Towards measuring atomic parity violation effects in francium

Mukut Ranjan Kalita
TRIUMF

CAP 2019

Gerald Gwinner, Tim Hucko, Michael Kossin, Andrew Senchuk, Anima Sharma
University of Manitoba

John Behr, Alexandre Gorelov, Matt Pearson
TRIUMF

Eduardo Gomez
Universidad Autónoma de San Luis Potosí

Luis Orozco
University of Maryland

Seth Aubin
William & Mary
Chartered 1693

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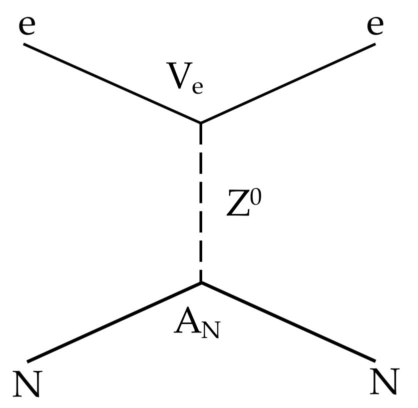
Atomic parity violation (aka APNC, PNC)

- Atomic physics experiment, we use laser cooling and trapping techniques and study electronic transitions dominated by electromagnetism.
- Small contribution to electronic transitions by Z boson exchange leading to parity violation effects.

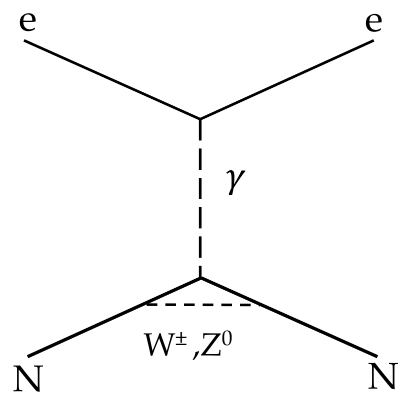
Nuclear spin independent:

Weak neutral interaction between electrons and nucleons (mostly neutron)

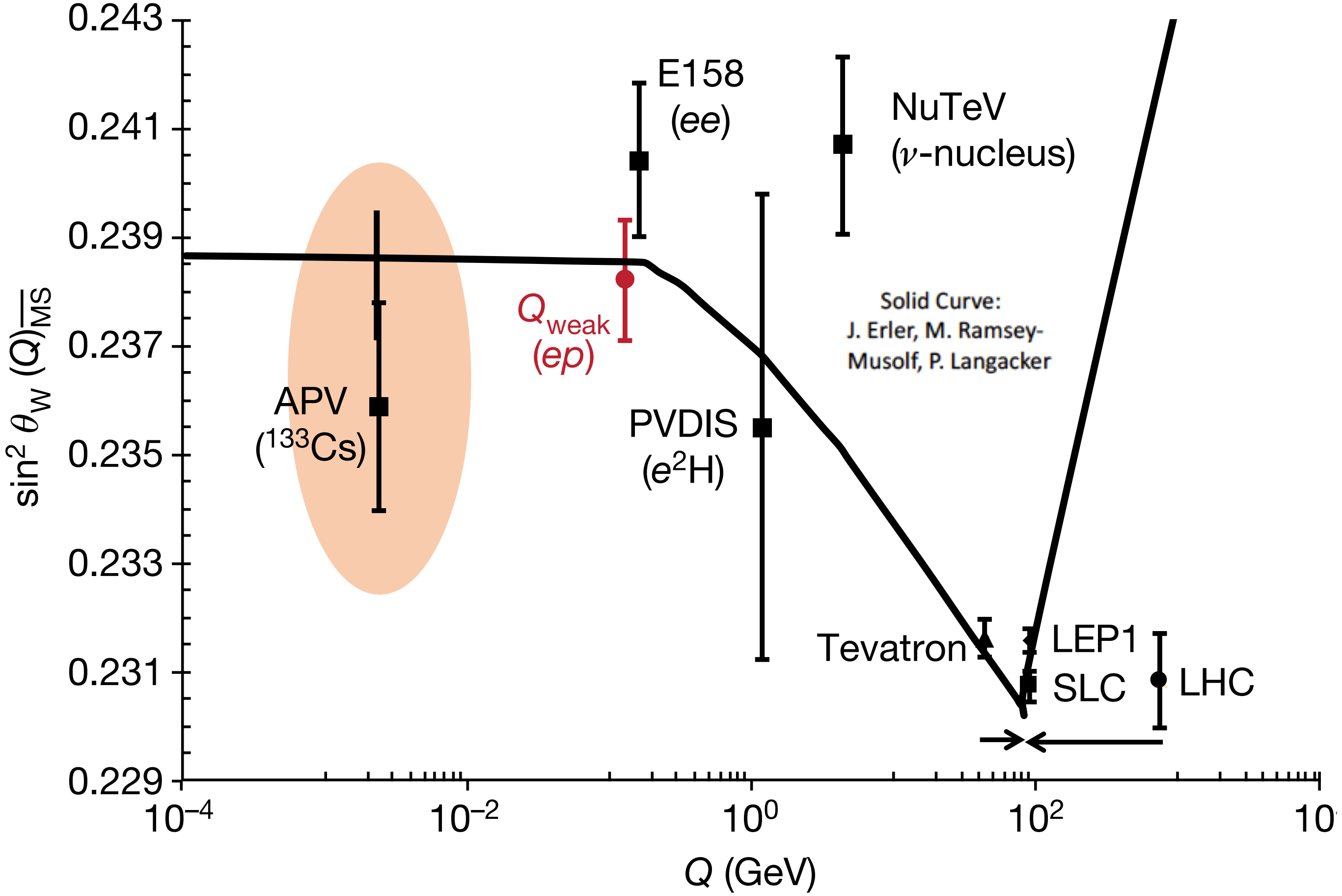


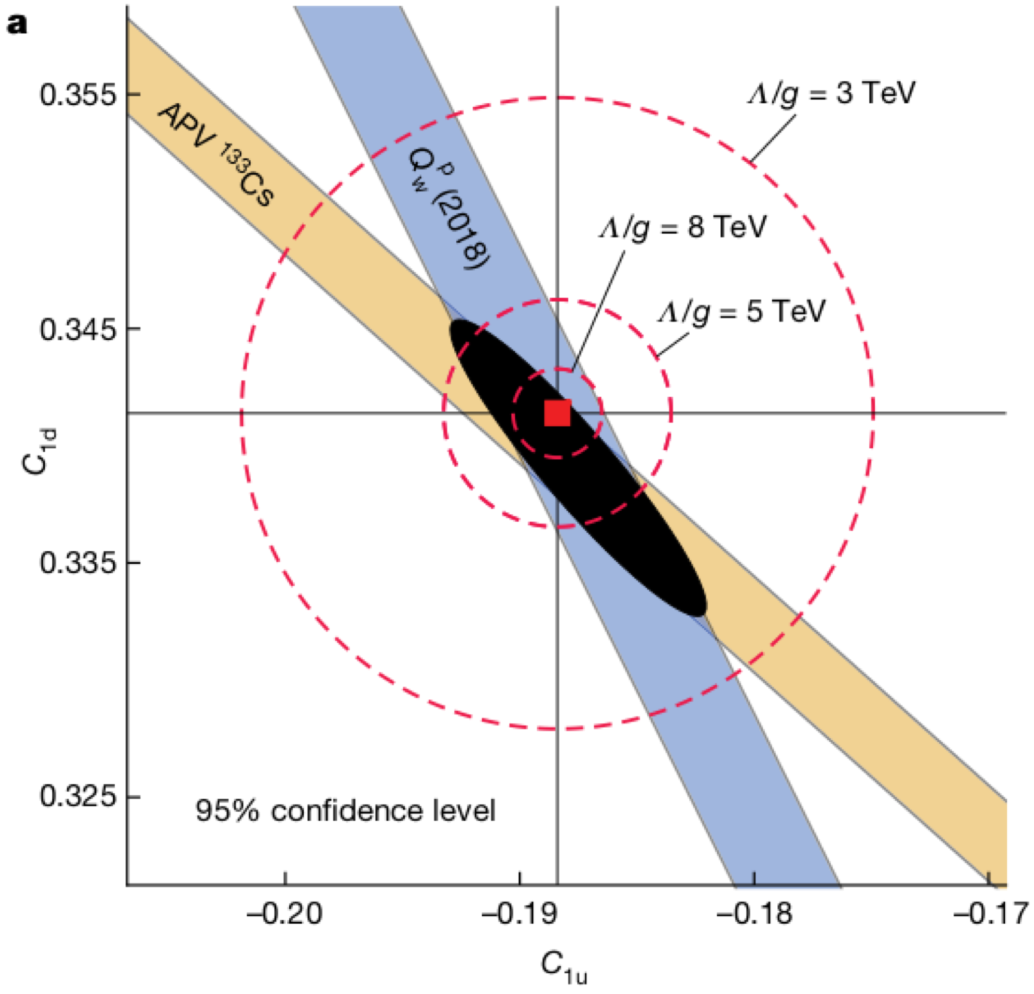
Nuclear spin dependent:

Main contribution from anapole moment of heavy nuclei.



Atomic parity violation (aka APNC, PNC)





- Test SM at low energies
- Search for extra bosons

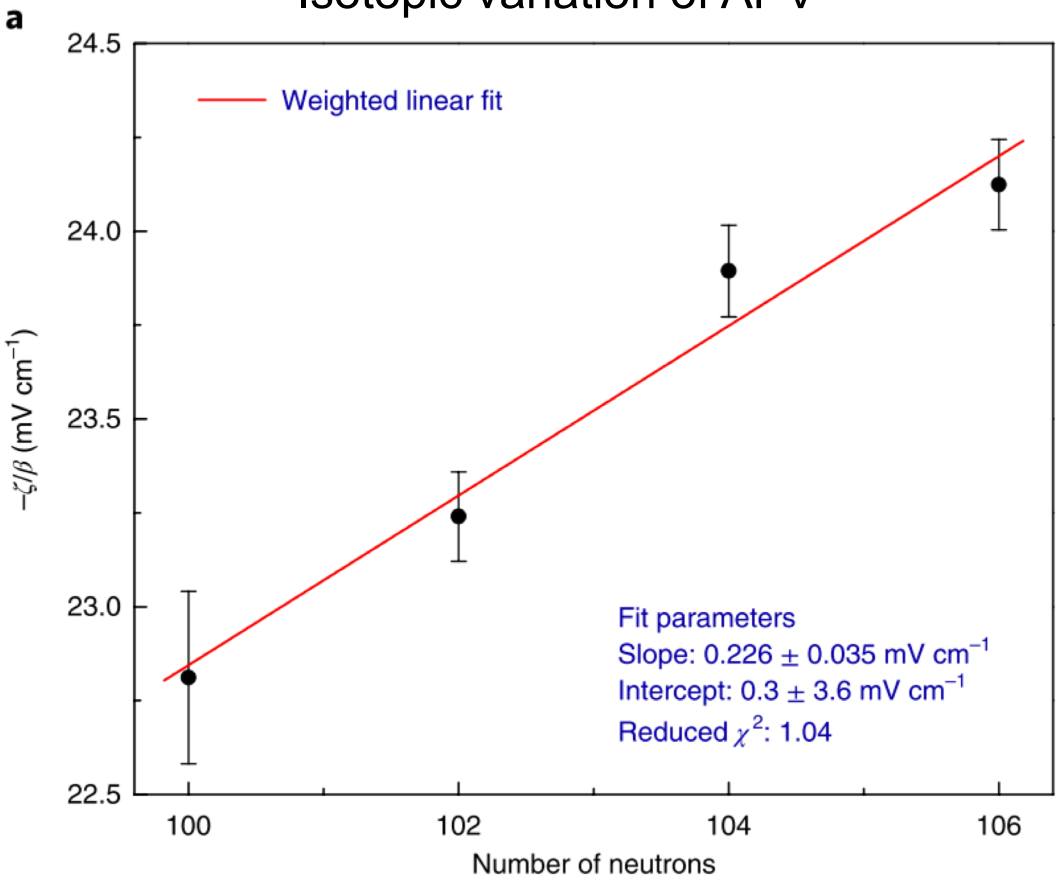
Q_{weak} Collaboration, Nature 557, 207–211 (2018)

