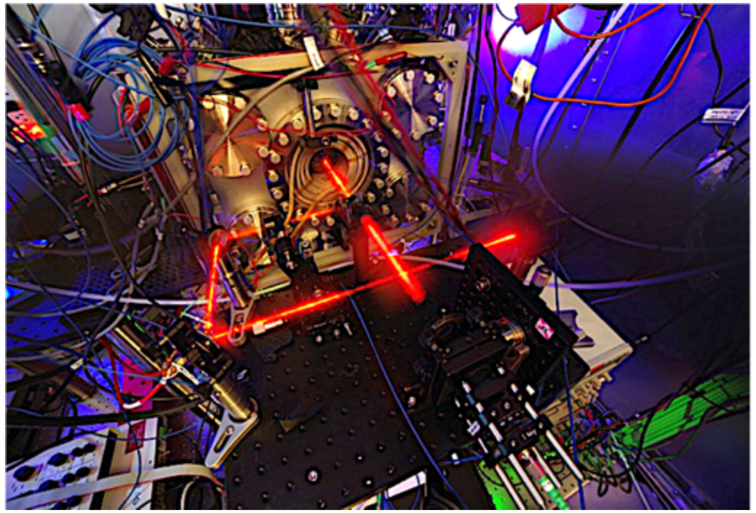
Testing parity and time reversal symmetry violation using francium and radium



Mukut Ranjan Kalita

TRIUMF

Postdoctoral Fellow

- ❑ Fr Atomic parity violation experiment at TRIUMF
- ❑ ^{225}Ra experiment at Argonne National Laboratory

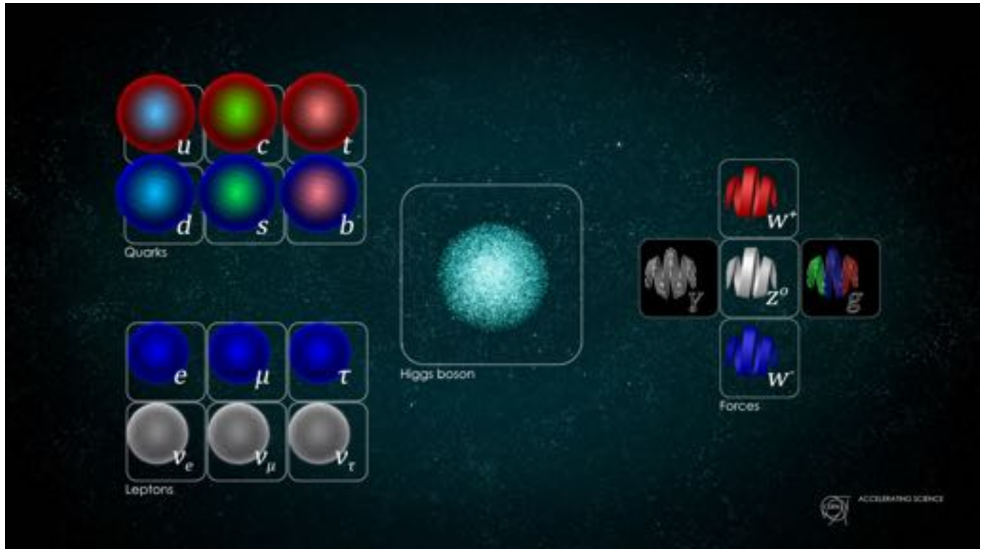
Operational funding by NSERC, NSF, NRC/TRIUMF. Infrastructure support by DOE and NRC/TRIUMF. Student support by the U. of Manitoba, travel support by CONACYT and Fulbright.

Support by DOE office of nuclear physics

Discovery, accelerated

Goal of these experiments:

- ❑ Test the standard model

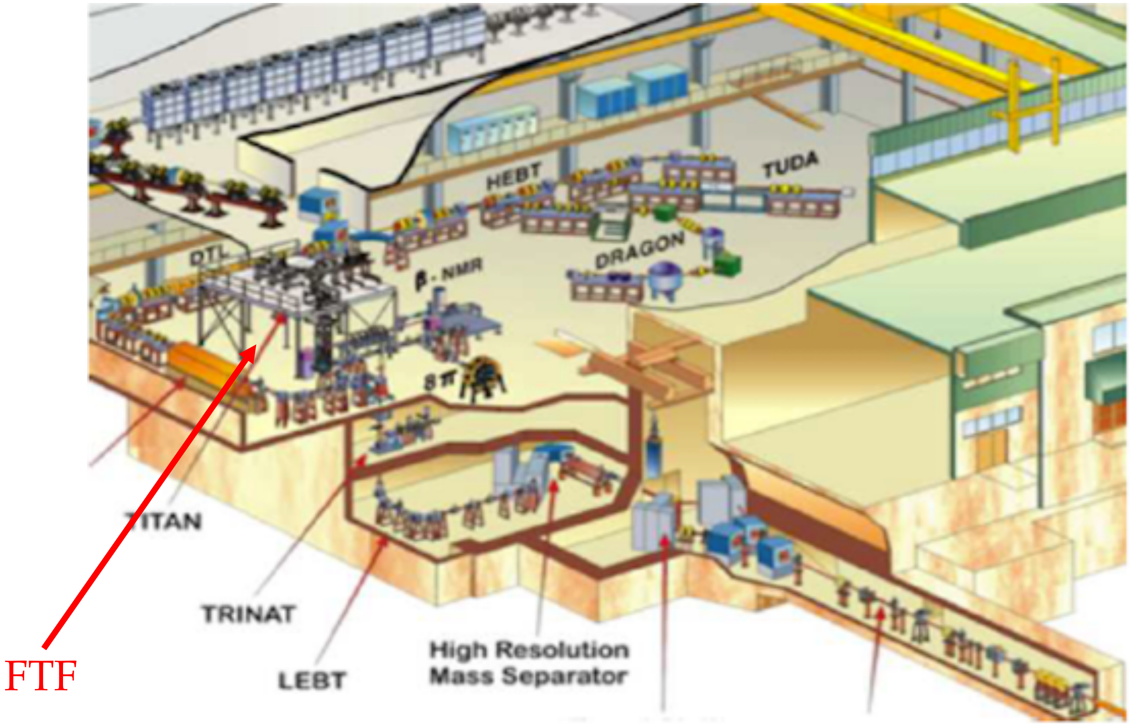


Credits: CERN

- ❑ SM is very successful, but it is not complete, e.g. does not explain:
- ➢ Matter antimatter asymmetry.
- ➢ Does not account for dark matter, dark energy, gravity etc.
- ✓ Need to look for new physics beyond the SM and search for new particles and new forces.
- ❑ One approach is to look for them directly in high energy collisions in accelerators.
- ❑ Complementary approach is to look for effects due to these yet unseen particles and forces in systems such as atoms and molecules.
- ❑ The experiments that I am going to describe falls in this second category of approach.

The Fr experiment:

- ❑ Fr experiment at TRIUMF.



- ❑ We study electronic transitions of Fr using lasers.
- ❑ Electronic transitions are dominated by electromagnetic interactions.
- ❑ Electrons in an atom can also take part in weak interaction.

The Fr experiment: parity

- Parity symmetry: invariance under spatial inversion (x, y, z → -x,-y,-z).

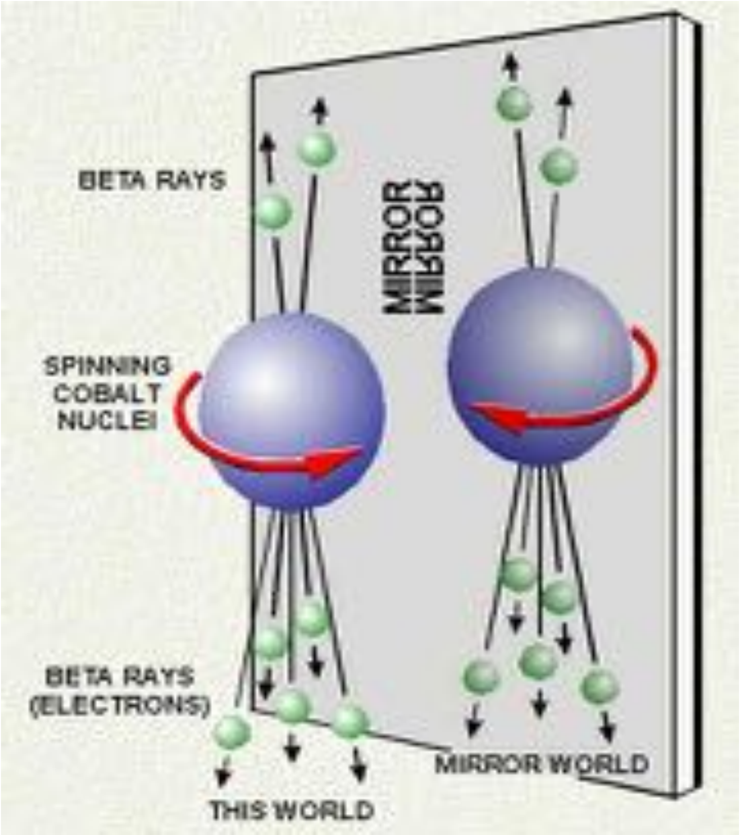
The Fr experiment: weak interaction violates parity

- Parity symmetry: invariance under spatial inversion (x, y, z → -x,-y,-z).
- 1950-1956: weak interaction? (Ramsey, Purcell, Weyl, Lee, Yang).
- 1957: experimental evidence of parity violation in weak interaction.

The Fr experiment: weak interaction violates parity

- Parity symmetry: invariance under spatial inversion (x, y, z → -x,-y,-z)
- 1950-1956: weak interaction? (Ramsey, Purcell, Weyl, Lee, Yang).
- 1957: experimental evidence of parity violation in weak interaction.
- Experiment

$$^{60}Co \rightarrow {}^{61}Ni + e^- + \bar{\nu}_e$$



http://physics.nist.gov/GenInt/Parity/cover.html]

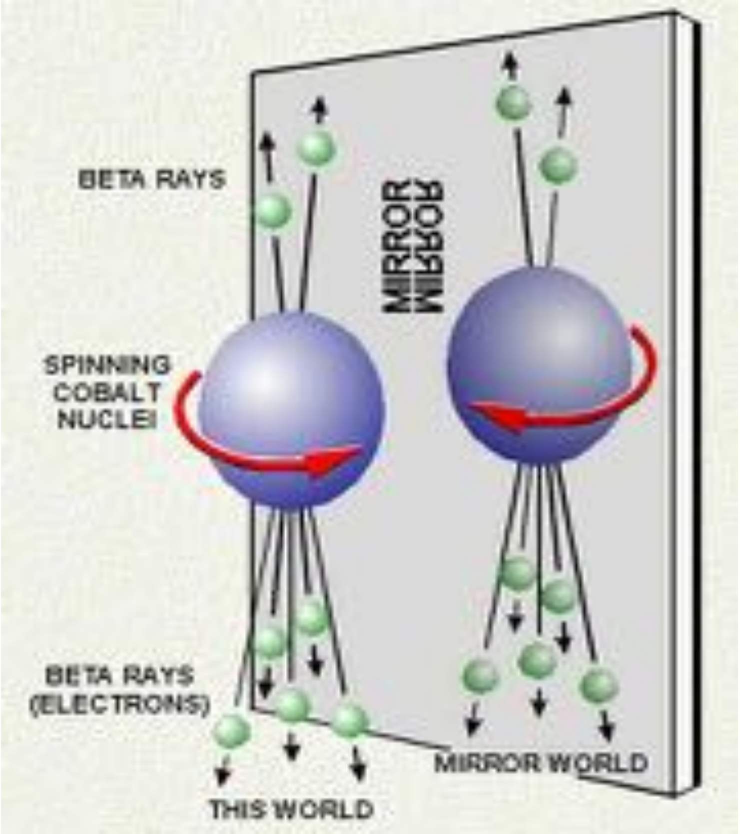
1957: C.S. Wu et al. Phys. Rev. 105,1413.

The Fr experiment: weak interaction violates parity

- ❑ Parity symmetry: invariance under spatial inversion (x, y, z → -x,-y,-z)
- ❑ 1950-1956: weak interaction? (Ramsey, Purcell, Weyl, Lee, Yang).
- ❑ 1957: experimental evidence of parity violation in weak interaction.
- ❑ Experiment

$$^{60}Co \rightarrow {}^{61}Ni + e^- + \bar{\nu}_e$$

$$n \rightarrow p + e^- + \bar{\nu}_e$$



http://physics.nist.gov/GenInt/Parity/cover.html]

- ❑ Weak interaction due to charged W bosons

→ Particle changes identity

1957: C.S. Wu et al. Phys. Rev. 105,1413.
1957: Nobel Prize in Physics, C. N. Yang and T.D. Lee

The Fr experiment: weak interaction, neutral Z boson

- Weak interaction due to neutral Z bosons (presence of Z: central prediction of the theory of electro weak interactions (*S. L. Glashow, A. Salam and S. Weinberg*).

→ Identity of the interacting particles do not change. (Fr remains as Fr), short range.

Parity violation in atomic physics:

- 1959: Before SM, estimates in hydrogen (Zel'dovich).
- 1960s: experimental search in molecular oxygen and atomic lead (Null results).
- Indirect evidence of Z boson in 1973 (Gargamelle bubble chamber, neutrino interaction)

1979: Nobel Prize in Physics, S. L. Glashow, A. Salam and S. Weinberg
1958-59:, Zel'dovich Sov. Phys. JETP 6, 1184 Sov. Phys. JETP 9, 682
1973: F J Hasert et al. Phys. Lett. ***46*** *121. F J Hasert et al. Phys. Lett.* ***46*** *138.*

The Fr experiment: weak interaction, neutral Z boson

- ❑ Weak interaction due to neutral Z bosons (presence of Z: central prediction of the theory of electro weak interactions (*S. L. Glashow, A. Salam and S. Weinberg*).

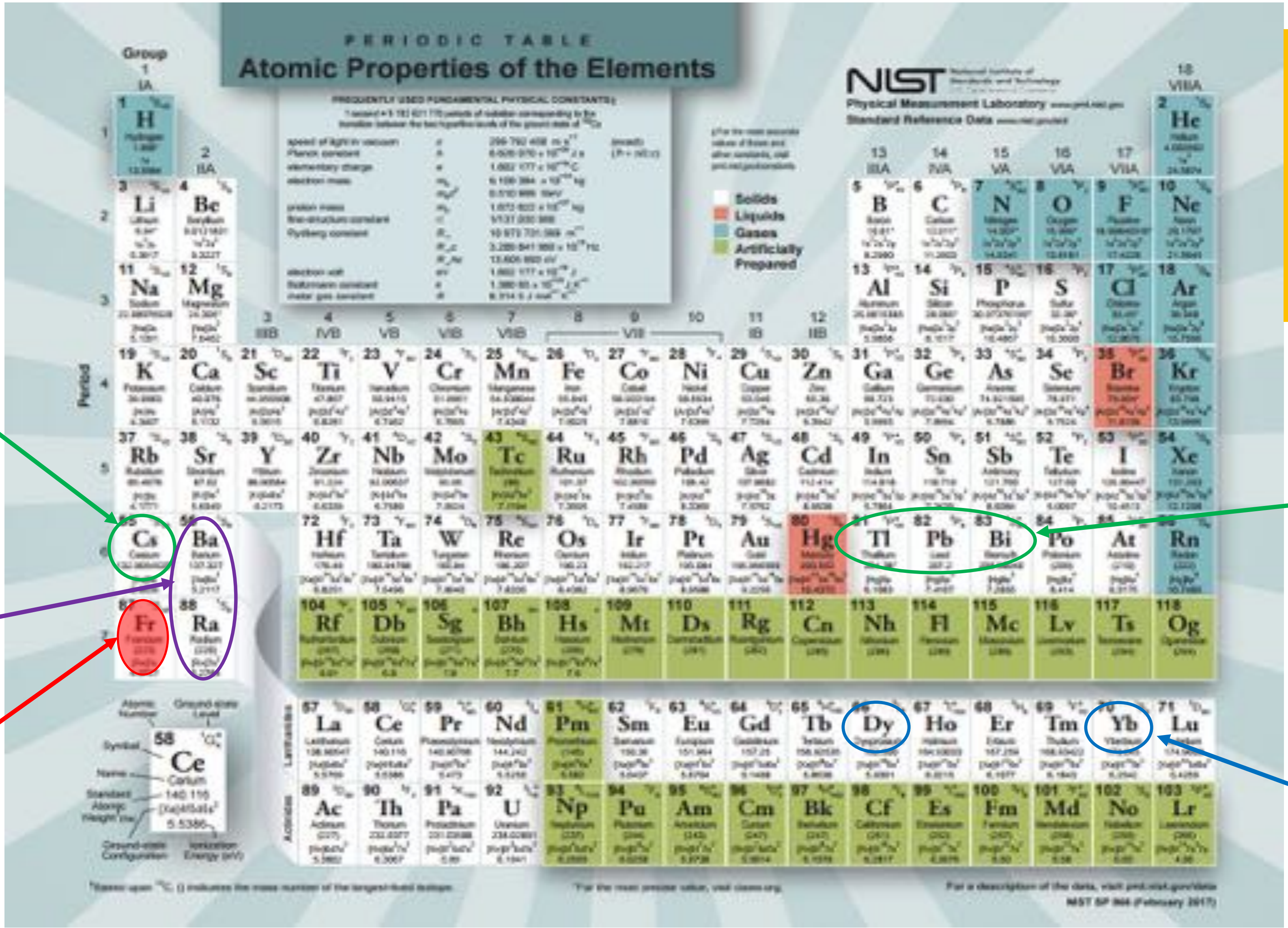
→ Identity of the interacting particles do not change, (Fr remains as Fr), short range.

