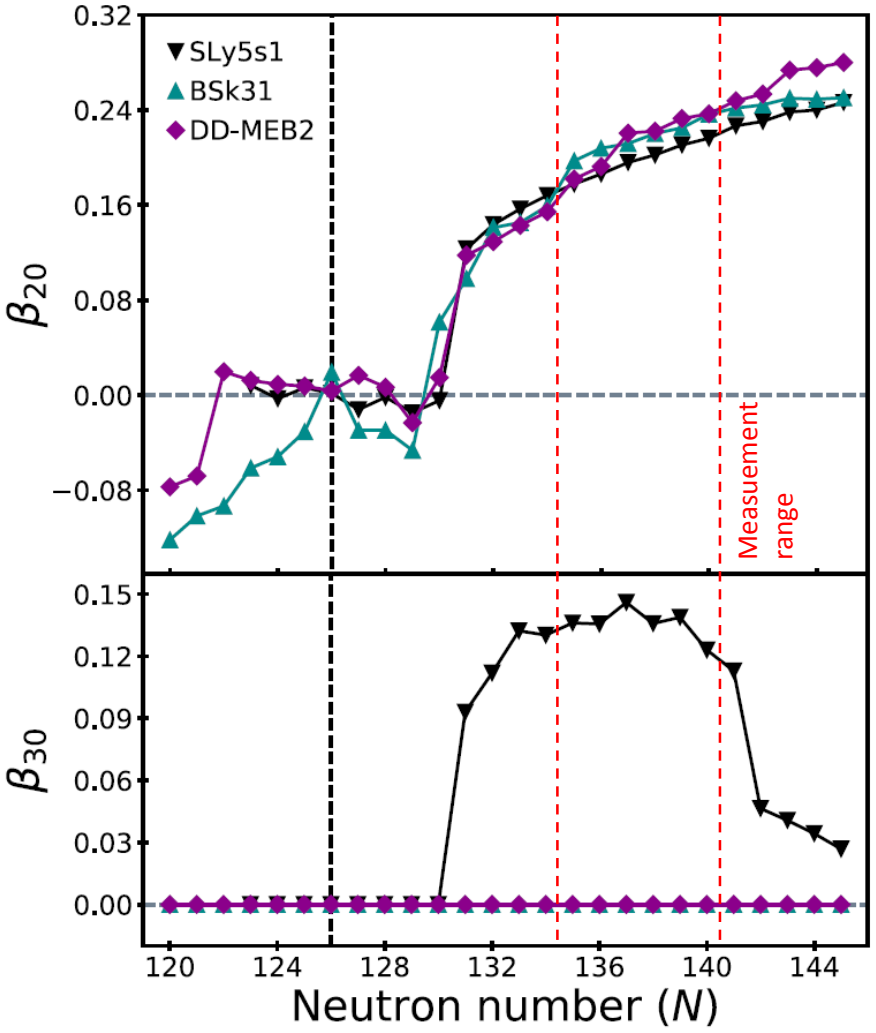
Electric multipole moments



- $\delta\langle r^2\rangle$ *a priori* potentially arising from different multipole contributions
- Larger β_{20} values if no octupole deformation
- Disentanglement by additional observables
  - B_{20} as inferred from *B(E2)* in neighboring Th
  - Observed parity doublets in Ac
  - Measurements of spectroscopic quadrupole moment Q_S

Fig. from Verstraelen et al., Phys. Rev. **C** 100, 044321 (2019)

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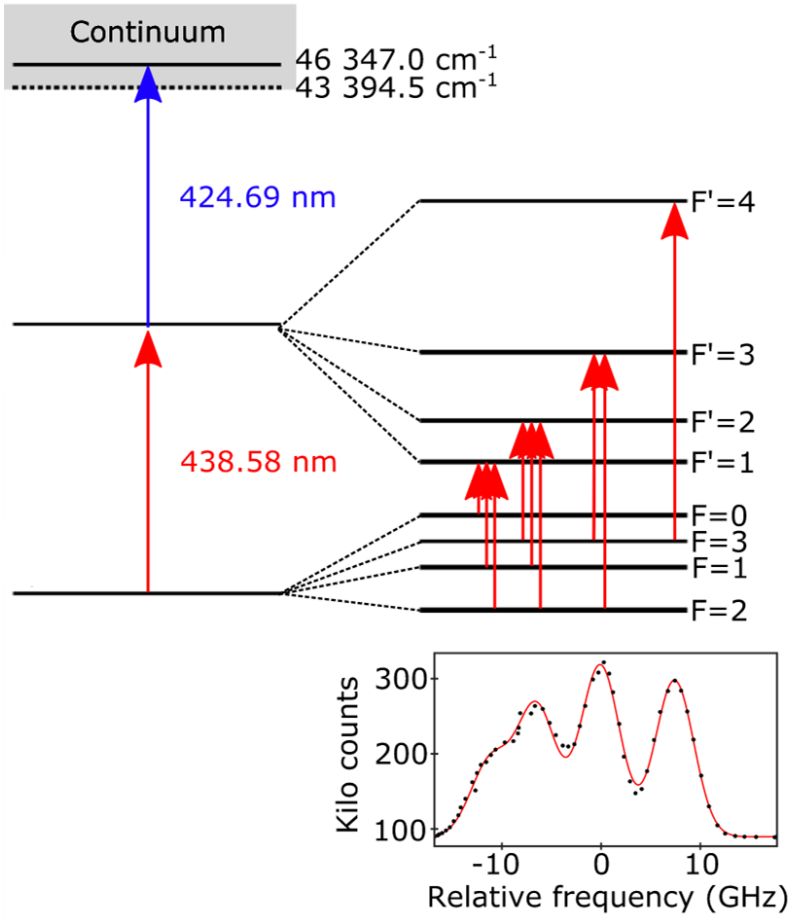
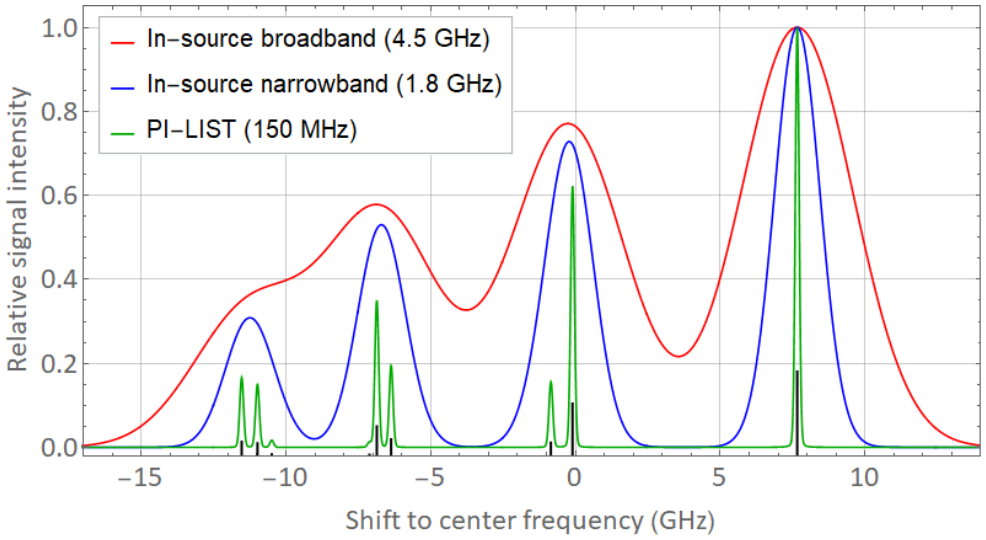
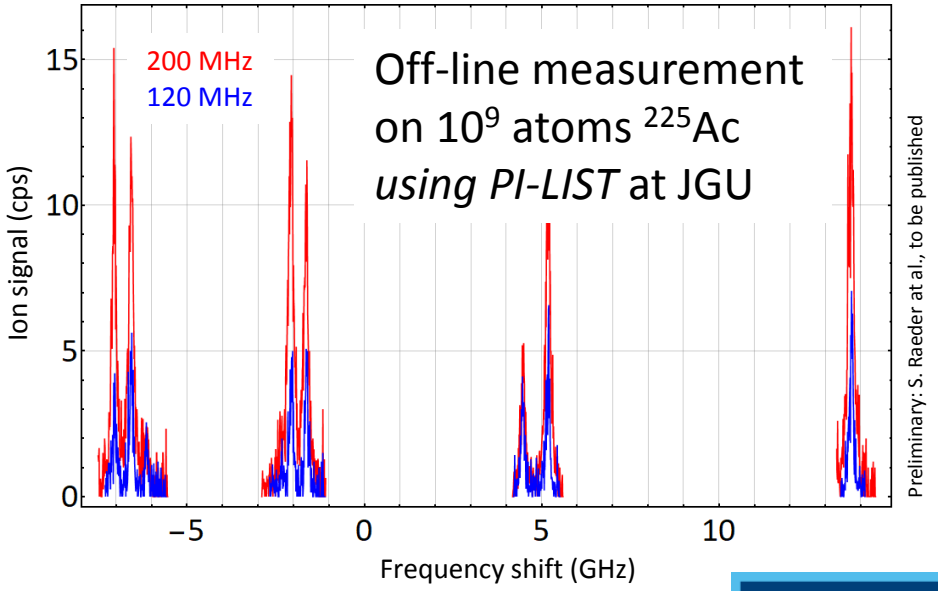
High resolution in-source spectroscopy







