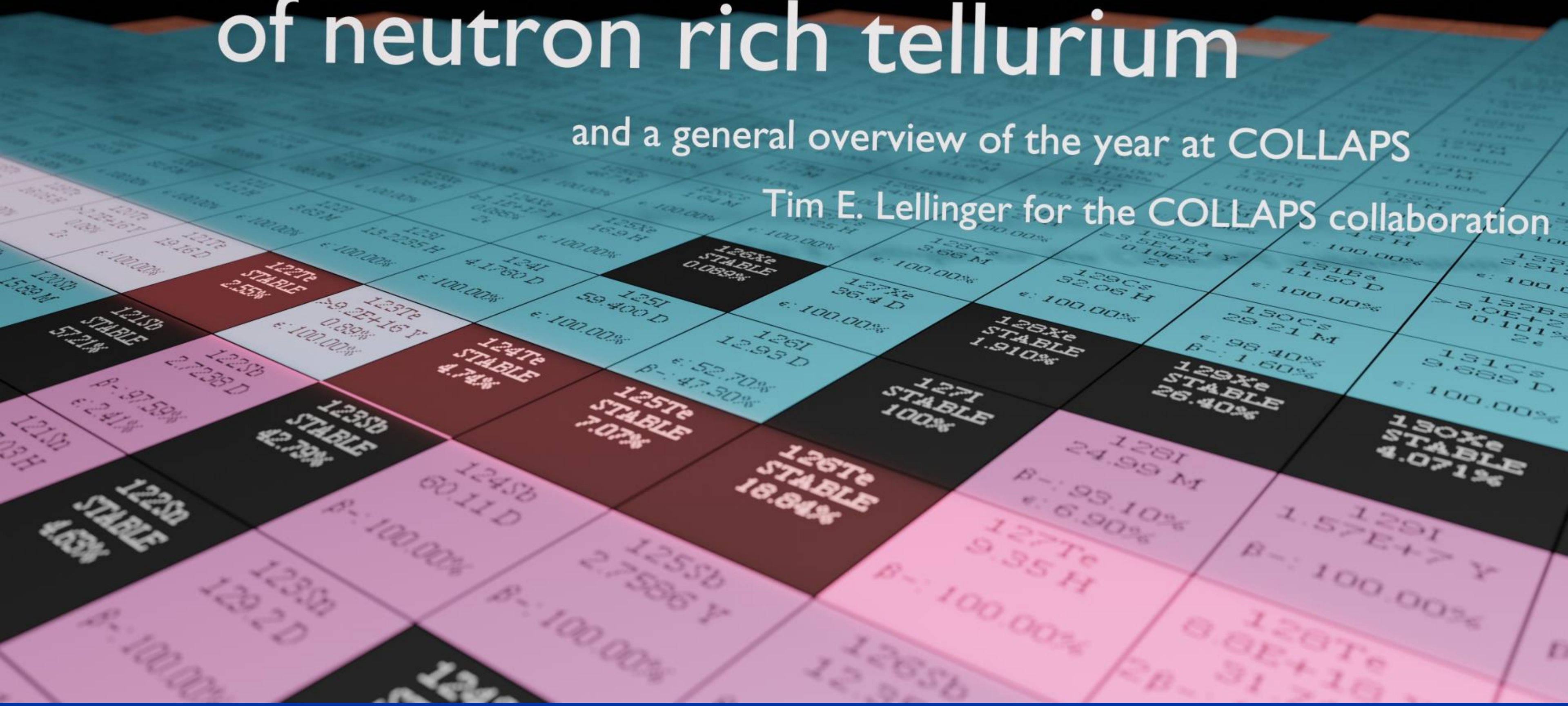
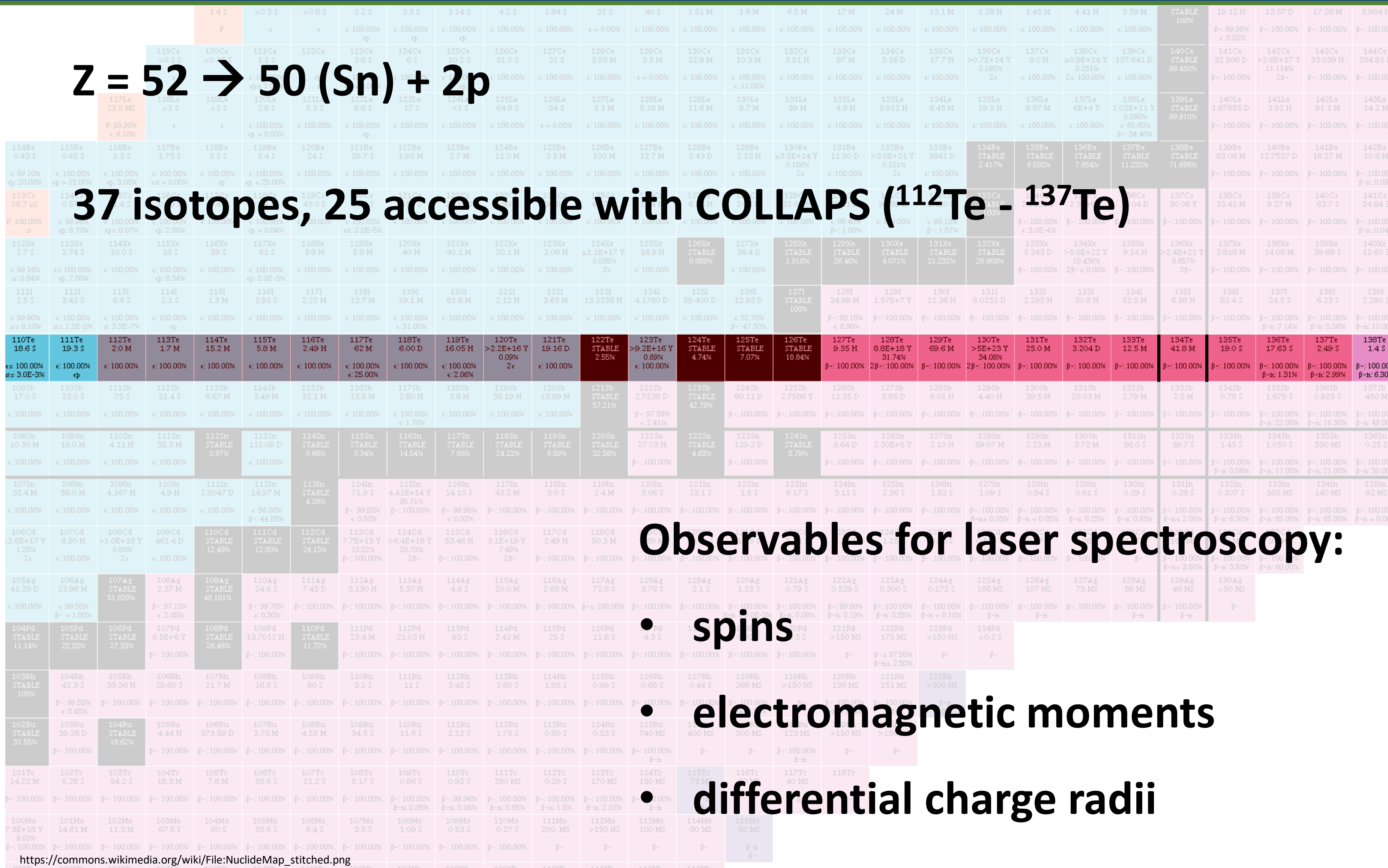
High resolution laser spectroscopy of neutron rich tellurium

and a general overview of the year at COLLAPS

Tim E. Lellinger for the COLLAPS collaboration



Tellurium physics case



Z = 52 → 50 (Sn) + 2p

37 isotopes, 25 accessible with COLLAPS (^{112}Te - ^{137}Te)

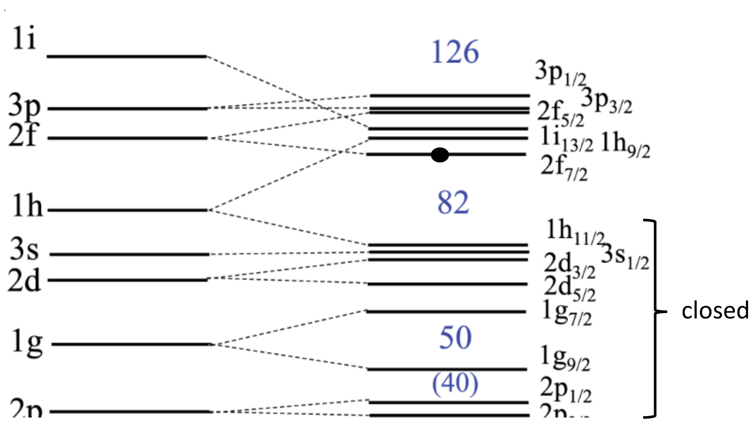
Observables for laser spectroscopy:

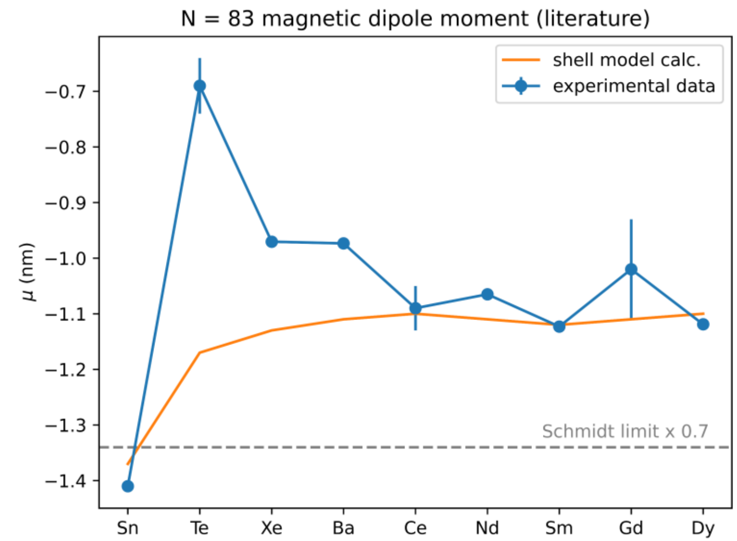
- spins
- electromagnetic moments
- differential charge radii

https://commons.wikimedia.org/wiki/File:NuclideMap_stitched.png

The physics case of ^{135}Te

Hagino, K., Maeno, Y. A nuclear periodic table. *Found Chem* **22**, 267–273 (2020)





add. data from https://doi.org/10.1103/PhysRevC.102.051301

- (simple shell model picture): single neutron over closed 82 core
- Single particle like for tin: doubly magic + 1n
- Otherwise: Contribution from valence protons

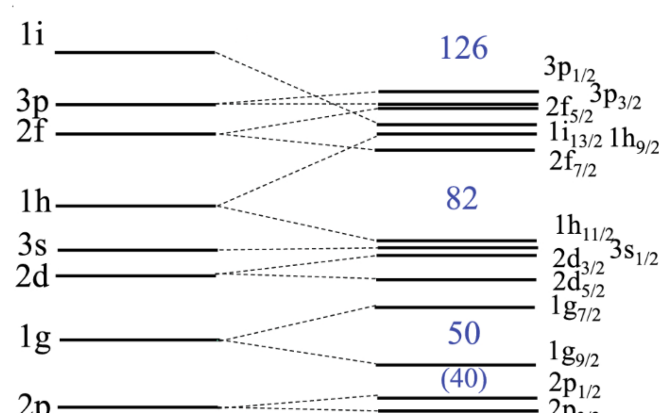
→ Should be decently described by theory

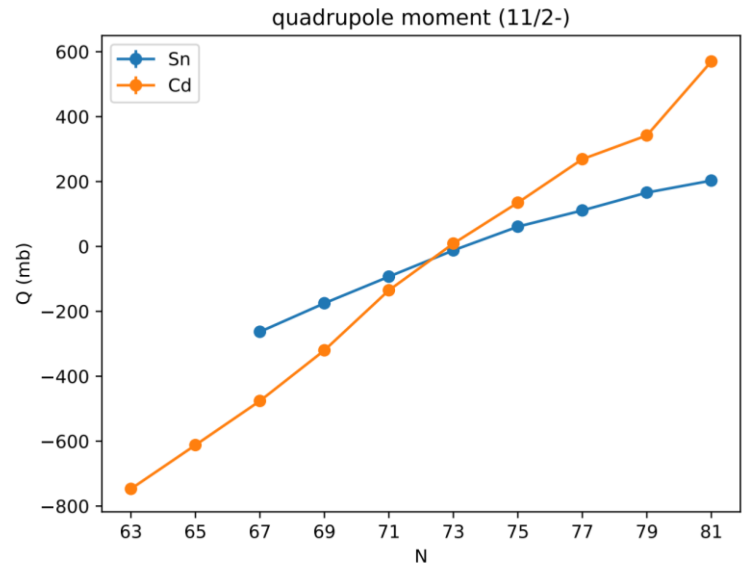
But: Large deviation for tellurium

11/2 isomeric chains

- Long chains of 11/2 isomeric states in Cd, Sn, Te
- Single unpaired neutron in h11/2 shell
- Parity defining orbital → pure wave function
- Cd, Sn completely different!

Goal: Compare effect of two valence protons of tellurium to two holes of cadmium





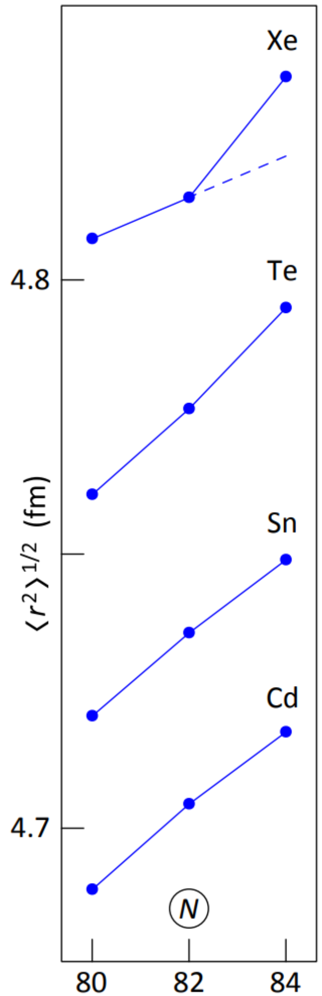
Charge radii at the shell closure

N = 82 shell closure

→"kink" in charge radius

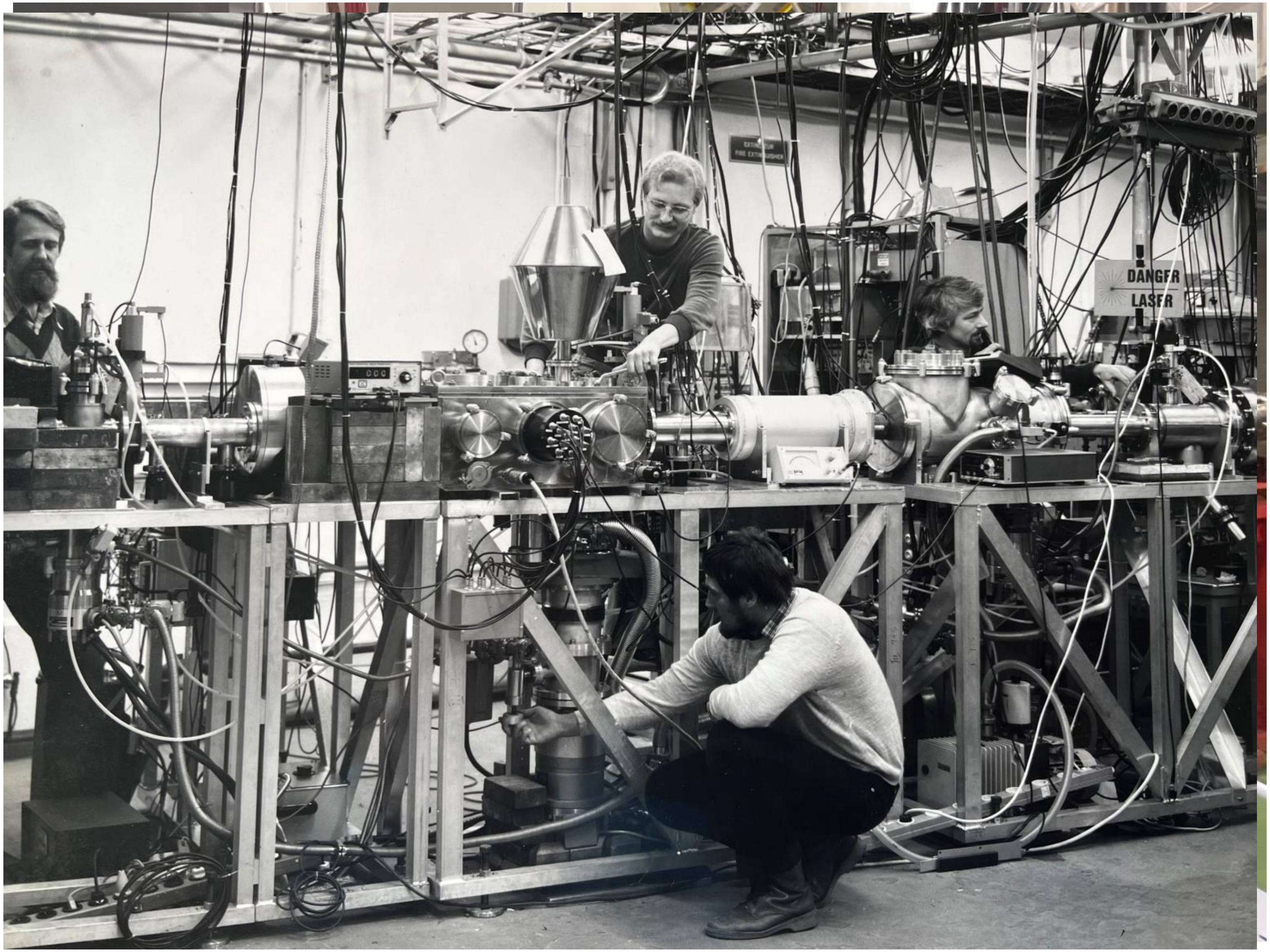
Any "quenching"?