Parity violation in atomic physics:

- ❑ 1959: Before SM, estimates in hydrogen (Zel'dovich).
- ❑ 1960s: experimental search in molecular oxygen and atomic lead (Null results).
- ❑ Indirect evidence of Z boson in 1973 (Gargamelle bubble chamber, neutrino interaction)
- ❑ 1974: APV is enhanced in heavy atoms (Z^3 enhancement, Bouchiat & Bouchiat).
- ❑ Experimental programs in Cs, Bi, Tl.
- ❑ 1978: first experimental observation of APV in Bi (Novosibirsk).
- ❑ Since then parity violation has been observed in multiple atoms.
- ❑ Direct evidence of Z boson in 1983 (CERN).

1979: Nobel Prize in Physics, S. L. Glashow, A. Salam and S. Weinberg
1958-59: Zel'dovich Sov. Phys. JETP 6, 1184 Sov. Phys. JETP 9, 682
1960s: L.C. Bradley 111 and N.S. Wall, Nuovo Cimento, R. Poppe, Physica (Utrecht) 50, 48
1973: F J Hasert et al. Phys. Lett. ***46*** *121. F J Hasert et al. Phys. Lett.* ***46*** *138.*
1974: Bouchiat & Bouchiat J. Phys. Conf. Ser. 35, 899
1978: L. M Barkov et al. JETP Lett. 28, 503
1983: Arnison, G., et al., Phys. Lett. B 122, 103, Phys. Lett. B 126, 398.

APV experiments: good experiments and good theory → good test



Experiments

measure : A_{APV}

For SM tests→

$A_{APV} = k_{APV}\, Q_W$

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

Follow up at Purdue (in preparation).

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

APV 18 x larger

Th. can be done ≈ Cs

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

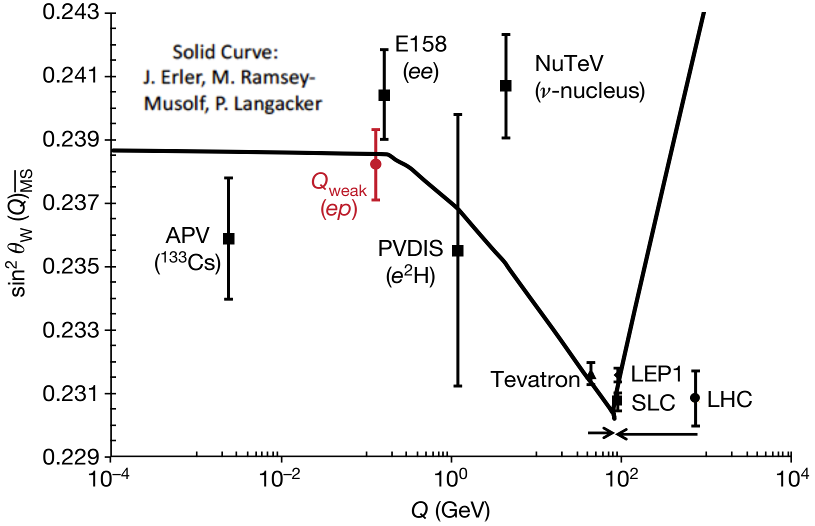
Yb (exp.) 0.5%

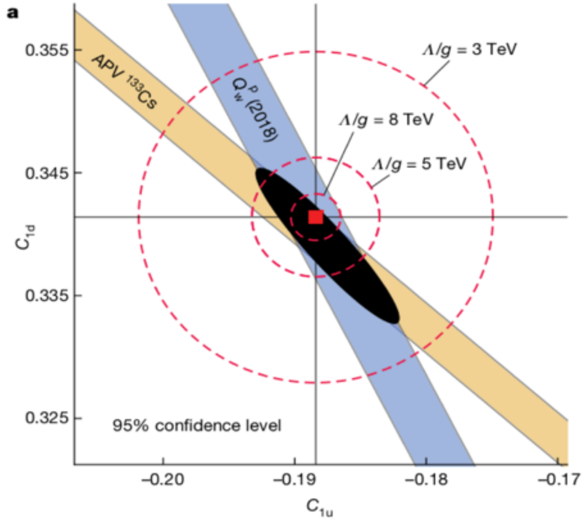
Antypas et al. Nat. Phys. ***15****, 120–123 (2019)*

Ginges et al.: initiated program for Fr theory to 0.1%.
(see e.g. PRA ***98****, 032504 (2018))*

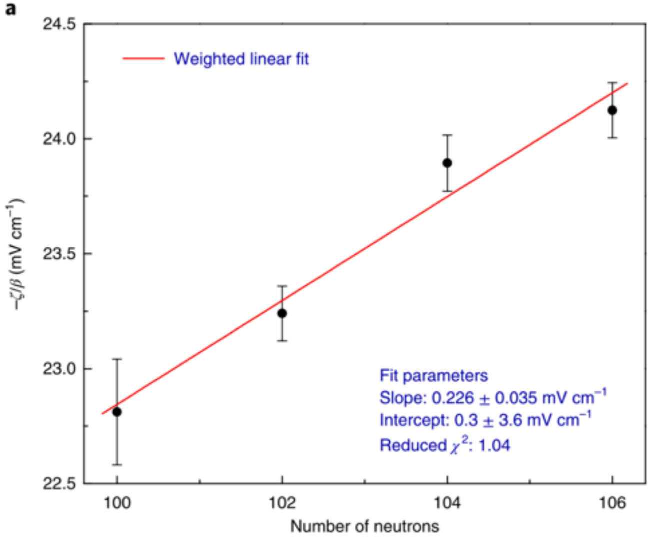
The Fr experiment:

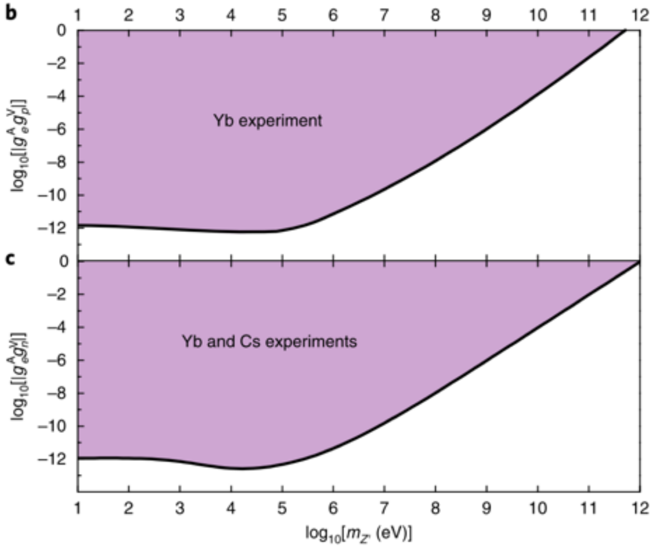
- ❑ Test SM at low energies
- ❑ Search for extra bosons





Q$_{weak}$ Collaboration, *Nature 557, 207–211 (2018)*
M. S. Safronova et al. R. M. P. ***90****, 025008 (2018)*
G. Toh et al. arXiv:1905.02768v2



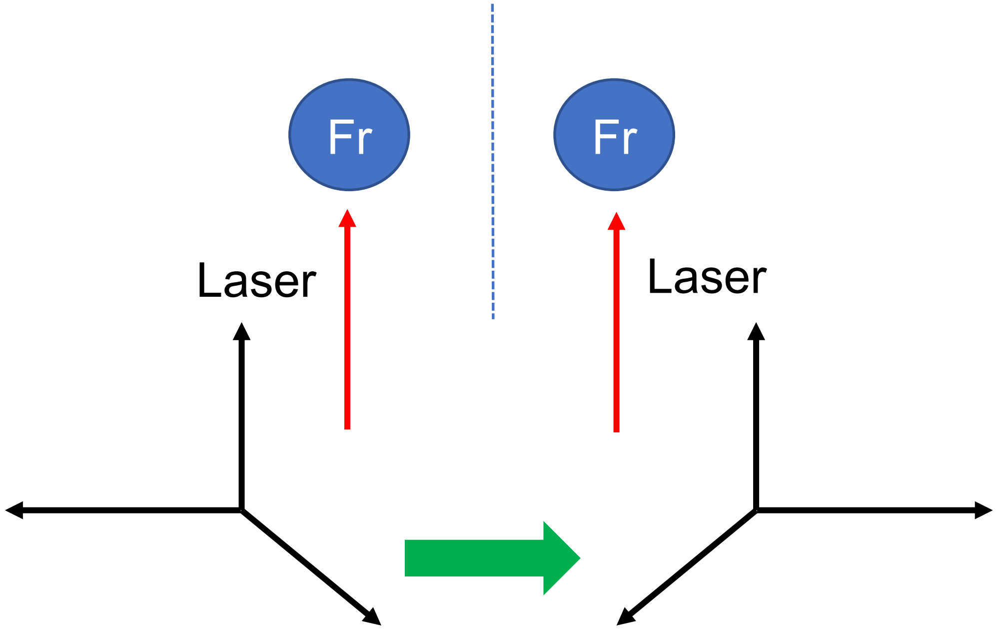


Isotopic variation of APV, bounds on z$^{/}$ boson mediated interactions

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

The Fr experiment:

- ❑ Choose an electric dipole forbidden transition e.g. 7s→8s in Fr.
- ❑ Small transition rate due to APV effects (≈ 10^{-20} of allowed in Fr).

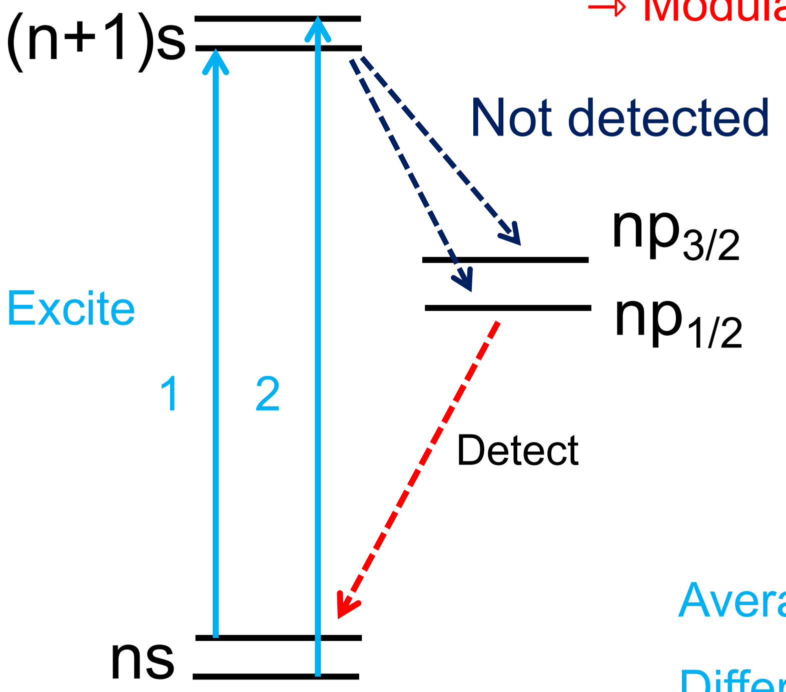


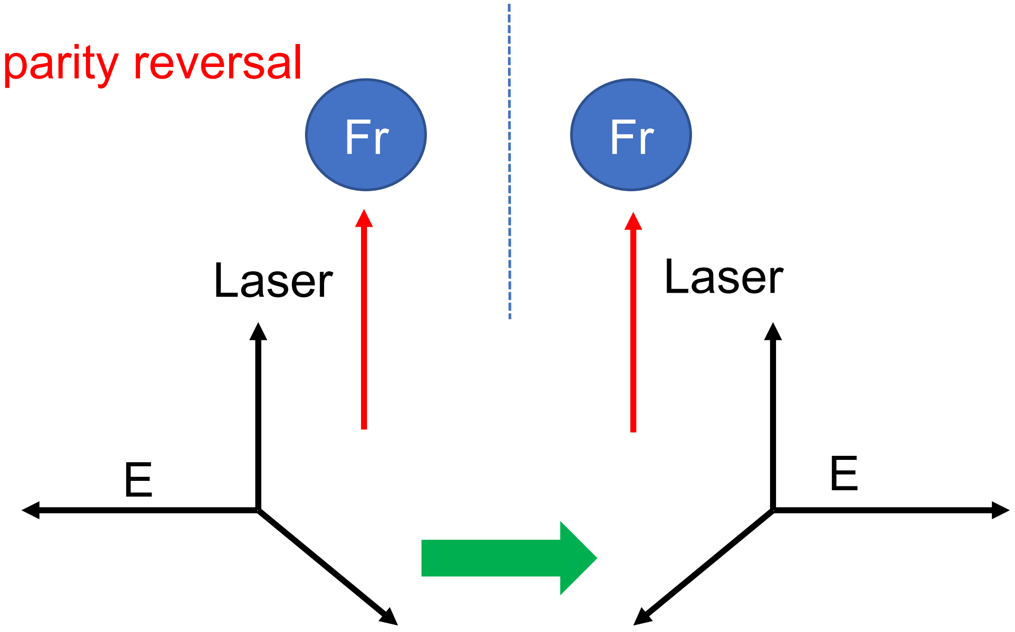
The Fr experiment: Stark-induced ns → (n+1)s transition

- Choose an electric dipole forbidden transition e.g. 7s→8s in Fr.
- Small transition rate due to APV effects (≈ 10^{-20} of allowed in Fr).
- Use Stark Interference technique. *(M. Bouchiat & Bouchiat, J. Phys. 36, 493, (1975))*
- $R \propto |A_{stark}+A_{PNC}|^2 \approx (A_{stark})^2 \pm 2Re(A_{stark}A_{APV}^*)$

Interference term changes sign upon parity reversal

→ Modulation of decay fluorescence



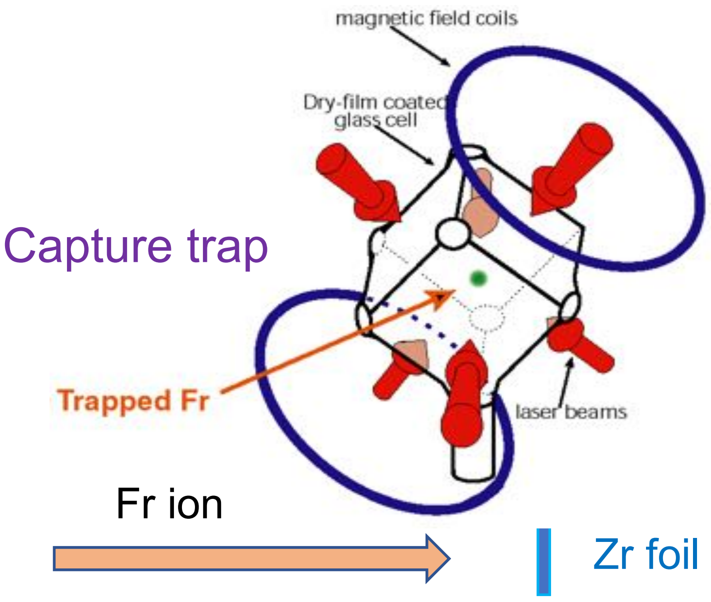


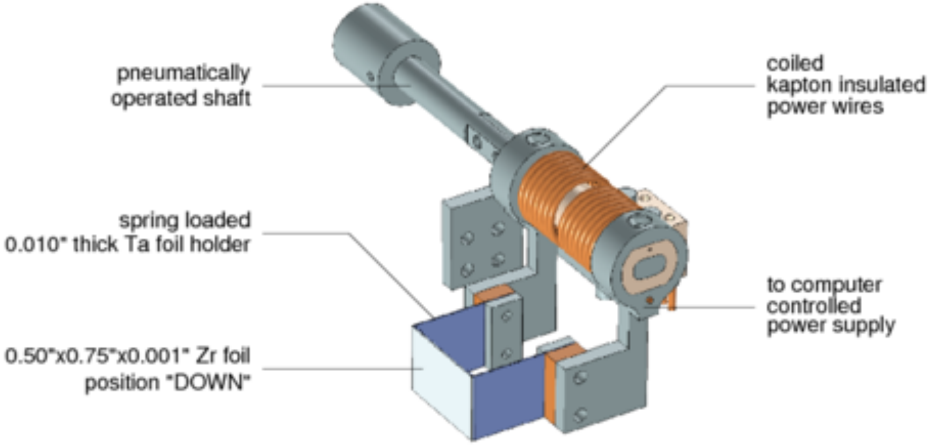
Average of 1 and 2: nuclear spin independent APV

