Laser spectroscopy of neutron-deficient thulium isotopes

INTC-P-673-ADD-1

✔ Optical measurements, including Tm isotopes measured at ISOLDE so far

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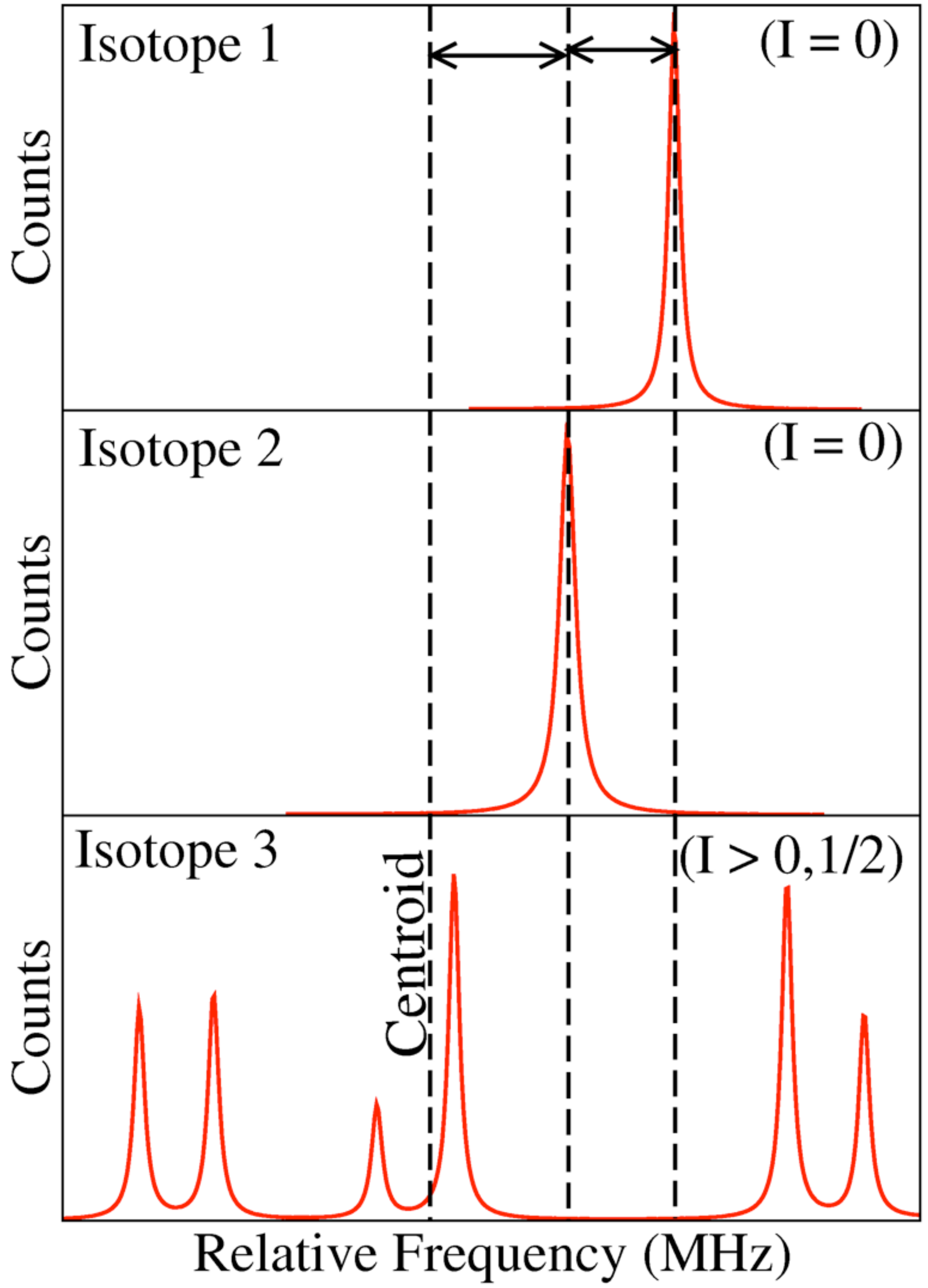
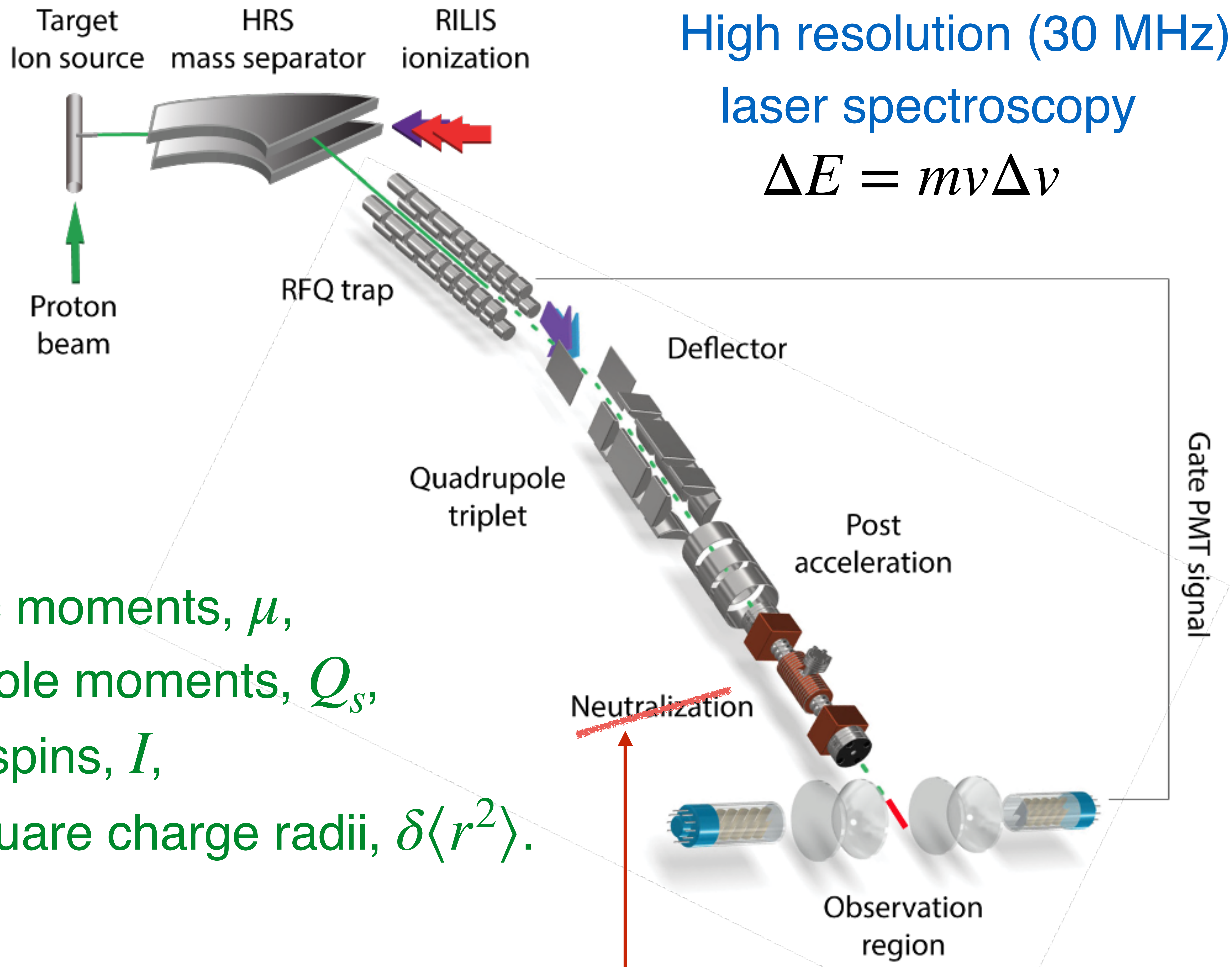
Laser Spectroscopy with COLLAPS