M. S. Safronova et al. Rev. Mod. Phys. ***90****, 025008*

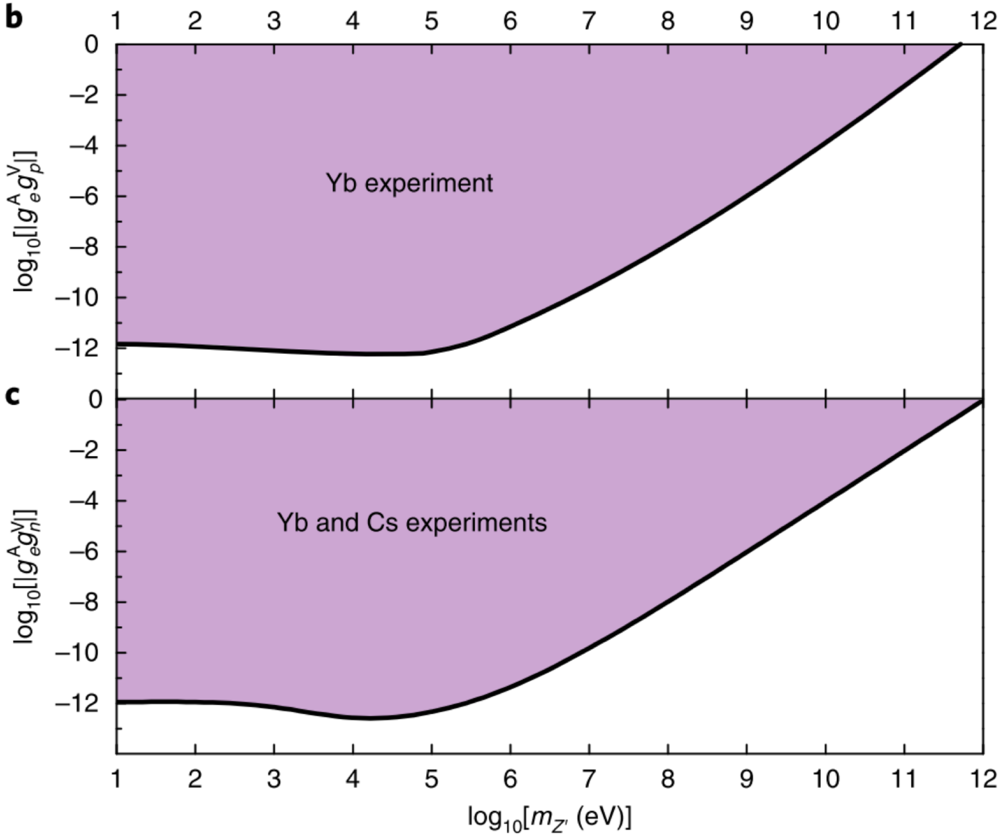
G. Toh et al. arXiv:1905.02768v2

Atomic parity violation (aka APNC, PNC)

Isotopic variation of APV



Bounds on z/ boson mediated interactions



D. Antypas et al. *Nat. Phys.* **15**, 120–123 (2019)

*R. Diener et al. Phys. Rev. D **86**, 115017*

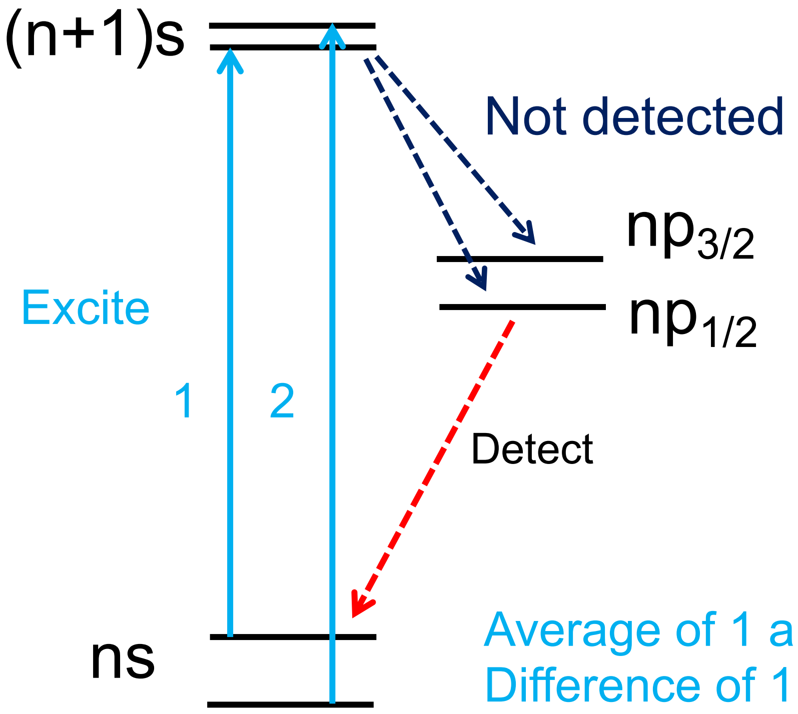
- Test SM at low energies
- Search for extra bosons

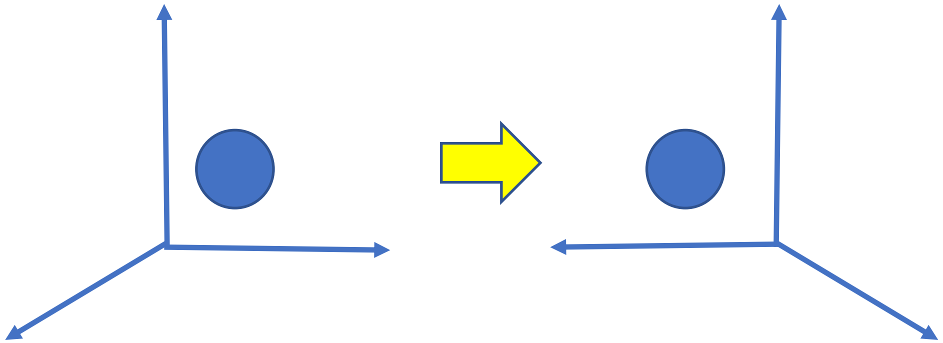
Measuring APV in ns → (n+1)s transition in heavy alkali atoms

- Electric dipole forbidden.
- Small transition probability due to APV effects (≈ 10^{-20} of allowed in Fr).
- Use Stark Interference technique. *(M. Bouchiat, C. Bouchiat J. Phys. (Paris) 36 (1975), 493)*

$$R \propto |A_{stark}+A_{APV}|^2 \approx (A_{stark})^2 \pm 2Re(A_{stark}A_{APV}^*)$$

Interference term changes sign upon parity reversal





→ Modulation of decay fluorescence

Average of 1 and 2: nuclear spin independent APNC
Difference of 1 and 2: Anapole

From measurement to extracting Q_w

Modulation of decay fluorescence measurement ➛ A_{APV} / A_{stark}

A_{stark} calibrated by separate measurements

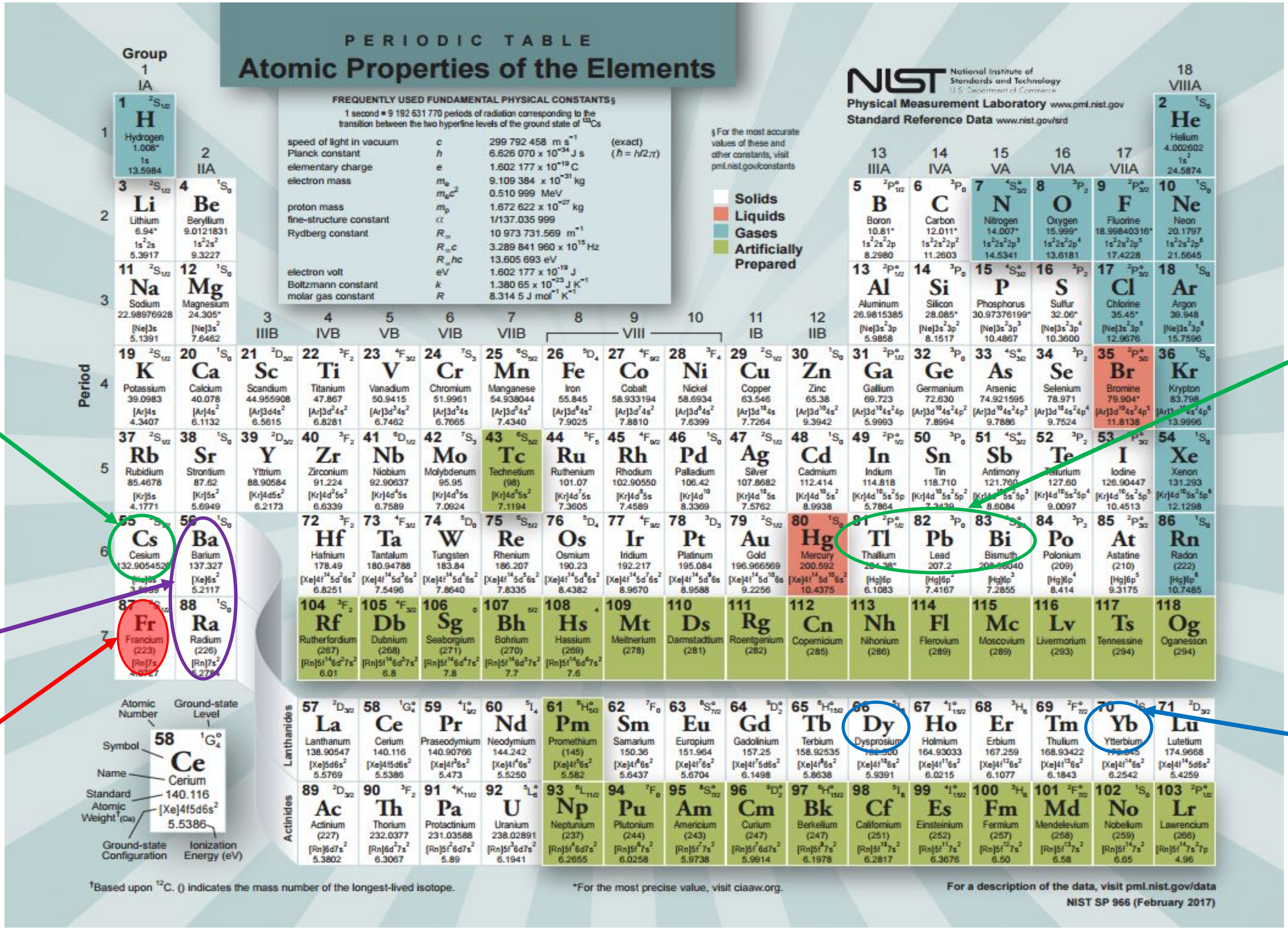
$A_{APV} = k_{PV}\, Q_w$

Atomic structure factor from theory (→ k_{PV})

Weak charge (→ Q_w)

Good experiment and good theory⇒ good test

APV experiments:



Best measurement so far (Boulder) 0.35% (exp.) measurement. *Science 275 (1997) 1759*

Purdue Elliot et at. (in preparation).