Difference of 1 and 2: Anapole

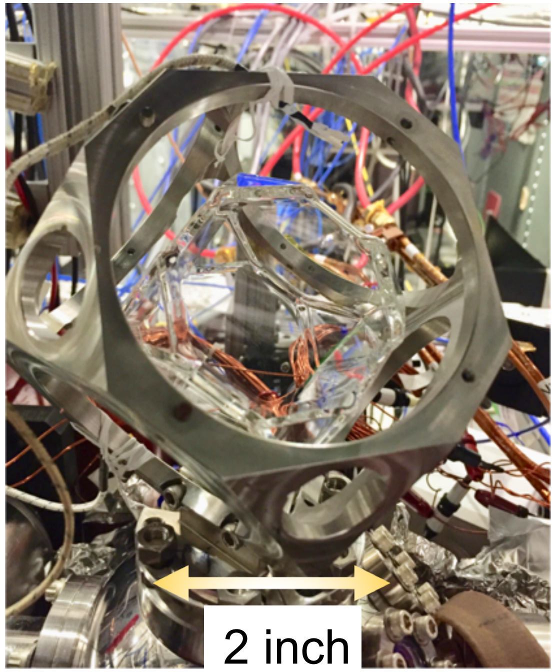
The Fr trapping facility

- No stable Fr → TRIUMF
- UC_x target
- Up to 2 $\times 10^9$ /s delivered





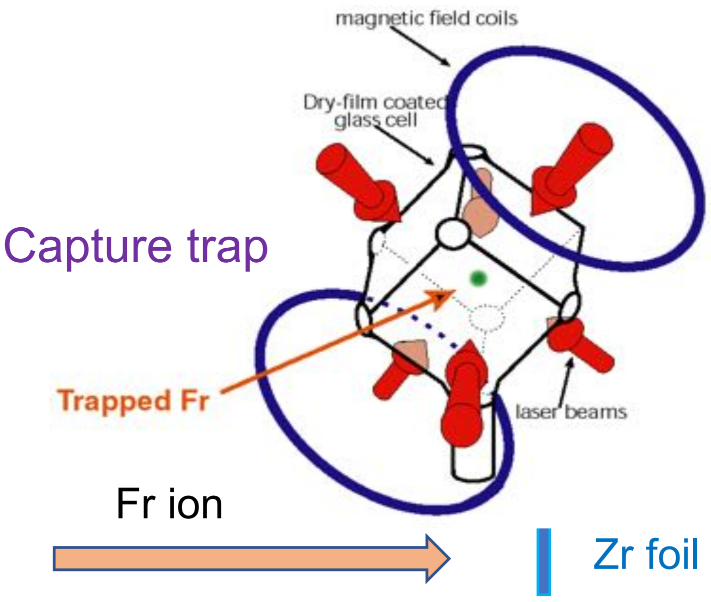
(A.I. Gorelov et. al. (in prep))

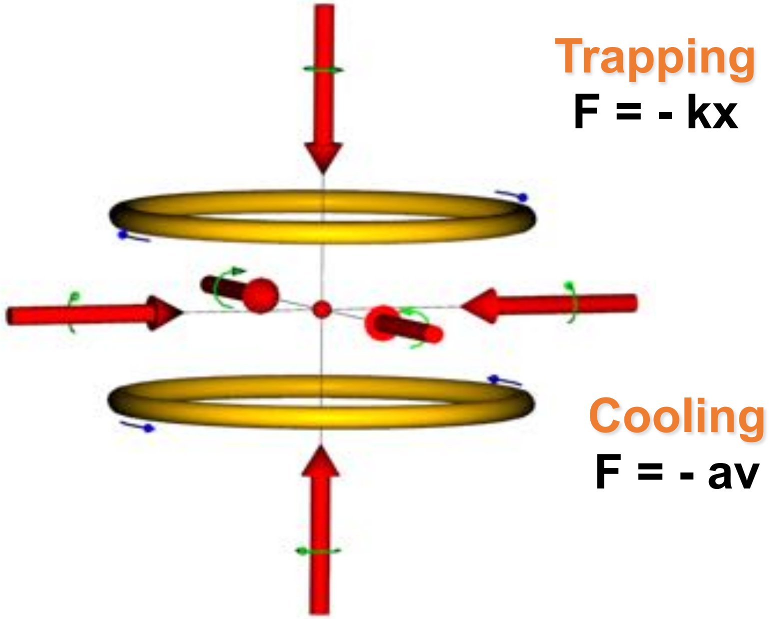


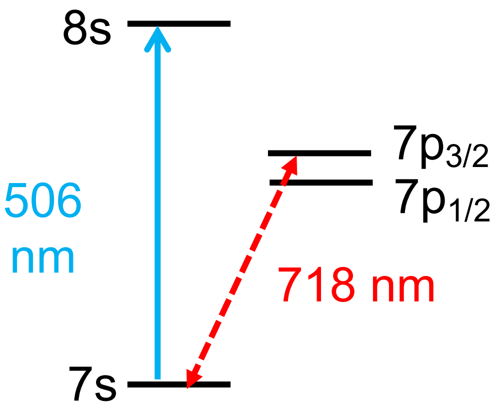
The Fr trapping facility

- ❑ No stable Fr → TRIUMF
- ❑ UC_x target
- ❑ Up to 2×10^9 /s delivered

- ❑ 2 lasers to trap
- ❑ ≈ 1 million atoms trapped







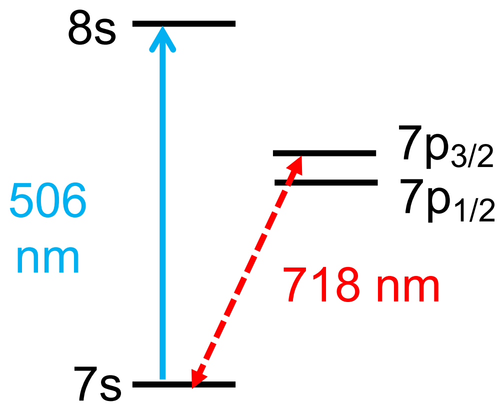
Other Fr traps:

- ❑ INFN Legnaro (Italy).
- ❑ Tohoku University (Japan).

The Fr trapping facility

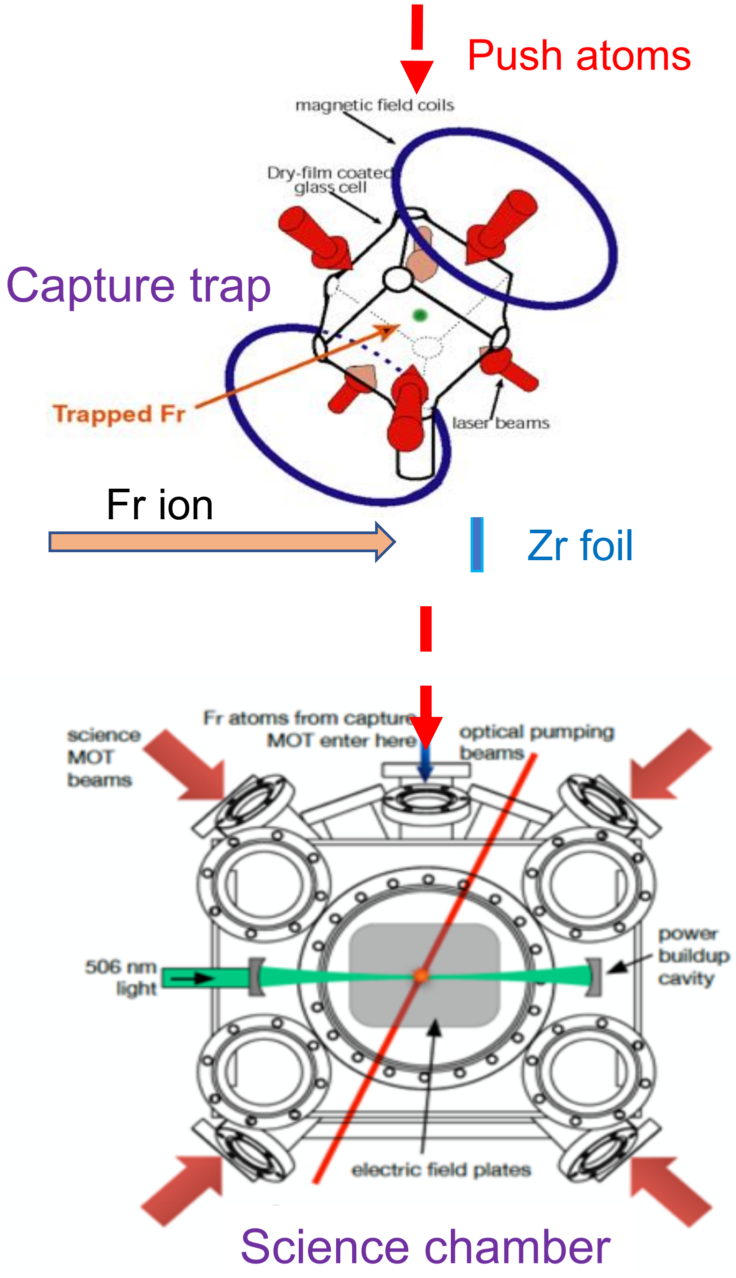
- ❑ No stable Fr → TRIUMF
- ❑ UC_x target
- ❑ Up to 2 ×10^9 /s delivered

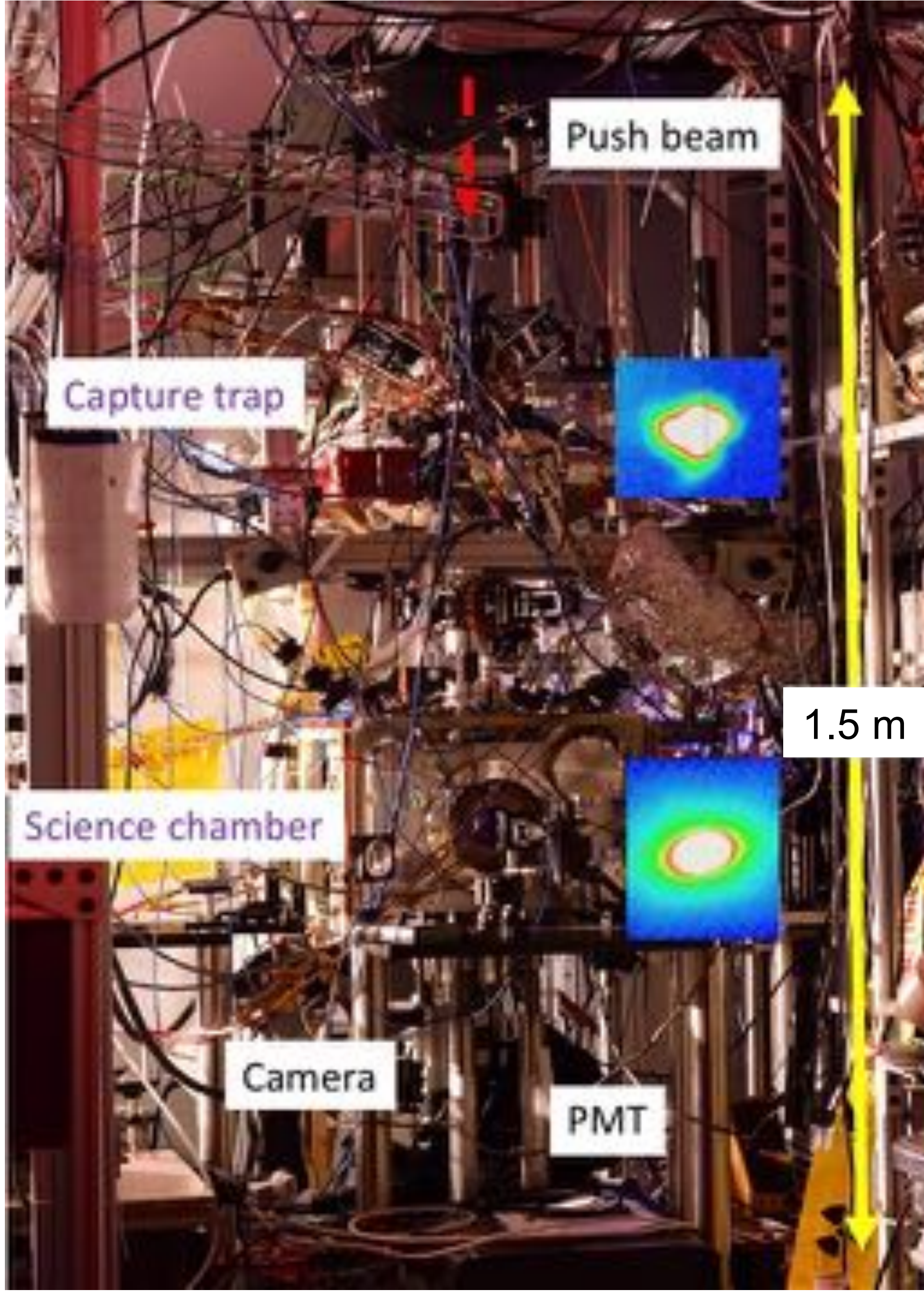
- ❑ 2 lasers to trap
- ❑ ≈ 1 million atoms trapped
- ❑ Up to 50% transfer
- ❑ 20 s lifetime



Other Fr traps:

- ❑ INFN Legnaro (Italy).
- ❑ Tohoku University (Japan).





Tune apparatus with Rb

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

Completed measurements at the francium trapping facility upper trap

- ❑ 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.

- ❑ 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 “good” nuclei for APNC/anapole.

