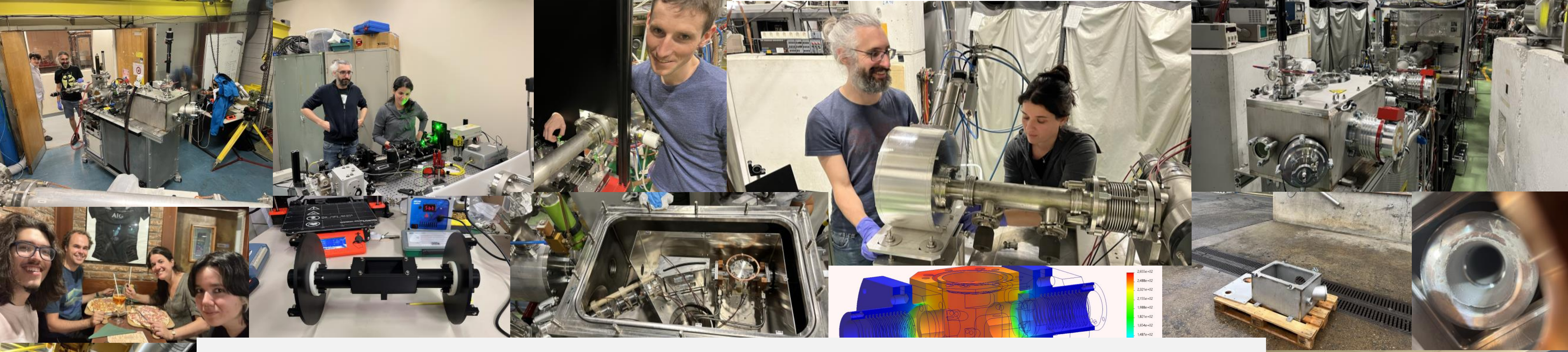
disclaimer

Some plots of unpublished data were removed or altered.



From thallium to calcium

Pushing the limits of CLS at COLLAPS in 2023

The COLLAPS experiment

- **Col**linear **la**ser s**p**ectro**s**copy (CLS) on radioactive isotopes
- Operating since 1978

Measurement principle:

1) Overlap laser beam and ion bunch collinearly
2) Focus ion bunch into optical detection
3) Scan beam energy → scan transition frequency
4) (opt.) neutralize ion bunch via charge exchange
5) Measure fluorescence in optical detection

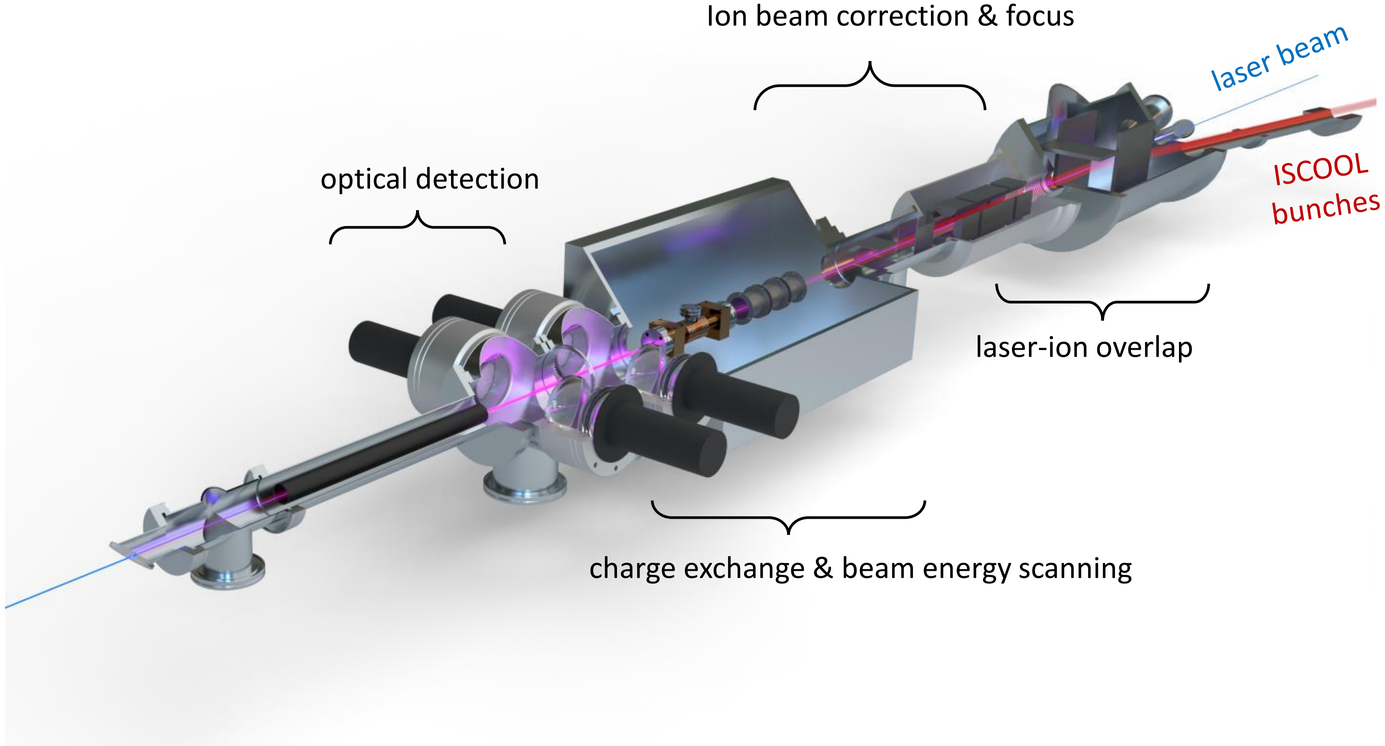
Advantages:

- collinear geometry → no doppler broadening, limited mostly by natural linewidth
- only needs a single narrowband CW laser
- insensitive to isobaric contamination

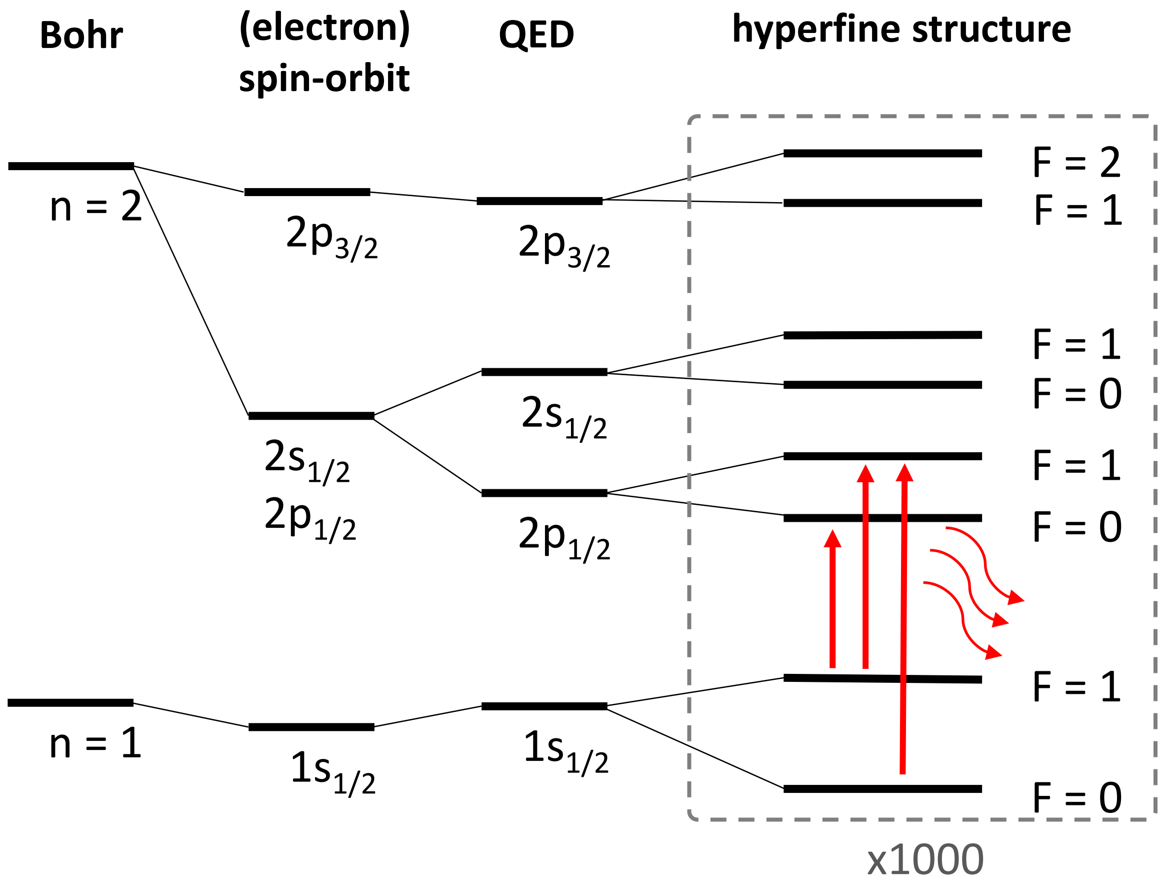
Disadvantages:

- Limited by photon detection efficiency and laser stray light

→ Need more specialized detection setups for very rare cases

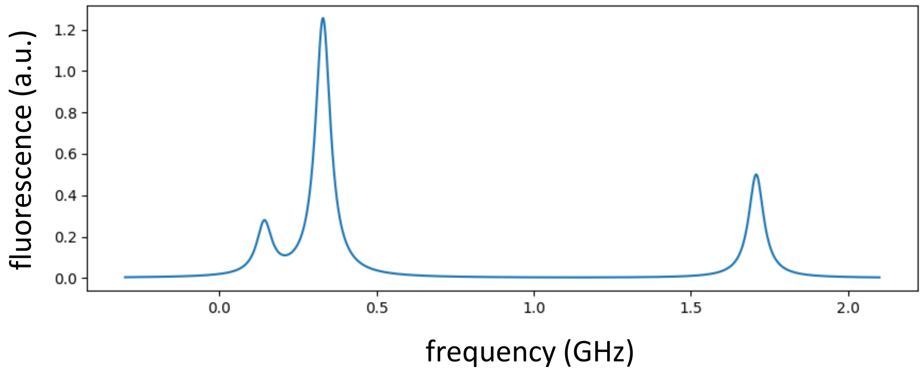


Nuclear moments from laser spectroscopy

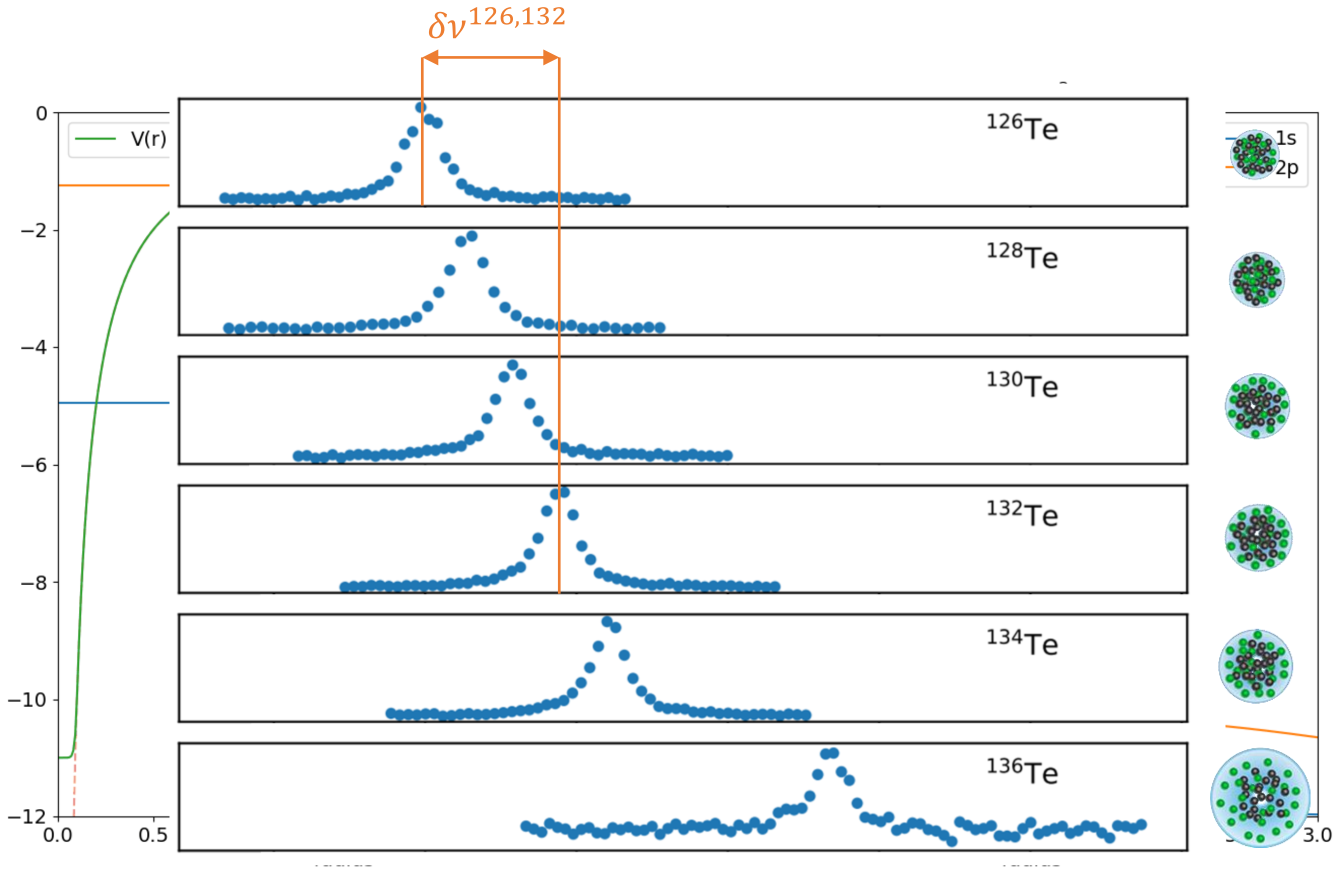


hyperfine structure → "nuclear signature"

- number of peaks → spin
- splitting of the peaks
  - magnetic dipole moment
  - electric quadrupole moment



Charge radii from laser spectroscopy



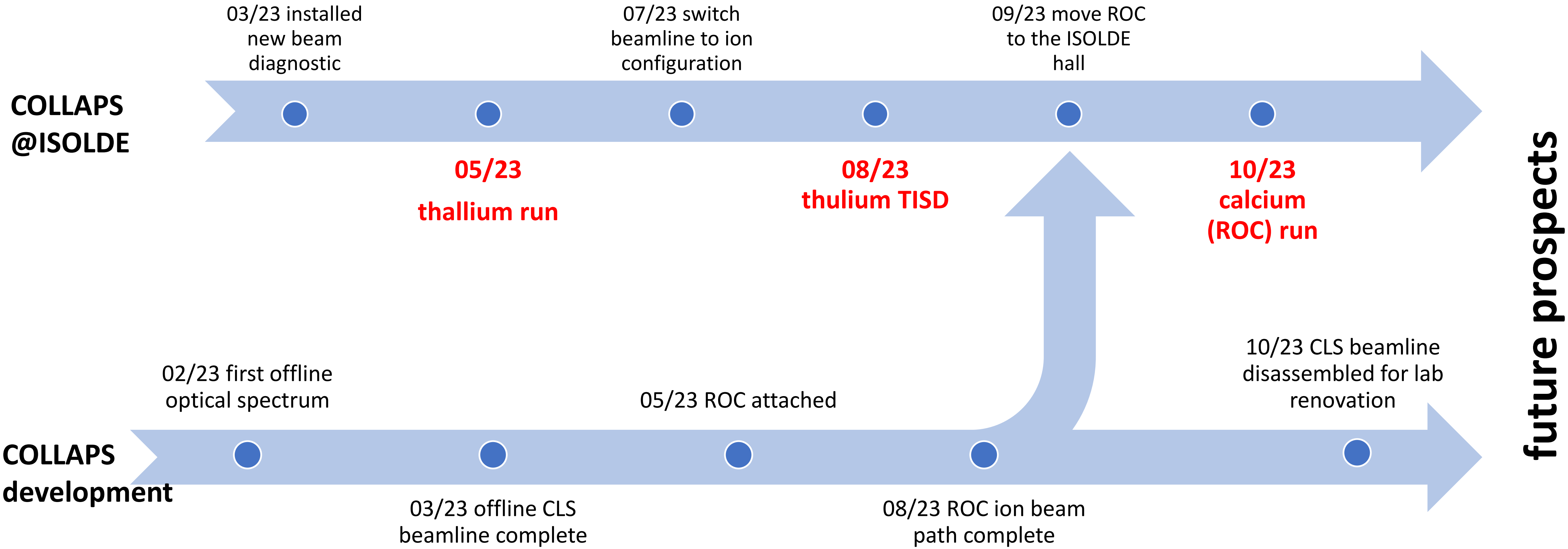
electron orbitals respond differently to charge distribution of nucleus

→Measure difference in charge radius from shift in resonance

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

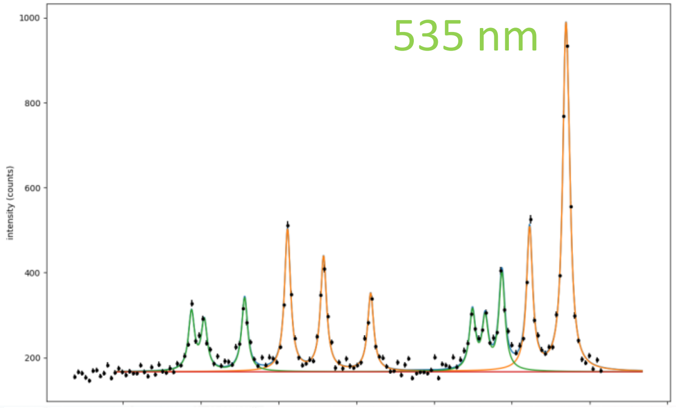
All observables: Purely based on atomic physics, no nuclear theory input needed!