Extraction of Q_S prevented

by in-source Doppler broadening

➔ Sub-Doppler spectroscopy technique

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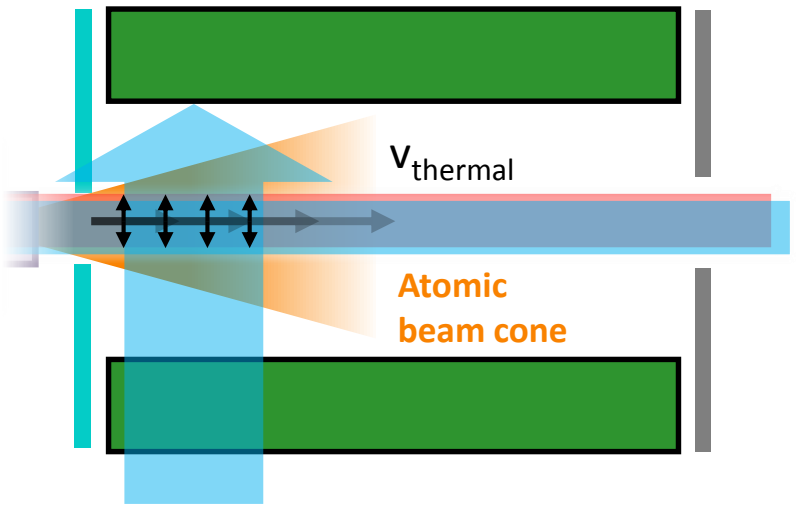
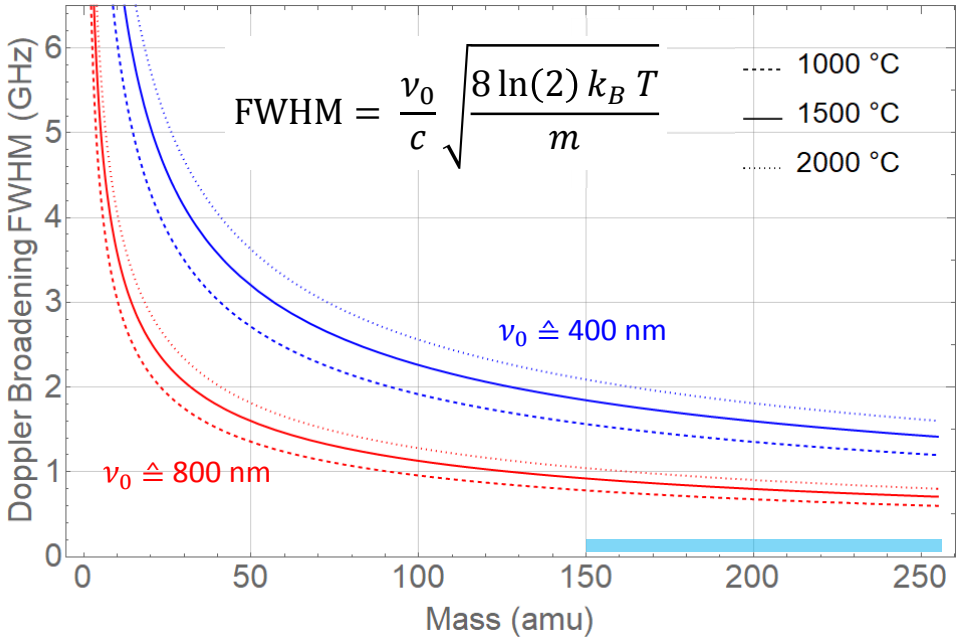
Sub-Doppler in-source spectroscopy: PI-LIST