Planned exp. using ions (Groningen, U. of Washington, UCSB)

APNC 18x larger

Th. can be done ≈ Cs

Range of isotopes available

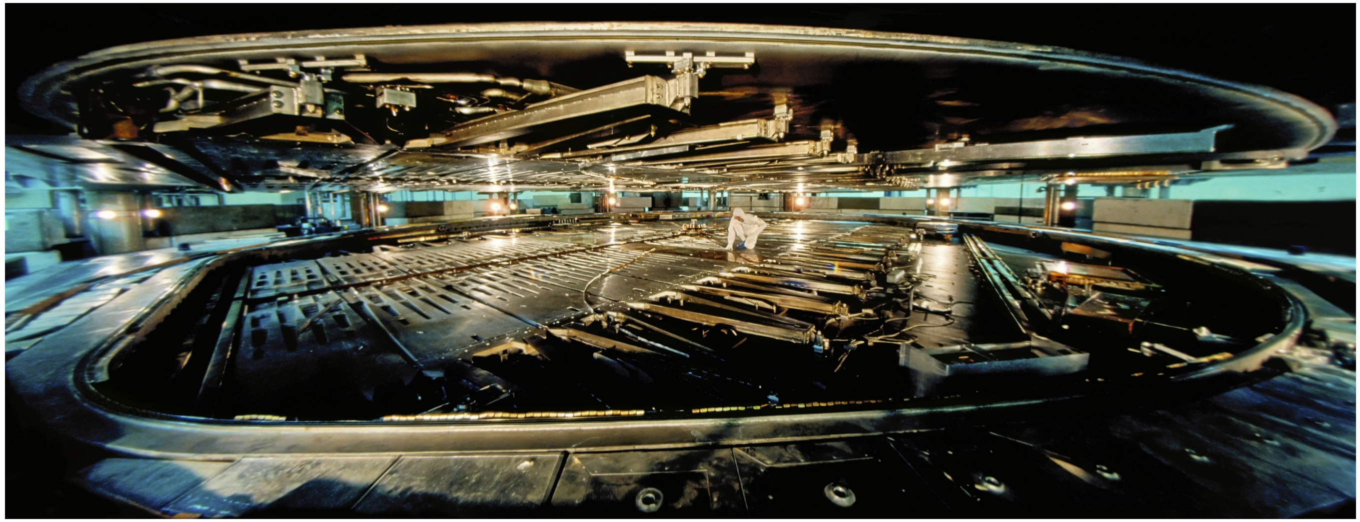
Efforts to push Cs, Fr theory to 0.1%. *(PRA **98**, 032504 (2018))*

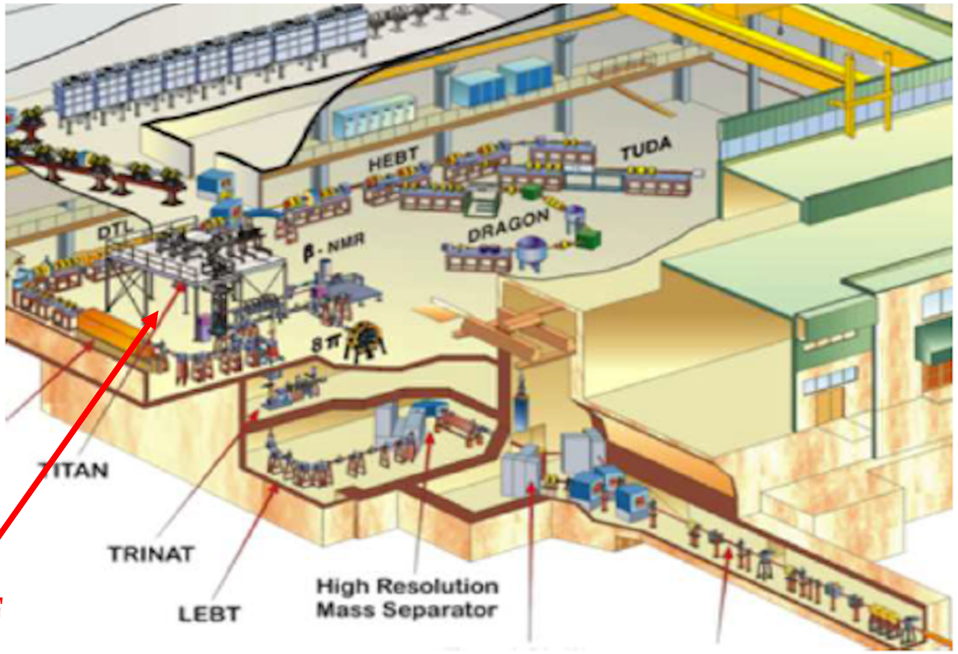
1-2% measurement done. Theory at several % level.

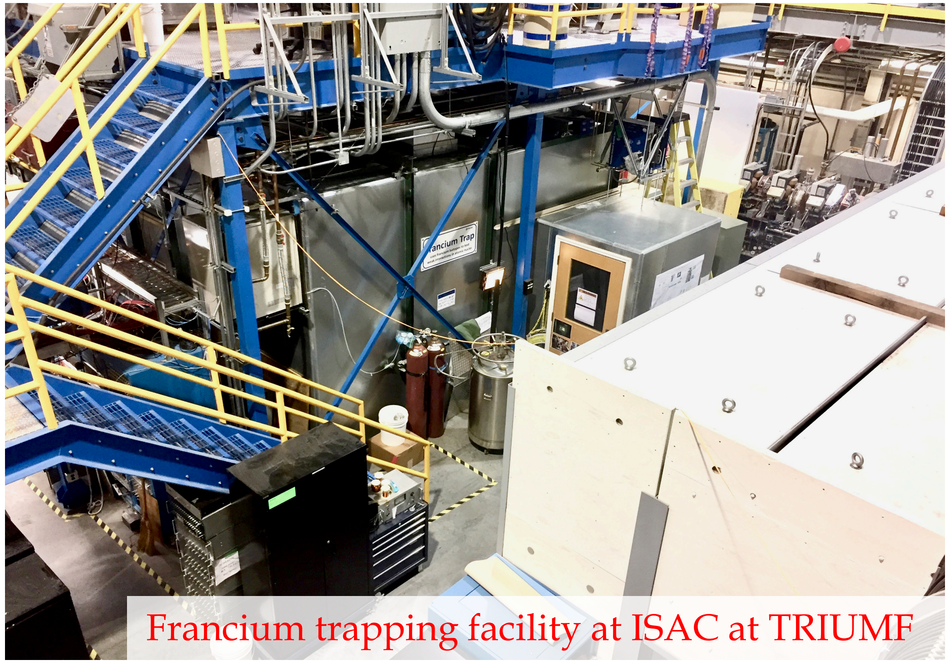
Yb (exp. 0.5% level) *Nat. Phys.* ***15****, 120–123 (2019)*

The francium trapping facility

Fr has no stable isotope → experiment at TRIUMF
500 MeV proton beam, UC_x target.

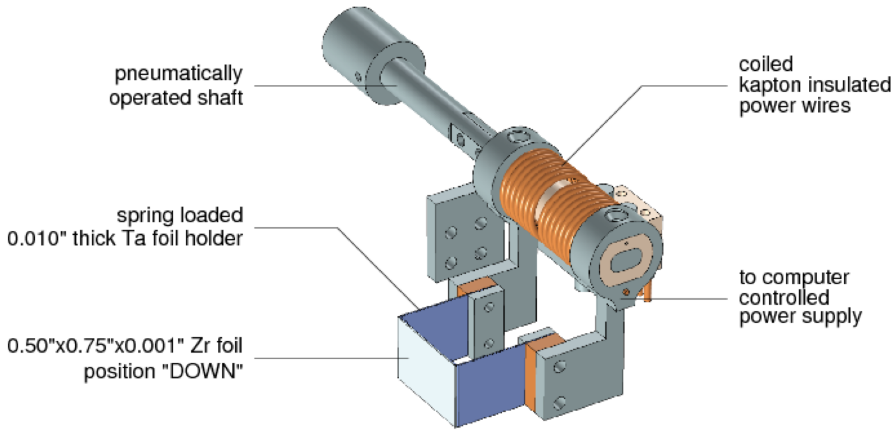




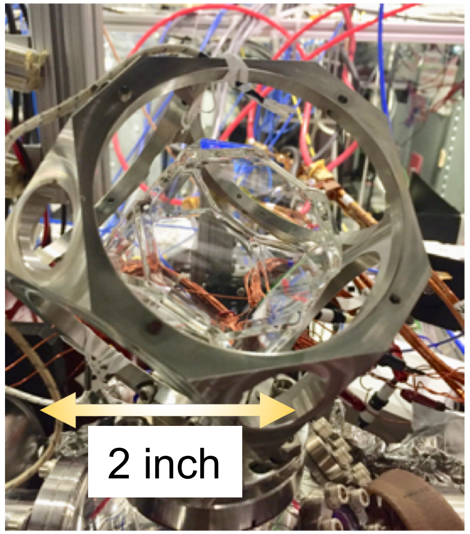

Francium trapping facility at ISAC at TRIUMF

The francium trapping facility

- Ions up to 2 ×10^9 /s delivered

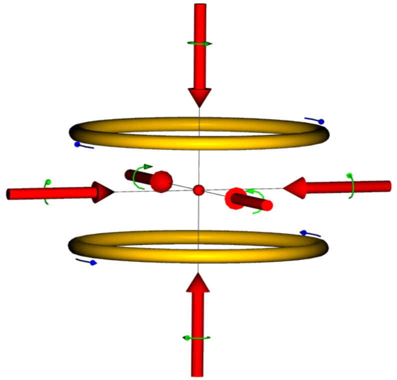


Other Fr traps:
- INFN Legnaro (Italy).
- Tohoku University (Japan).

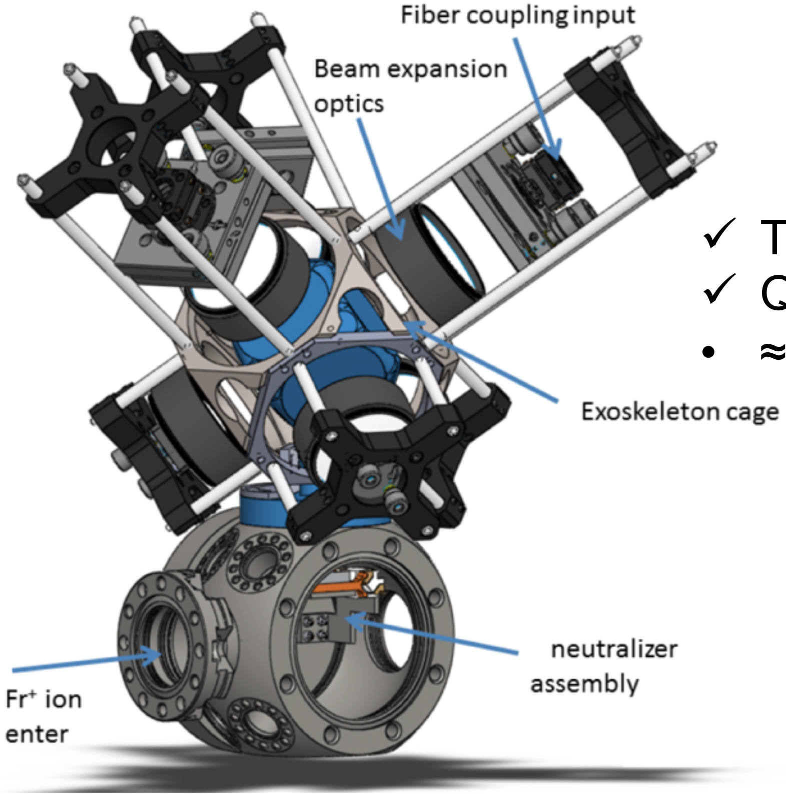


- Glass cell with non stick coating

(J. A. Fedchak et al. NIM Phys. R A 391 (1997) 405-416)