High resolution (30 MHz) laser spectroscopy

$$\Delta E = mv\Delta v$$

Magnetic moments, μ,

Quadrupole moments, Q_s,

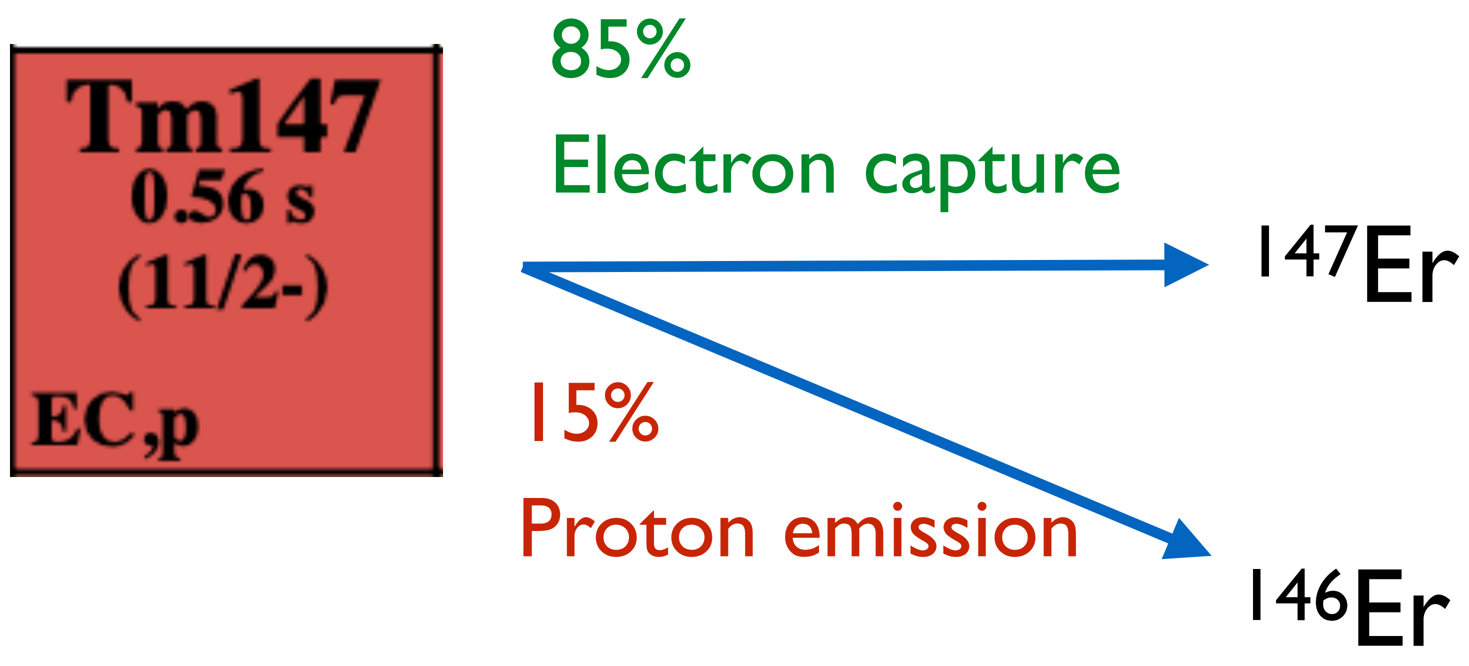
Nuclear spins, I,

Mean-square charge radii, $\delta\langle r^2\rangle$.

Precision and nuclear model independent measurements

Very efficient spectroscopy of ions

The proton emitter ^{147}Tm



Ultimate case: Laser spectroscopy of ^{147}Tm

➜ First laser measurement of any proton emitter
➜ First charge radius measurement of any proton emitter
➜ Expect to see an increase in the charge radius
➜ Will drive development of DFT coupling to an open-quantum system

Track the behaviour of the charge radii en route…

➜ To determine the magnitude of the increase, need systematics of radii leading to ^{147}Tm
➜ Does the charge radii continue the same smooth trend until ^{147}Tm?

Part of a wider programme, eg. laser spectroscopy of ^{53m}Co proposed at JYFL.

Physics cases on the way to ^{147}Tm

Laser measurements

- No laser measurements of moments or radii in the region across the $N = 82$ shell closure
- Upward kink in the radii across shell closure?
- Benchmark DFT calculations in the region and continue development ready for ^{147}Tm.
- Only tentative spin assignments down from ^{153}Tm.
- Confirm spin systematics of isomers ➜ may help unravel proton spectra of ^{146}Tm

Mass measurements

- Ability of ISOLTRAP to analyse beam content
- Lack of data around ^{151}Tm to give accurate strength of $N = 82$ shell gap ➜ S_{2n}, δS_{2n}
- No ground or isomeric state measurements ^{149,150}Tm
- Wealth of long-lived and low-lying isomers ➜ benchmark nuclear structure calculations
- Many excitation energies $^{151-157}$Tm tentative from decay spectroscopy - isomers resolved?
- Level ordering unclear eg. ^{152,154}Tm

Letter of Intent I245 — 2023 beamtime (6 shifts)

Primary aims:

- Establish yields from a Ta foil target + PSB + RILIS
- Identify a strong transition in the ion
- **Confirm sensitivity to moments**