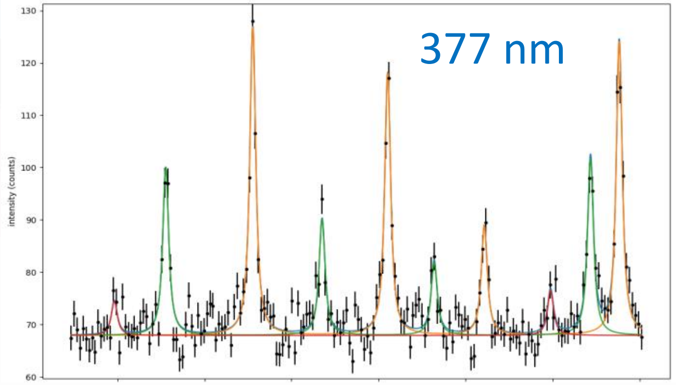
COLLAPS 2023 overview



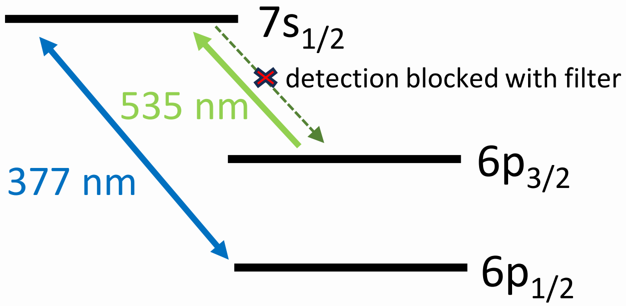
Studying ^{183}Tl – ^{205}Tl

^{184}Tl



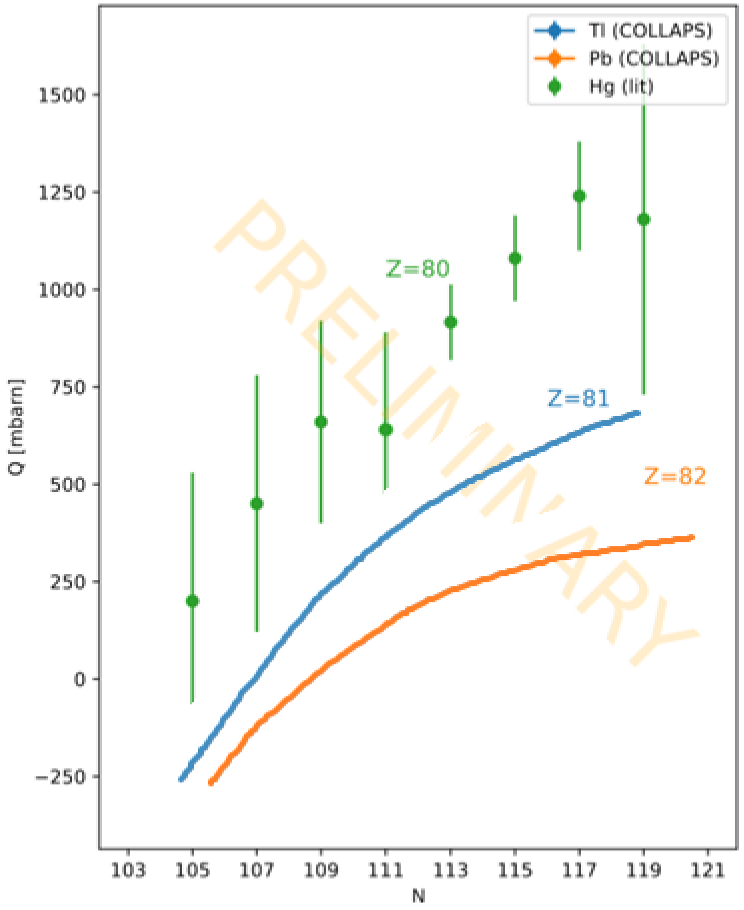


- Conducted from 9th to 15th of May
- Total of 16 shifts
- Measured 25 isotopes and 16 isomers
- Two different laser transitions used to constrain the hyperfine parameters
- Enhanced sensitivity on green transition due to stray light free measurement



Quadrupole moments thallium isomers

$i_{13/2}$ isomers



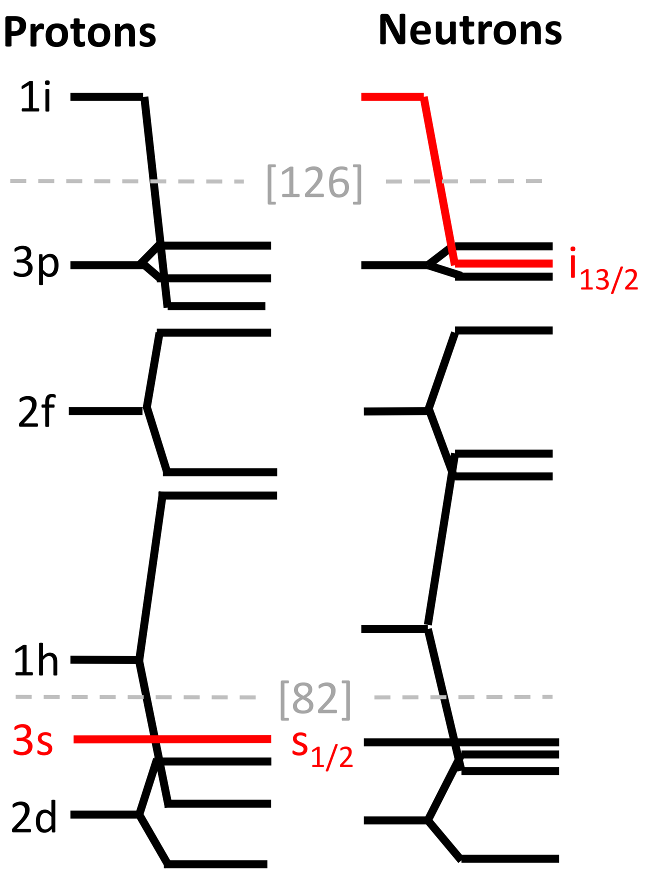
Single particle picture?

- Protons shouldn't contribute to Q (Pb, Hg closed, Tl defined by $s_{1/2}$)

→Q defined entirely by $i_{13/2}$ neutron orbit

→Simple picture: Should be the same for all three elements

→Measurement: Same trend, different slope and offset



Feasibility of ^{147}Tm

So far, no laser spectroscopy measurements of proton emitters

→ Rare decay mode that only occurs near the proton drip line
→ Comparatively low yields
→ **measure charge radius of Tm isotopic chain**

Goal of the LOI:

1) Quantify the production of thulium isotopes (and contaminants)
2) Test sensitivity of two different laser transitions to charge radius

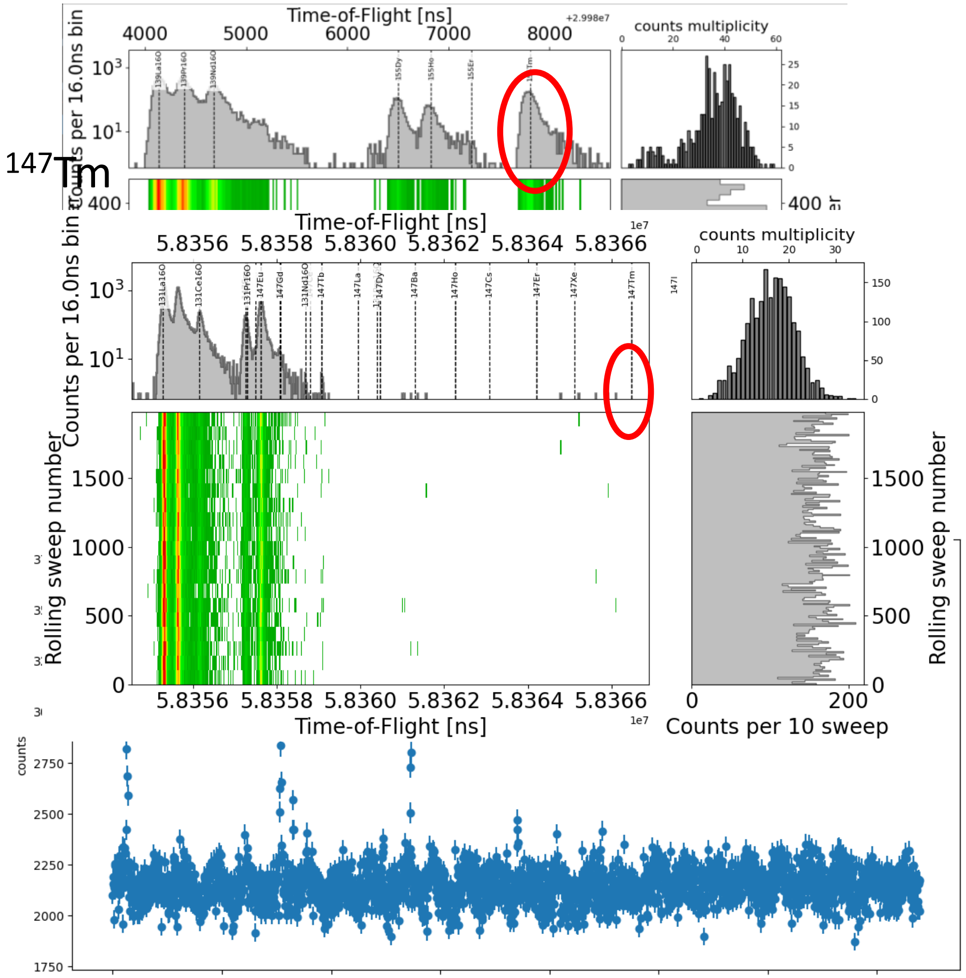
➔ 6 shift LOI together with ISOLTRAP in August