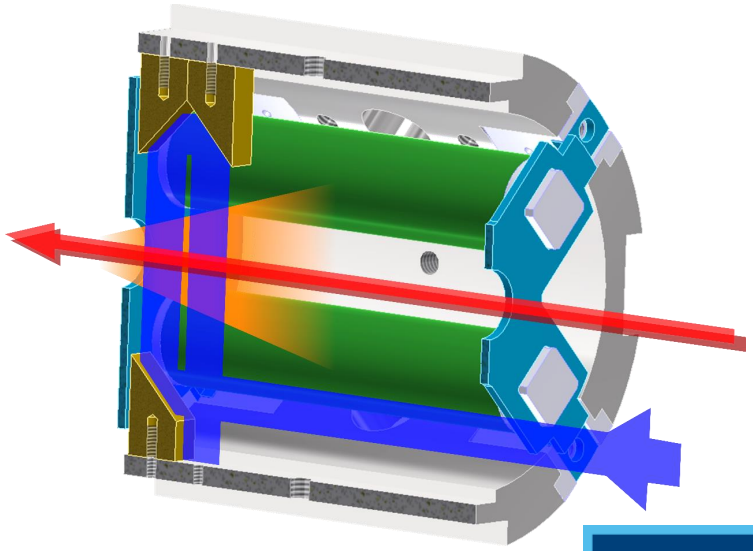
ISOLDE's LIST ion source





Narrow band spectroscopy laser
(Fiber link CRIS + RILIS,
used for 2-photon spectroscopy 2018)

- Resolution enhancement
  by order of magnitude (< 200 MHz)
  at cost of factor 1000 in intensity
  compared to standard RILIS
- Operation mode change possible at any time



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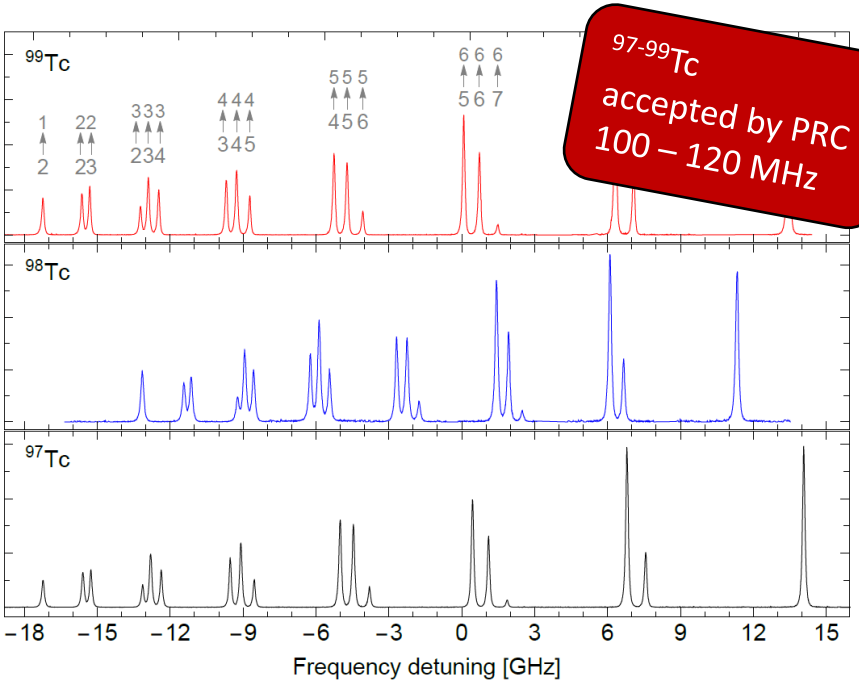
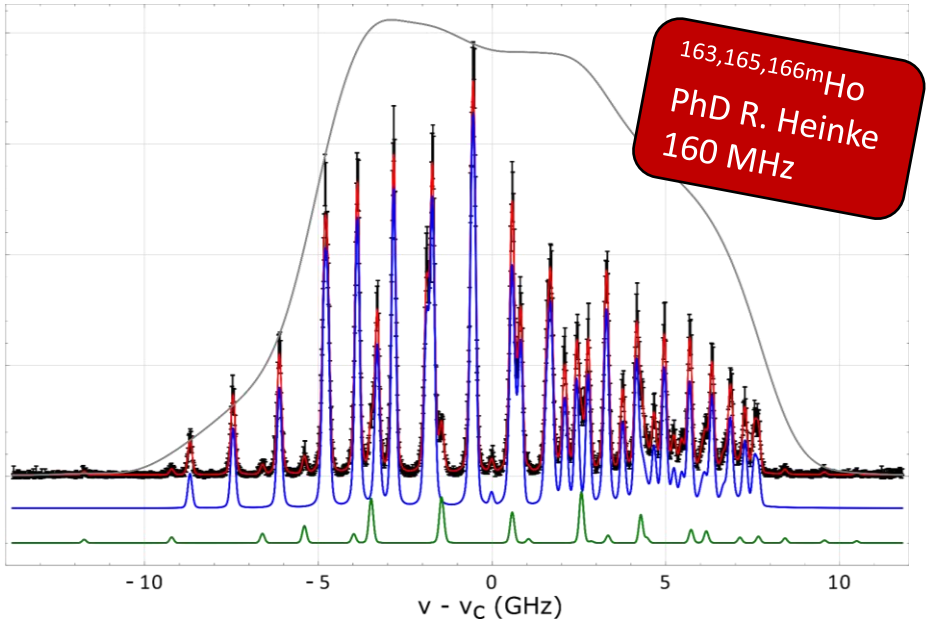
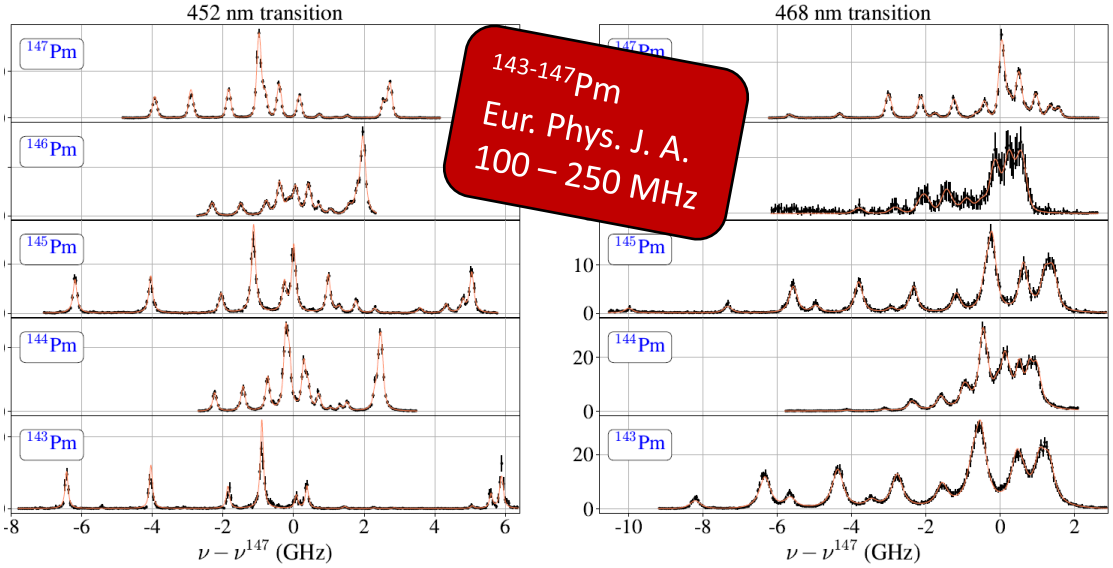
PI-LIST high-resolution spectroscopy at JGU