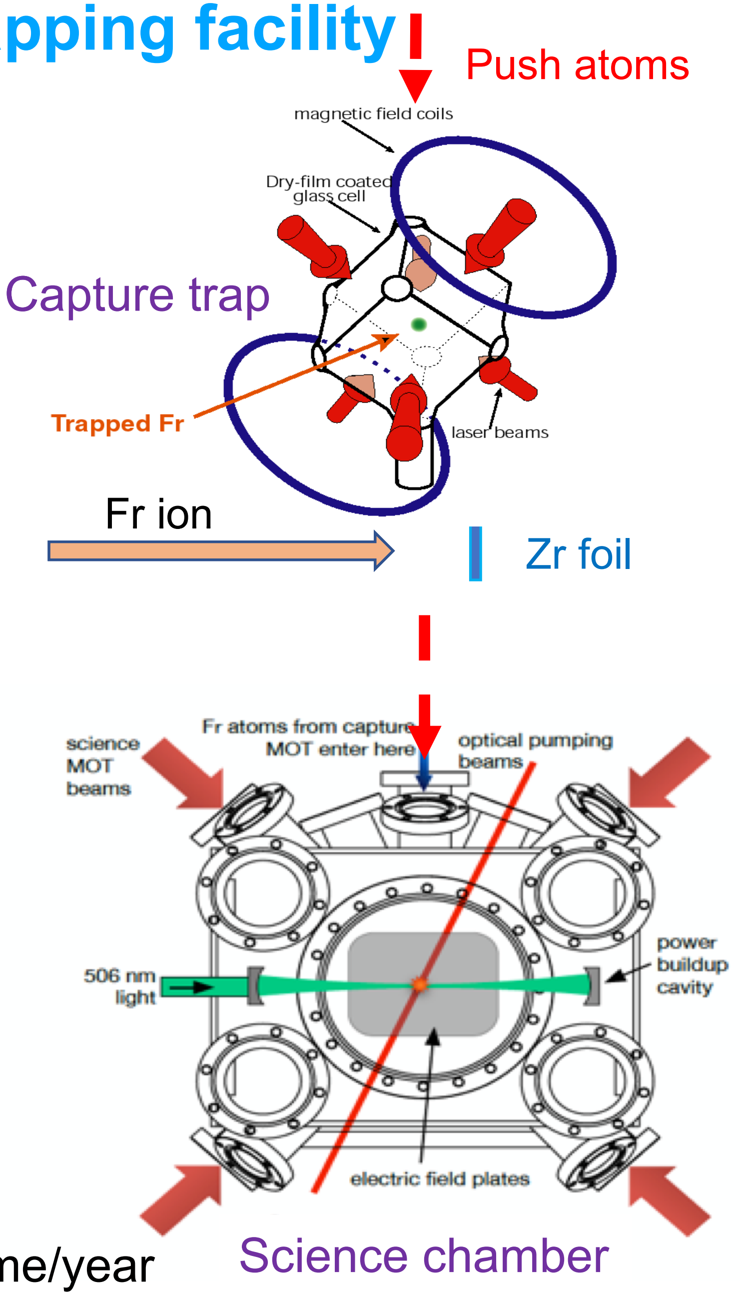
Magneto optical trap
Trapping F = -kx
Cooling F = -av

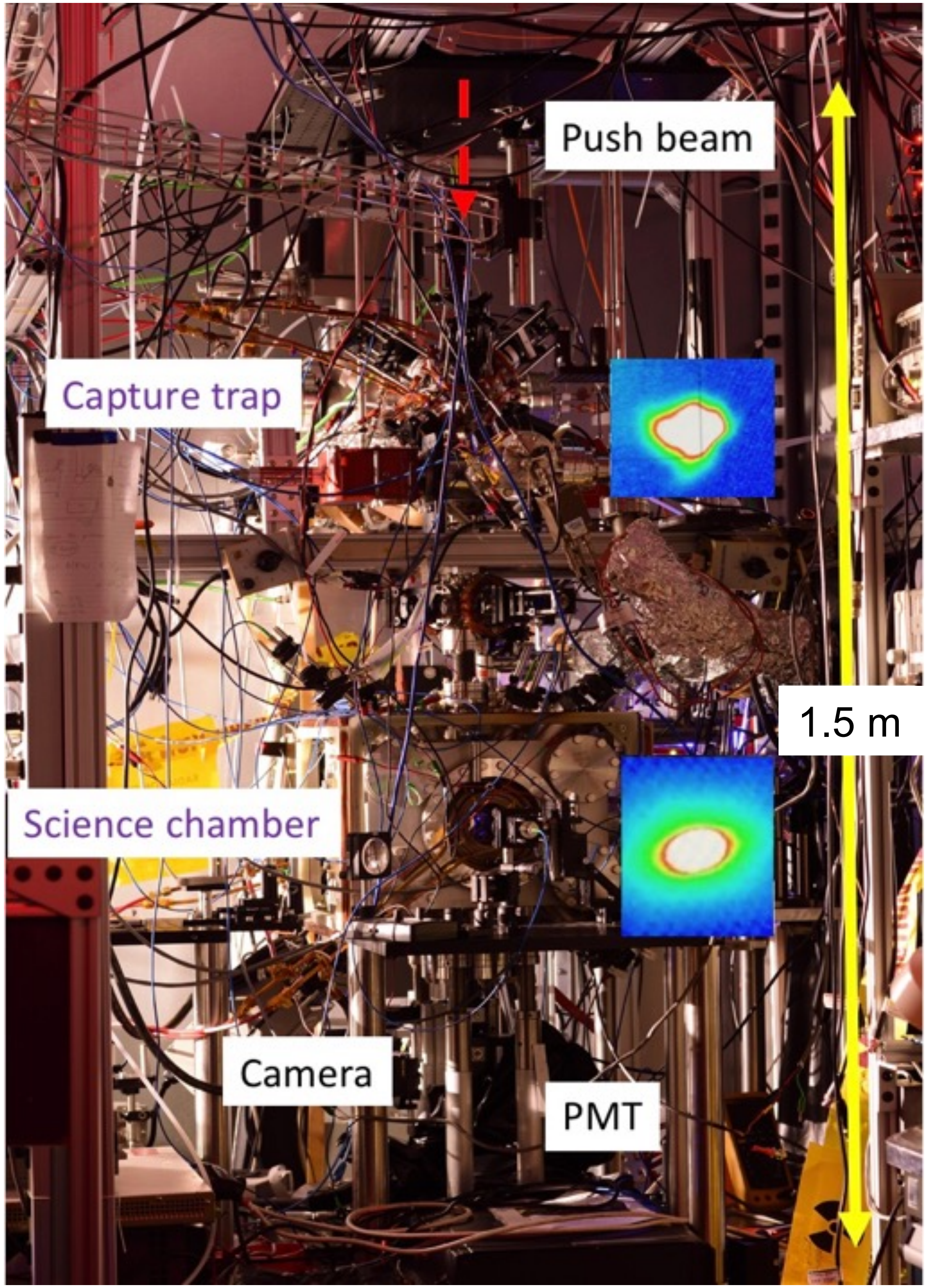


- ✓ Two lasers.
- ✓ Quadrupole B field.
- ≈ 1 million atoms trapped

The francium trapping facility

- Up to 50% transfer
- 20 s lifetime





- 5, 6 days of beamtime/year
  - ➢ Tune with Rb

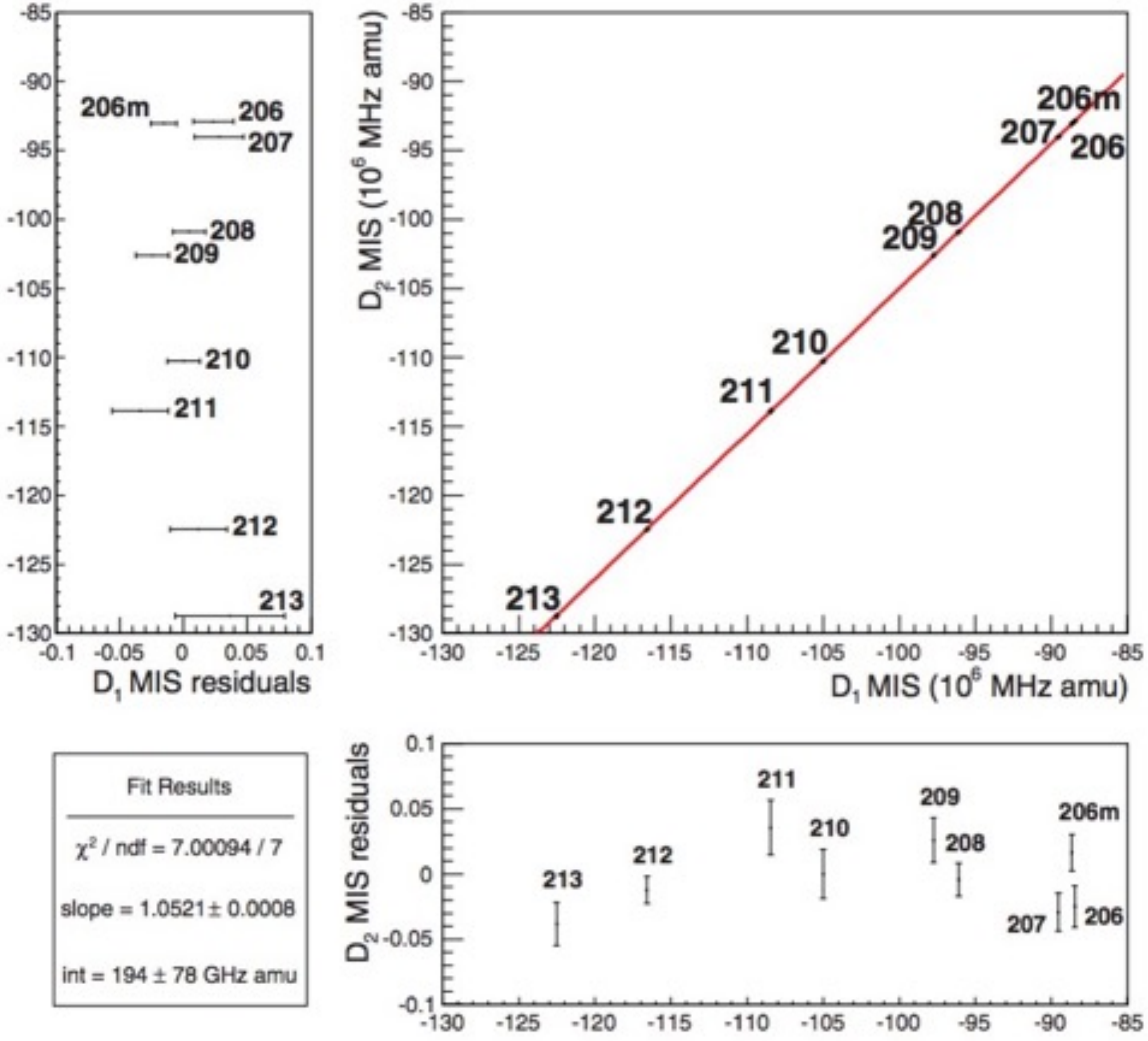
*M. Tandecki et. al. JINST **8**, P12006 (2013)*

Completed measurements at the francium trapping facility

❖ D1 isotope shifts in a string of light Fr isotopes.

Collister et. al. Phys. Rev. A 90 052502 (2014) and A 92, 019902(E) (2015).

➢ Benchmarks state of the art atomic theory.



These are all dipole allowed transitions !