Goal: Compare "kink" in charge radius to Sn, Xe, Cd…



https://cds.cern.ch/record/1601818/files/INTC-CLL-011.pdf

COLLAPS beamline



Photographic service CERN, 237-04-80

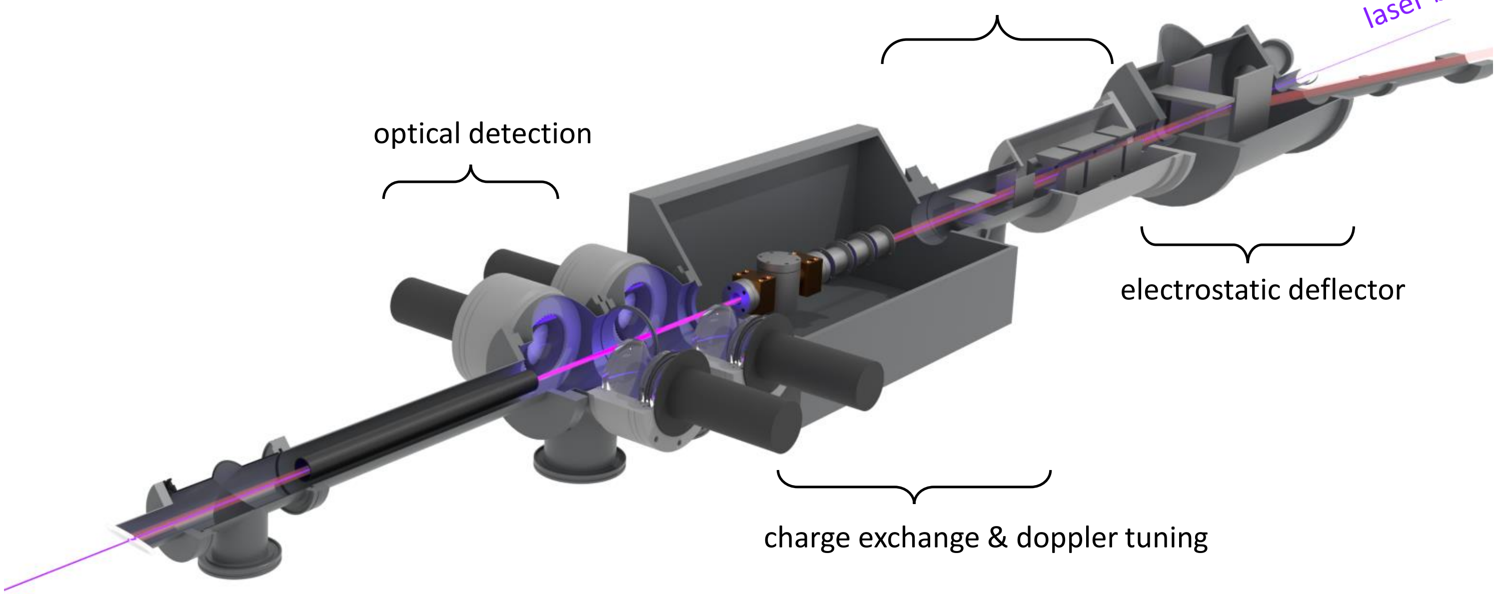
COLLAPS beamline

Measurement principle:

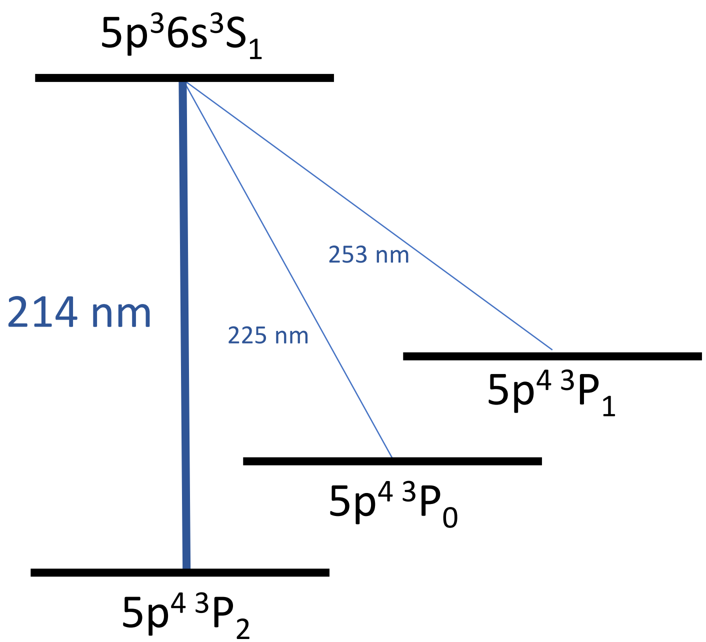
1) Overlap laser beam and ion bunch collinearly
2) Focus ion bunch into optical detection
3) Neutralize ion bunch via charge exchange and scan beam energy
4) Measure fluorescence in optical detection

Advantages:

1) collinear geometry → no doppler broadening
2) only need a single narrowband CW laser
3) insensitive to isobaric contamination



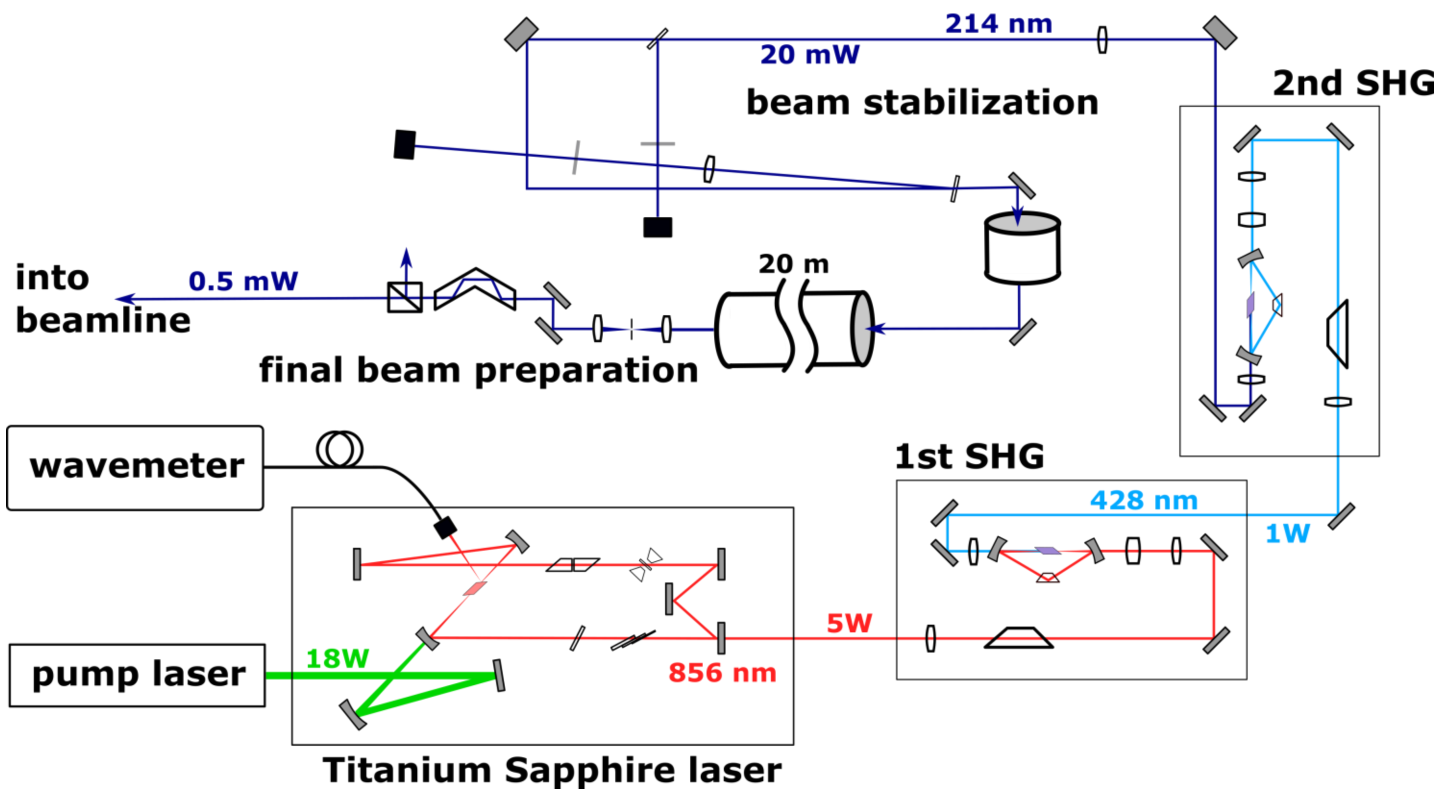
Tellurium atomic level scheme



Why choose the 214 nm transition?