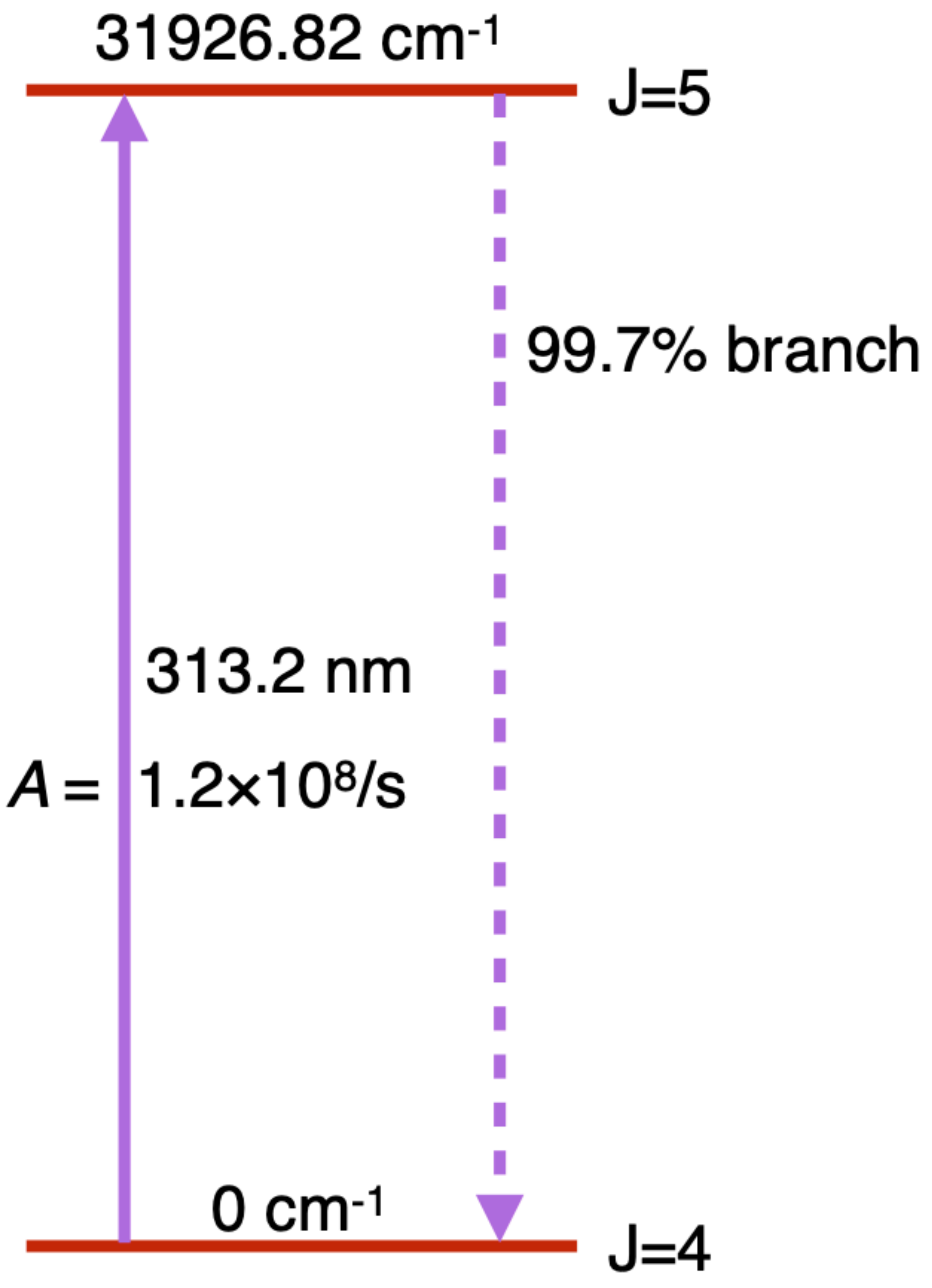
$$A = \frac{\mu}{I}\frac{B_e(0)}{J} \qquad B = Q_s V_{zz}$$