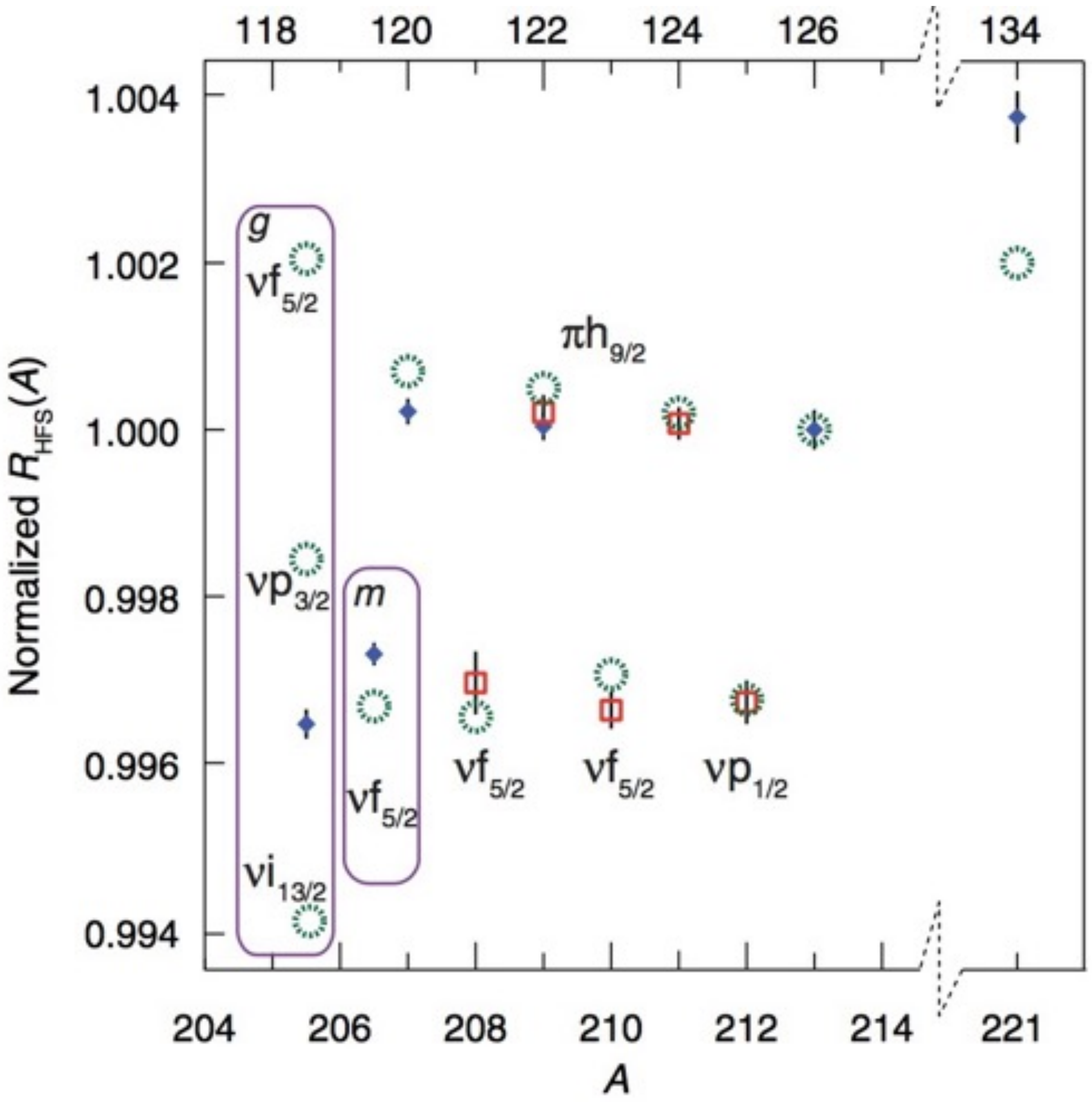
R. Collister, PhD, 2015 (U. of Manitoba)
J. Zhang, PhD, 2014 (U. of Maryland)

Completed measurements at the francium trapping facility

❖ Hyperfine anomaly in light Fr isotopes.

Zhang et. al. Phys. Rev. Lett. 115 042501 (2015)

➢ Reconfirms that in terms of nuclear structure 208-213 are “simple” nuclei for APNC/anapole.



These are all dipole allowed transitions !

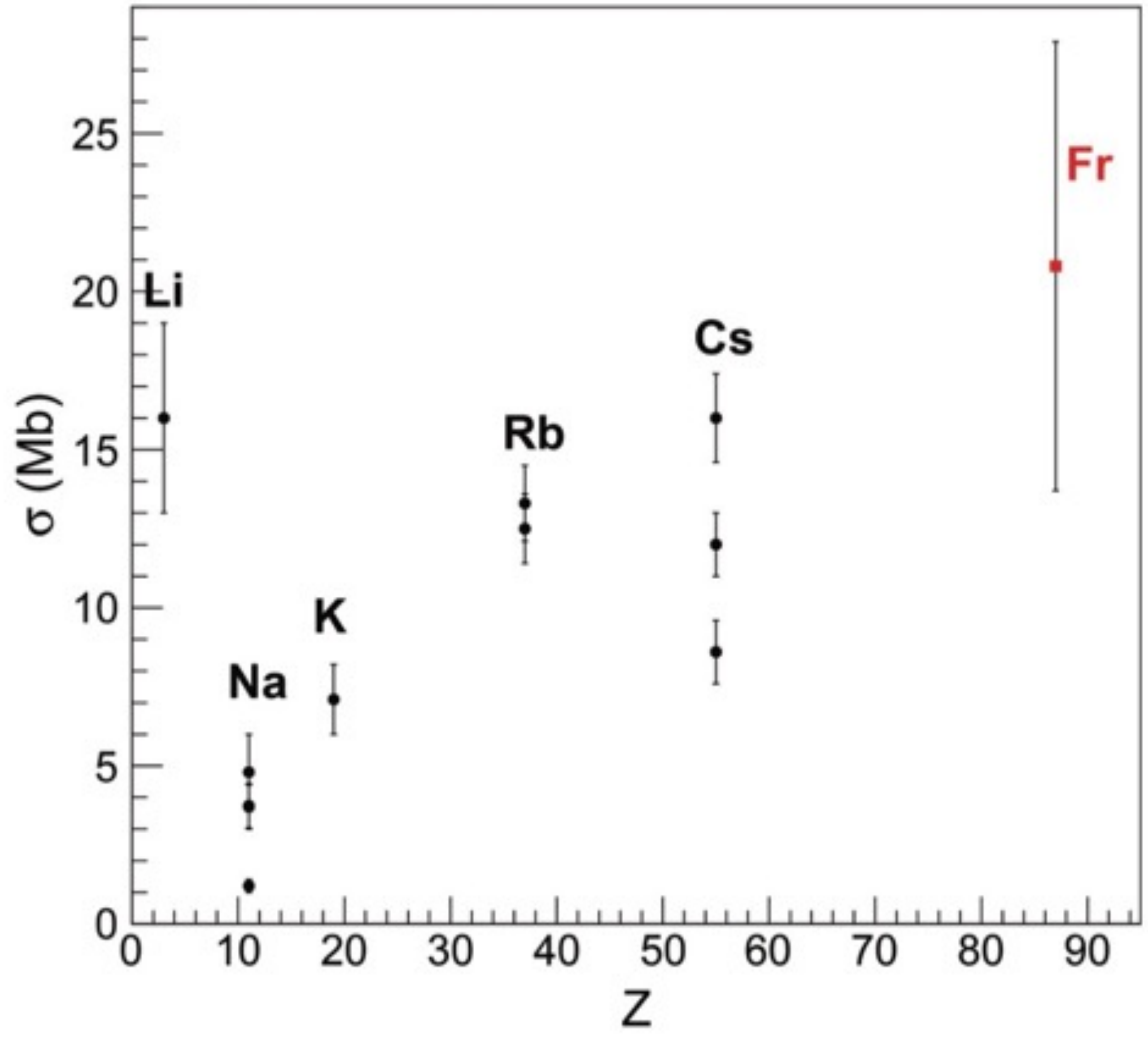
R. Collister, PhD, 2015 (U. of Manitoba)
J. Zhang, PhD, 2014 (U. of Maryland)

Completed measurements at the francium trapping facility

- ❖ Francium $7p_{3/2}$ photoionization

  Collister et. al. Can. J. Phys (2017)

- ➢ Determines loss of atoms from trap during spectroscopy



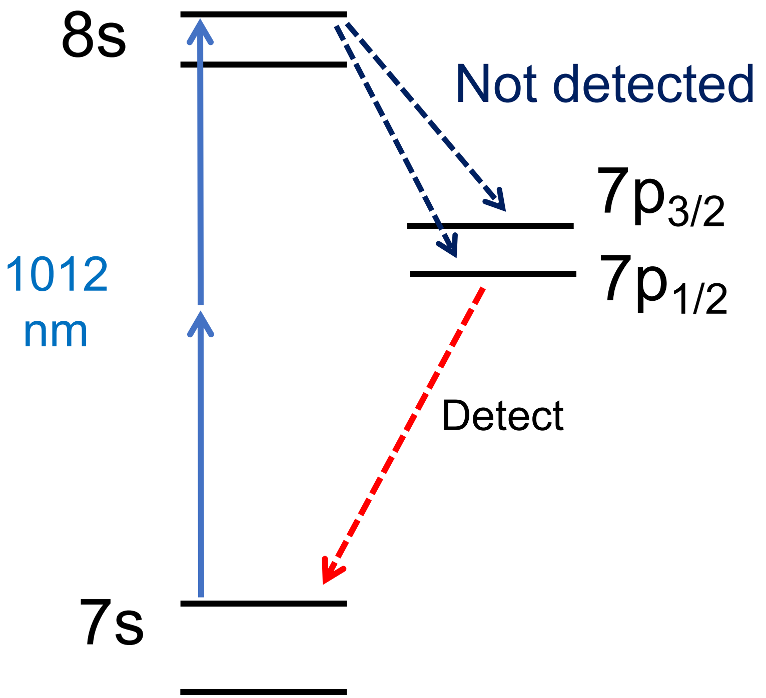
These are all dipole allowed transitions !

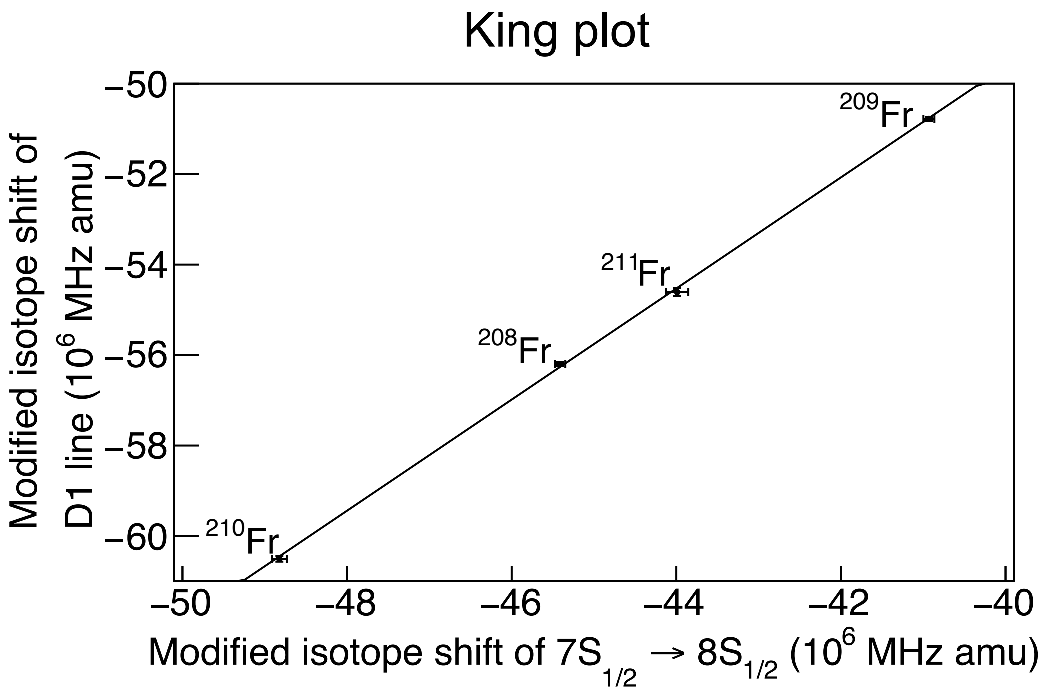
R. Collister, PhD, 2015 (U. of Manitoba)
J. Zhang, PhD, 2014 (U. of Maryland)

Completed measurements at the francium trapping facility

- Observed for the first time 7s-8s transition using two photon spectroscopy in ^{208}Fr, ^{209}Fr, ^{210}Fr, ^{211}Fr, ^{213}Fr.