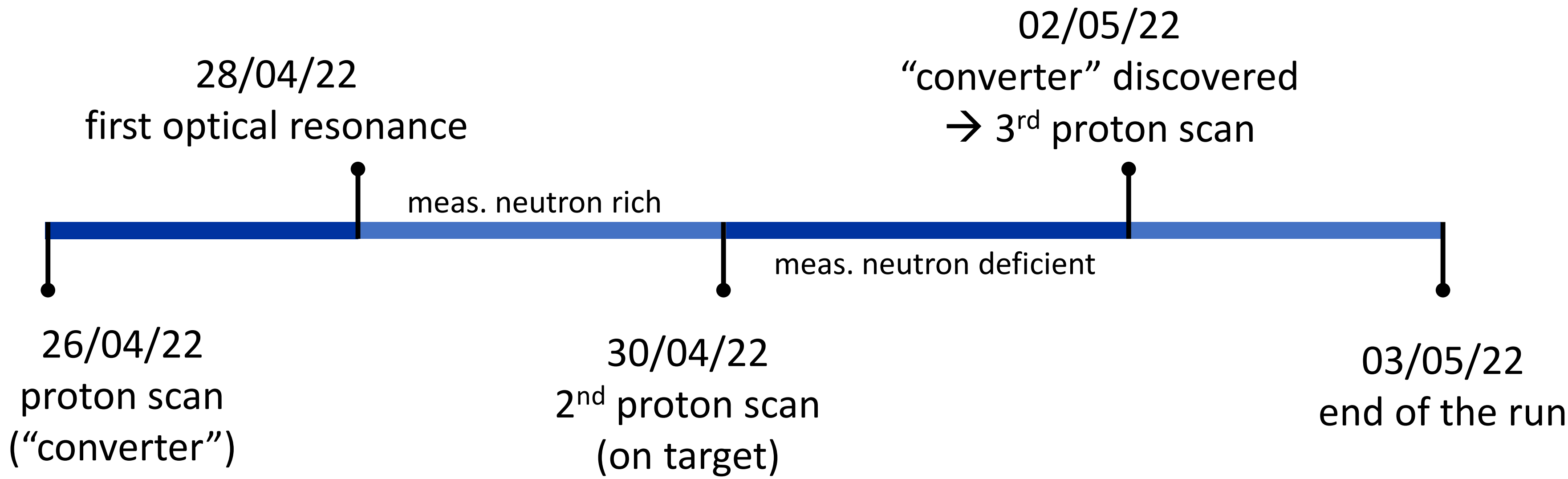
- (Simulated) $5p^4\,^3P_2$ ground state most populated in charge exchange process (>50%)
- Highly sensitive to “nuclear signature”
  - Ground state sensitive to quadrupole moment
  - Upper state sensitive to dipole moment
  - S→P transition sensitive to charge radii
- Challenge: Laser system to produce 214 nm light

Laser setup for 214 nm



➔ Stable operation during the entire run

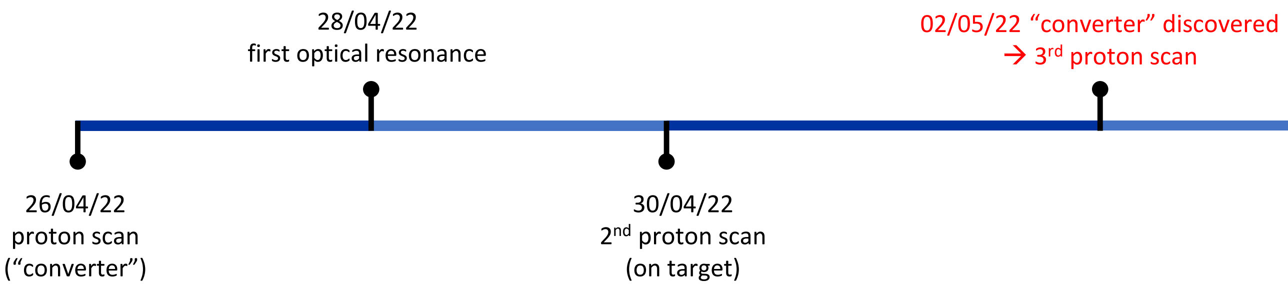
Overview of the run



→ Measured ^{112}Te - ^{136}Te with 10 isomers

→ 328 (!) usable spectra in total

Curiosity: Copper neutron converter



- Shoot on converter → steer p-beam “down”

- Confusion over which way is up/down

➔ Ended up hitting the copper blocks instead of the real converter

https://cds.cern.ch/record/2759094

➔ **A “makeshift spallation neutron source” for neutron-rich Te isotopes at ISOLDE**

Ulli Köster, Jochen Ballof[1], Cyril Bernerd[2], Katerina Chrysalidis[3], Reinhard Heinke[3], Bruce Marsh[3], João Pedro Ramos[4], Edgar Reis[3], Sebastian Rothe[3], Simon Stegemann[3], Liss Vazquez Rodriguez[3], COLLAPS collaboration

[1] *CERN, present address MSU*
[2] *KU Leuven - CERN*
[3] *CERN*
[4] *CERN, present address: SCK CEN*

Spins

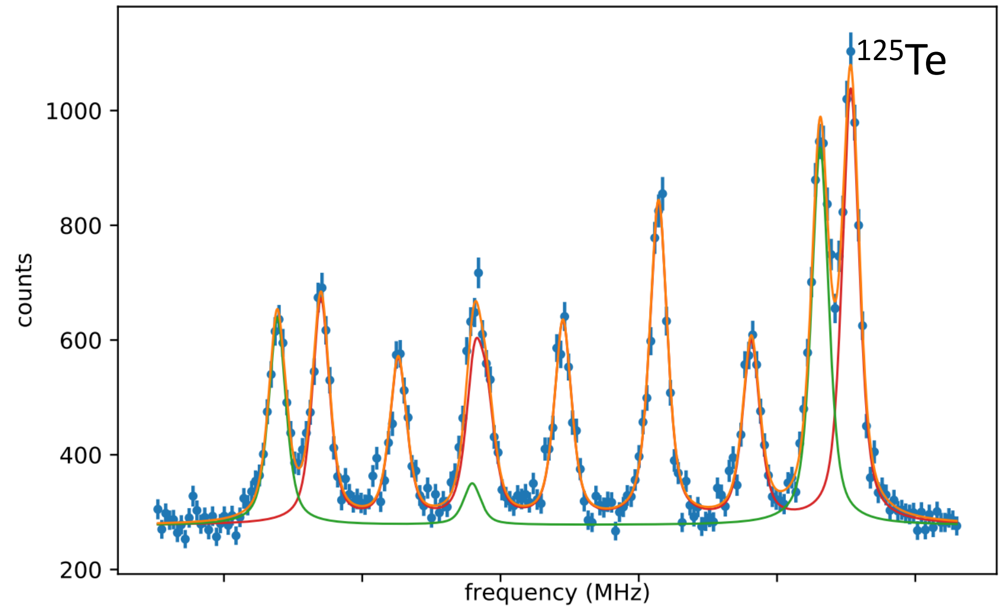
^{112}Te z: 52 n: 60 Jπ: 0+ $T_{1/2}$:2.0 m 0.2 decay ec β+ 100%	^{113}Te z: 52 n: 61 Jπ: (7/2+) $T_{1/2}$:1.7 m 0.2 decay ec β+ 100%	^{114}Te z: 52 n: 62 Jπ: 0+ $T_{1/2}$:15.2 m 0.7 decay ec β+ 100%	^{115}Te z: 52 n: 63 Jπ: 7/2+ $T_{1/2}$:5.8 m 0.2 decay ec β+ 100%	^{116}Te z: 52 n: 64 Jπ: 0+ $T_{1/2}$:2.49 h 0.04 decay ec β+ 100%	^{117}Te z: 52 n: 65 Jπ: 1/2+ $T_{1/2}$:62 m 2 decay ec β+ 100% β+ 25%	^{118}Te z: 52 n: 66 Jπ: 0+ $T_{1/2}$:6.00 d 0.02 decay ec 100%	^{119}Te z: 52 n: 67 Jπ: 1/2+ $T_{1/2}$:16.05 h 0.05 decay ec β+ 100% β+ 2.06%	^{120}Te z: 52 n: 68 Jπ: 0+ $T_{1/2}$:stable	^{121}Te z: 52 n: 69 Jπ: 1/2+ $T_{1/2}$:19.17 d 0.04 decay ec β+ 100%	^{122}Te z: 52 n: 70 Jπ: 0+ $T_{1/2}$:stable	^{123}Te z: 52 n: 71 Jπ: 1/2+ $T_{1/2}$: 9.2 10^{16}y decay ec 100%	^{124}Te z: 52 n: 72 Jπ: 0+ $T_{1/2}$:stable
^{125}Te z: 52 n: 73 Jπ: 1/2+ $T_{1/2}$:stable	^{126}Te z: 52 n: 74 Jπ: 0+ $T_{1/2}$:stable	^{127}Te z: 52 n: 75 Jπ: 3/2+ $T_{1/2}$:9.35 h 0.07 decay β- 100%	^{128}Te z: 52 n: 76 Jπ: 0+ $T_{1/2}$: 7.7 10^{24}y 0.4 10^{24} decay 2β- 100%	^{129}Te z: 52 n: 77 Jπ: 3/2+ $T_{1/2}$:69.6 m 0.3 decay β- 100%	^{130}Te z: 52 n: 78 Jπ: 0+ $T_{1/2}$: 0.79 10^{21}y decay 2β- 100%	^{131}Te z: 52 n: 79 Jπ: 3/2+ $T_{1/2}$:25.0 m 0.1 decay β- 100% β- 100%	^{132}Te z: 52 n: 80 Jπ: 0+ $T_{1/2}$:3.204 d 0.013 decay β- 100%	^{133}Te z: 52 n: 81 Jπ: (3/2+) $T_{1/2}$:12.5 m 0.3 decay β- 100%	^{134}Te z: 52 n: 82 Jπ: 0+ $T_{1/2}$:41.8 m 0.8 decay β- 100%	^{135}Te z: 52 n: 83 Jπ: (7/2-) $T_{1/2}$:19.0 s 0.2 decay β- 100%	^{136}Te z: 52 n: 84 Jπ: 0+ $T_{1/2}$:17.63 s 0.09 decay β- 100% β- n 1.31%	^{137}Te z: 52 n: 85 Jπ: (7/2-) $T_{1/2}$:2.49 s 0.05 decay β- 100% β- n 2.99%