- **Confirm sensitivity to $\delta\langle r^2\rangle$**

$$\delta\nu^{A,A'} = \frac{A'-A}{AA'}M + F\,\delta\langle r^2\rangle^{A,A'}$$

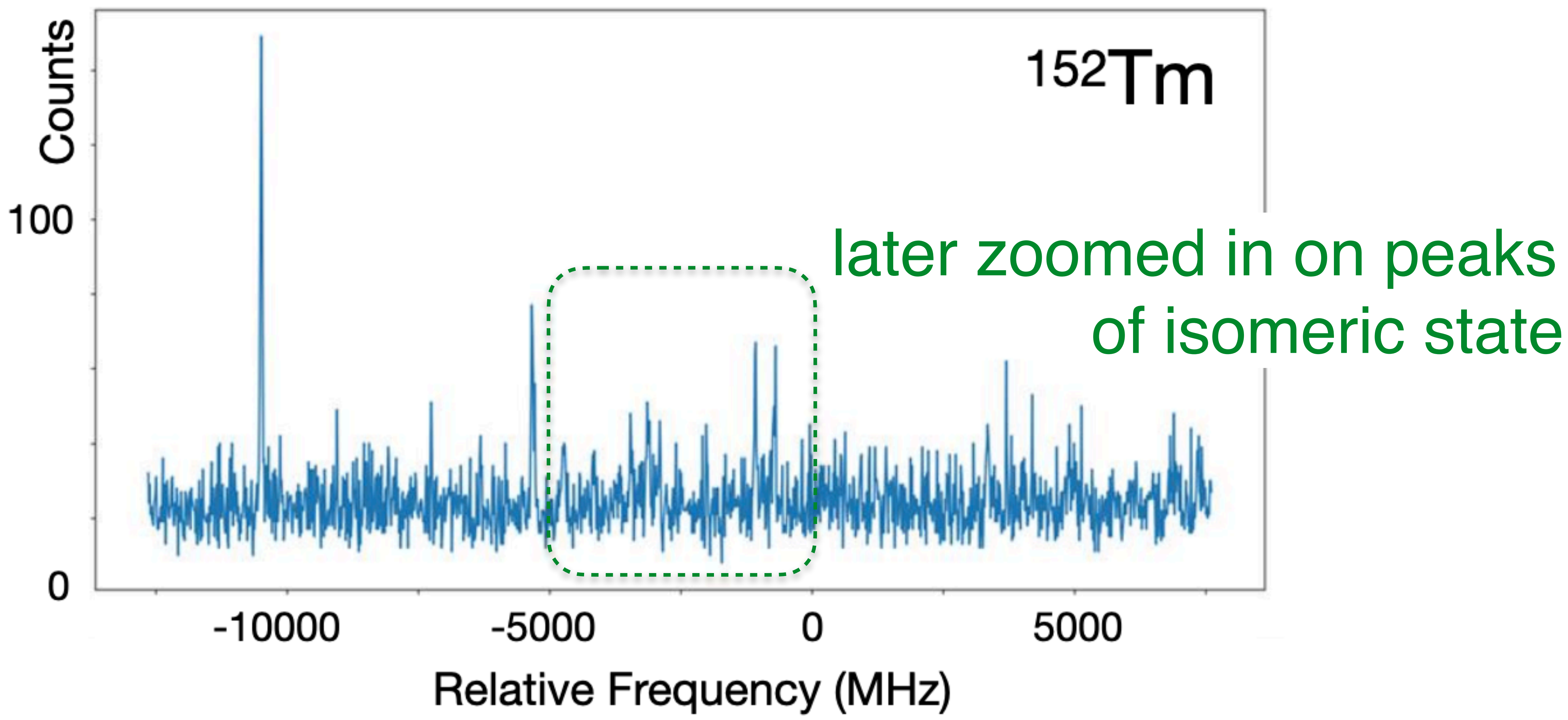
Difficulties encountered:

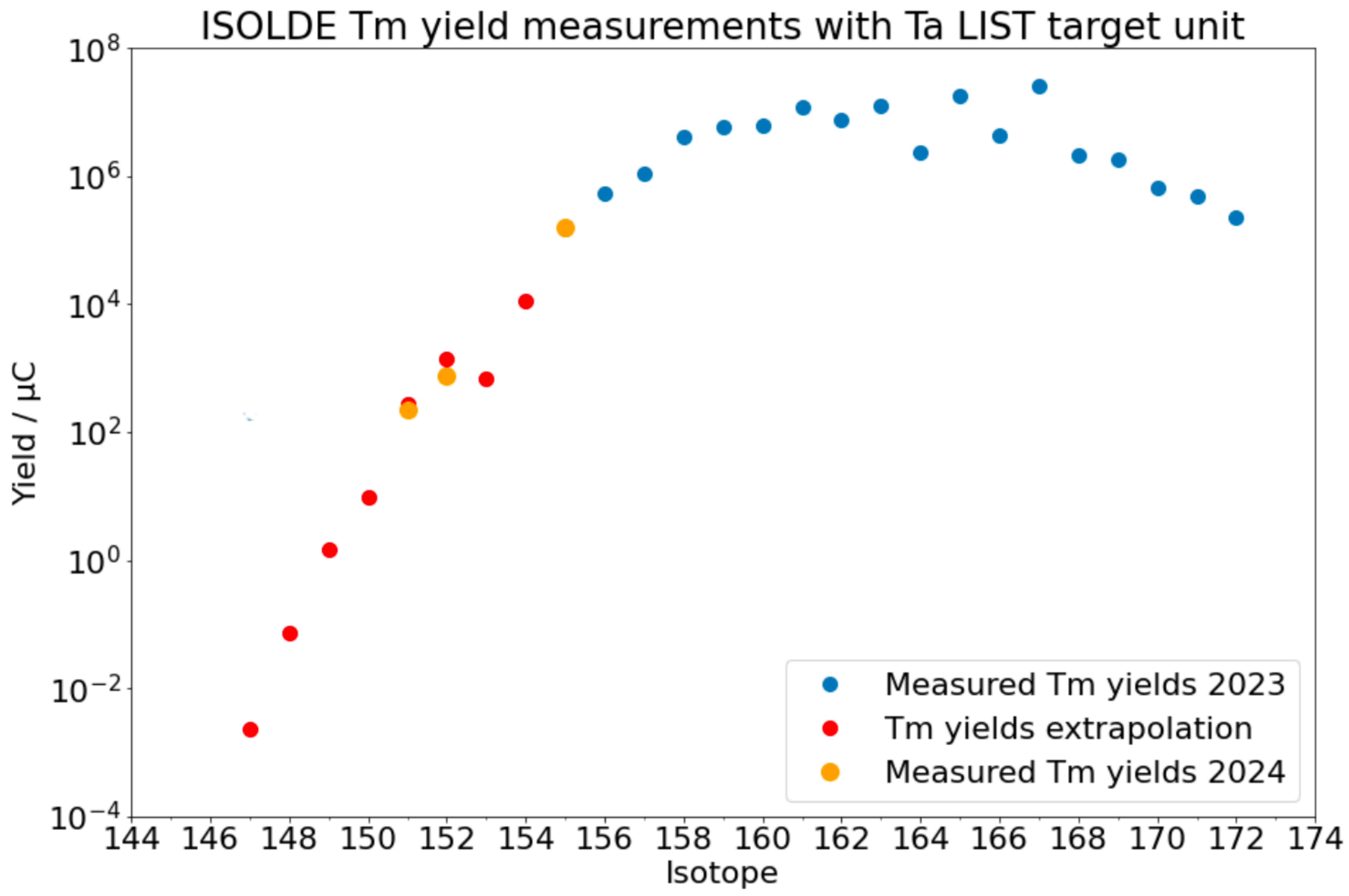
- Overwhelming contamination below ^{155}Tm
  - ➜ Identified using ISOLTRAP as rare-earth oxides
- Target failure / Loss of protons