97-99Tc
accepted by PRC
100 – 120 MHz



163,165,166mHo
PhD R. Heinke
160 MHz



143-147Pm
Eur. Phys. J. A.
100 – 250 MHz

Resolution benchmark:

- 60 MHz @ U, Rb

Overall efficiency:

- 10^{-4} … 10^{-5}

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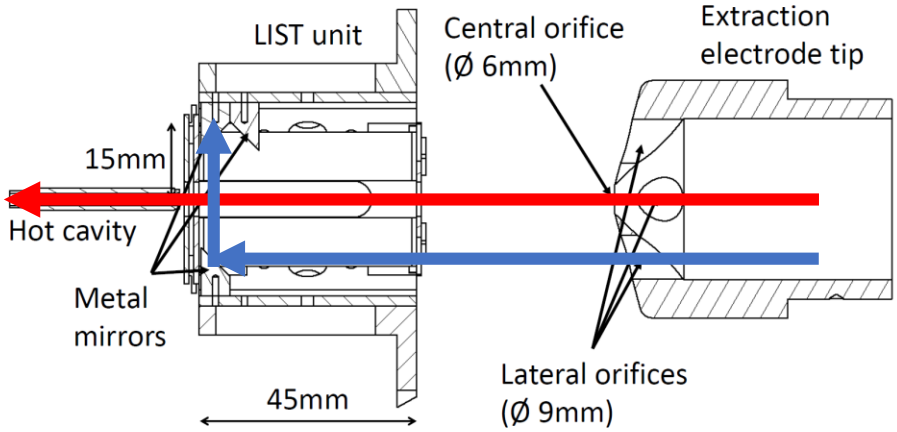
Implementation at ISOLDE: Adapted extractor



- Extensive simulation studies and off-line tests performed at JGU,

  > 1 year of routine operation without problems
- PI-LIST unit assembled at CERN
- Adaption of ISOLDE-type extractor approved by RBS team
- Test planned on Off-line 2 separator
- Test planned at on-line frontend *within LS2*

  ➔ optimum moment for integration!
- Activity within EU Marie Curie Network *LISA*

  ➔ dedicated manpower and support!

IISA

MARIE SKŁODOWSKA-CURIE ACTIONS

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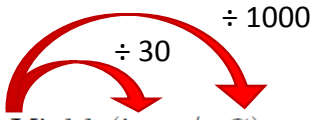
Shift planning and detection

Detection of produced ions vs. laser frequency adapted to yield and decay properties:



Isotope	$T_{1/2}$	Yield (ions/μC) RILIS	LIST	PI-LIST	Det.	Measurement	Shifts
^{222}Ac	63 s	2	0.1		α	IS, μ	2
^{223}Ac	2.10 min	1×10^3	30		α	IS, μ	2
^{224}Ac	2.78 h	9×10^5		9×10^2	ions	IS, μ, Q_s	1
^{225}Ac	9.92 d	3×10^7		3×10^4	ions	**Ref.**	0.5
^{226}Ac	29.37 h	3×10^6		3×10^3	ions	(IS, μ), Q_s	0.5
^{227}Ac	21.77 y	3×10^7		3×10^4	ions	**Ref. & Setup**	1.5
^{228}Ac	6.15 h	2×10^6		2×10^3	ions	(IS, μ), Q_s	0.5
^{229}Ac	62.7 min	3×10^5		3×10^2	ions/β	(IS, μ), Q_s	1
^{230}Ac	122 s	3×10^2	10		β	IS, μ	2.5
^{231}Ac	7.5 min	2×10^3	70		β	IS, μ	2.5
^{232}Ac	1.98 min	80	3		β	IS, μ	2.5
^{233}Ac	145 s	70	2		β	IS, μ	2.5
Total:							**19**

Single ion counting with MagneToF

Lower resolution and decay detection at ISOLDE Decay Station (annular Si detector + plastic scintillators)

ISOLDE Decay Station

TAC: Contamination of beam instrumentation (FC's)?