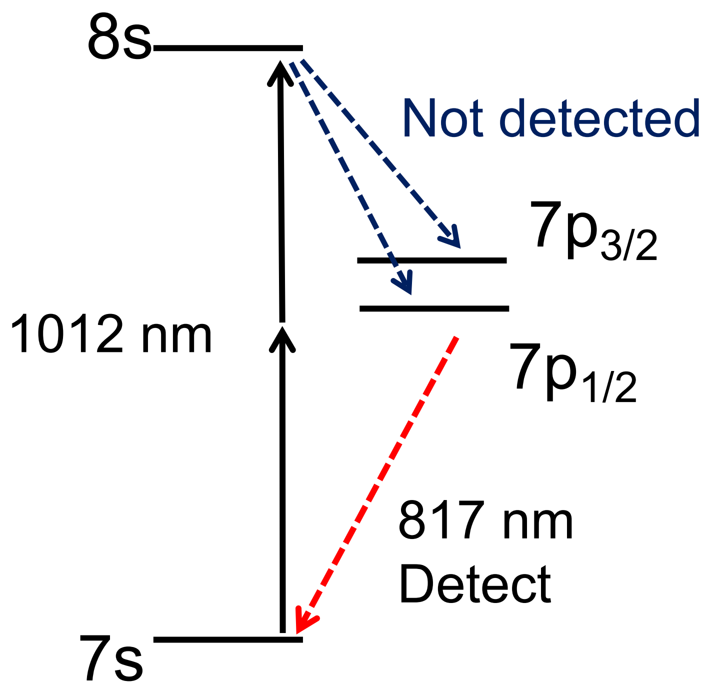
- ❑ Francium $7p_{3/2}$ photoionization

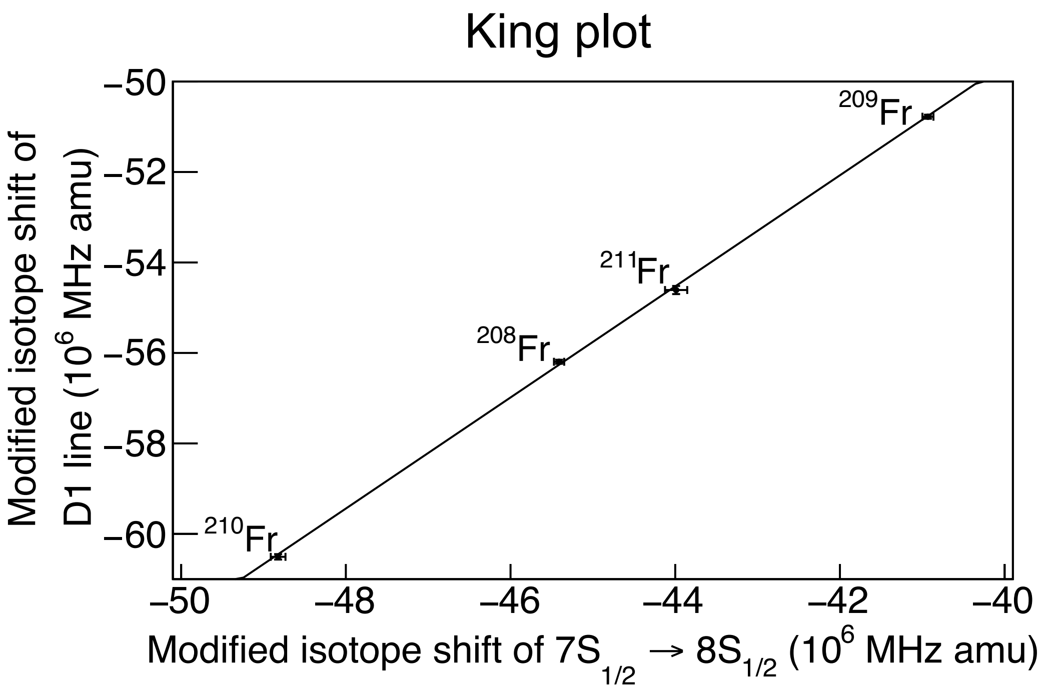
  Collister et. al. Can. J. Phys (2017)

- ➢ Determines trap loss.

Completed measurements at the francium trapping facility lower trap

- Two photon spectroscopy: 7s-8s transition 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 ∝ $(\Delta\Psi(0)^2)_{D1} / (\Delta\Psi(0)^2)_{SS}$

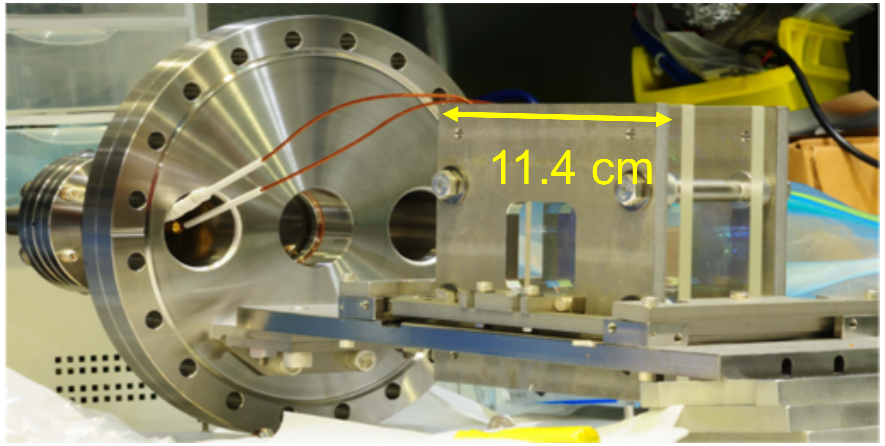
1.228 ± 0.019 (experiment)

1.234 ± 0.010 (*ab. initio* theory)

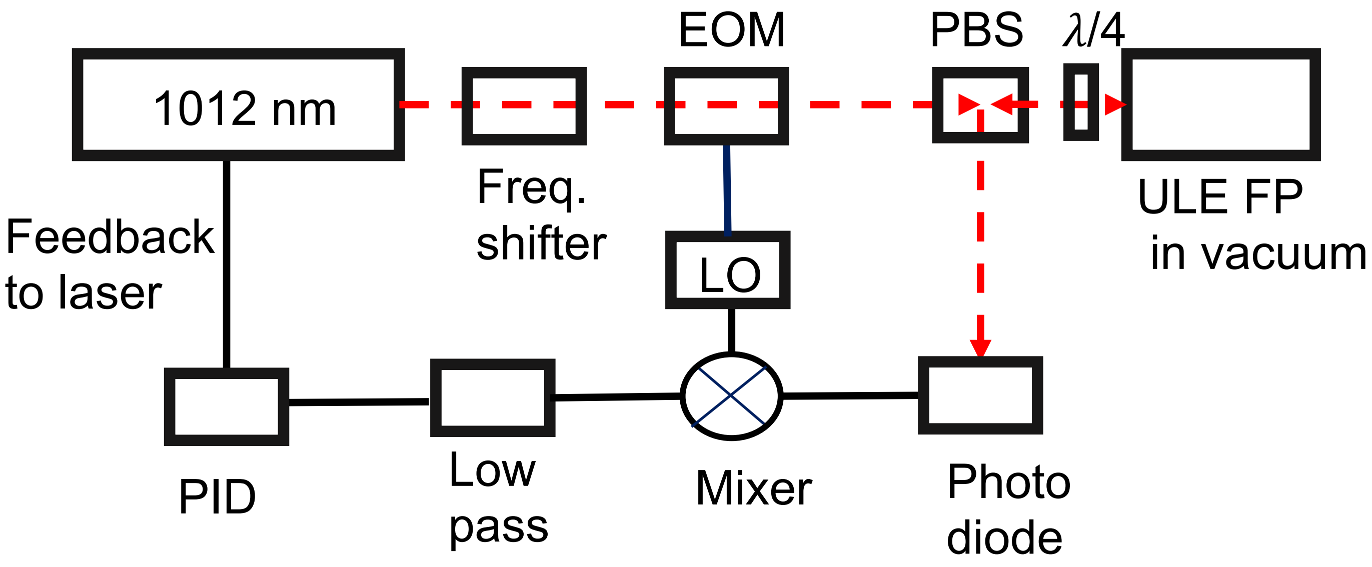
M. Kalita et al. with theory by V. Dzuba, V. Flambaum, M. Safronova Phys. Rev. A 97, 042507 (2018)

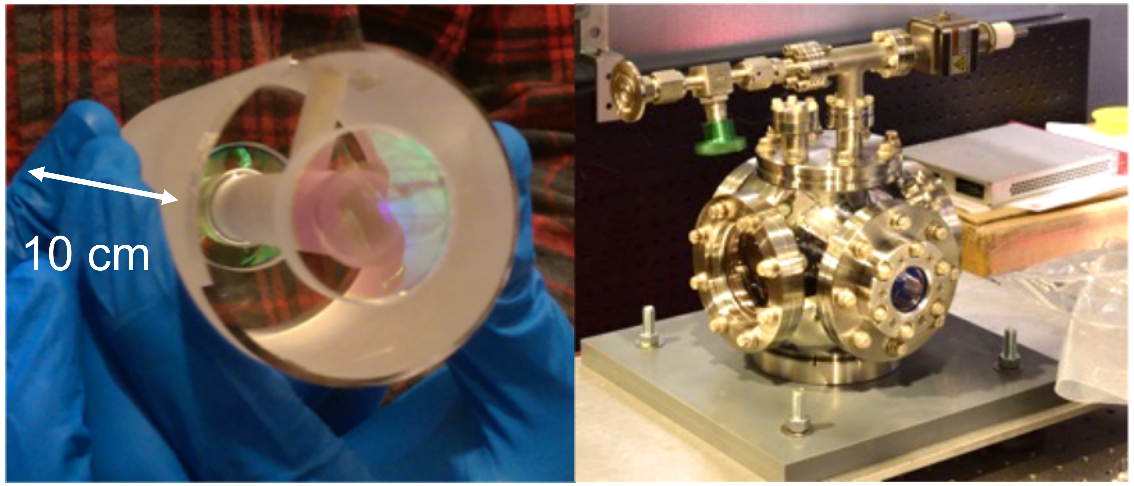
The Fr experiment: transparent electrodes, ultra precise laser lock

- ❑ 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 !



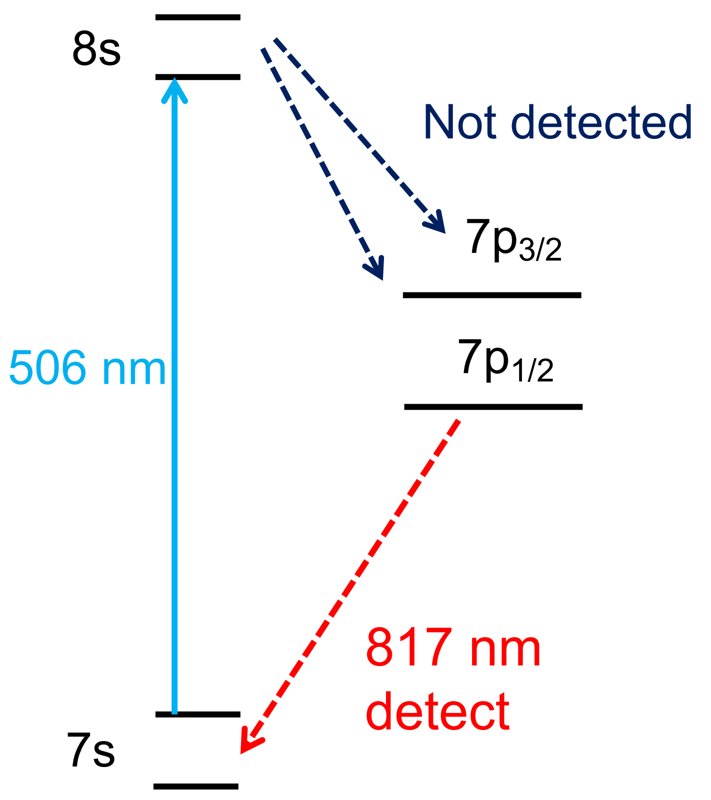
- ❑ Laser lock for 506 nm based on ULE Fabry Perot cavity.

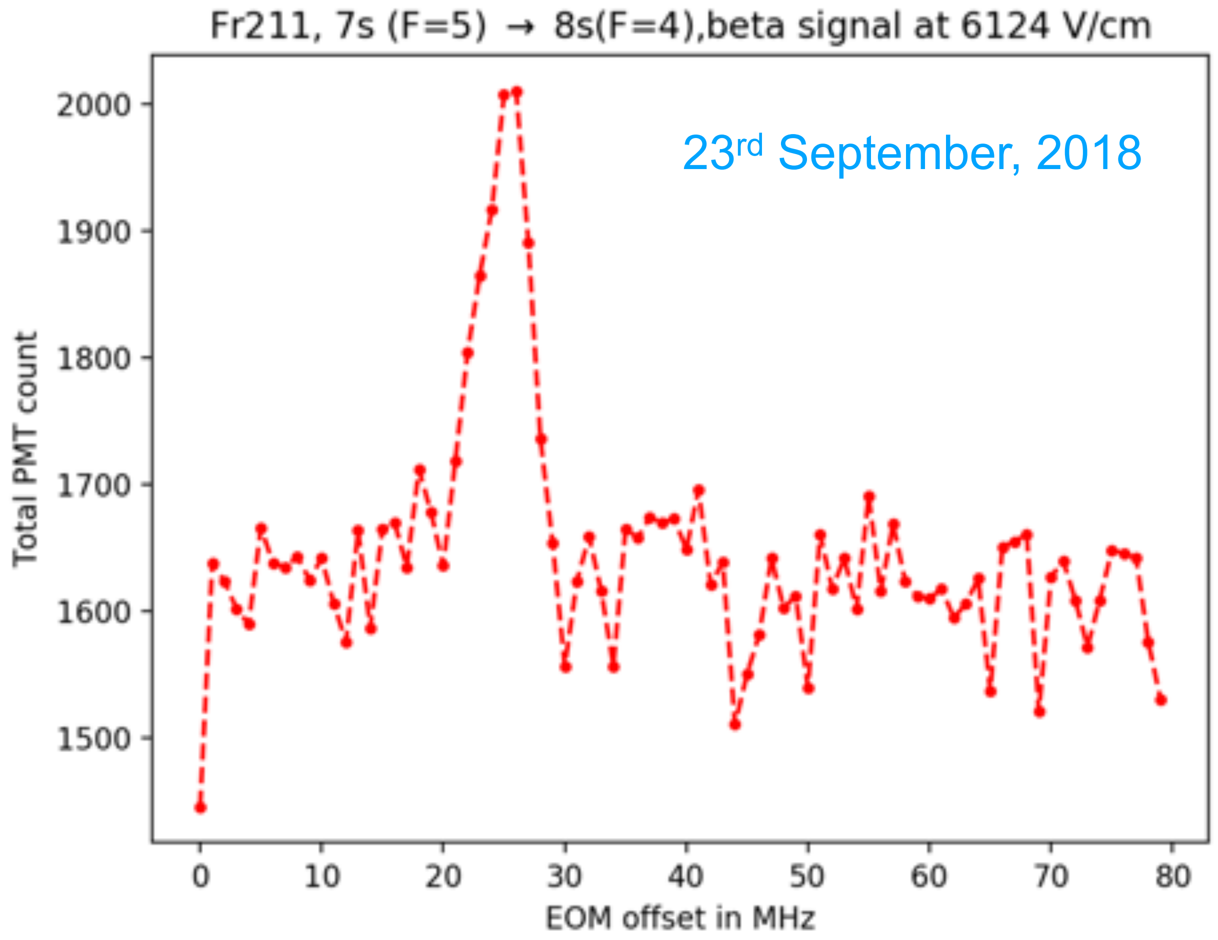




The Fr experiment: Stark induced 7s → 8s observed in September 2018 !

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

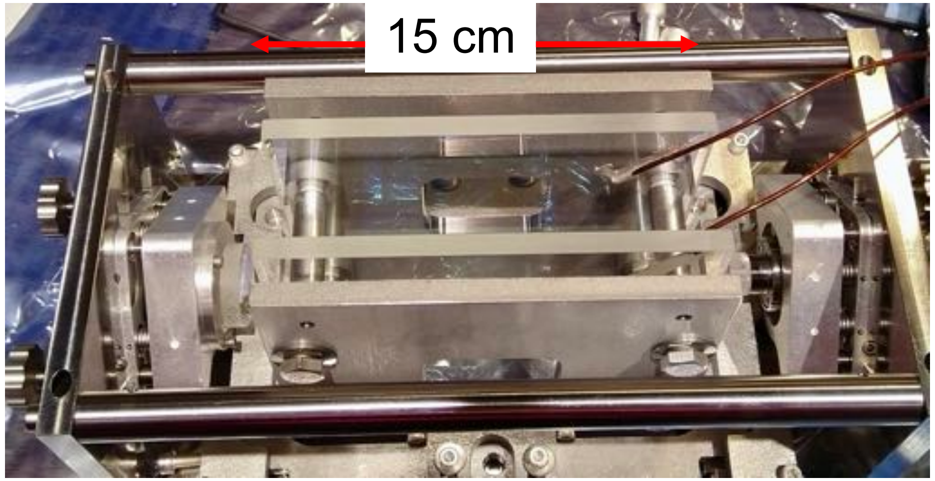


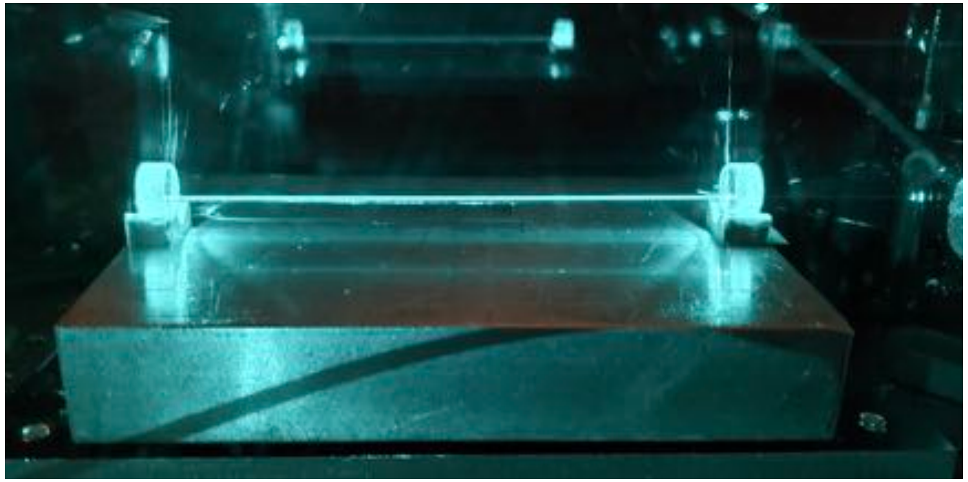


- ❑ We will use this transition to do our PNC experiment.
- ❑ *We have also observed the equivalent 5s-6s transitions in ^{87}Rb.*

The Fr experiment: laser power build up cavity in vacuum

- ❑ Lock power build up cavity to ULE cavity stabilized laser.
- ❑ Aim → factor of 2000 build up.