from IAEA – Nuclear Data Section (on 16/11/2022)

Ideal case → Just count peaks

More complex cases:

- Peaks overlapping
- Isomers present
- Limited statistics
- Peak count not unambiguous for high spin states



Spins

^{113}Te, $7/2^{+}$ $11/2^{-}$

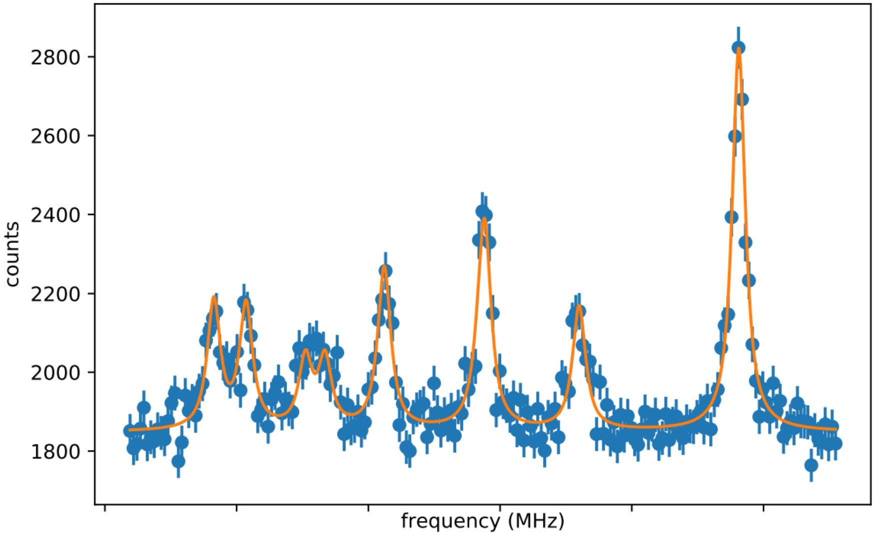
This graph contained unpublished data and was therefore removed to comply with the open access policy of the COLLAPS collaboration

→ Spin 7/2 doesn't fit at all (with reasonable parameters)

→ Maybe Spin 11/2?

Further analysis required…

Nuclear moments



Get hyperfine parameters A,B from fit

→ Related to nuclear moments

$$\Delta\nu = \frac{A}{2}C + B\frac{\frac{3}{4}C(C+1) - I(I+1)J(J+1)}{2I(2I-1)J(2J-1)}$$

$$A = \frac{\mu_I B_e(0)}{hIJ} \qquad B = \frac{eQ_s}{h}\frac{\partial^2 V}{\partial z^2}$$