➔ Only setup / cross checks in standard RILIS mode

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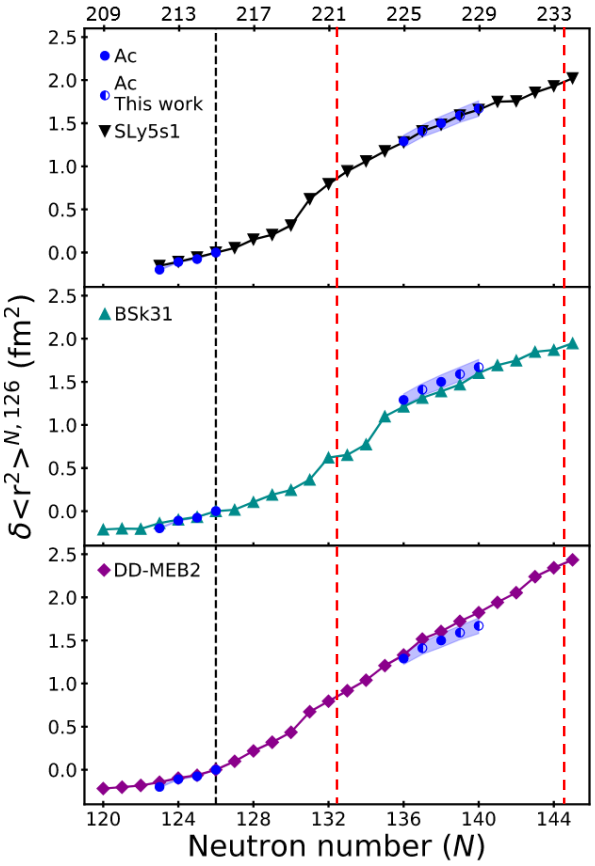
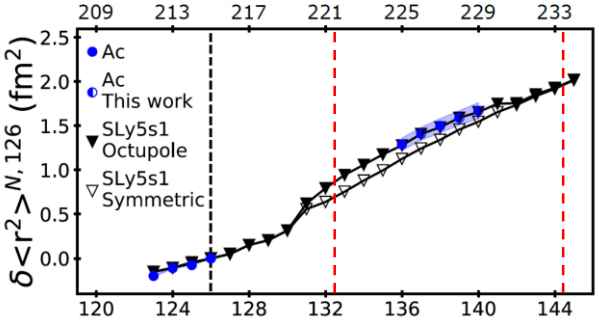
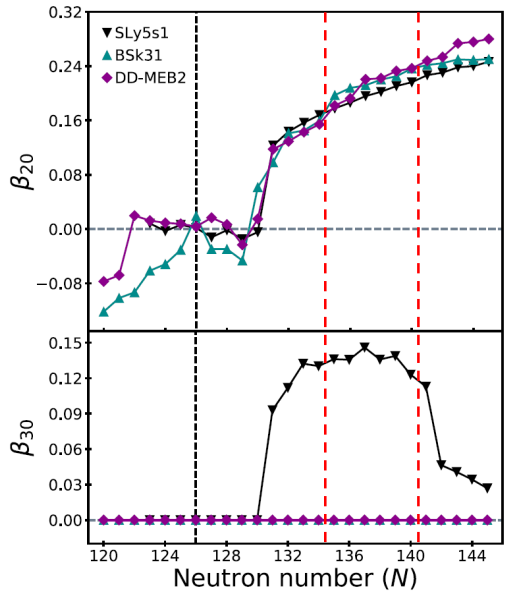
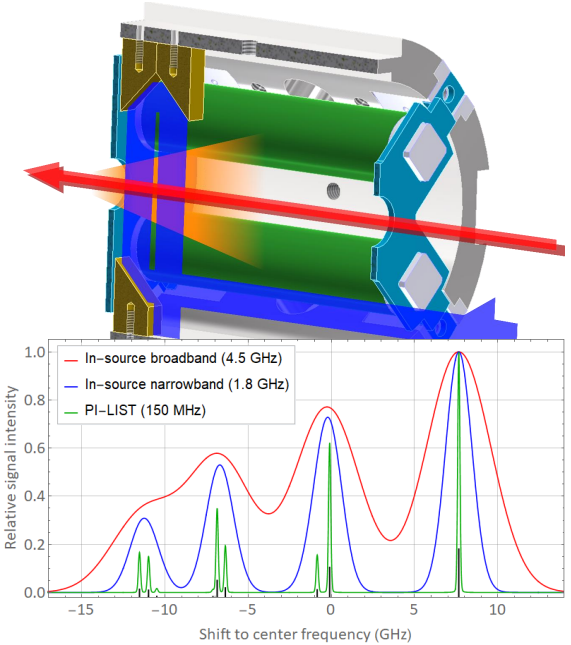
Summary









- Measurement on $^{222\text{-}233}$Ac isotope chain
- Extraction of $\delta\langle r^2\rangle$, I, μ, Q_S
- Pin down octupole behavior in Ac region by probing state-of-the-art theoretical models
- Achieve required resolution and selectivity with PI-LIST and IDS

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Collaboration

B. Andel[1], A. N. Andreyev[2], M. Au[3], A. E. Barzakh[4], A. J. Brinson[5], K. Chrysalidis[3], T. E. Cocolios[1], B. S. Cooper[6], J. Cubiss[2], H. De Witte[1], K. Dockx[1], D. V. Fedorov[4], V. N. Fedosseev[3], K. T. Flanagan[7], R. F. Garcia Ruiz[5], F. P. Gustafsson[1], R. Heinke[1], J. Johnson[1], M. Kadja[8], V. Leask[1,3], R. Lica[9], B. A. Marsh[3], P. L. Molkanov[4] G. Neyens[1,3], H. A. Perrett[7], S. Raeder[10], B. Reich[3], C. M. Ricketts[7], S. Rothe[3], M. D. Seliverstov[4], S. M. Udrescu[5], P. Van Duppen[1], A. R. Vernon[1], E. Verstraelen[1], K. Wendt[8], J. Wessolek[7], S. G. Wilkins[3], W. Wojtaczka[1], X. F. Yang[6]

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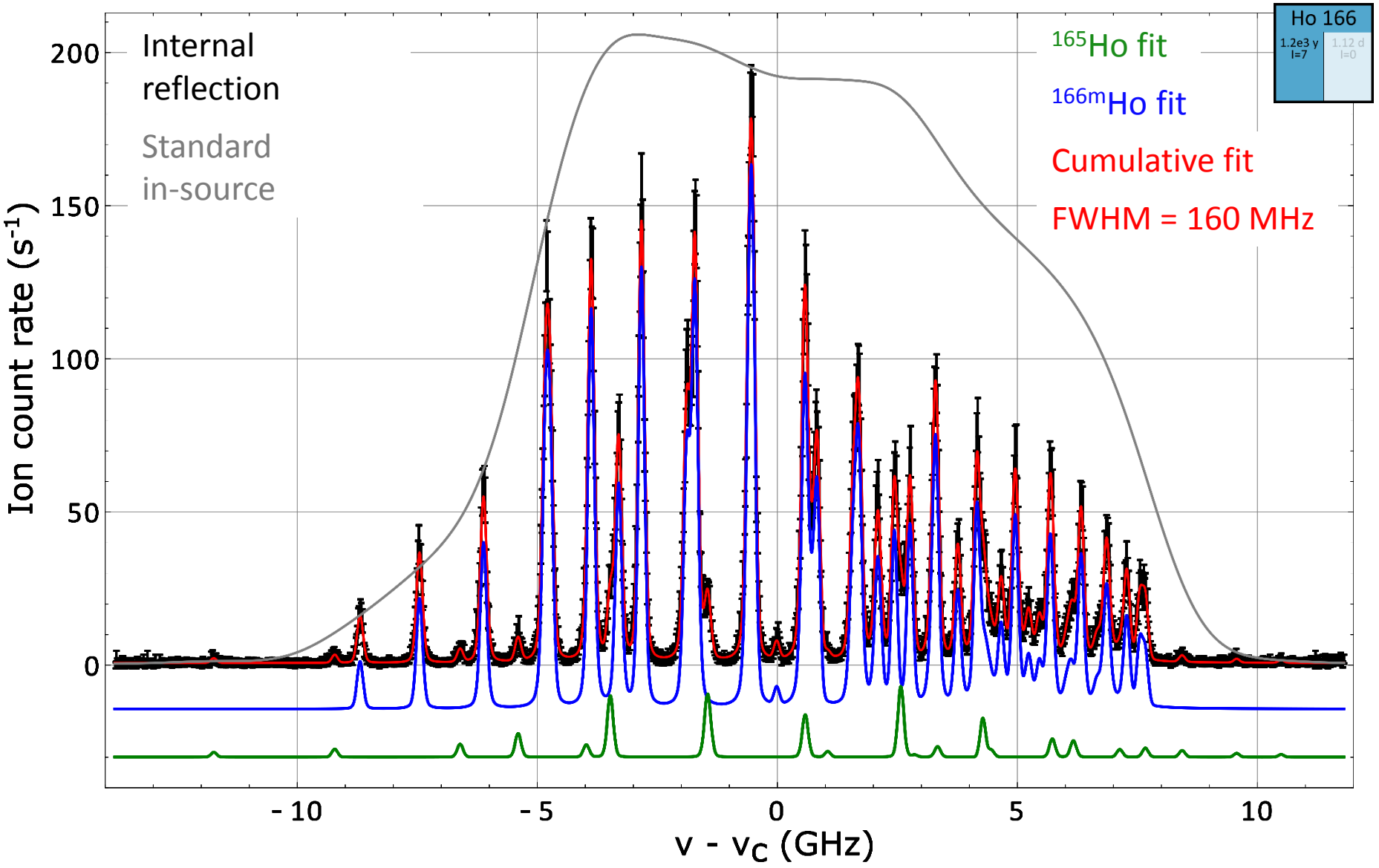
Backup slides