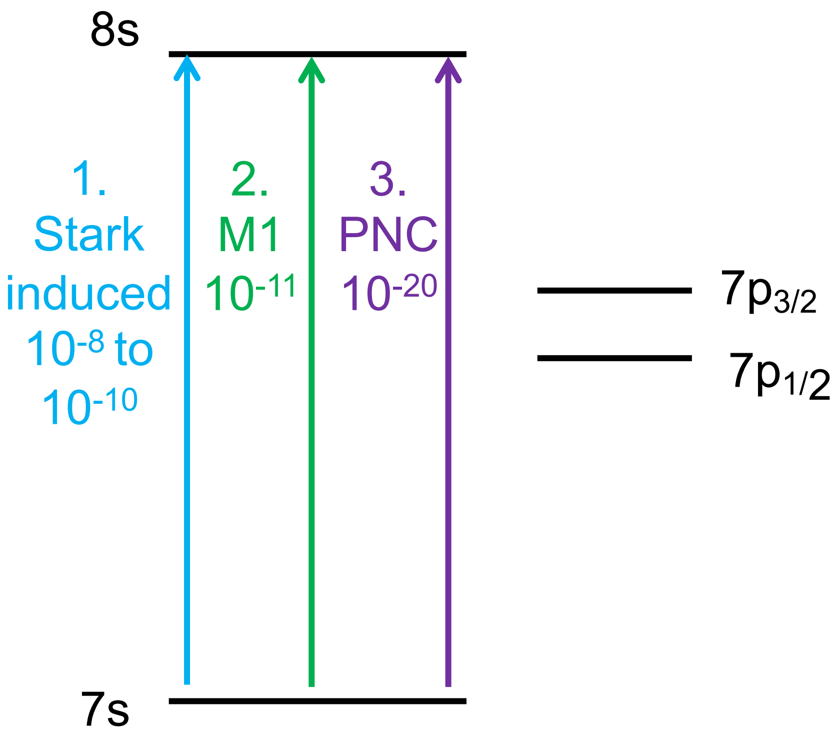


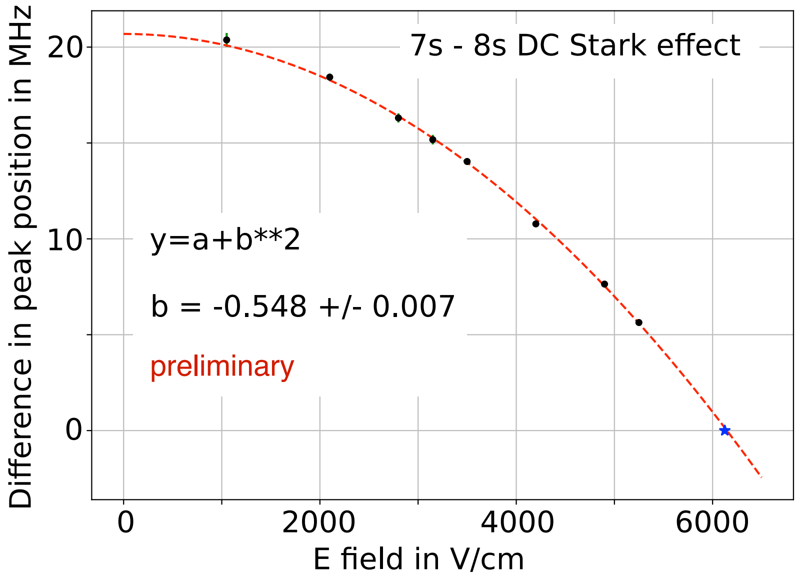
- ❑ On the bench factor of 1000 build up (March)

- ❑ In vacuum now, lower finesses, build up 80.
- ❑ Characterize mechanical stability of the chamber.
- ❑ Using it to do Rb 5s-6s spectroscopy.

The Fr experiment: current status

- ❑ Stark induced 7s-8s in Fr and 5s-6s in Rb
- ❑ Preliminary DC Stark shift measurement in 7s-8s in Fr and 5s-6s in Rb
- ❑ Measure M1/$\boldsymbol{\beta}$.



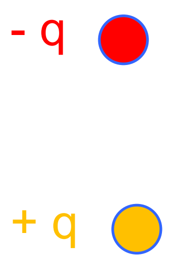


The Ra experiment:

The Ra experiment: search for permanent EDM

- Charge “+ q” displaced by “r” from charge “– q” creates an EDM

$$\vec{d} = q\vec{r}$$

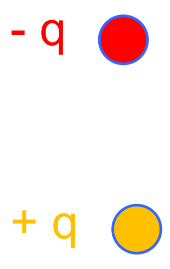


- For a particle EDM indicates a displacement between its center of mass and its center of charge.

$$\vec{d} = \int \vec{r}\,\rho_q d^3r$$

The Ra experiment: search for permanent EDM

- Charge “+ q” displaced by “r” from charge “– q” creates an EDM



$$\vec{d} = q\vec{r}$$

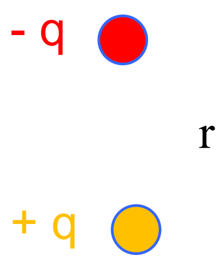
- For a particle EDM indicates a displacement between its center of mass and its center of charge.

$$\vec{d} = \int \vec{r}\,\rho_q d^3r$$

- EDM lies along the spin.

The Ra experiment: search for permanent EDM

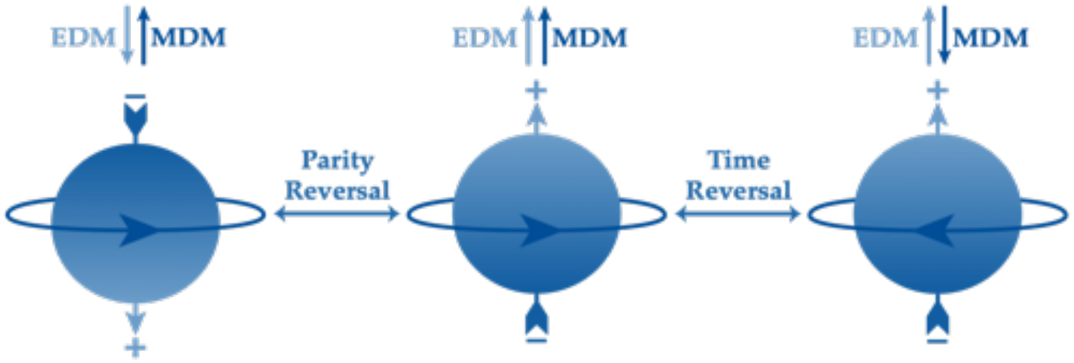
- ❑ Charge "+ q" displaced by "r" from charge "– q" creates an EDM



$$\vec{d} = q\vec{r}$$

- ❑ For a particle EDM indicates a displacement between its center of mass and its center of charge.

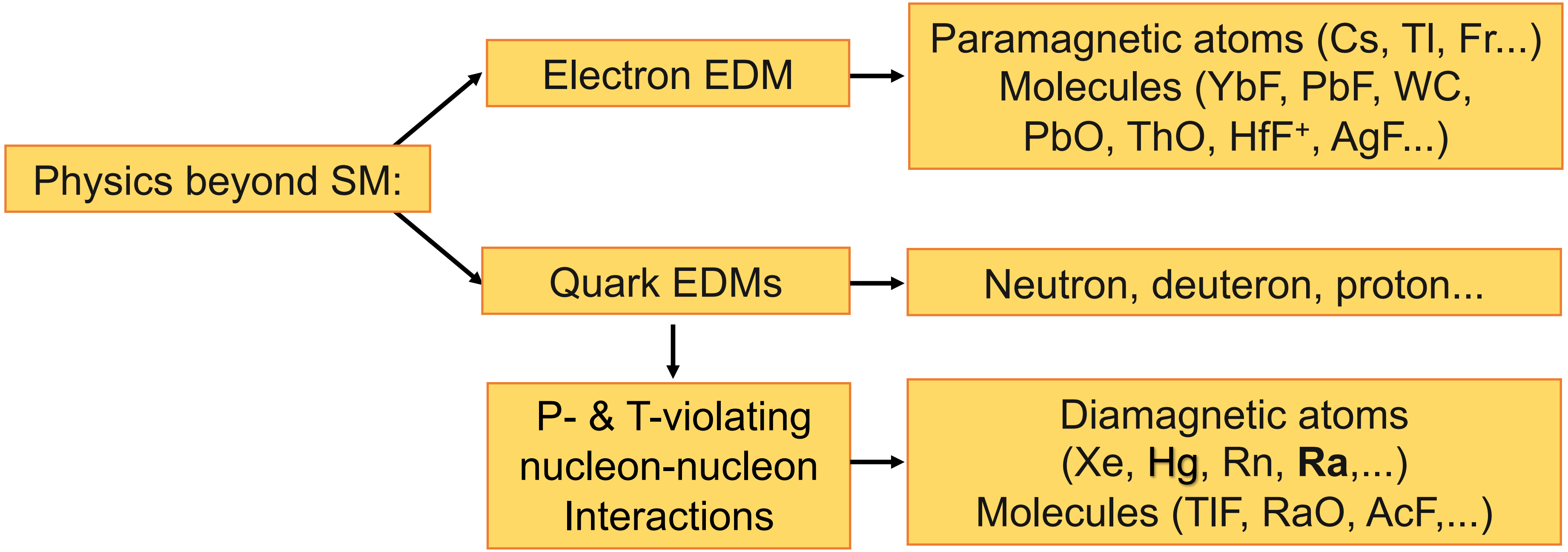
$$\vec{d} = \int \vec{r}\,\rho_q d^3r$$



- ❑ EDM lies along the spin.
- ❑ EDM violates *T* in a non-degenerate system.
- ❑ Under the *CPT* theorem *T* violation indicates *CP* violation.
- ❑ Non-zero EDM is a direct signature of CP violation.

The Ra experiment: permanent EDM, CP violation

- CP-violation necessary to explain matter-antimatter asymmetry (Sakharov conditions).
- CP-violation within the CKM matrix is not enough to explain this observation.
- Some extensions of SM includes additional sources of CP violation and also sensitive to EDMs.



A. D., Sakharov, JETP Lett. 5, 24 (1967)

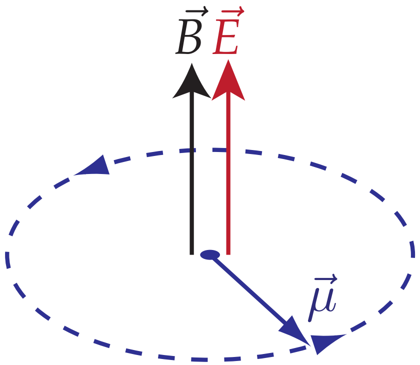
The Ra experiment: permanent EDM violates T reversal symmetry

- ❑ First EDM search in 1950s with neutron #
- ❑ As we just saw, EDM search has been extended to other systems since then.
- ❑ EDM null so far.

Sector	Exp. Limit (*e* cm)	Location	Method	Standard Model (*e* cm)
Electron	1.1×10^{-29}	Harvard (ACME)	ThO molecules in a beam	10^{-38} *
Neutron	1.8×10^{-26}	PSI	UCN	10^{-32} **
Nuclear	7.4×10^{-30}	U. Washington	^{199}Hg atoms in a cell	10^{-33} ***

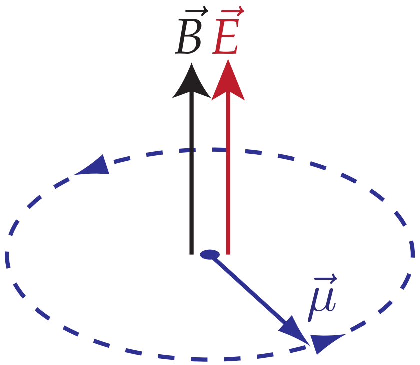
#E.M Purcell and N.F. Ramsey, phys. Rev.78, 807(1950)
**B.C. Regan et al., PRL 88 (2002) 071805*
***Chupp, Advances in Atomic, Molecular, and Optical Physics, Volume 59, 2010*
****Ramsey-Musolf, "EDMs: New CPV?", 2009*

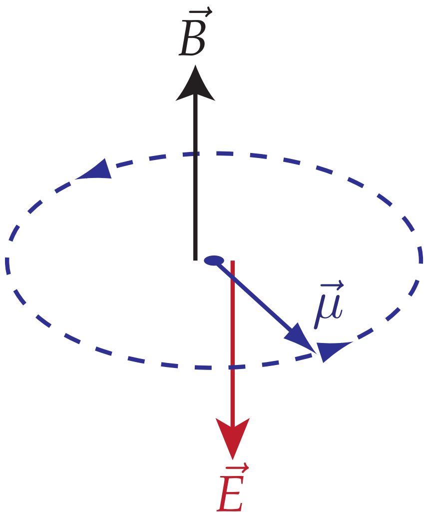
The Ra experiment: EDM measurement principle



$$h\nu_{+} = 2\mu B + 2dE$$

The Ra experiment: EDM measurement principle

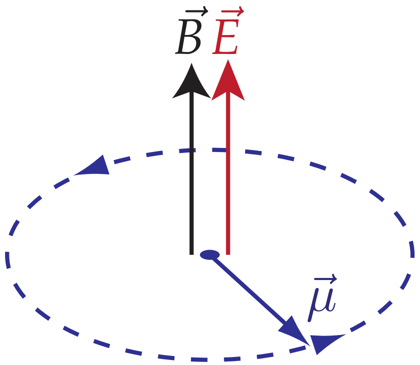


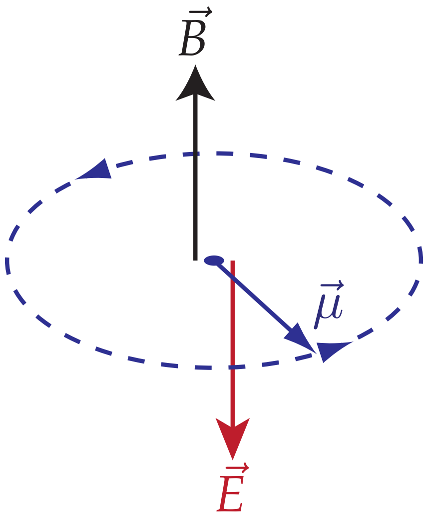


$$h\nu_+ = 2\mu B + 2dE$$

$$h\nu_- = 2\mu B - 2dE$$

The Ra experiment: EDM measurement principle





$$h\nu_{+} = 2\mu B + 2dE$$

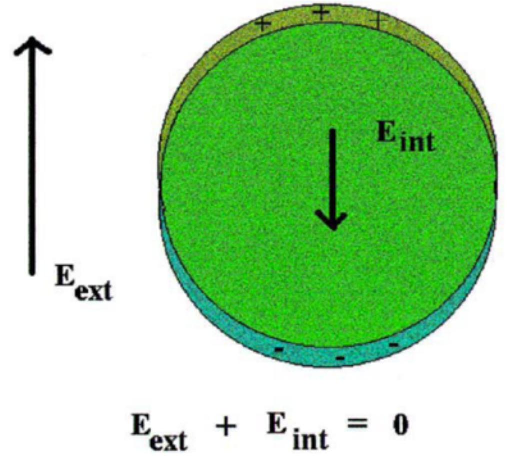
$$h\nu_{-} = 2\mu B - 2dE$$

$$\nu_{+} - \nu_{-} = \frac{4dE}{h}$$

B = 30 mG, E= 100 kV/cm
$\nu \rightarrow \approx 34$ Hz
For d = 1×10^{-26} e cm
$\nu_{+} - \nu_{-} \rightarrow \approx 1$ μHz

The Ra experiment: Schiff moment and EDM

- Neutral atom in an electric field: does not move



P. G. H. Sandars, Contemporary Physics, 42:2, 97-111, (2001)

The Ra experiment: Schiff moment and EDM

- Neutral atom in an electric field: does not move
- Schiff Theorem (1963):
- True for point-like nuclei.
- Not true for nuclei of finite volume.
- Schiff moment → difference in charge and EDM distribution of the nucleus.
- The interaction between atomic electrons and the nucleus is via the nuclear Schiff moment.
- Interaction term

H → S X

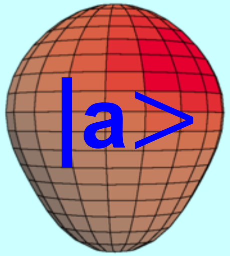
$$\vec{S} = \frac{\langle e r^2 \vec{r} \rangle}{10} - \frac{\langle r^2 \rangle \langle e \vec{r} \rangle}{6}$$

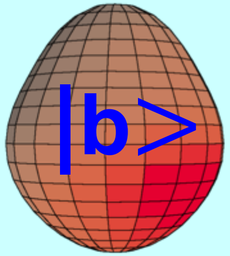
- Schiff moment enhanced in nuclei with both a quadrupole and octupole deformation and in heavy atoms.