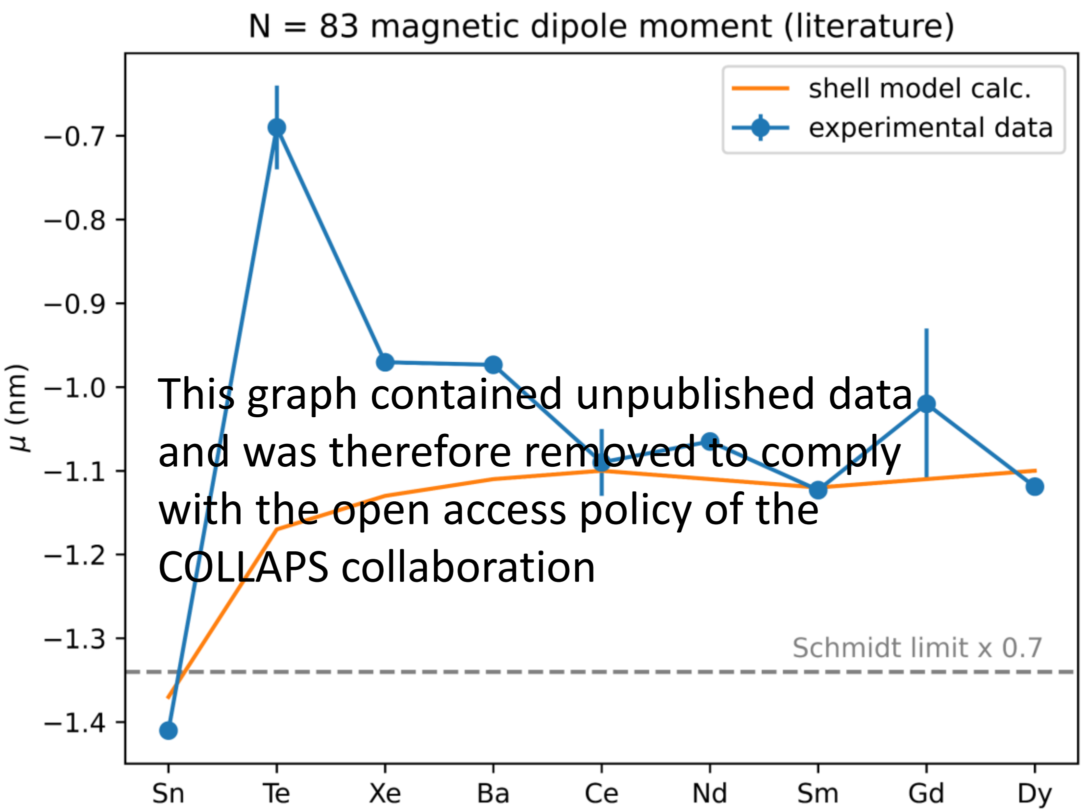
- $B_e(0)$ from NMR reference

  https://doi.org/10.1103/PhysRev.89.923

- Field gradient from theory = 5.83 x 10^{22} V/m^2

  DOI 1O.1007/sl0751-006-9505-0

Dipole moment of N = 83



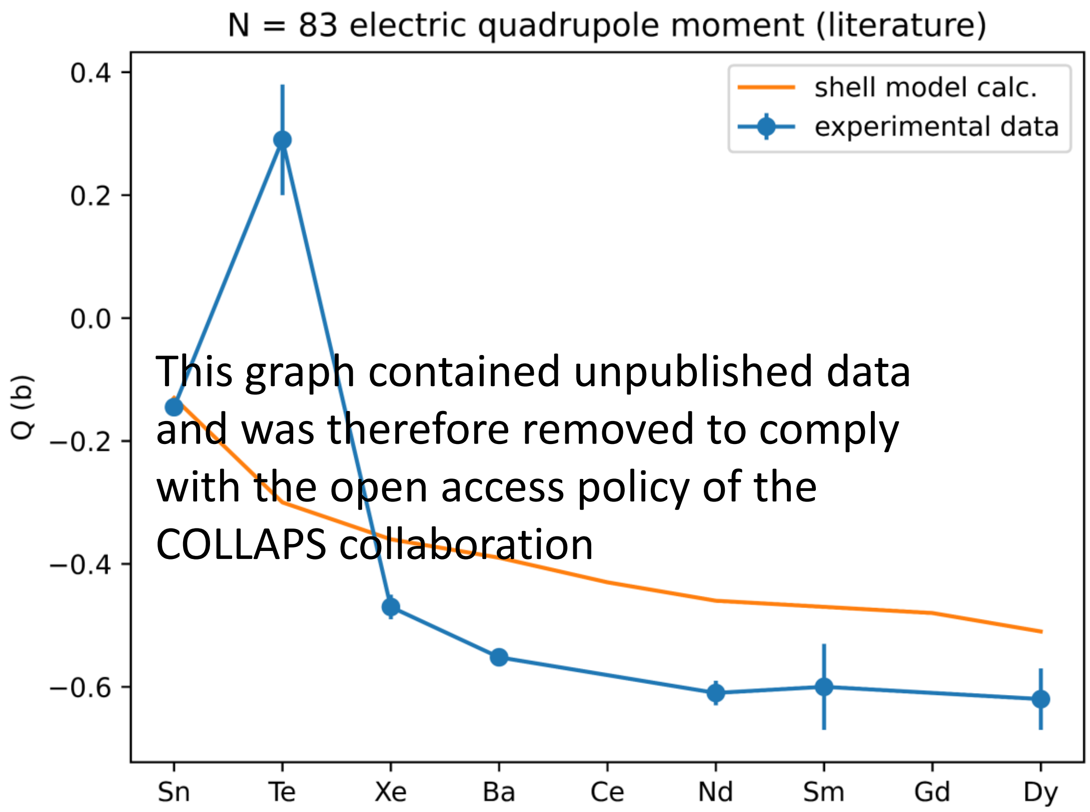
N = 82 + 1

"true" single particle state for Sn

Higher Z → positive contribution from valence protons

add. data and theory from https://doi.org/10.1103/PhysRevC.102.051301

Quadrupole moment of N = 83

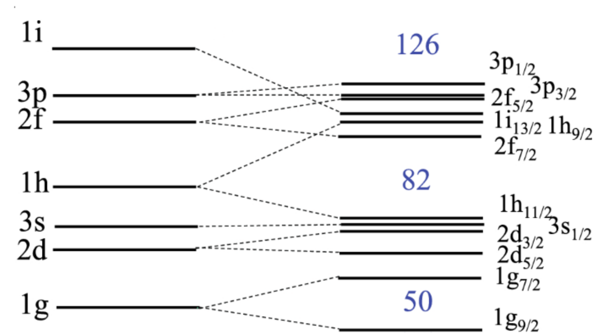


→ N = 83 “mystery”: Everything is well described in the end…

add. data and theory from https://doi.org/10.1103/PhysRevC.102.051301

$11/2^-$ dipole moment

This graph contained unpublished data and was therefore removed to comply with the open access policy of the COLLAPS collaboration



Hagino, K., Maeno, Y. A nuclear periodic table. *Found Chem* **22**, 267–273 (2020)

- Single unpaired neutron in $1h_{11/2}$ orbital
- "pure" state because only orbital with negative parity

Expected qualitatively similar trend to Cadmium

→ This did not turn out to be true

11/2^{-} quadrupole moment

This graph contained unpublished data and was therefore removed to comply with the open access policy of the COLLAPS collaboration

- Expected similar trend as Cd

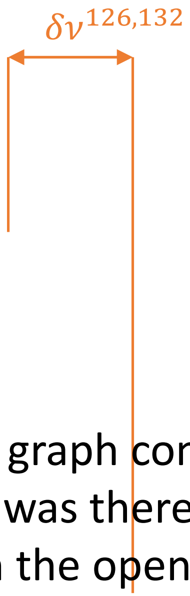
→Kind of correct

Linear trend as predicted by simple seniority scheme

$$\langle Q \rangle = \langle Q_{sp} \rangle \left[1 - 2\frac{n-1}{2j-1} \right]$$

Important difference: Te flattens out at high N

Isotope shift & charge radii



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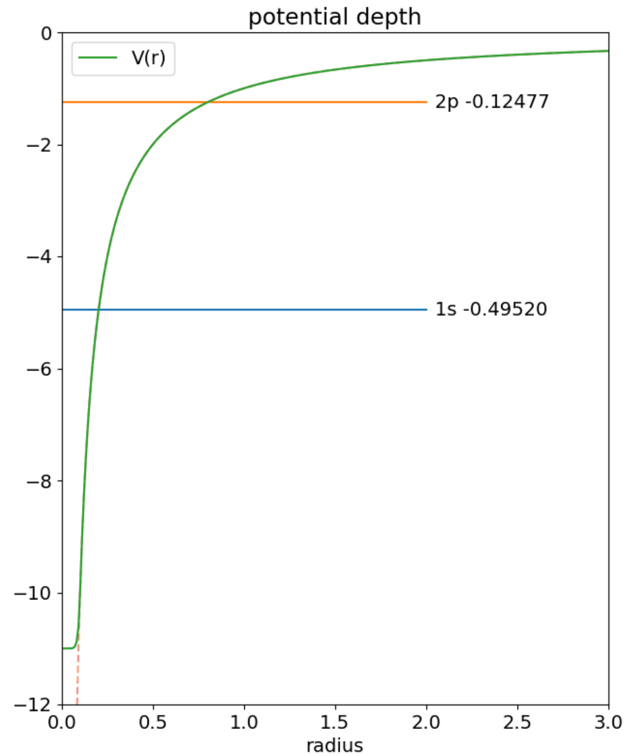


$$\delta\nu^{AA'} = K_{MS} \cdot \frac{M_{A'} - M_A}{M_A M_{A'}} + F\delta\langle r_c^2\rangle^{AA'}$$

Charge radii

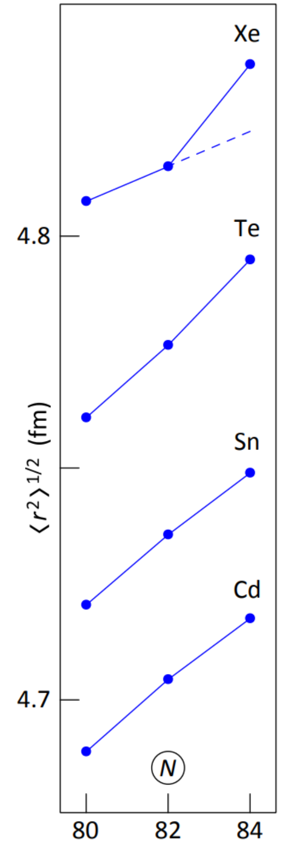
This graph contained unpublished data and was therefore removed to comply with the open access policy of the COLLAPS collaboration

Charge radii

Experiment

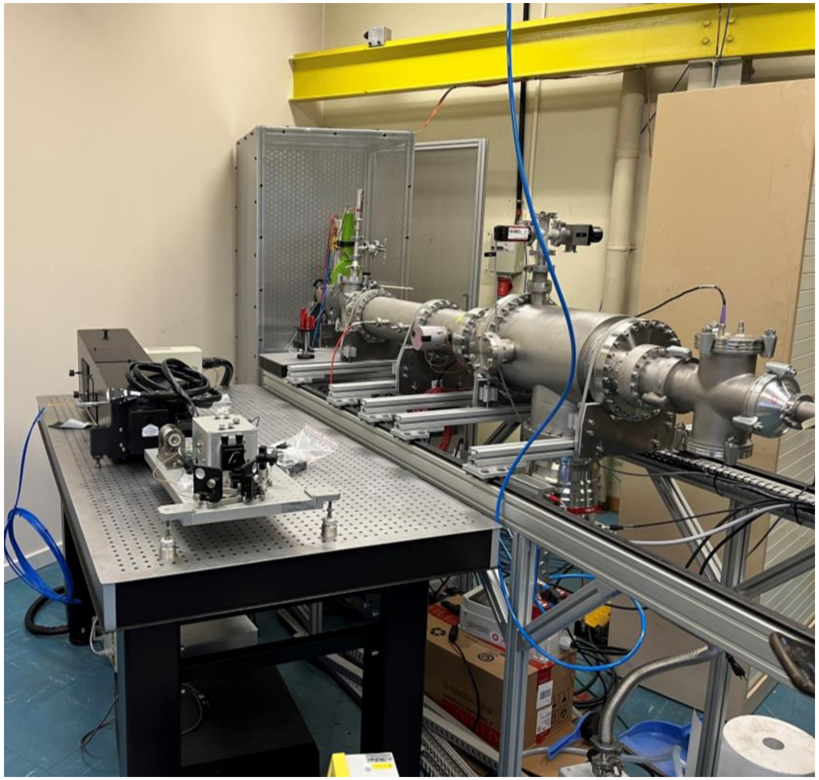
Quenching prediction

This graph contained unpublished data and was therefore removed to comply with the open access policy of the COLLAPS collaboration