PI-LIST Spectroscopy on ^{166m}Hoc



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Inverse odd-even-staggering in actinium

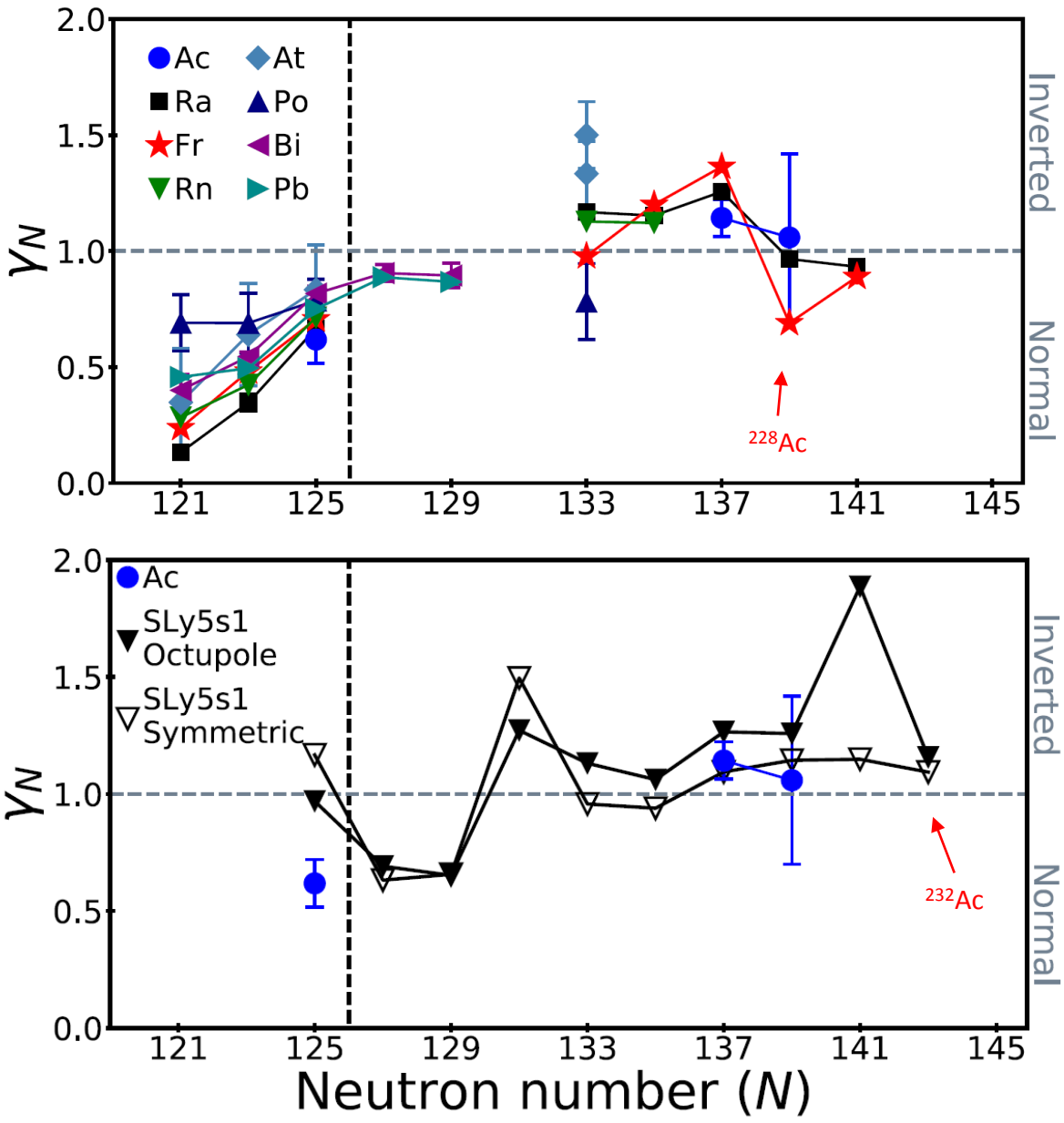

Fig. from Verstraelen et al., Phys. Rev. **C** 100, 044321 (2019)