E. A. Hinds, Physica, Scripta, Vol. T70, 34-41, (1997)
Auerbach, Flambaum & Spevak, PRL (1996)

The Ra experiment: Enhanced EDM sensitivity in ^{225}Ra

Enhanced Intrinsic Schiff Moment





$$S_{\mathrm{intr}} = eZR_N^3 \frac{3}{20\pi} \sum_{l=2} \frac{(l+1)\beta_l \beta_{l+1}}{\sqrt{(2l+1)(2l+3)}}$$

Haxton & Henley, PRL (1983)
Ginges and Flambaum (2004)

Enhanced Lab-Frame Schiff Moment

55 keV

$$\psi^- = (|a> -|b>)/\sqrt{2}$$

$$\psi^+ = (|a> +|b>)/\sqrt{2}$$

$$\mathbf{S}_z = \mathbf{S}_{\mathrm{intr}} \frac{2KM}{I(I+1)} \frac{\langle \psi_- | \mathbf{W} | \psi_+ \rangle}{E_+ - E_-}$$

Ginges and Flambaum (2004)

Enhanced Atomic EDM

Strong enhancement with increasing Z

$$d(^{225}\mathrm{Ra}) = -8.5\times 10^{-17} \left(\frac{S_z}{e\ \ \mathrm{fm}^3} \right) e\ \ \mathrm{cm}$$

Dzuba, Flambaum, Ginges, Kozlov (2002)

Enhancement Factor: EDM (^{225}Ra) / EDM (^{199}Hg)

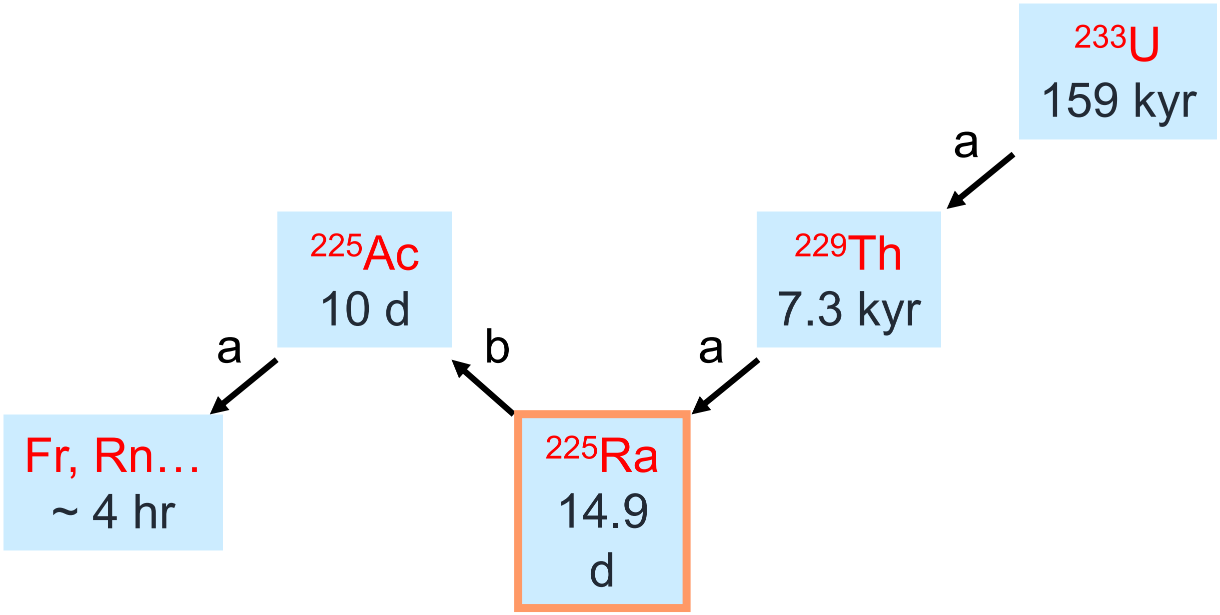
Skyrme Model	Isoscalar	Isovector
SIII	300	4000
SkM*	300	2000
SLy4	700	8000

Schiff moment of ^{225}Ra, Dobaczewski, Engel (2005)
Schiff moment of ^{199}Hg, Ban, Dobaczewski, Engel, Shukla (2010)

"[Nuclear structure] calculations in Ra are almost certainly more reliable than those in Hg."
– Engel, Ramsey-Musolf, van Kolck, Prog. Part. Nucl. Phys. (2013)

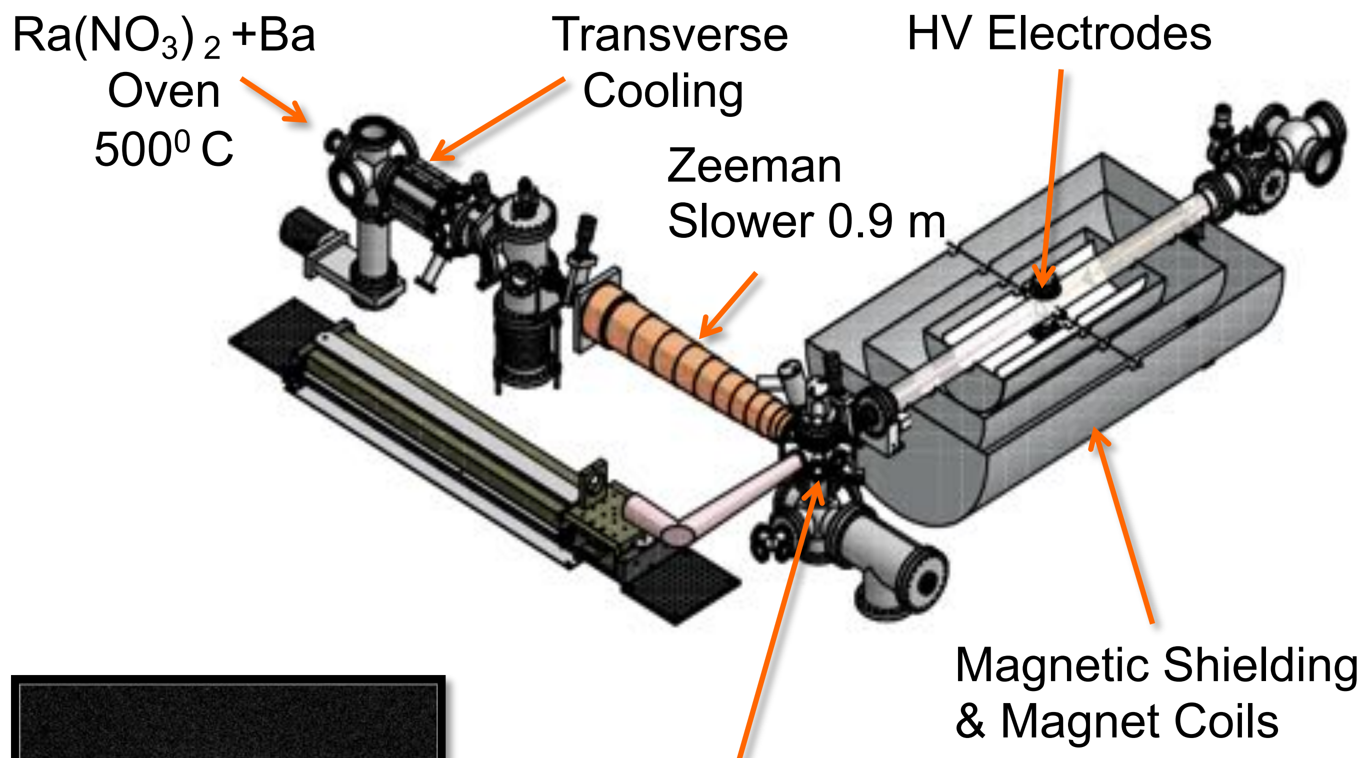
The Ra experiment: complications of using ^{225}Ra for the EDM search

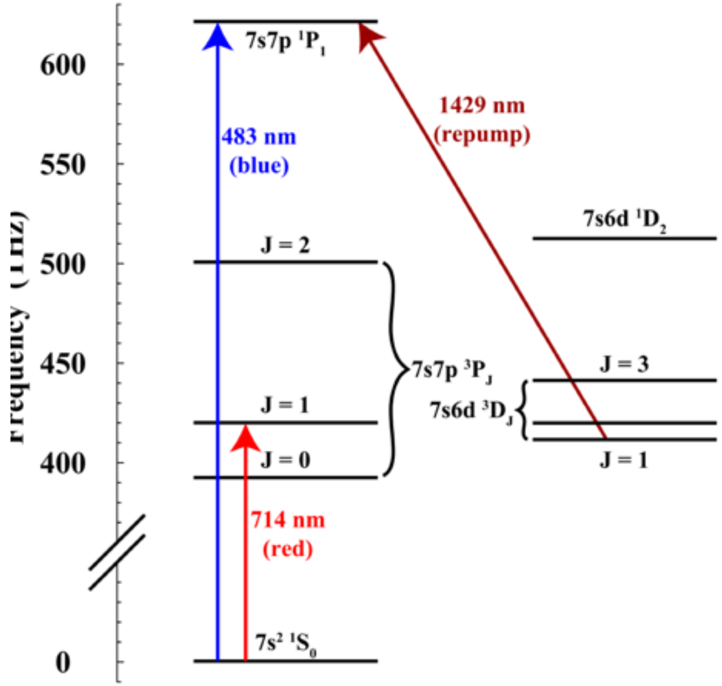
- ❑ Radioactive

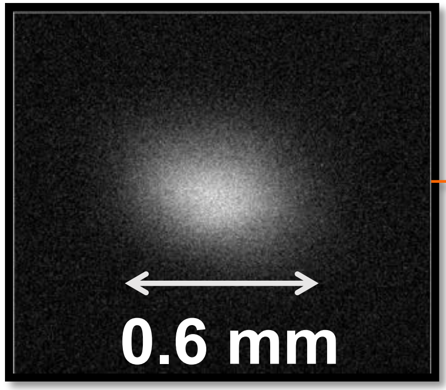


- ❑ 9 mCi (or ≈ 10^{14} atoms) ^{225}Ra ($t_{1/2}$ = 14.9 days, I = 1/2) sources from Oak Ridge National Lab.
- ❑ Test source: 4 μCi (or ≈ 10^{16} atoms) ^{226}Ra ($t_{1/2}$=1600 years, I = 0).
- ❑ Low vapor pressure
- ✓ Laser cooling and trapping.

The Ra experiment: collect atoms in a MOT







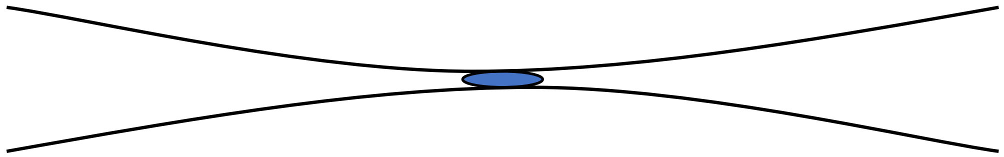
^{226}Ra MOT
20,000 atoms

Typical Parameters:

- ❑ Number → ~10,000(^{225}Ra)
- ❑ Temperature → ≈ 50 μK
- ❑ Ultra-high vacuum → @ 1×10^{-10} Torr.
- ❑ t_{trap} → ≈ 30-40 sec

J. R. Guest et al., PRL 98 093001 (2007)

The Ra experiment: optical dipole trap

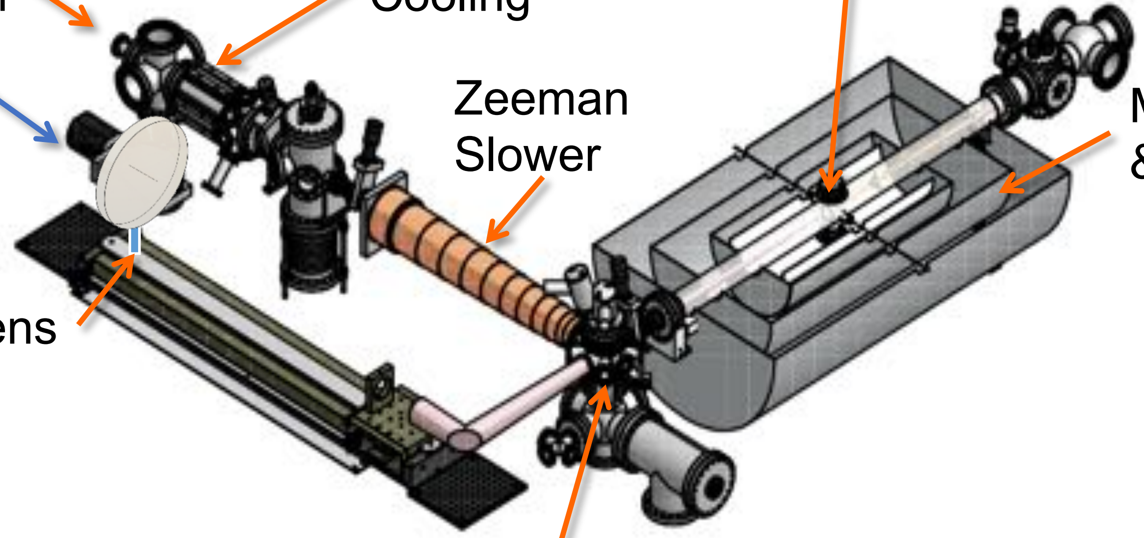


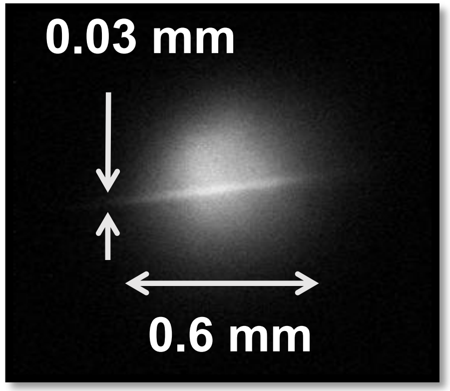
$$U = -\frac{1}{2}\alpha E_0^2$$

$$\text{Trap potential} \sim \frac{Intensity}{\left(f_{laser} - f_{atom}\right)}$$

- Atoms are trapped at the focus
- λ=1550 nm laser,   power = 50 Watt
- Focused to 100 μm diameter → trap depth 400 μK