P673 (IS740) — 2024 beamtime (13 shifts)

- Background suppressed substantially using a Laser Ion-Source Trap (LIST) (although yields suppressed also)
- Spectroscopic efficiency of transition optimised at COLLAPS to give 1 photon per 50 ions





- Failure of target (heating circuit) then failure of replacement target (sintering)
- ISOLTRAP not operational during the experiment due to a recent fault

Measurements to date (LOI245 + IS740)

- Nuclear moments and changes in mean-square charge radii for:
    - All ground states from ^{175}Tm to ^{152}Tm (24 isotopes)
    - Isomeric states in ^{174}Tm, ^{164}Tm, ^{162}Tm, ^{161}Tm, ^{160}Tm, ^{155}Tm, ^{154}Tm, ^{153}Tm…

- Existence of isomeric states not listed databases in a couple of cases
- Spin corrected in at least one case

  (and all spins are tentative down from ^{153}Tm

- Two peaks measured for the isomeric state in ^{152}Tm
- Peaks observed for ^{151}Tm, which marks the shell closure.

Extending measurements with COLLAPS (ionic line)

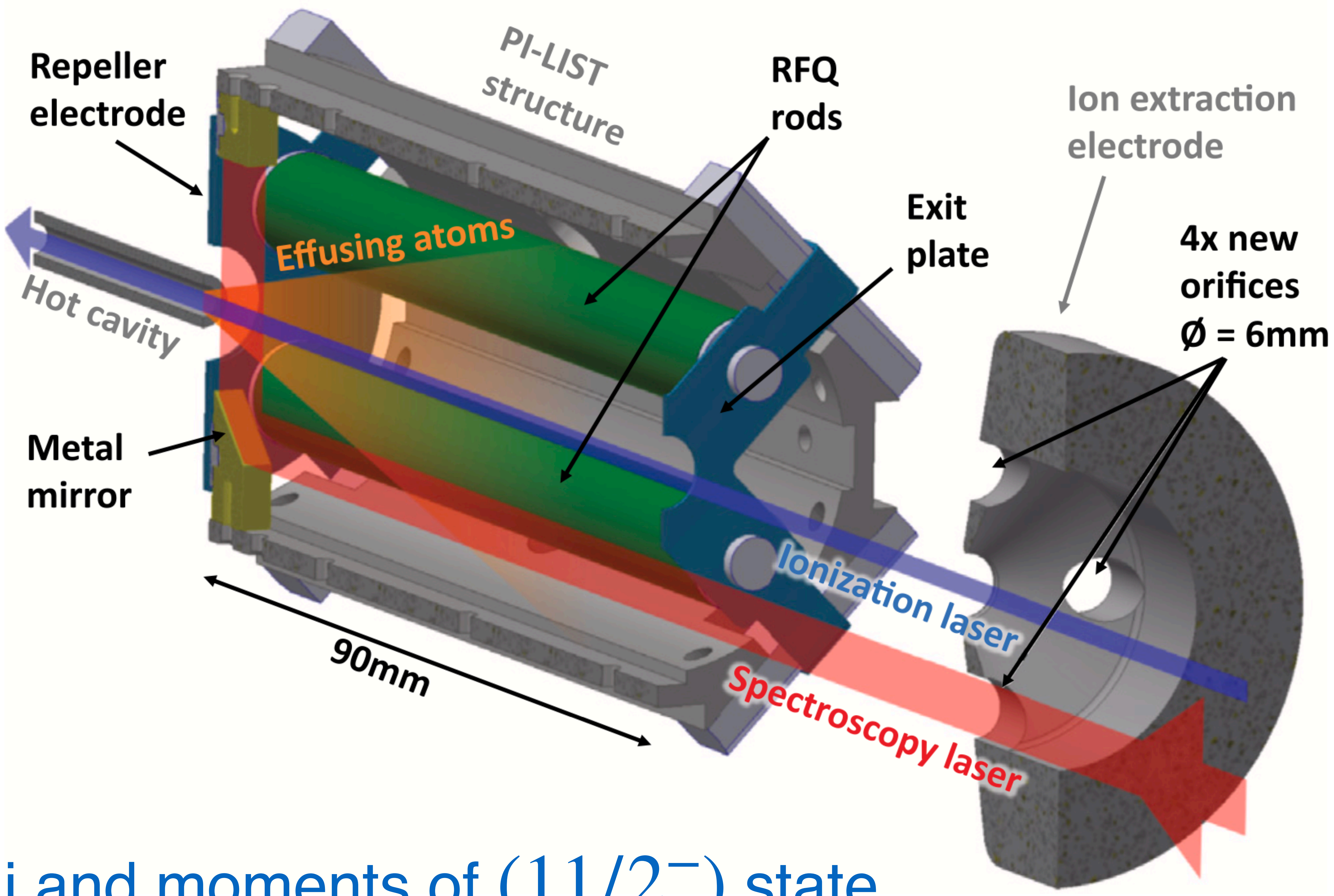
- Repeat ^{152}Tm to measure a third peak of the isomeric state