(this is what ChatGPT thinks a proton emitter looks like)

Feasibility of ^{147}Tm

^{155}Tm

^{147}Tm



- Measured from ^{155}Tm to ^{175}Tm
- Found some unknown (really) long-lived isomers

→ COLLAPS efficiency great

→ both tested transitions work

→ some nice physics output already

Large contamination for the very neutron deficient cases

→ buncher overfilling, ion source saturated

→ full proposal with LIST to reduce contamination

Measuring neutron rich calcium

Measure Ca across N = 32 shell gap (^{53,54}Ca)

Experimental challenges for laser spectroscopy of ^{53}Ca, ^{54}Ca :

- lifetime of 461 ms, 107 ms
- yield of 20 ions/s, 2 ions/s at ISOLDE
- >3 orders of magnitude more stable beam contamination

→needs a more sensitive detection setup than existing fluorescence detection

Evidence for a new nuclear 'magic number' from the level structure of ^{54}Ca

D. Steppenbeck[1], S. Takeuchi[2], N. Aoi[3], P. Doornenbal[2], M. Matsushita[1], H. Wang[2], H. Baba[2], N. Fukuda[2], S. Go[1], M. Honma[4], J. Lee[2], K. Matsui[5], S. Michimasa[1], T. Motobayashi[2], D. Nishimura[6], T. Otsuka[1,5], H. Sakurai[2,5], Y. Shiga[7], P.-A. Söderström[2], T. Sumikama[8], H. Suzuki[2], R. Taniuchi[5], Y. Utsuno[9], J. J. Valiente-Dobón[10] & K. Yoneda[2]

Masses of exotic calcium isotopes pin down nuclear forces

F. Wienholtz[1], D. Beck[2], K. Blaum[3], Ch. Borgmann[3], M. Breitenfeldt[4], R. B. Cakirli[3,5], S. George[1], F. Herfurth[2], J. D. Holt[6,7], M. Kowalska[8], S. Kreim[3,8], D. Lunney[9], V. Manea[9], J. Menéndez[6,7], D. Neidherr[2], M. Rosenbusch[1], L. Schweikhard[1], A. Schwenk[7,6], J. Simonis[6,7], J. Stanja[10], R. N. Wolf[1] & K. Zuber[10]

Unexpectedly large charge radii of neutron-rich calcium isotopes

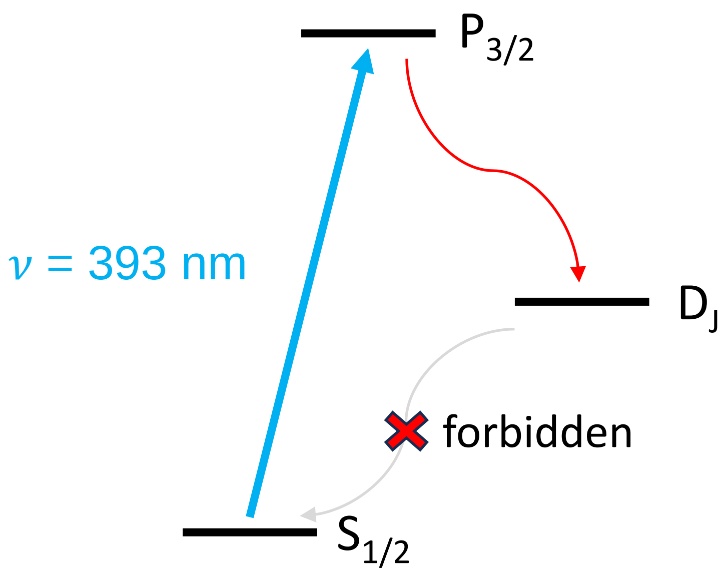
R. F. Garcia Ruiz[1*], M. L. Bissell[1,2], K. Blaum[3], A. Ekström[4,5], N. Frömmgen[6], G. Hagen[4], M. Hammen[6], K. Hebeler[7,8], J. D. Holt[9], G. R. Jansen[4,5], M. Kowalska[10], K. Kreim[3], W. Nazarewicz[4,11,12], R. Neugart[3,6], G. Neyens[1], W. Nörtershäuser[6,7], T. Papenbrock[4,5], J. Papuga[1], A. Schwenk[3,7,8], J. Simonis[7,8], K. A. Wendt[4,5] and D. T. Yordanov[3,13]

➔ **R**adioactive detection after **o**ptical pumping and state selective **c**harge exchange (ROC)

R F Garcia Ruiz et al, *Development of a sensitive setup for laser spectroscopy studies of very exotic calcium isotopes*

The ROC method

Relevant Ca II level scheme



Idea: Exploit electronic structure of Ca II

Use laser to excite S→P transition

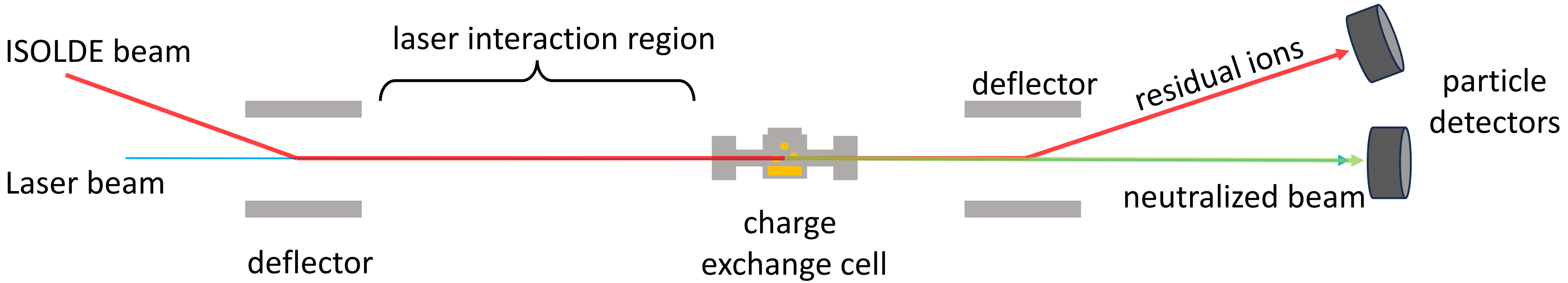
→If laser on resonance, electron will be permanently "pumped" to D-states

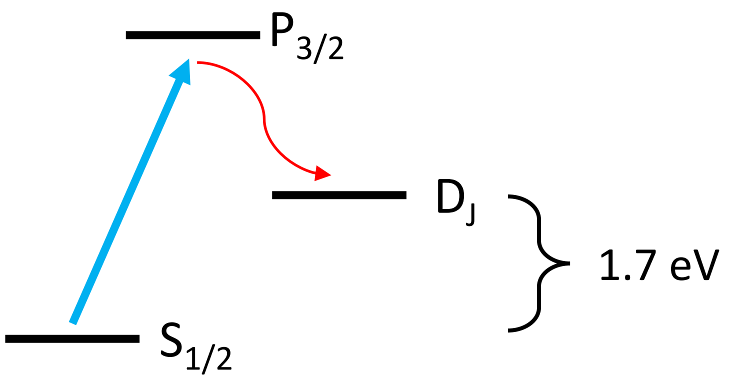
→Then: detect electronic state change to find out if laser was on resonance

→ High efficiency because of particle detection while still retaining the advantages of CLS