➔ No "quenching"

Other projects at COLLAPS in 2022

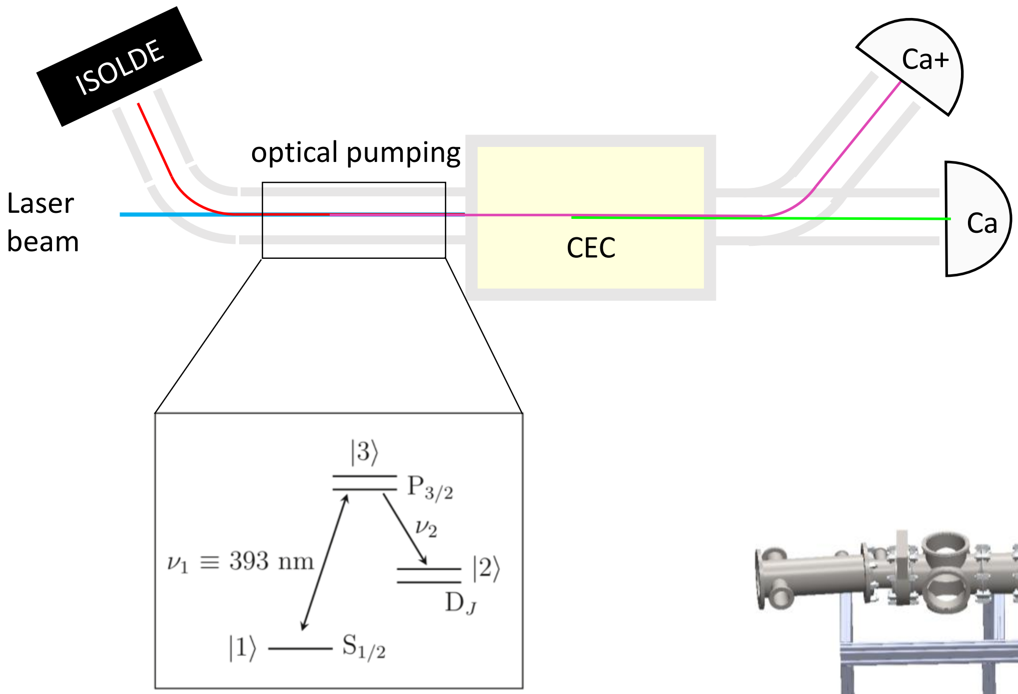


- Offline setup in Bd. 275
- Basically, a copy of COLLAPS + ion source/mass separator
- First ion beam trough in October
- Waiting for laser

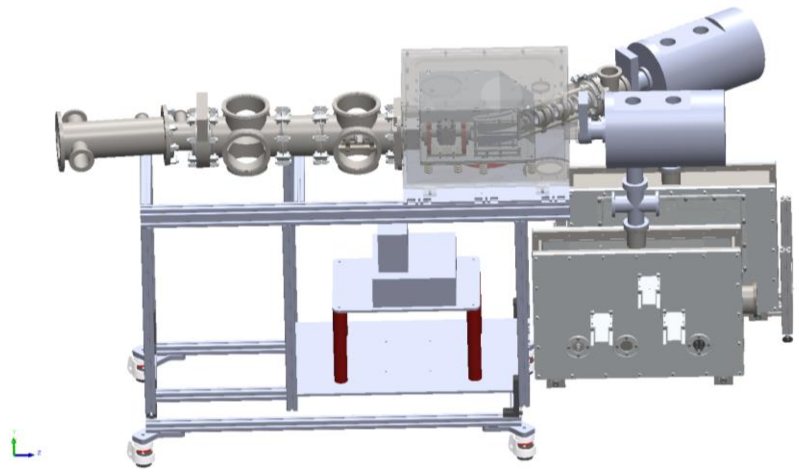
→Test platform for new techniques

First case: ROC

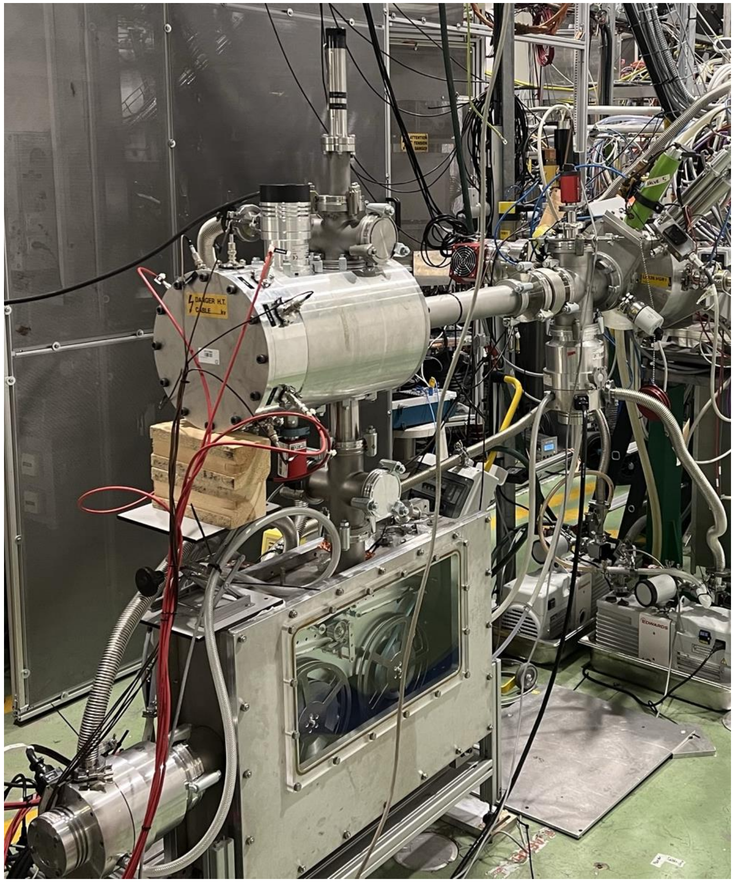
ROC (Radioactive detection after optical pumping and state selective charge exchange)



- Particle detection technique
- Use CEC to detect if laser in resonance
- Goal: charge radii of $^{54,53}Ca$

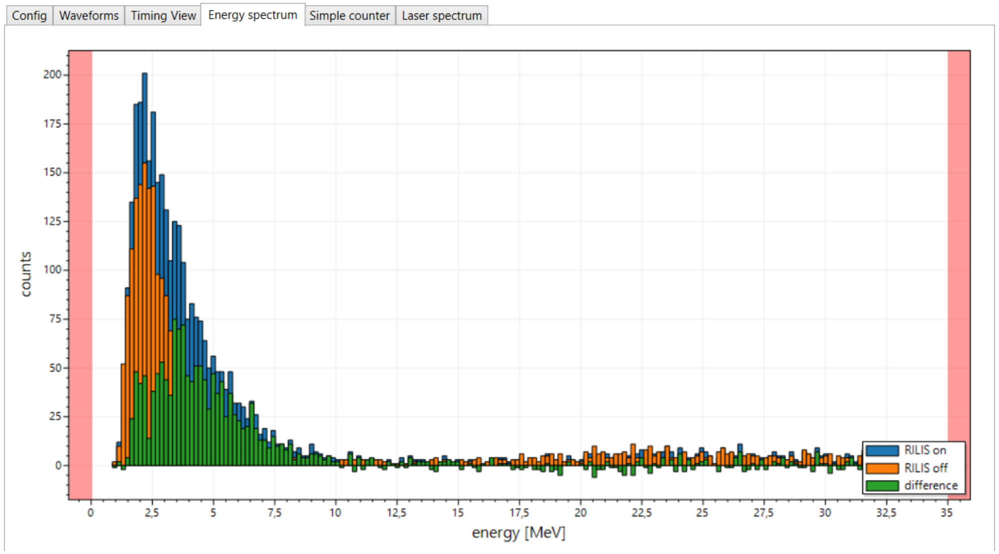


ROC detector test



- Test production and detector efficiency for $^{54,53}Ca$
- Single tape station on LA1
- Part of TISD 1.7 GeV test

→4 counts per proton pulse for ^{54}Ca



Thank you

COLLAPS

TECHNISCHE UNIVERSITÄT DARMSTADT

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG

KU LEUVEN

Federal Ministry of Education and Research

ISOLDE

Not included slides following – proceed at own risk!