- Continue measurement of ^{151}Tm (gs and m)
  - Marks the shell closure
  - Continues to track the $11/2^-$ state
  - Also a $1/2^+$ isomeric state

- Explore spectroscopy of ^{150}Tm and measure the yield
  - Expect to see upward kink in the charge radii crossing the shell closure
  - (1^+) and (6^-) states, assigned a half life of 2.2 seconds

Going further: PI-LIST + IDS

- Scan the first step while using gamma detection at IDS



- Resolution improved to a few 100 MHz
- Favourable gamma multiplicity
- Spectroscopy of ^{150}Tm and ^{149}Tm

  ➜ Passing the $N = 82$ shell closure

  ➜ Continue to track systematics of radii and moments of $(11/2^{-})$ state

- Efficiency loss of around a factor of 10 in going to PI-LIST from normal LIST but will be more than compensated by selectivity of decay tagging than single-ion counting.
- Contaminants identified by ISOLTRAP are also much longer lived.

Calibration of atomic line using COLLAPS

- Need to calibrate atomic factors:

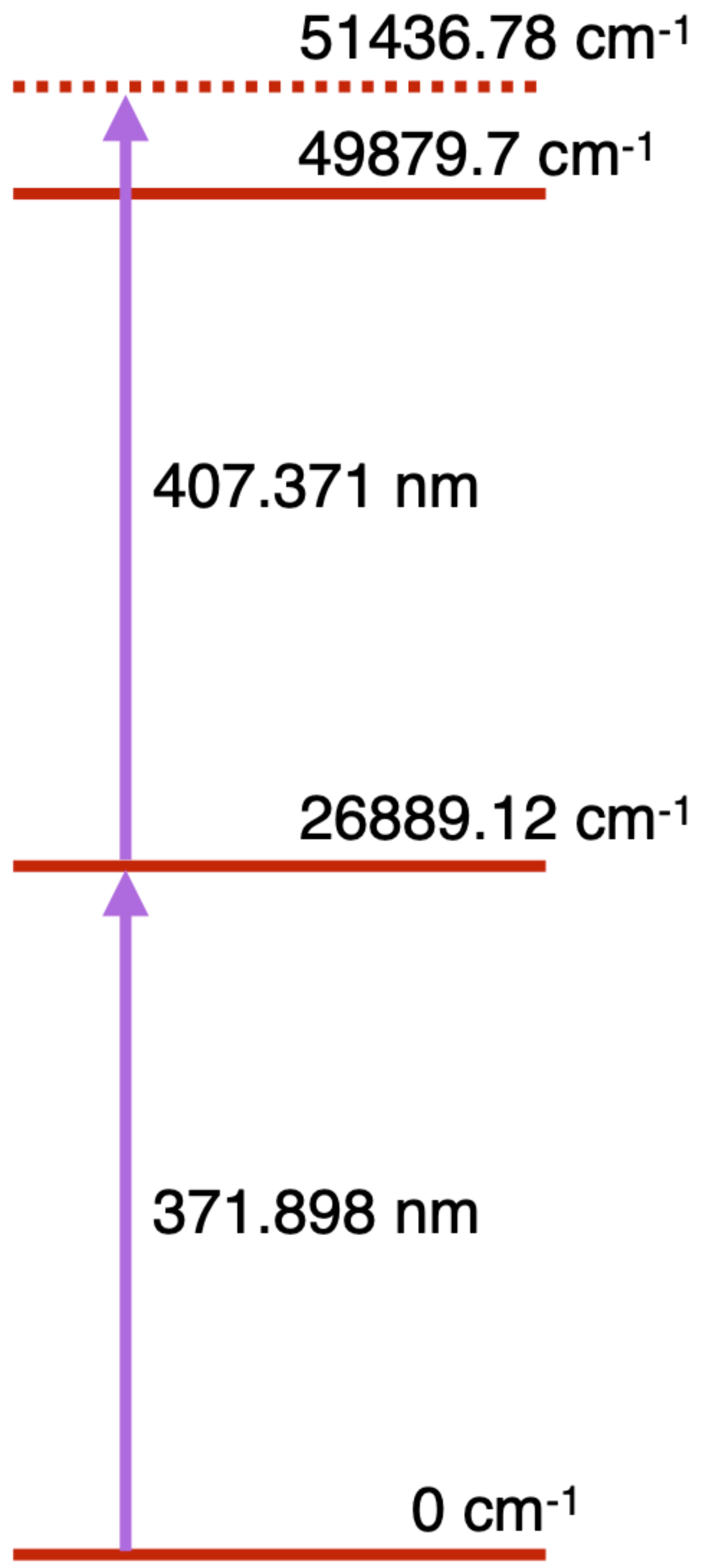
$$A = \frac{\mu}{I}\frac{B_e(0)}{J} \qquad B = Q_s V_{zz} \qquad \delta\nu^{A,A'} = \frac{A'-A}{AA'}M + F\,\delta\langle r^2\rangle^{A,A'}$$