Charge exchange as an electronic state detector

Essential ROC setup



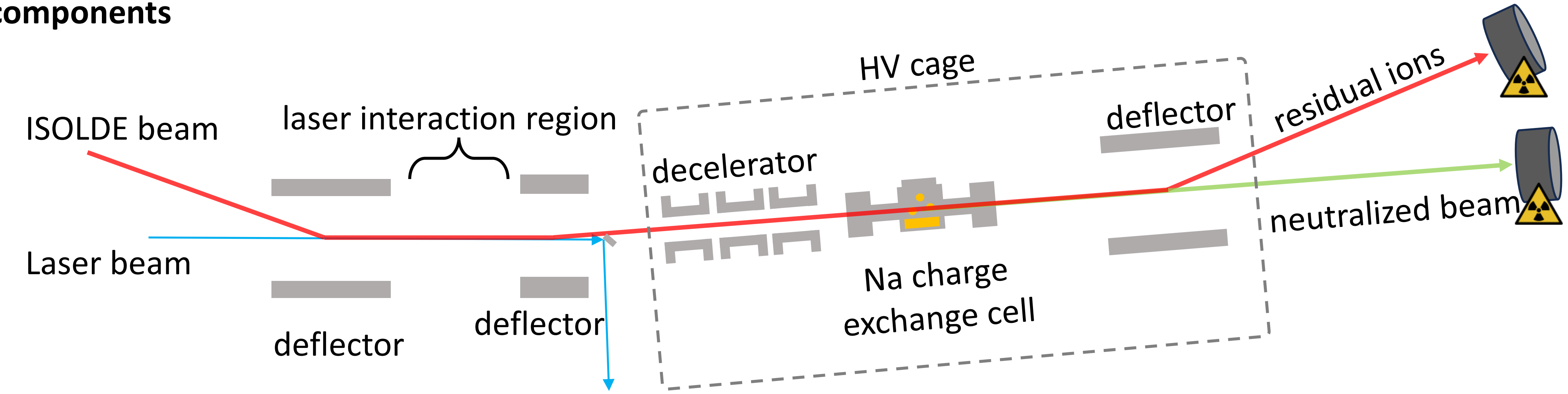


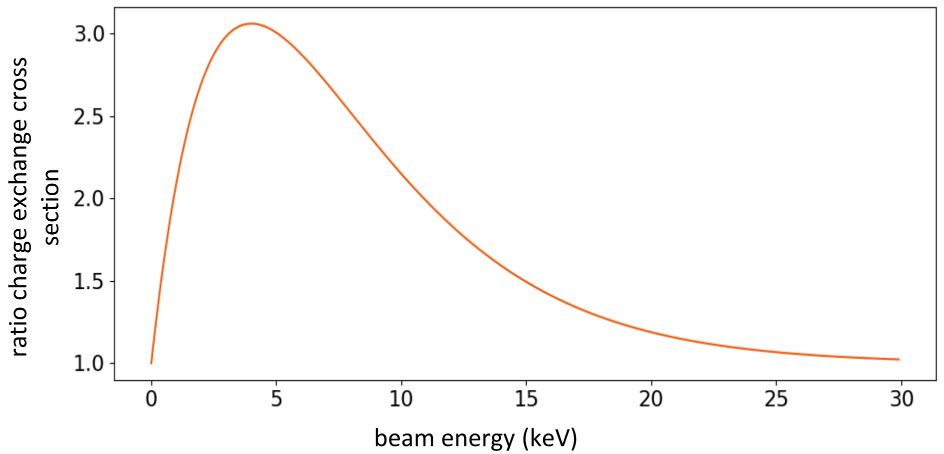
→ S, D state have different exchange cross sections
→ Use charge exchange as state detector

Separate ions from atoms afterwards for resonance detection

Charge exchange as an electronic state detector

All components





Charge exchange cross section only different at low beam energies!

→ Decelerate the beam, then perform charge exchange at 4 keV
→ CEC needs to be on HV platform!
→ HV section also needs to be short, since neutralized beam can't be refocussed

Real setup and beamtime summary

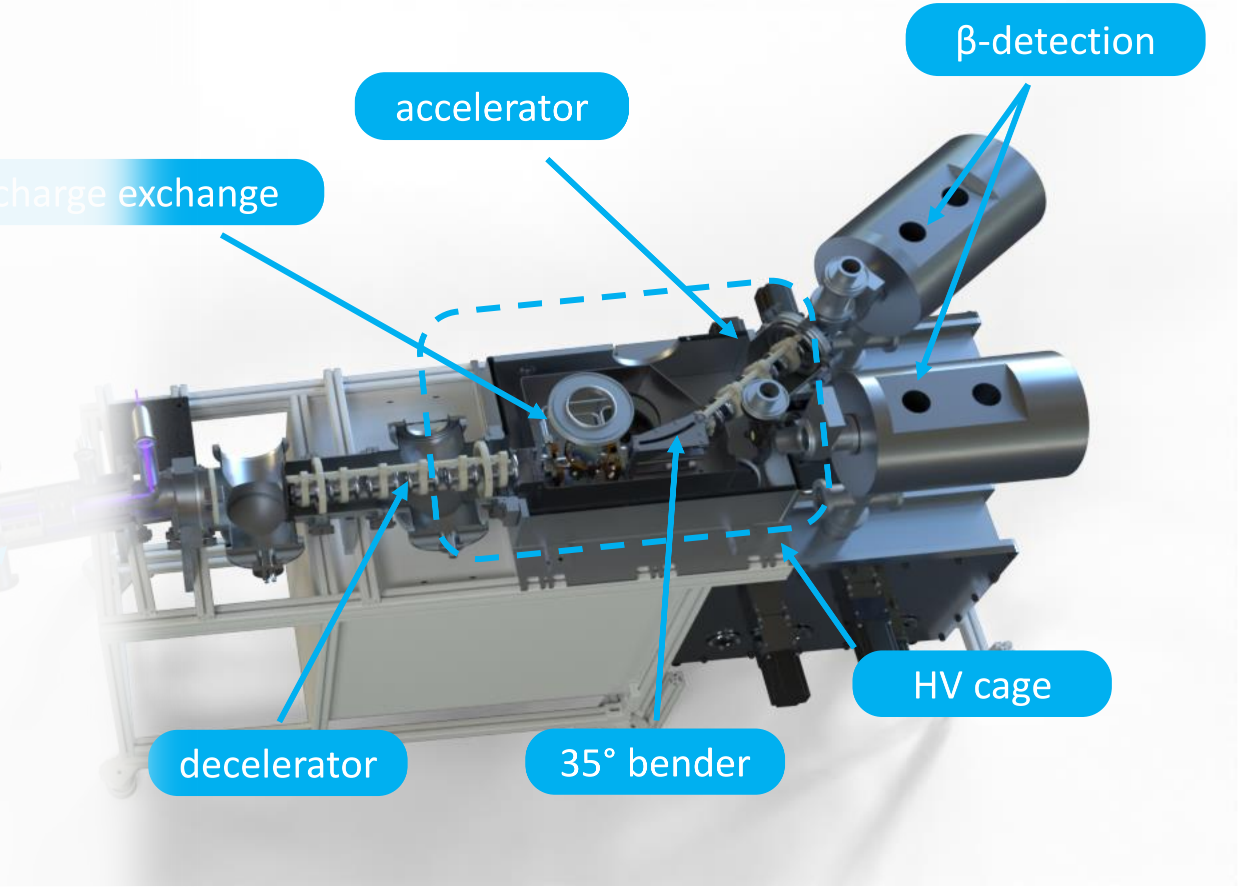
Took ISOLDE beam from 27th of September to 2nd of October

Went surprisingly well considering it is a brand-new setup

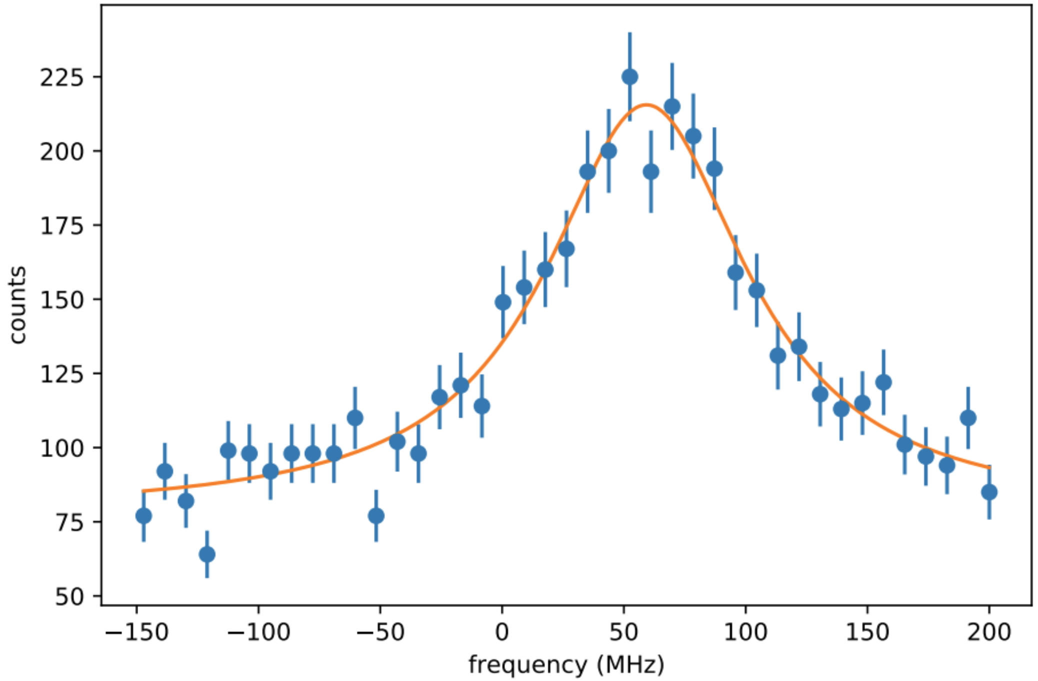
- Ion tune worked great (70% efficiency to the atom detector)
- New data acquisition system worked well
- Tape station worked flawlessly for the entire run (≈ 50 km)