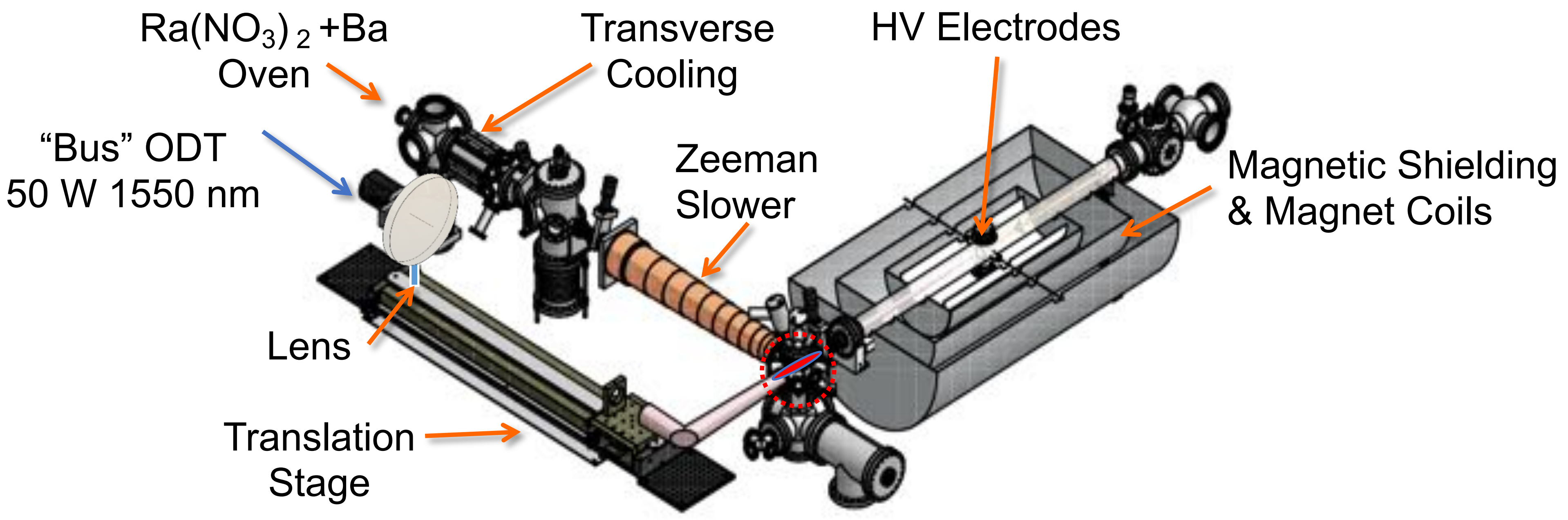
The Ra experiment: transfer atoms from MOT to “bus” ODT



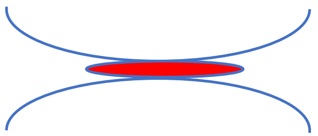


MOT+ODT
≈ unity efficiency

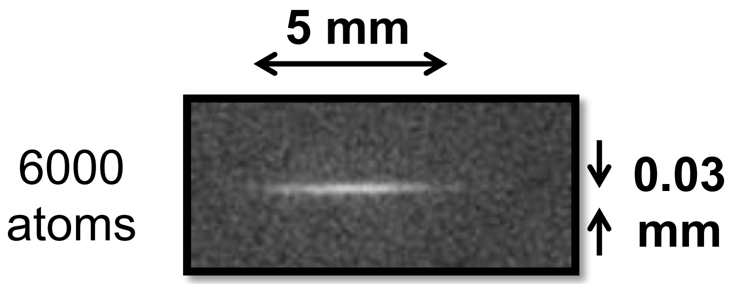
The Ra experiment: transport to science chamber



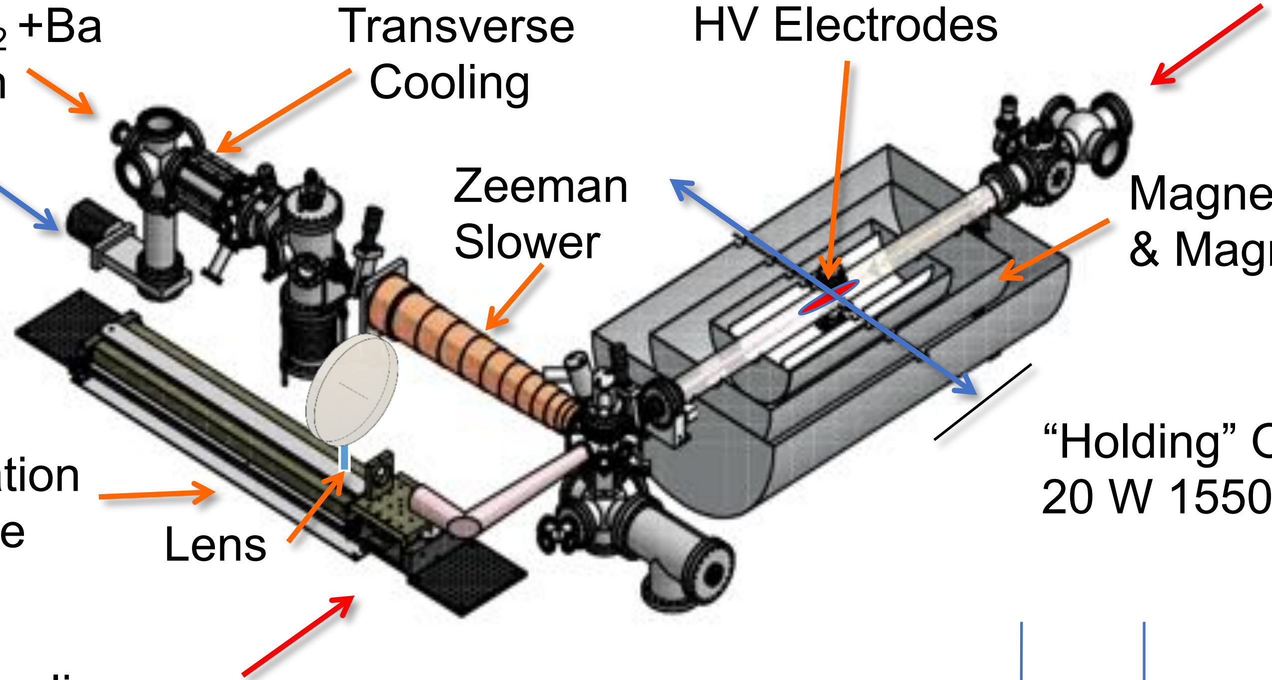
ODT Transport (1 meter, 9s)

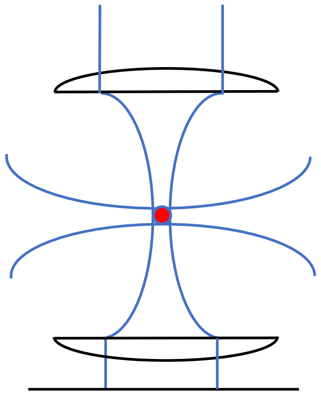


Traveling Wave
"Bus" ODT

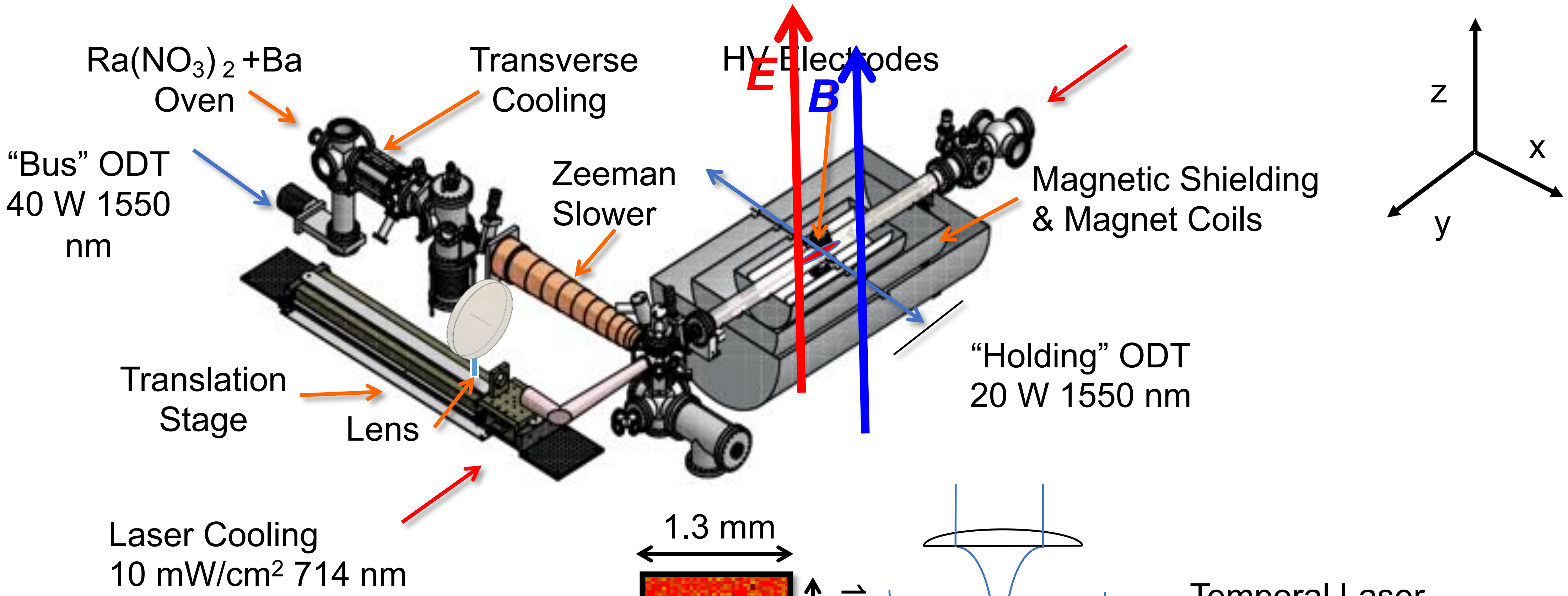


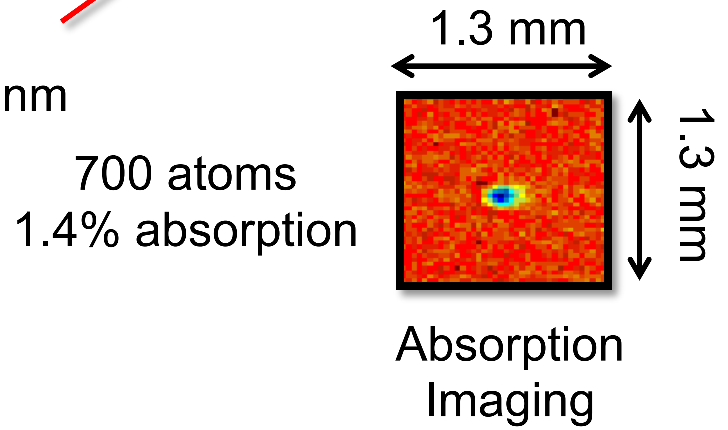
The Ra experiment: “bus” to “holding” ODT

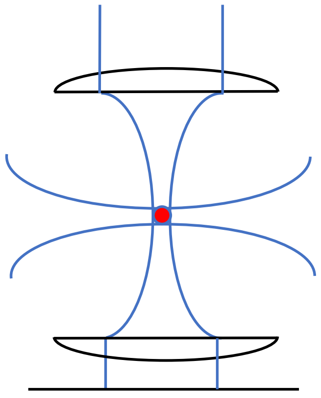




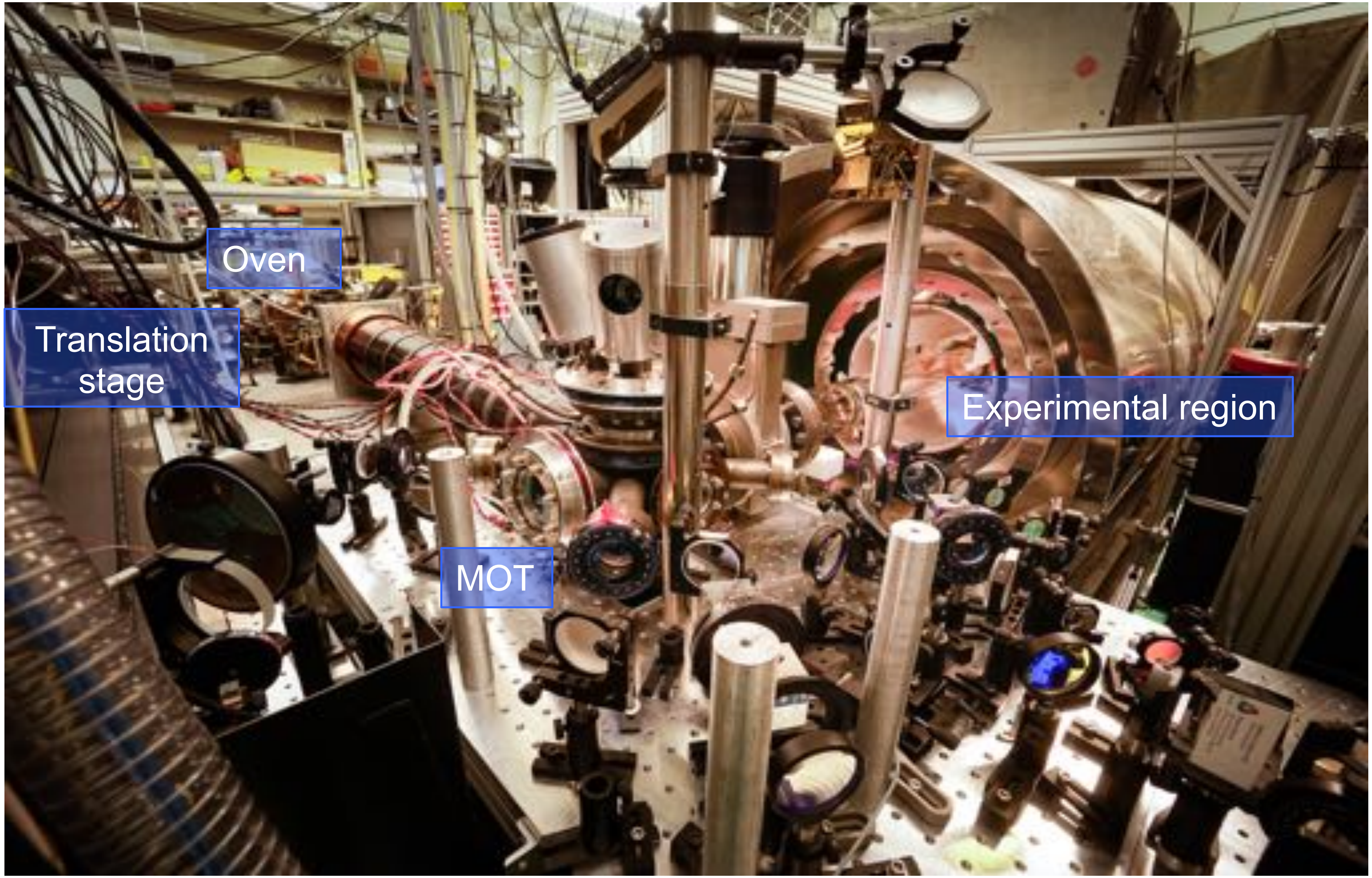
The Ra experiment: "bus" to "holding" ODT