which requires radioactive beam.

- Moreover, the ratio of the hyperfine A and B coefficients between the upper and lower states of the transition can be established

➜ Constrains the hyperfine structure fitting by eliminating 2 of the 5 parameters

- Will also assist with calculation of field and mass shift factors.



Beam request

- Collinear laser spectroscopy of ^{152m,151g,151m,150}Tm using the ionic transition

  3 shifts for ^{152m,151g,151m}Tm and 3 shifts ^{150}Tm

- Spectroscopy of ^{150,149}Tm and an initial exploration beyond using PI-LIST and IDS

  1 shift of optimisation of PI-LIST
  4 shifts for measuring ^{150,149}Tm and 3 shifts for an exploration towards ^{147}Tm

- Collinear laser spectroscopy of two or three isotopes on an atomic line
  to calibrate the constant A and B ratios for the atomic line used for PI-LIST (1st step)

  1 shift for measuring a few more intensely produce isotopes

- Mass measurements with ISOLTRAP from ^{155}Tm downwards, and beam diagnostics

  3 shifts for $^{149–155}$Tm

Total: 18 shifts

TAC comments

Stated that yields are feasible.

Comments to the proponents/INTC:

- Please do not overheat the target too early due to risk of sintering! In September 2024, this happened after 2-3 days of operation already.
- target material development is necessary to maintain target integrity also at higher temperatures required for release:
  - Shape / arrangement of the foils
  - Sintering inhibitors (alternating with W) -> RIST target, TRIUMF

Have learned more about optimal heating and proton intensity to preserve yields.

Aspects where yield is less critical (eg. calibration of atomic line) can be towards the end.

Collaboration

B. Cheal[1], L. V. Rodríguez[2,3], R. Heinke[4,5], A. Ajayakumar[5], A. N. Andreyev[6], M. Au[5], S. Bai[7], C. Bernerd[5], K. Blaum[3], H. Bodnar[8], P. Campbell[4], K. Chrysalidis[5], J. Cubiss[6,9], T. Fabritz[2,8], R. F. García Ruíz[10], P. F. Giesel[11], J. Hughes[1], P. Imgram[12], A. A. H. Jaradat[4,5], F. Koehler[8], K. Koenig[8], D. Lange[3], T. Lellinger[2,8], I. Lopp[8] D. Lunney[13], K. M. Lynch[4], E. Matthews[8], W. Nazarewicz[14], R. Neugart[3,15], G. Neyens[12], L. Nies [2], W. Nörtershäuser[8], R. D. Page[1], J. Palmes[8], P. Plattner[3], J. R. Reilly[5], M. Reponen[16], P. G. Reinhard[17], S. Rothe[5], R. Sánchez[18], Ch. Schweiger[3], L. Schweikhard[11], S. Stegemann[5], T. Stora[5], S. M. Wang[19], J. Wessolek[4,5], J. Wilson[6], X. F. Yang[7], D. T. Yordanov[13]

Broad collaboration of COLLAPS, ISOLTRAP, TISD, RILIS, PI-LIST, IDS

Represents the best opportunity to measure nuclear moments and radii of a proton emitter at ISOLDE