Some problems with the CEC/HV limited the sensitivity

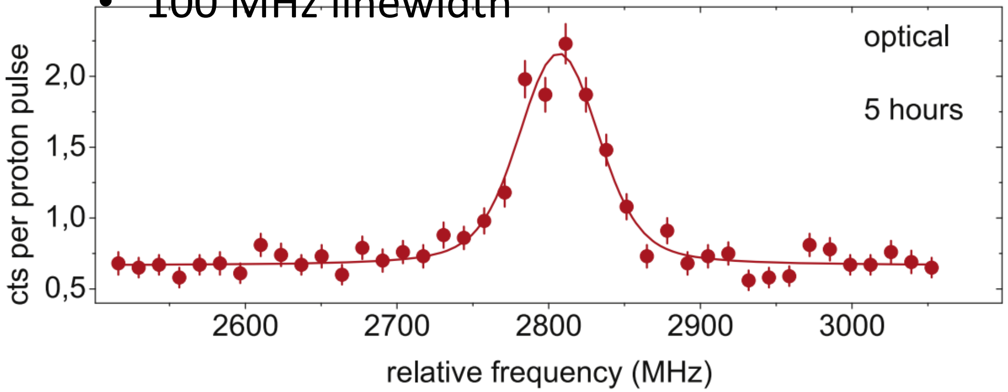
→ Measured ^{52}Ca as a “sanity check” (≈ 200 ions/s)
→ Then measured ^{53}Ca (≈ 20 ions/s)



^{52}Ca – the most exotic test case



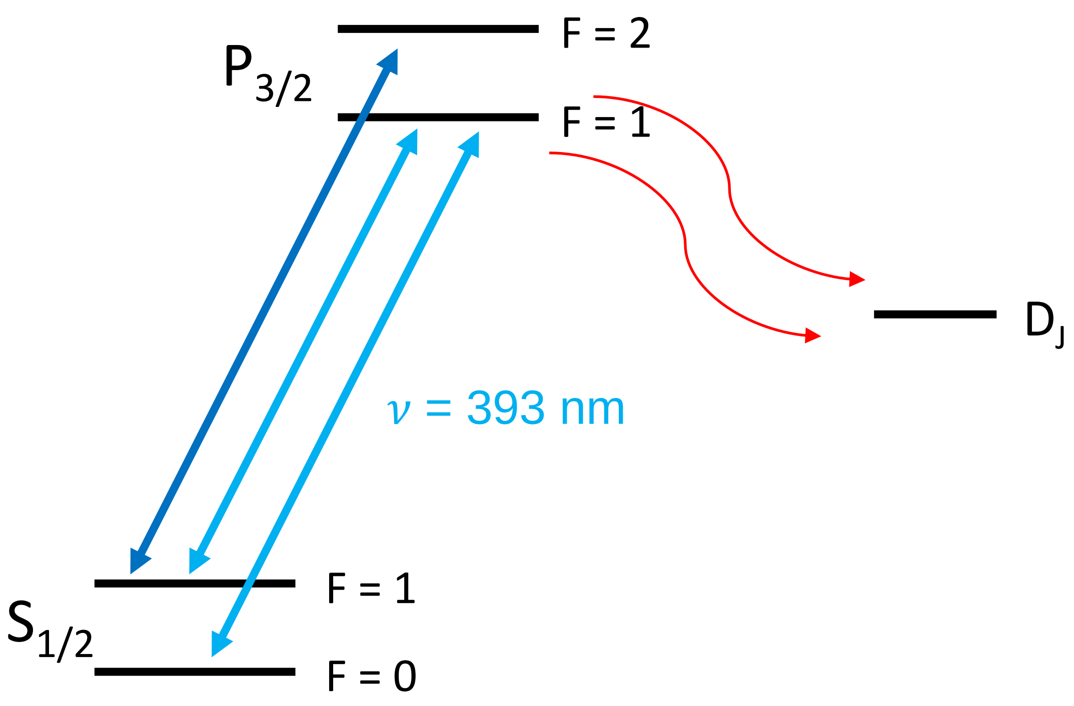
- ≈ 200 ions/s yield
- statistics of about 40 minutes
- 100 MHz linewidth



R F Garcia Ruiz et al, *Development of a sensitive setup for laser spectroscopy studies of very exotic calcium isotopes*

- **Isotope shift consistent with previous COLLAPS measurement**
- **Reduced measurement time by 8x compared to fluorescence detection!**

^{53}Ca: ROC with hyperfine splitting

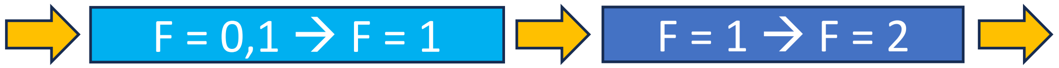


Population transfer not only to the D-states but also between the lower hyperfine states!

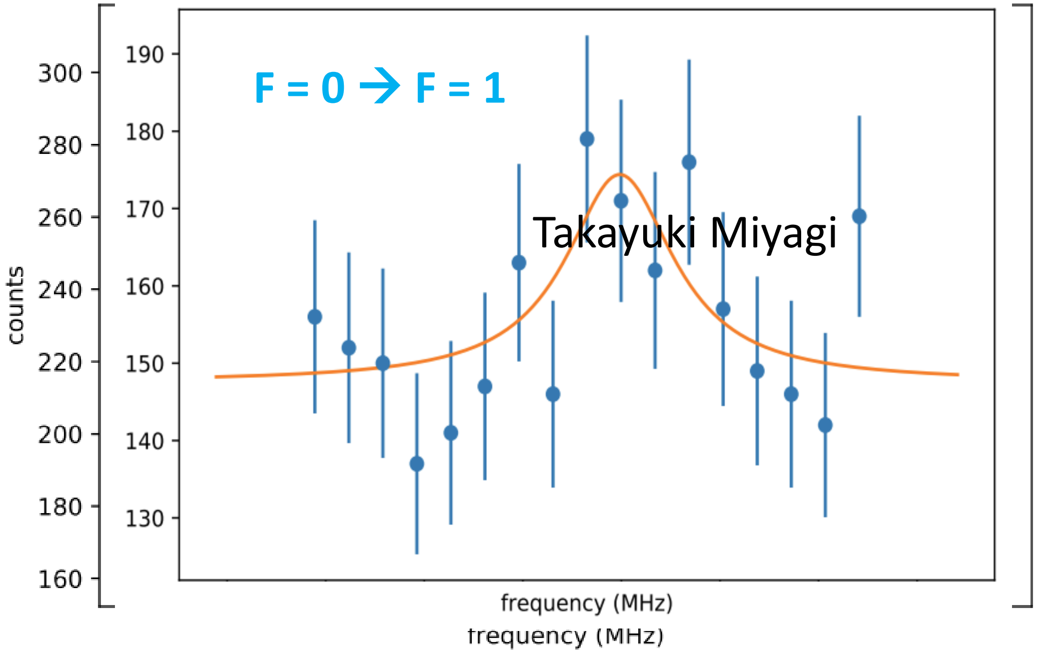
→No efficient population transfer possible