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Nuclear moments in actinium

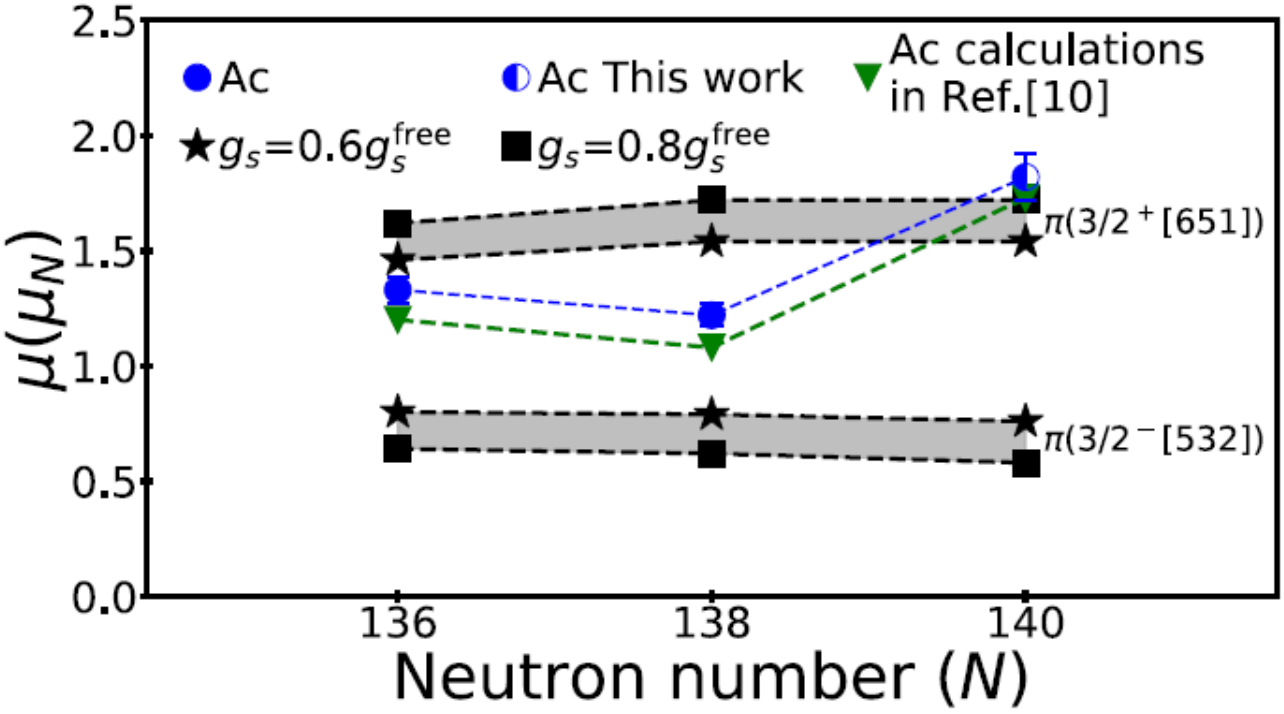

Fig. from Verstraelen et al., Phys. Rev. **C** 100, 044321 (2019)