  Radioactive lifetime ($T_{1/2}$) from 50 s to 192 s.
- Isotope shifts.





$$\left(\frac{M_A M_{A'}}{M_A - M_{A'}}\right)\delta\vartheta_{IS,D1} = (N_{D1} + S_{D1}) - (N_{SS} + S_{SS})\frac{F_{D1}}{F_{SS}} + \frac{F_{D1}}{F_{SS}}\left(\frac{M_A M_{A'}}{M_A - M_{A'}}\right)\delta\vartheta_{IS,SS}$$

Slope ∝ $(\Delta\Psi(0)^2)_{D1} / (\Delta\Psi(0)^2)_{SS}$

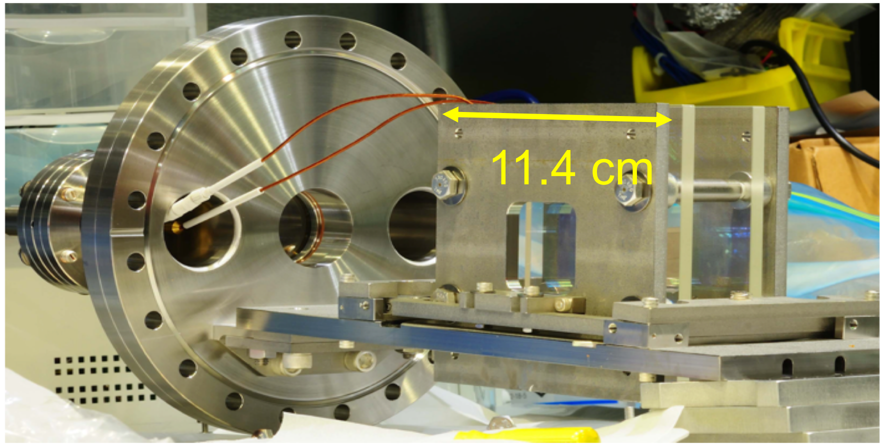
1.228 ± 0.019 (experiment)

1.234 ± 0.010 (*ab. initio* theory)

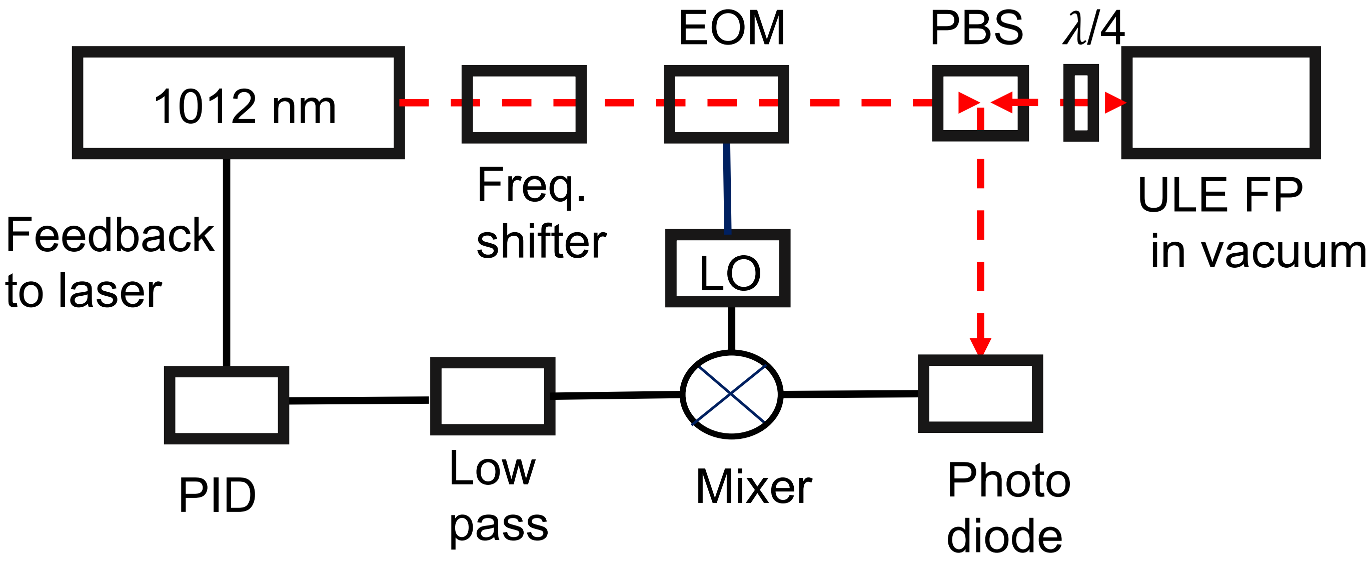
M. Kalita et al. with theory by V. Dzuba, V. Flambaum, M. Safronova Phys. Rev. A 97, 042507 (2018)

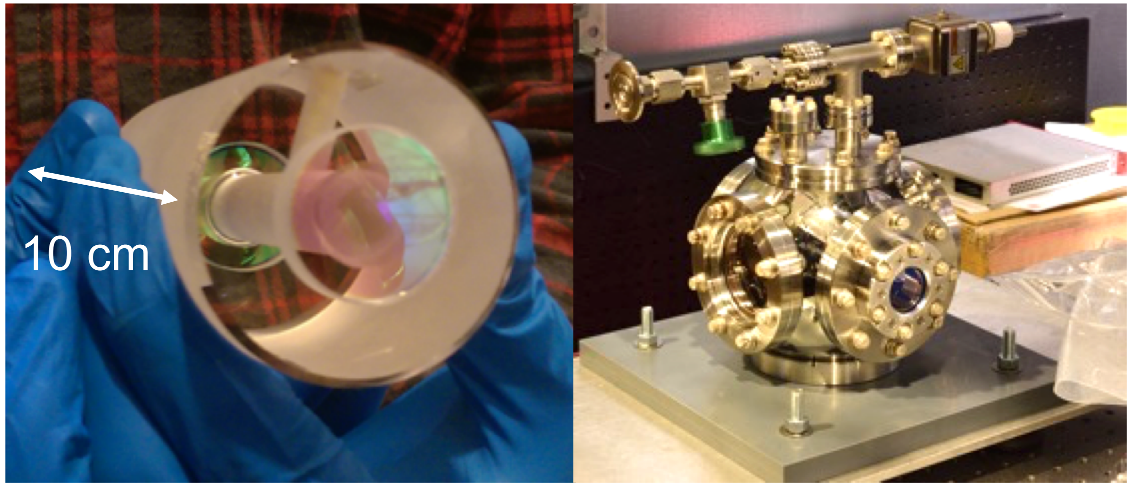
Transparent electrodes, ultra precise laser lock for 7s → 8s

- ➢ Transparent Electric field plates with ITO coating.
- ✓ Works at 10^{-10} Torr, up to 6200 V/cm without sparks for hours at a time.
- ✓ Operate magneto optic trap between the field plates !



- ➢ Laser lock for 506 nm based on ULE Fabry Perot cavity.
- ✓ < 200 kHz drift in 6 hr → absolute stability at the 10^{-10} level !