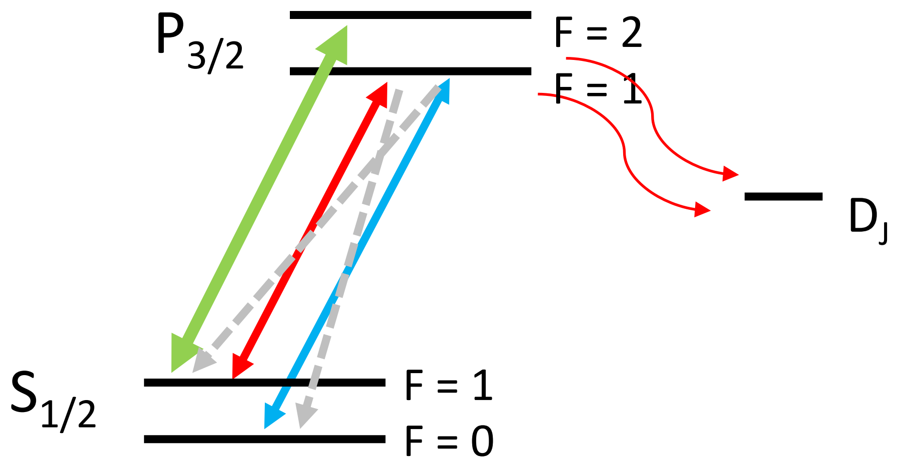
Solution: Sequential multi-step pumping

Split up optical interaction region

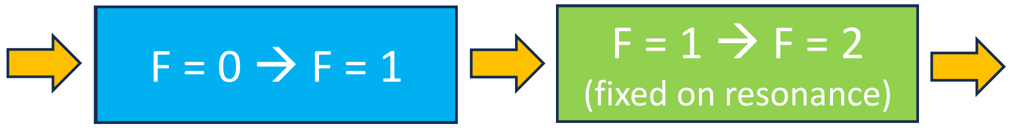


^{53}Ca: ROC with hyperfine splitting

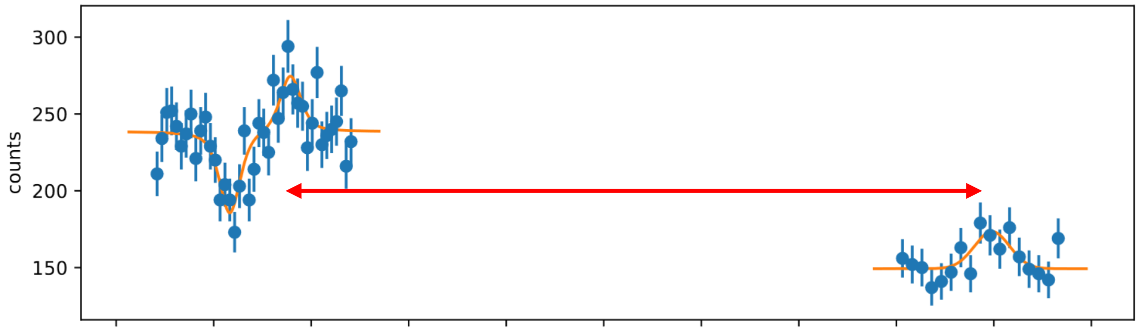




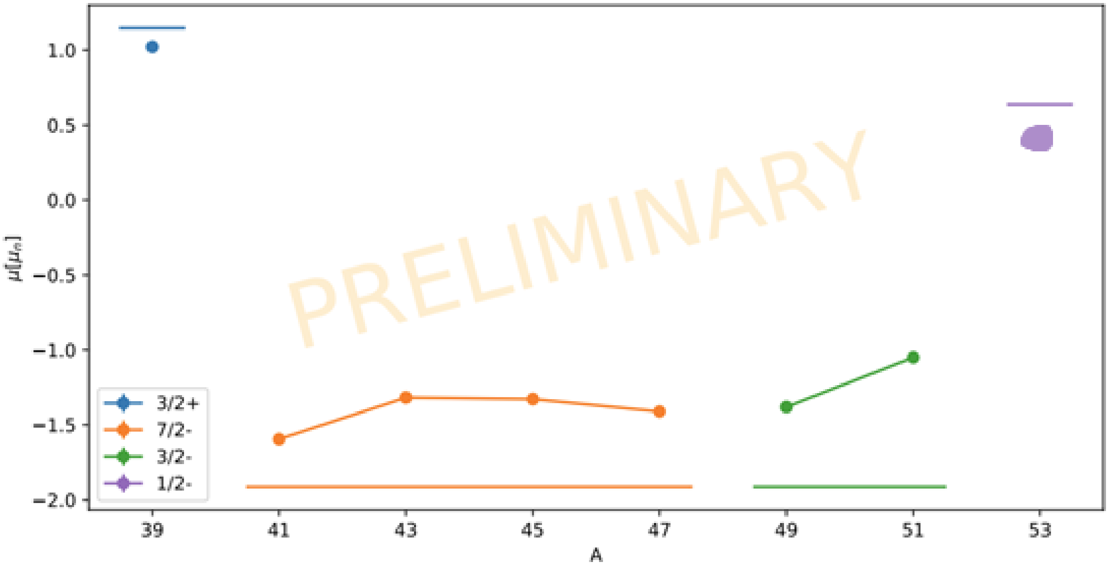
Optical interaction region configuration



^{53}Ca – spin and magnetic moment



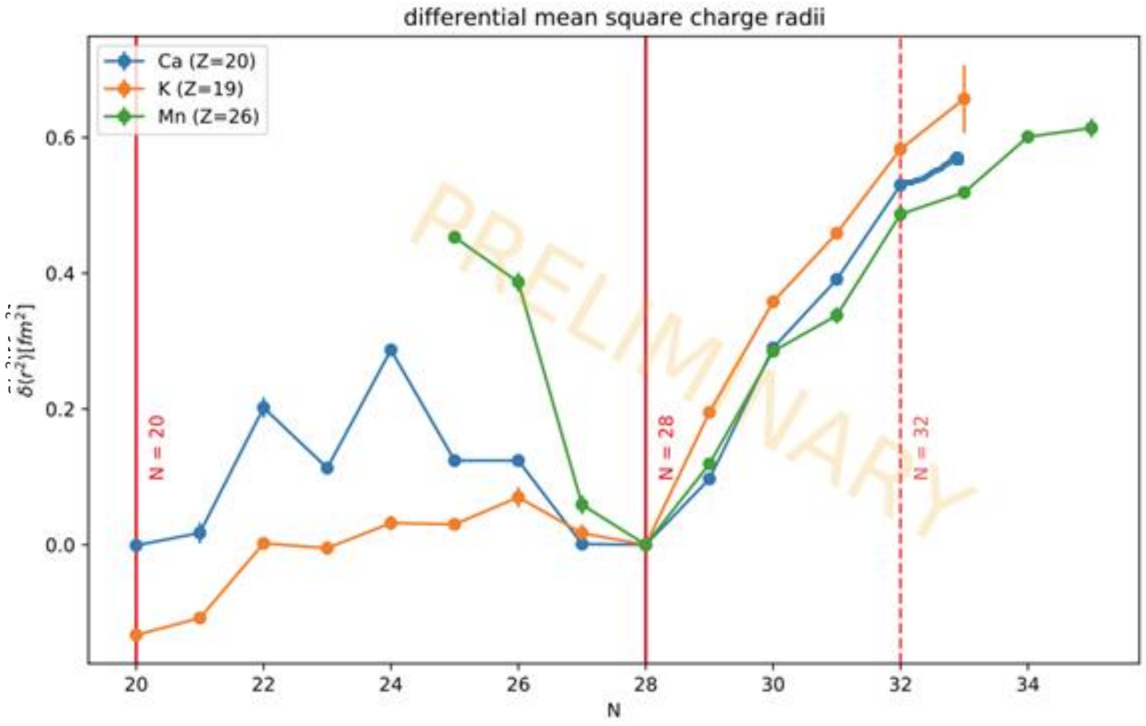
- Unambiguous spin assignment I = ½
- Determine magnetic moment from hyperfine splitting



- Excellent ab-initio theory prediction (deviated ≈5%)*
- Single-particle like? In between ^{41}Ca and ^{49}Ca…

* For details on the theory see https://arxiv.org/pdf/2311.14383.pdf
Special thanks to Takayuki Miyagi and Matthias Heinz for providing the value for ^{53}Ca

^{53}Ca – charge radius



- ^{52}Ca was "unexpectedly large"
- Seems to flatten out compared to $^{51,52}Ca$
  - → Could also be larger odd-even staggering
- Need ^{54}Ca to make conclusions

With data from:

R. F. Garcia Ruiz et al., *Unexpectedly large charge radii of neutron-rich calcium isotopes*
Á. Koszorús et al., *Charge radii of exotic potassium isotopes challenge nuclear theory and the magic character of N = 32*
H. Heylen et al. *Changes in nuclear structure along the Mn isotopic chain studied via charge radii*

Outlook to 2024

Upcoming experiments:

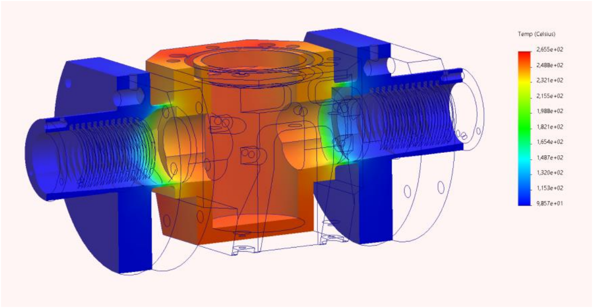
- Fix CEC and measure ^{54}Ca!
- Full beamtime on thulium with LIST