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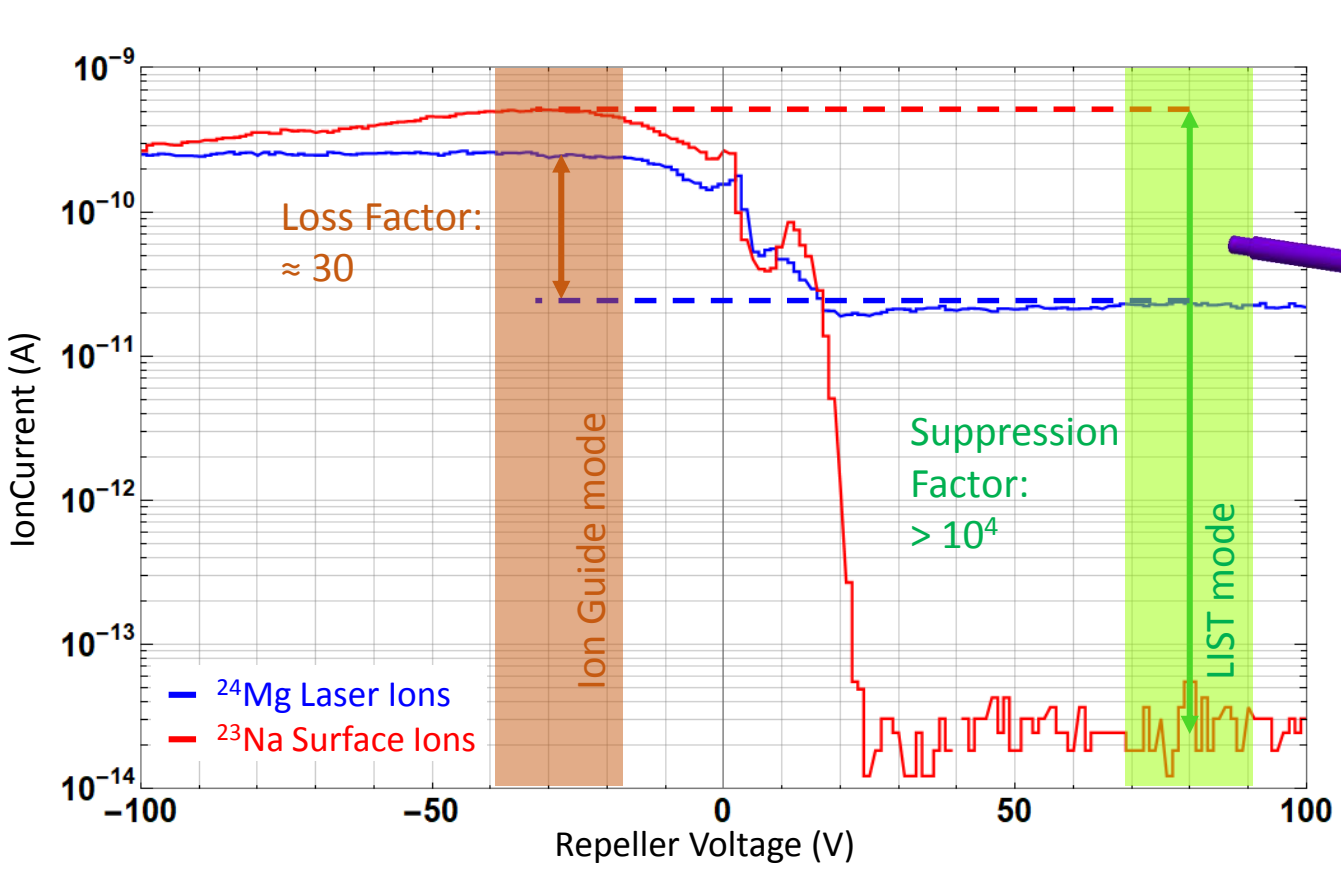
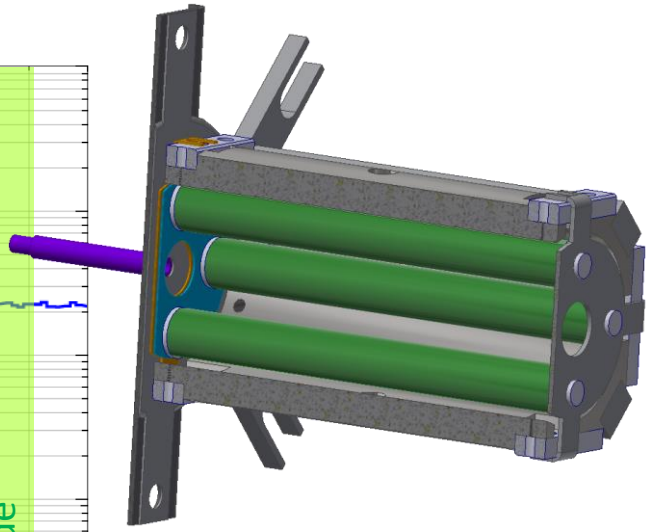
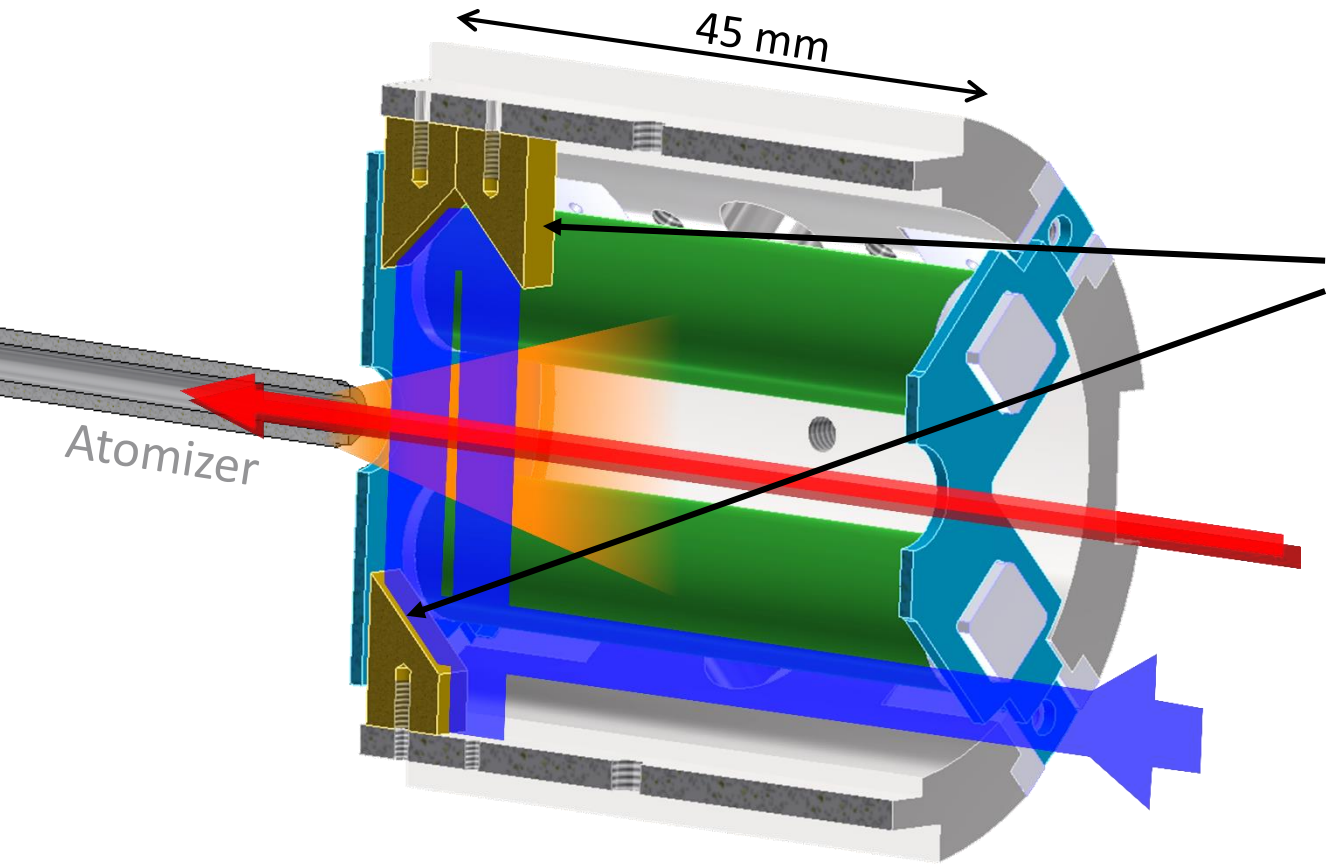
Standard LIST for IS614 (2018)



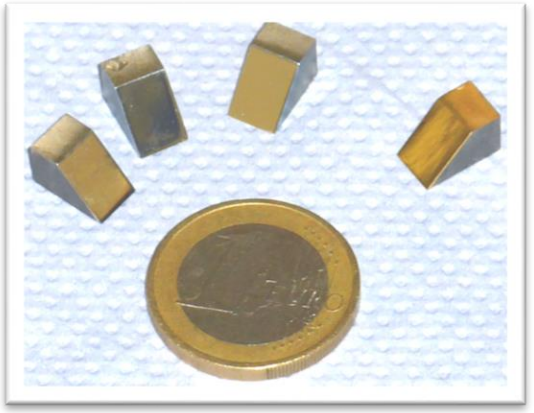


Radioisotopes (β counting)		
	Before run	After run (4 days)
Loss Factor (^{22}Mg, $T_{1/2}$ = 3.9s)	28	26
Suppression Factor (^{21}Na, $T_{1/2}$ = 22.5s)	$1.0 \cdot 10^6$	$1.6 \cdot 10^6$

The Laser Ion Source and Trap LIST



Metallic mirrors



Machined at
JGU mechanical workshop

Optional surface treatment
by pulsed laser deposition

- Transversal reflection by **robust metallic mirror** surfaces
- **Off-axis guiding** of spectroscopy laser through ion beam line

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Efficiency considerations

Loss factors

RILIS → LIST ~ 30

LIST → PI-LIST ~ 4

PI-LIST opt. ~ 10

~ 1,000 → Overall efficiency 10^{-4} .. 10^{-5}

Operation mode	Estimated efficiency (%)
Standard RILIS	20
LIST ion guide mode	10
LIST suppression mode	0.2
External PI mode (BB)	0.1
Internal PI mode (BB)	0.1 .. 0.02
External PI mode(NB)	0.001 .. 0.02