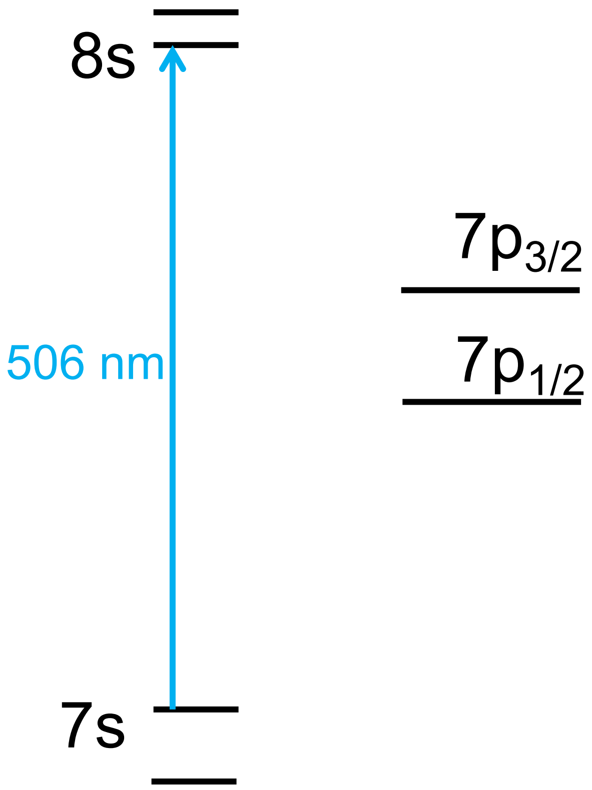




Masters thesis A.C. Dehart, U of Manitoba, 2018

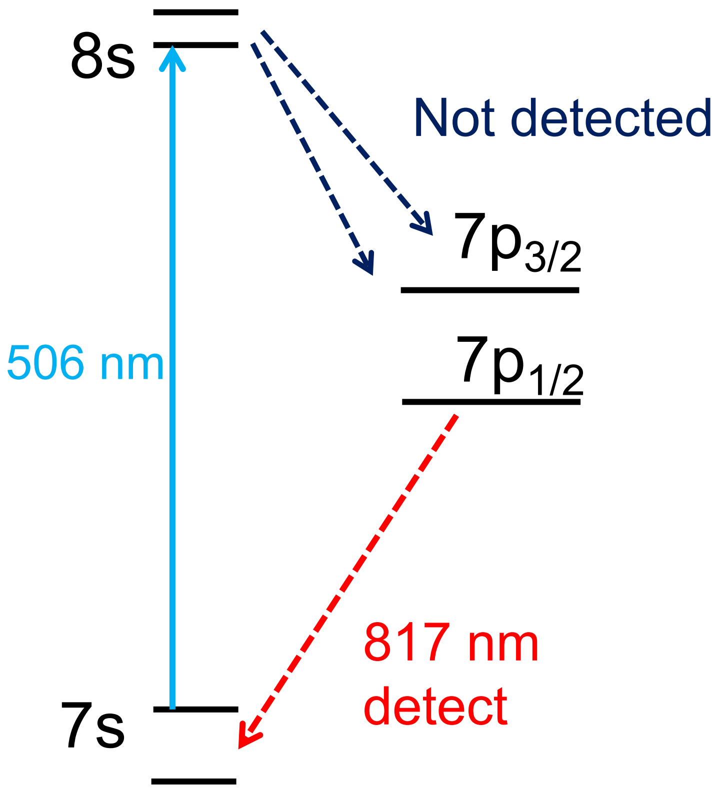
Basis for PNC : Stark induced 7s → 8s

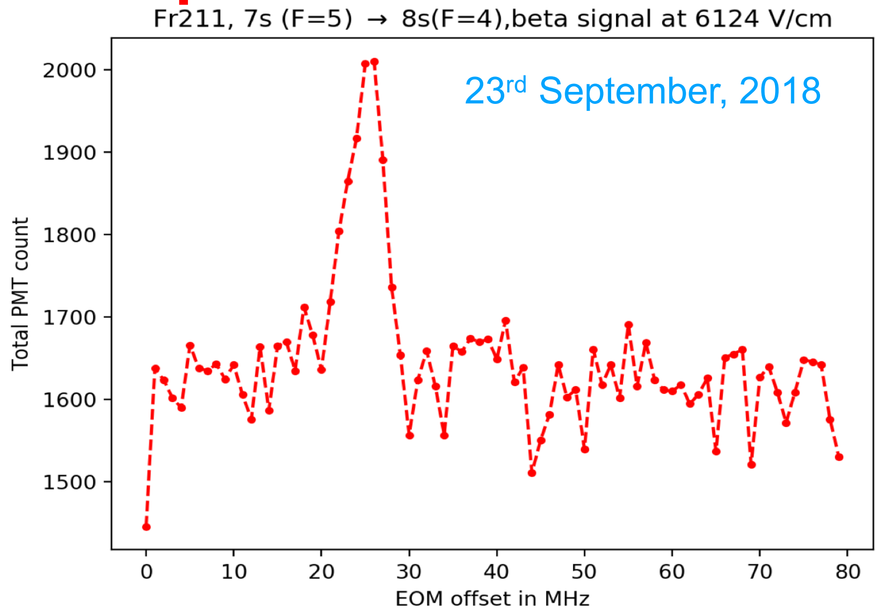
- Laser locked to ULE Fabry Perot cavity.
- E field using ITO electrodes.

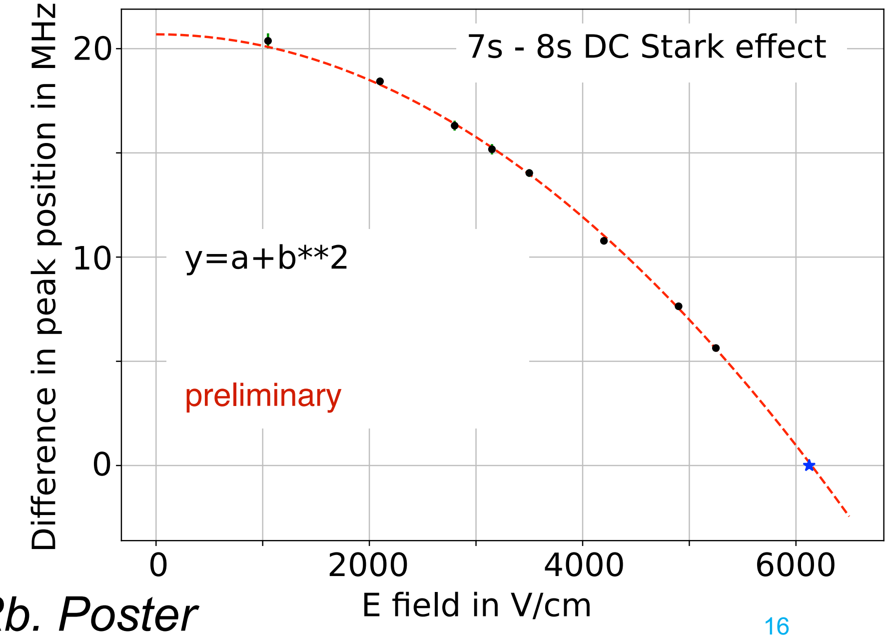


Basis for PNC : Stark induced 7s → 8s observed in September 2018 !

- Laser locked to ULE Fabry Perot cavity.
- E field using ITO electrodes.



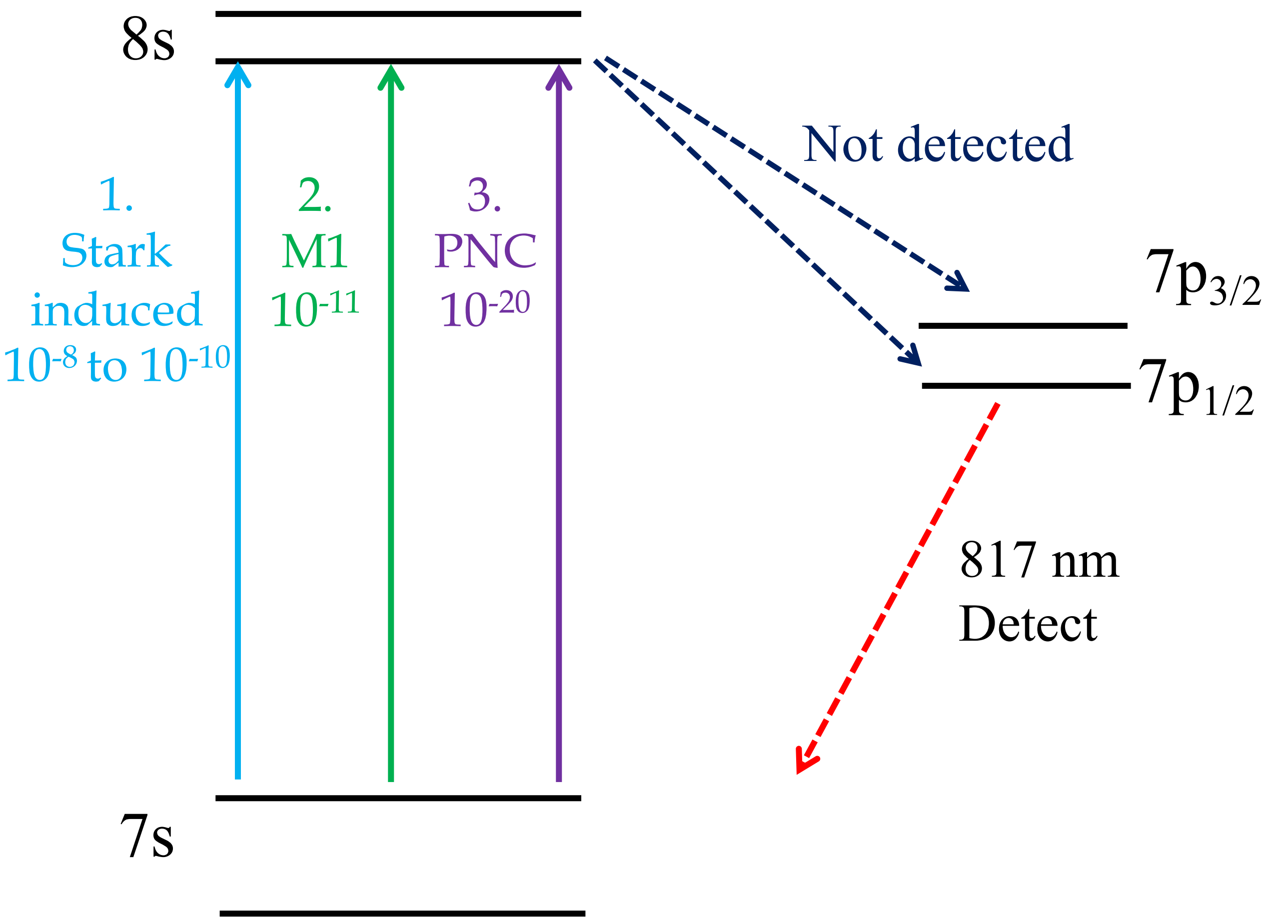




- This is the transition we will use to do our PNC experiment.
- 10^{-9} times smaller than allowed transition

- *Side note: we have also observed the equivalent transitions in ^{87}Rb. Poster*

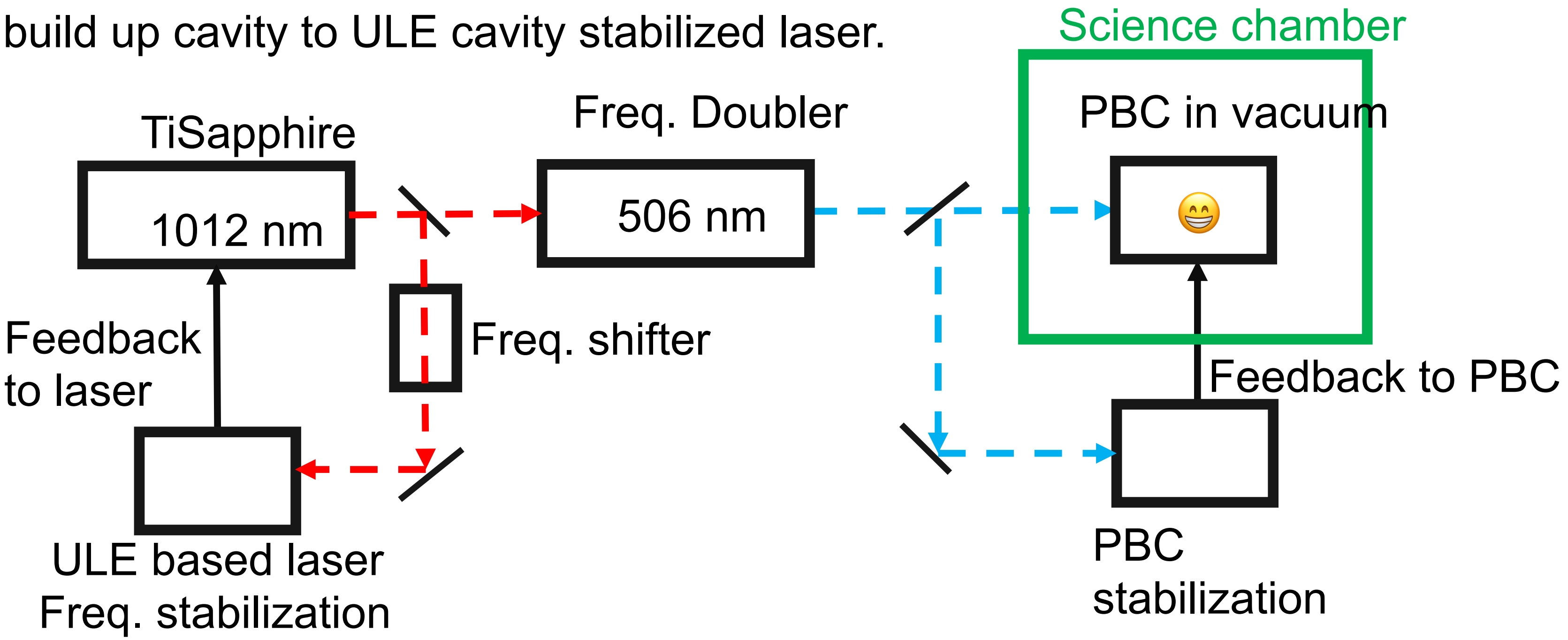
Things to do before attempting Stark interference:

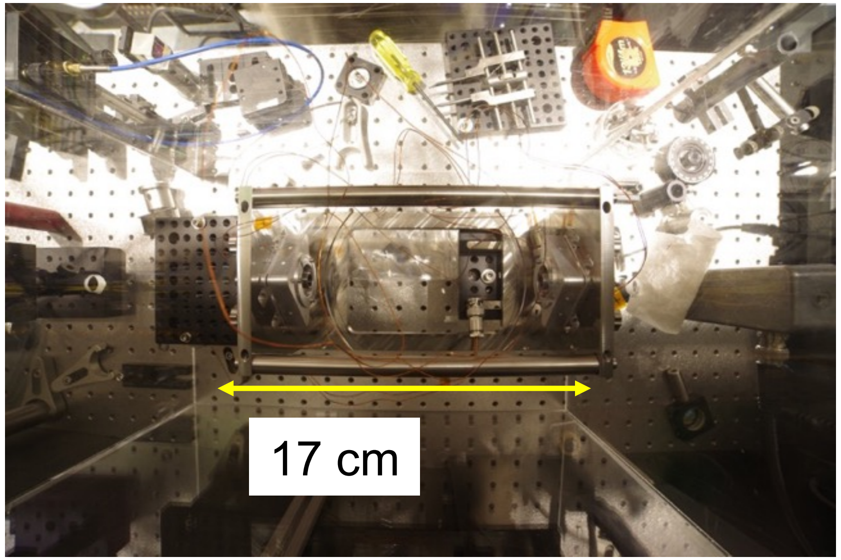


- Magnetic dipole transition M_{hf} and $M_{rel.}$
- Measure M_{hf} / A_{stark} .
- M_{hf} can be calculated accurately
- Calibrate A_{stark}
- Use calibrated A_{stark} in A_{APV} / A_{stark}

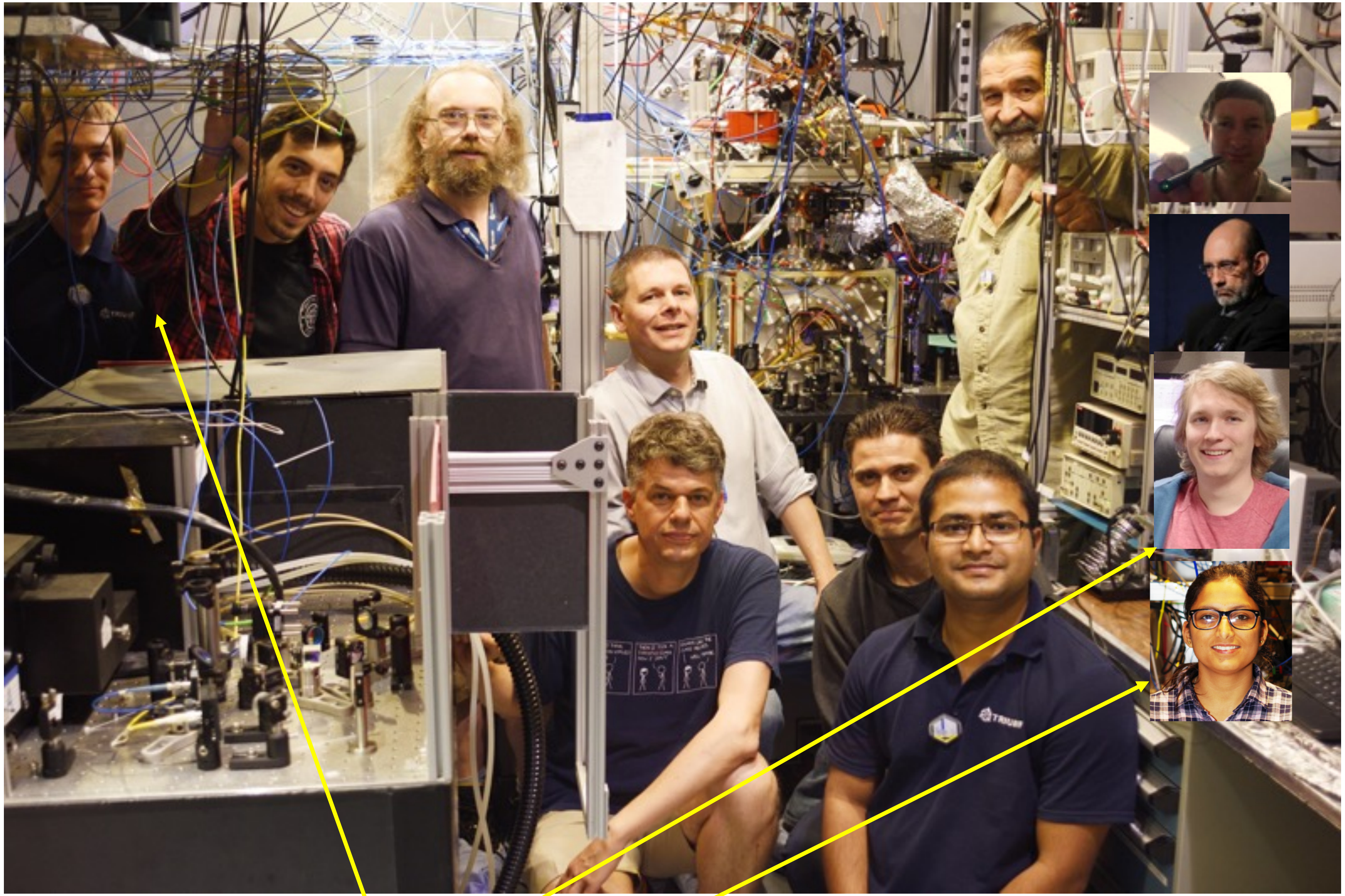
System upgrade: increase power for 7s → 8s using a cavity in vacuum

- Lock power build up cavity to ULE cavity stabilized laser.





- Aim for first generation: factor of 1000 build up
  - Install late summer, 2019



From left to right: Michael Kossin, A.C. DeHart, Matt Pearson, Seth Aubin, Gerald Gwinner, Eduardo Gomez, Mukut Kalita, Alexandre Gorelov, John Behr, Luis Orozco, Tim Hucko, Anima Sharma. Not in the picture: Andrew Senchuk

Conclusion:

- We can routinely trap francium at the Francium Trapping Facility at TRIUMF and transfer them to our measurement region.

- We have observed the 7s-8s transition in several isotopes using two photon spectroscopy.

- Recently, we have observed the single photon Stark induced 7s-8s transition in ^{211}Fr for the first time
- This is the transition we will use to do our PNC experiment.

- We are preparing for measurement of magnetic dipole transition in the 7s-8s in Fall 2019.

- We are aiming to do our first attempt at observing the PNC effect in francium in a year or two.

Thank You

Back up slides after this

Neutron Skins, a correction to atomic PNC

- Weak $e^{-} - p$ coupling $\approx 1 - 4\sin^2\theta_W \approx 0$

So mostly sensitive to weak $e^{-} - n$ coupling

$\langle s|H_W|p\rangle \mathrel{\tilde{\propto}} Z^2 N$

- Momentum transfer:

  $Q \approx$ 2.4 MeV/c Cs, 9 MeV/c Fr $\rightarrow$

  $\lambda \sim 82, 22$ fm $\Rightarrow$ Sensitivity to $\langle r^2_{\mathrm{neutron}}\rangle$

- Brown Derevianko Flambaum PRC 2009, Summarizing nuclear phenomenology and experiment:

For ^{133}Cs, 0.23±0.05% correction

For ^{211}Fr, 0.41±0.12% correction

- Sil et al. 2 EFT's spanning symmetry energy agrees (PRC 2005):

JLAB's PREXI 2012

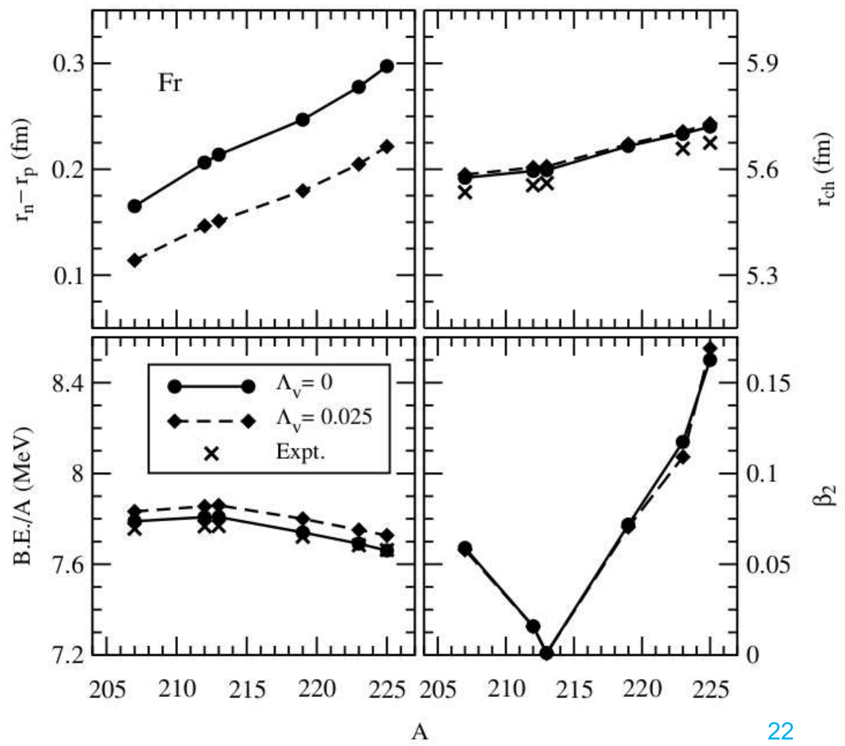
Parity-violating e^{-} + ^{208}Pb

Q tuned to neutron skin

Model independent $\rightarrow$

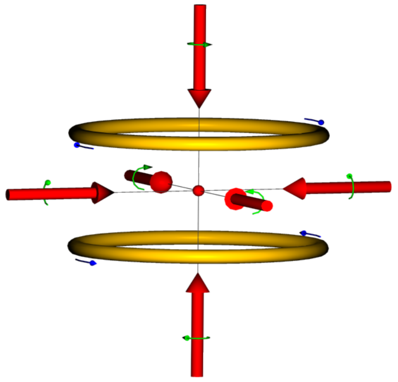
neutron skins larger by 2 ± 1

We hope PREXII refines this



The francium experiment

· Accounting for correlations in some systematic uncertainties between the two measurement periods, the combined result is Aep = −226.5 ± 7.3 (statistical) ± 5.8 (systematic) p.p.b. The total uncertainty achieved (9.3 p.p.b.) sets a new level of precision for parity-violating electron scattering (PVES) from a nucleus



Magneto optical trap
Trapping F = -kx
Cooling F = -av

to $-\zeta/\beta$ of $(-\zeta/\beta)_p = (Q_p/Q_w)(-\zeta/\beta)_{N=103} \approx -1.2\,\mathrm{mV\,cm^{-1}}$. **b**, Bounds on light Z'-mediated PV electron–proton interactions. The black line represents the 1σ limit on the particular coupling, shown for a large range of the boson mass $m_{Z'}$. The coloured region in the plot corresponds to the parameter space excluded by the Yb experiment. The low-mass ($m_{Z'} < 100$ eV) limit for the coupling is $|g_e^A g_p^V| = 1.6 \times 10^{-12}$, and the corresponding large-mass asymptotic limit ($m_{Z'} > 100$ MeV) is $|g_e^A g_p^V| / m_{Z'}^2 = 1.3 \times 10^{-6}\,\mathrm{GeV^{-2}}$. **c**, Bounds on light Z'-mediated PV electron–neutron interactions. This result comes from combining existing limits on the effective electron–nucleon coupling, derived from the Cs PV experiment[4], with the Yb experimental limits shown in **b**. The low-mass limit for the interaction is $|g_e^A g_n^V| = 1.2 \times 10^{-12}$, and the corresponding large-mass asymptotic limit is $|g_e^A g_n^V| / m_{Z'}^2 = 9.3 \times 10^{-7}\,\mathrm{GeV^{-2}}$.

Neutralizer:
- ✓ Zr, work function 4.0 eV, mechanically strong, ionization potential of Fr 4.1eV.
- ✓ Up-to 30% release, 800℃, 500,000 cycles.

(A. Gorelov et al. in preparation)