Ongoing developments:

- Expand development lab
- **Develop highly sensitive CLS techniques for continuous beam**

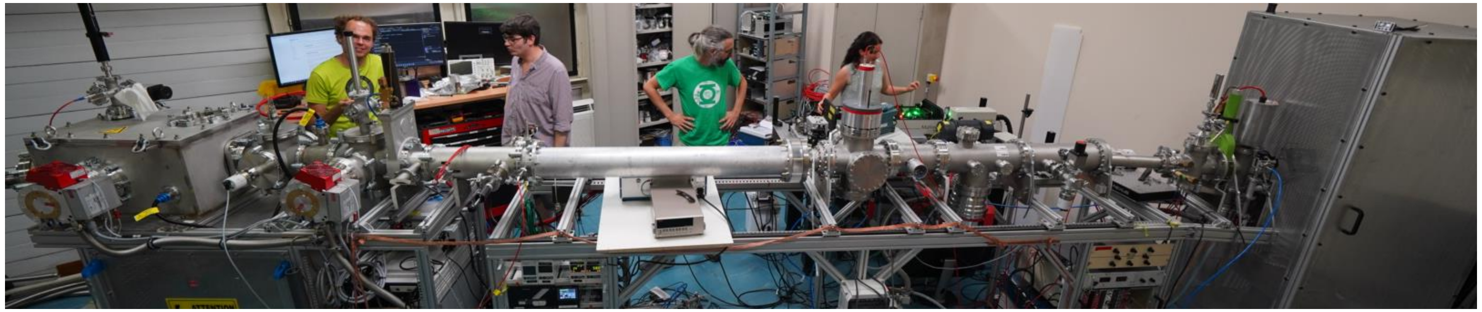
→ **State selective reionization**

new CEC design



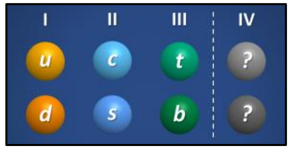
- **Fully funded by a new Max Planck group**
- **CERN project associate already in place**
- **CERN PhD student joining in September 2024**
- **MPIK postdoc joining in August 2024**
- **Renovation of the lab finished, big thanks to EP!**
- **New lasers already delivered**
- **Beamline design on the way**

COLLAPS development lab



Thank you

Quark picture put to the test

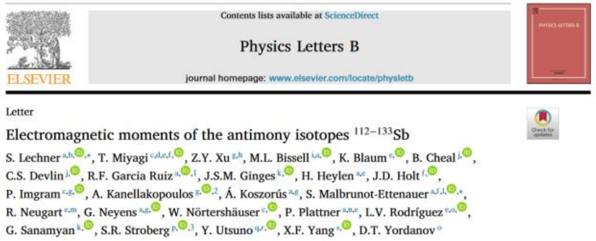


PHYSICAL REVIEW LETTERS **131,** 222502 (2023)

Editors' Suggestion | Featured in Physics

Nuclear Charge Radius of ^{26m}Al and Its Implication for V_{ud} in the Quark Mixing Matrix

P. Plattner,[1,2,3,*] E. Wood,[4] L. Al Ayoubi,[5] O. Beliuskina,[5] M. L. Bissell,[6,1] K. Blaum,[3] P. Campbell,[6] B. Cheal,[4] R. P. de Groote,[5,‡] C. S. Devlin,[4] T. Eronen,[5] L. Filippin,[7] R. F. Garcia Ruiz,[1,8] Z. Ge,[5] S. Geldhof,[9] W. Gins,[5] M. Godefroid,[7] H. Heylen,[1,3] M. Hukkanen,[5] P. Imgram,[10] A. Jaries,[5] A. Jokinen,[5] A. Kanellakopoulos,[9] A. Kankainen,[5] S. Kaufmann,[10] K. König,[10] Á. Koszorús,[4,9,‡] S. Kujanpää,[5] S. Lechner,[1] S. Malbrunot-Ettenauer,[1,11,†] P. Müller,[10] R. Mathieson,[4] I. Moore,[5] W. Nörtershäuser,[10] D. Nesterenko,[5] R. Neugart,[3,12] G. Neyens,[1,9] A. Ortiz-Cortes,[5] H. Penttilä,[5] I. Pohjalainen,[5] A. Raggio,[5] M. Reponen,[5] S. Rinta-Antila,[5] L. V. Rodríguez,[3,1,13] J. Romero,[5] R. Sánchez,[14] F. Sommer,[10] M. Stryjczyk,[5] V. Virtanen,[5] L. Xie,[6] Z. Y. Xu,[9] X. F. Yang,[9,15] and D. T. Yordanov[13]



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Letter

Electromagnetic moments of the antimony isotopes $^{112-133}$Sb

S. Lechner[a,b,*], T. Miyagi[c,d,e,f], Z.Y. Xu[g,h], M.L. Bissell[i,a], K. Blaum[c], B. Cheal[j], C.S. Devlin[j], R.F. Garcia Ruiz[a,1], J.S.M. Ginges[k], H. Heylen[a,e], J.D. Holt[f], P. Imgram[c,g], A. Kanellakopoulos[g,2], Á. Koszorús[a,g], S. Malbrunot-Ettenauer[a,f,l,*], R. Neugart[e,m], G. Neyens[a,g], W. Nörtershäuser[c], P. Plattner[a,n,e], L.V. Rodríguez[e,o], G. Sanamyan[k], S.R. Stroberg[p,3], Y. Utsuno[q,r], X.F. Yang[s], D.T. Yordanov[o]

Leftover slides – proceed at own risk

Opportunities for improvement and future

Priority Nr. 1: Fix charge exchange cell

→New design is already in the workshop…

→Hopefully fixes the coating and sparking issues

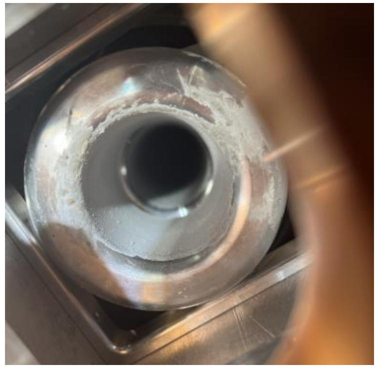
→Should increase sensitivity by another order of magnitude

Immediate future: improve ^{53}Ca, add ^{54}Ca

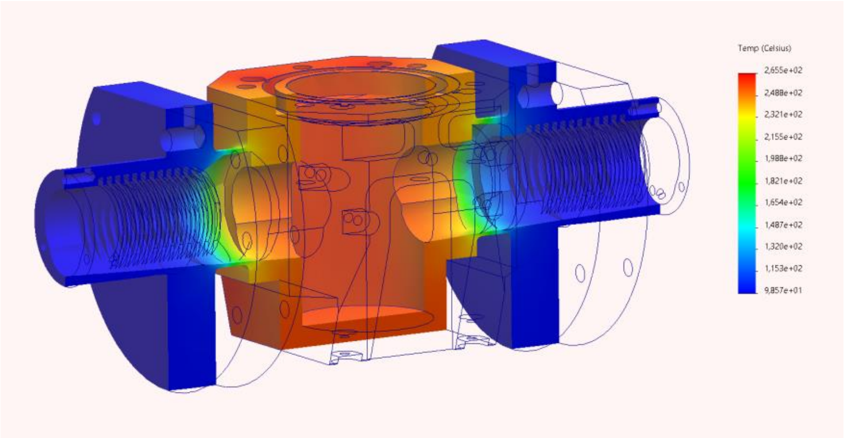
Afterwards: strontium & barium, maybe more with some development

sparking HV platform

coated decelerator



new cell design



ROC beamtime summary

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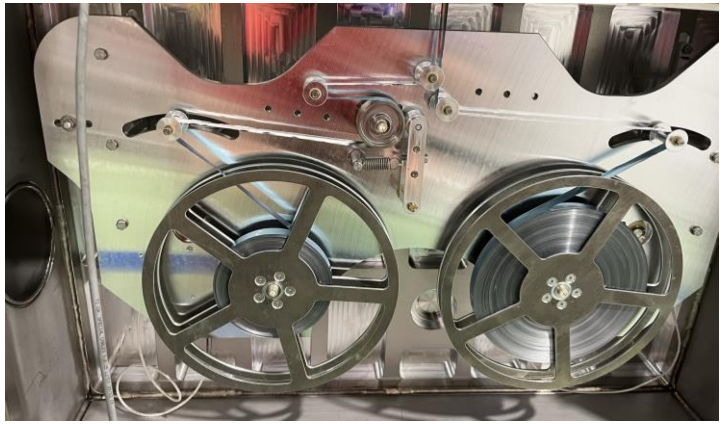
- Tape station worked flawlessly for the entire run (≈ 50 km)



Some problems with the CEC/HV limited the sensitivity in the end

→Measured ^{52}Ca as a “sanity check” (≈ 200 ions/s)

→Then measured ^{53}Ca (≈ 20 ions/s)