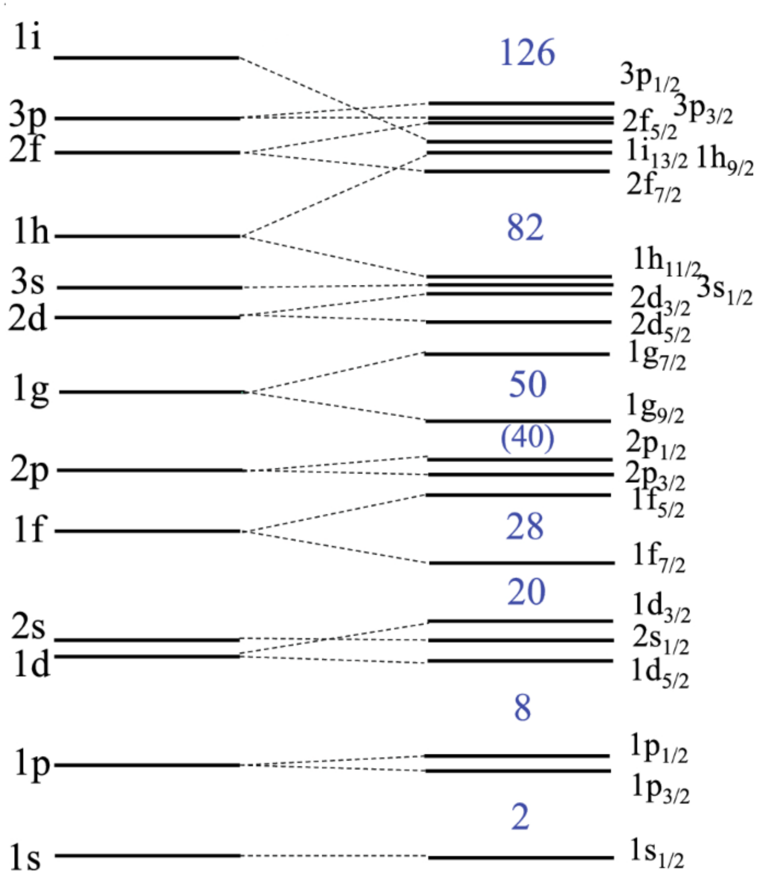
Single particle like states

1) N = 83 → N = 82 $^{(magic)}$ +1n

2) 11/2^{-} isomer chain

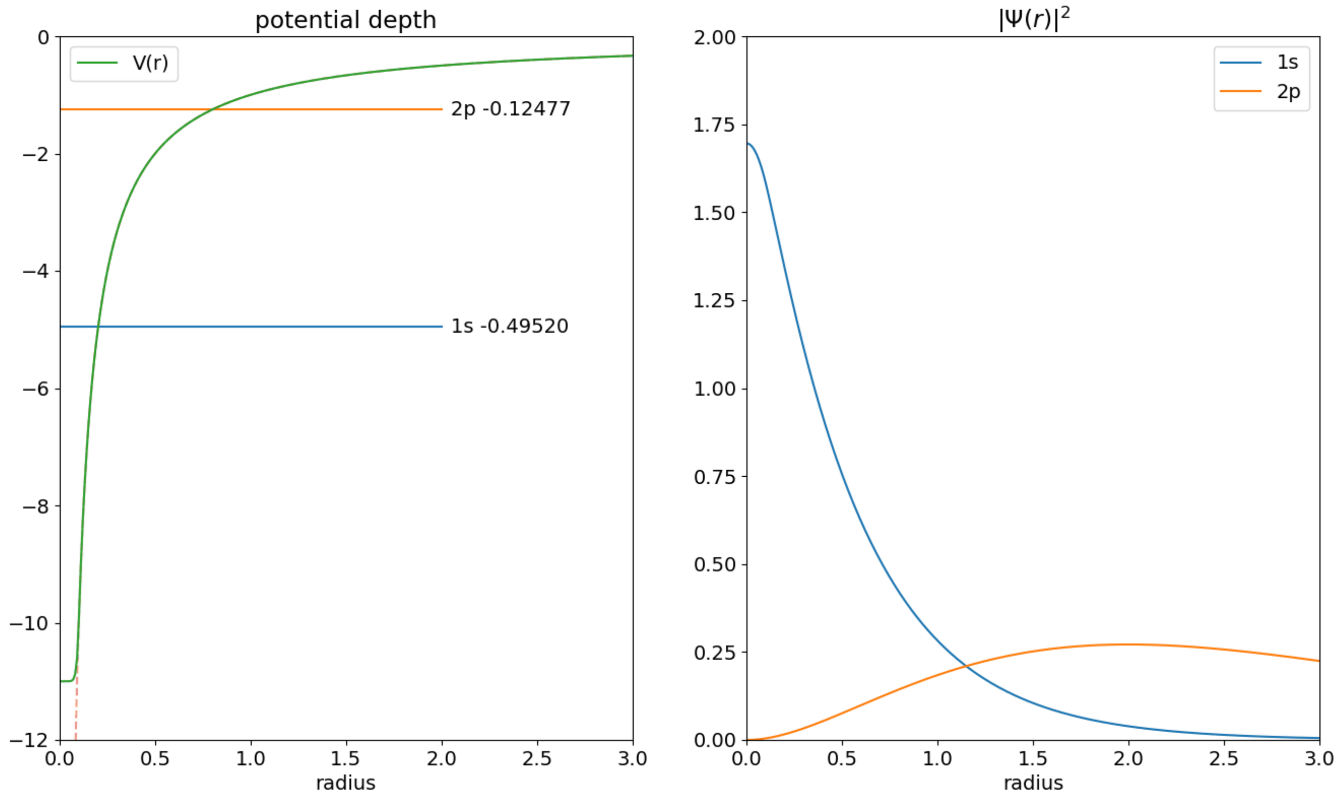
→ Single unpaired neutron in $1h_{11/2}$ orbital

→ "pure" state because only orbital with negative parity



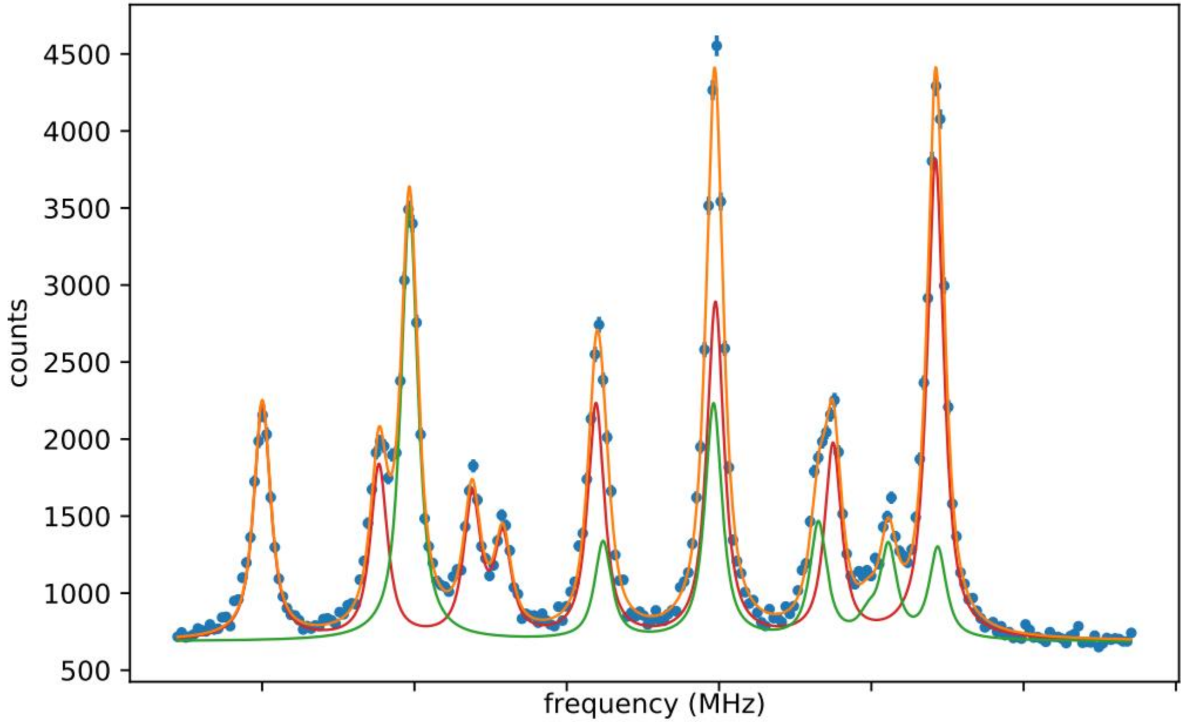
Hagino, K., Maeno, Y. A nuclear periodic table. *Found Chem* **22**, 267–273 (2020)

Charge radii



$$\delta\nu^{AA'} = K_{MS} \cdot \frac{M_{A'} - M_A}{M_A M_{A'}} + F\delta < r_c^2 >^{AA'}$$

^{133}Te – the special one



- Ground state Racah fixed
- Isomer only two peaks fixed to each other
- B ratio fixed to value from 115,135

→Tried various starting parameters (swapping peaks etc)

→Either converged to same value or not at all

ISOLDE setup

- UCn target on HRS target station
- Te mass marker for stable isotopes*
- RILIS (also on 214 nm transition)
- Bunching and cooling with ISCOOL

* Ended up being Thallium due to ambiguous handwriting

Overview of an atomic spectrum