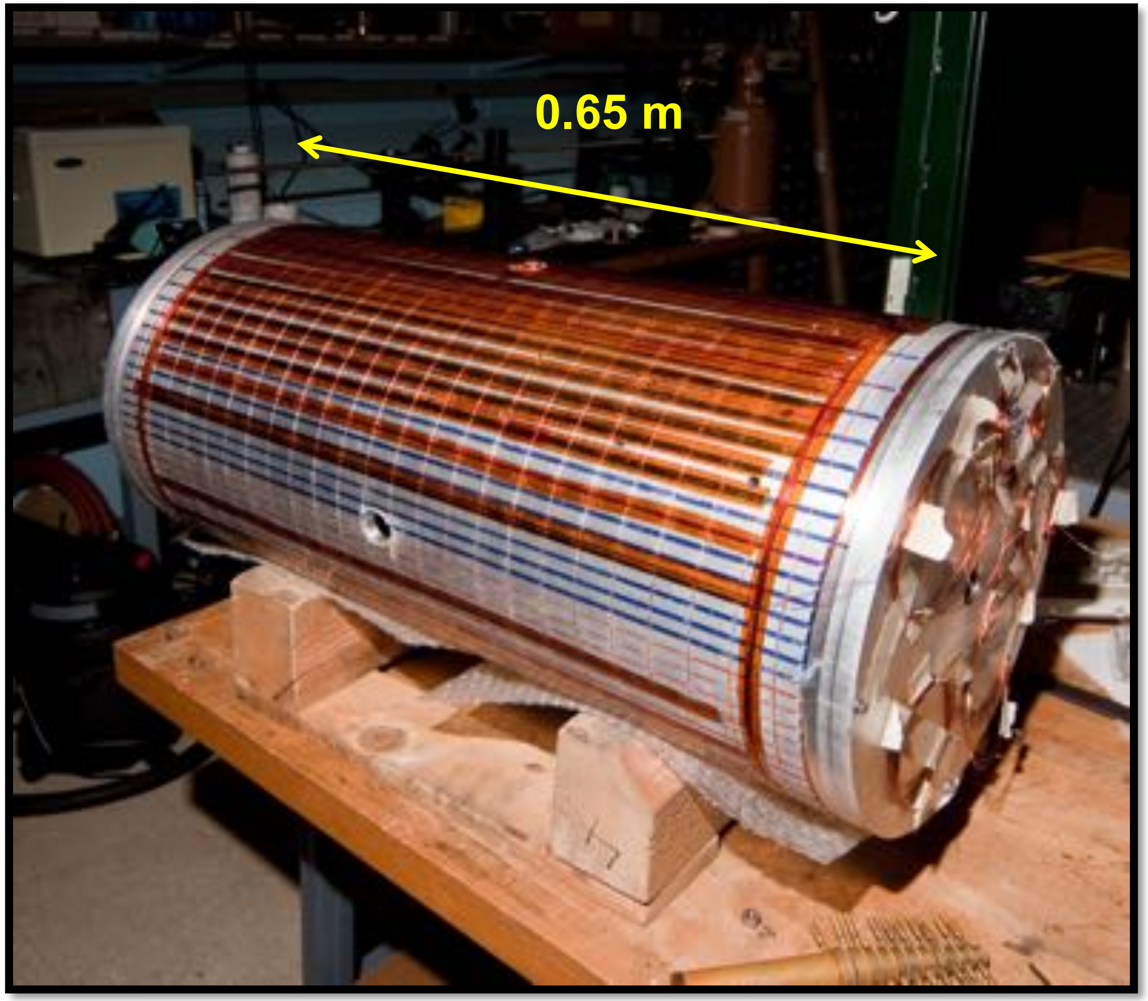


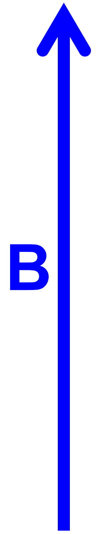


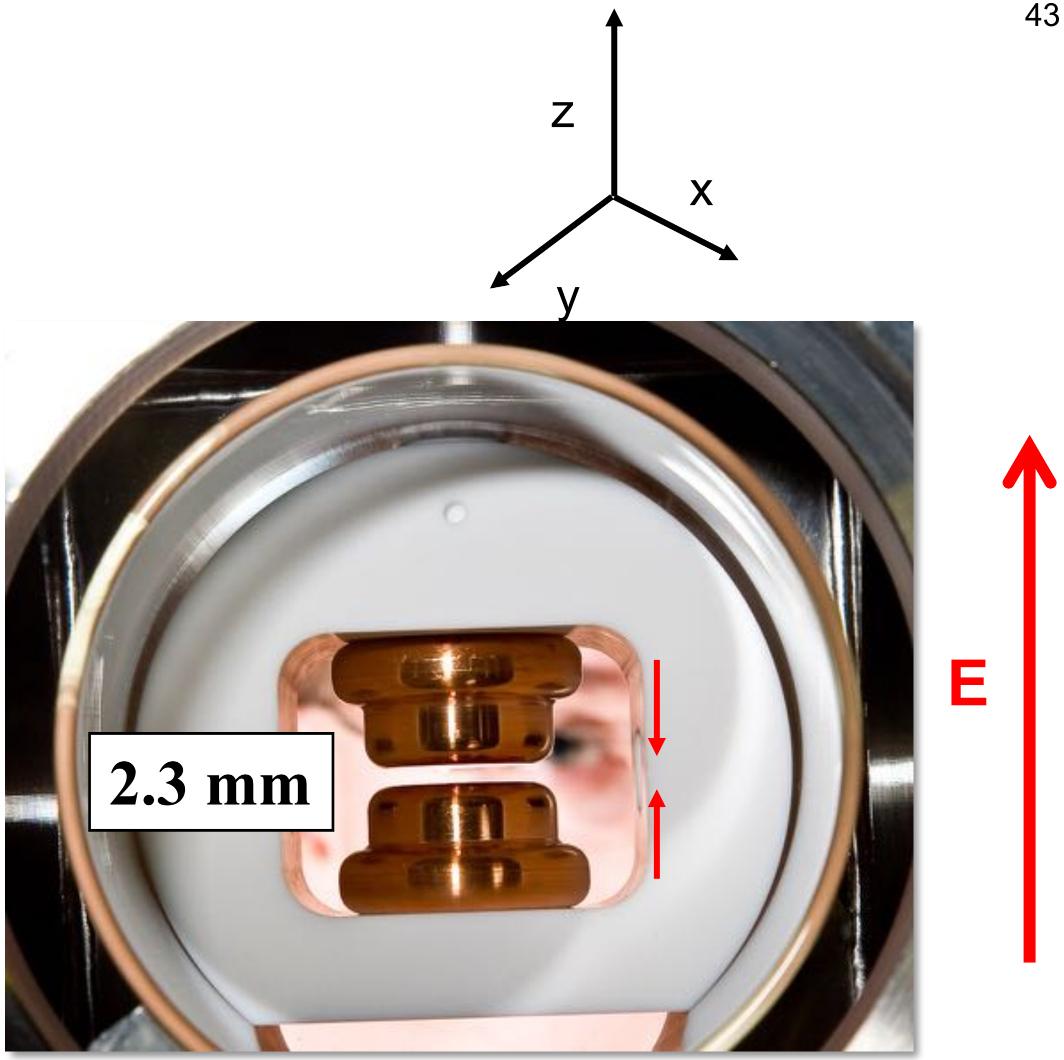
The Ra experiment:



The Ra experiment:



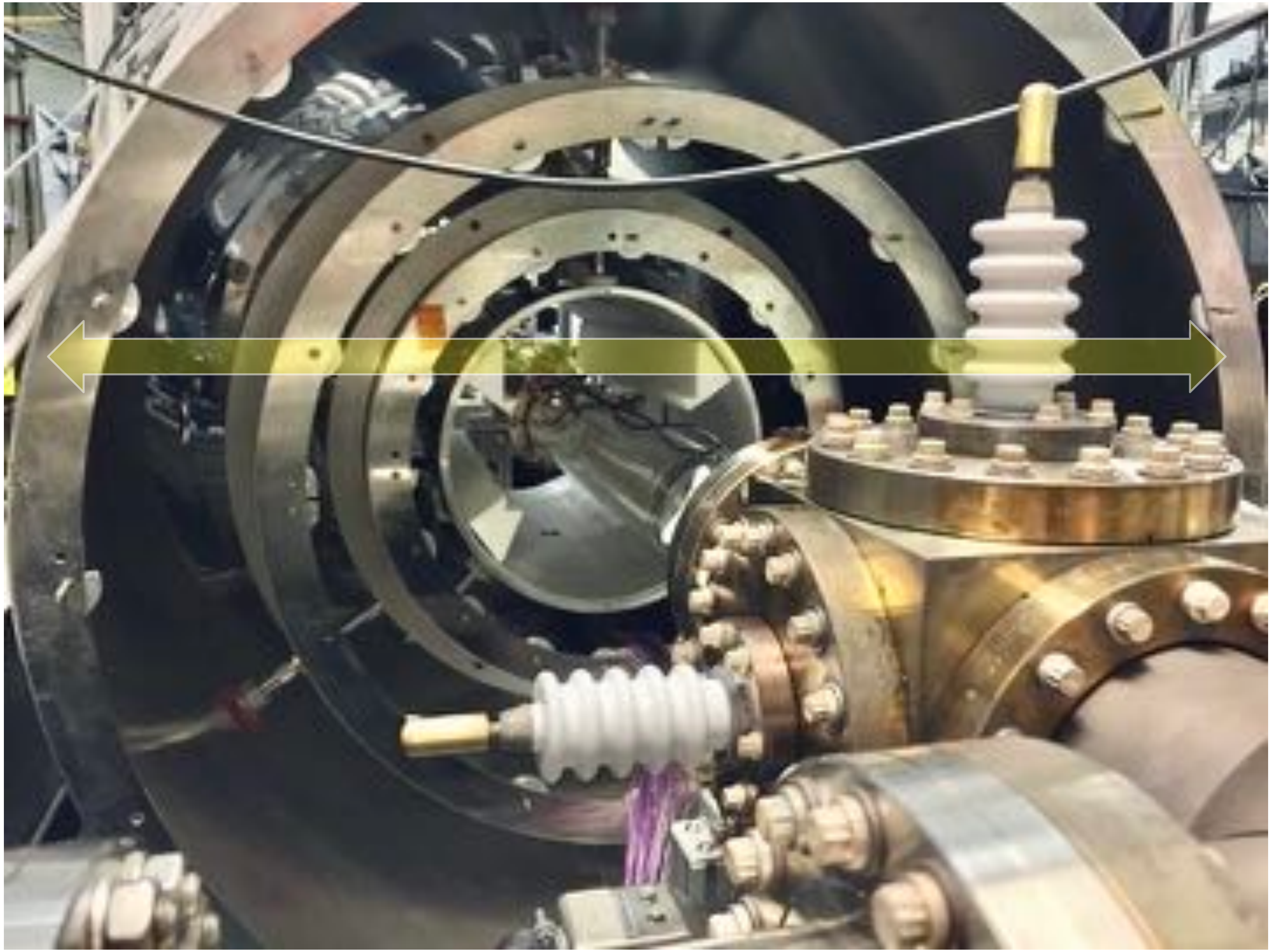




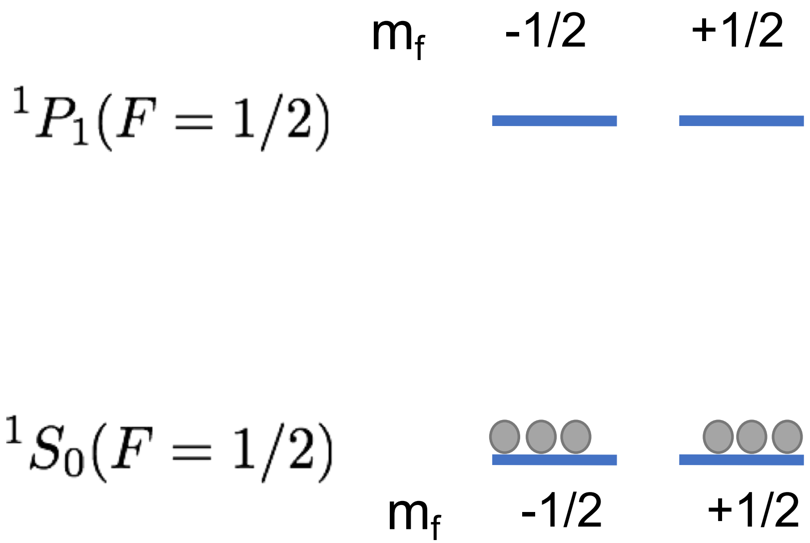
Magnetic Field : B = (15-30) mG
Uniformity: < 0.1%/cm along Z
Instability: < 0.01% over 50 sec

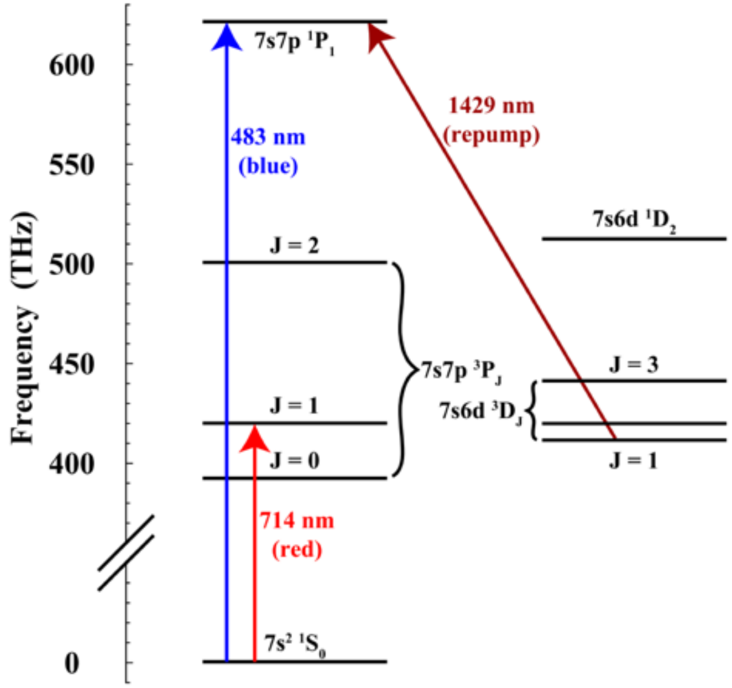
Electric Field : E = 67 kV/cm
Copper electrodes w/ 2.3 mm gap
Leakage current: < 2 pA

The Ra experiment:

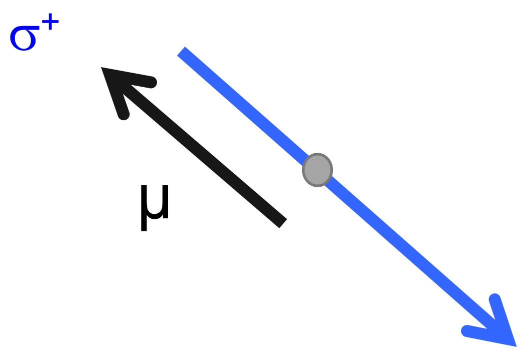


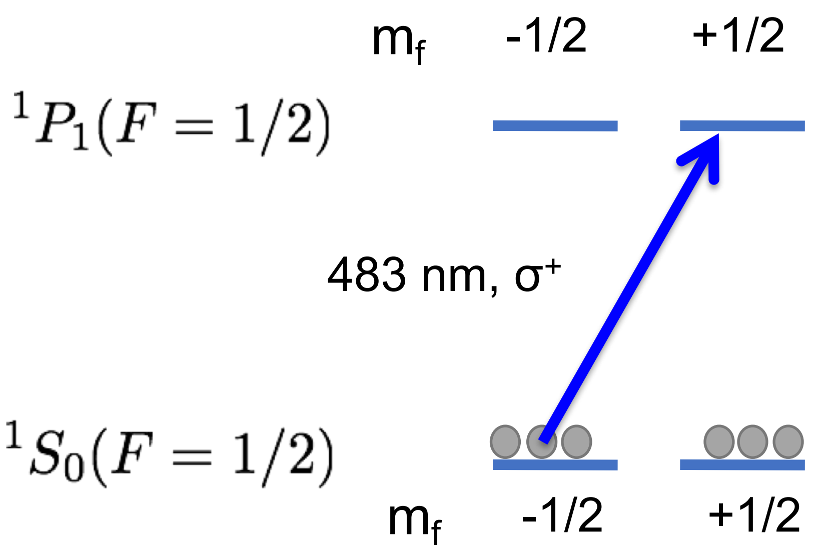
The Ra experiment: optical pumping and state detection

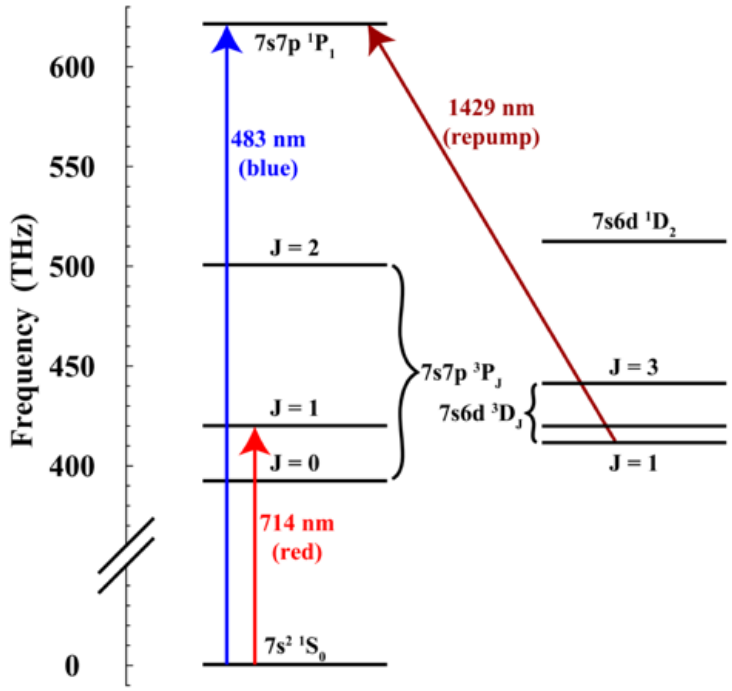




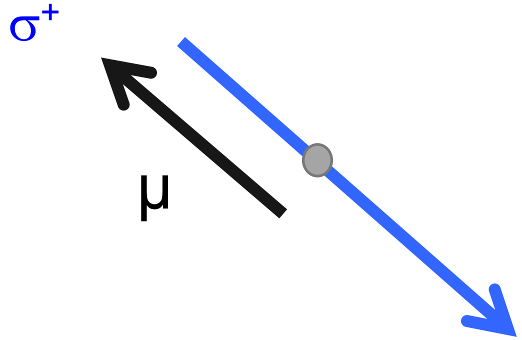
The Ra experiment: optical pumping and state detection

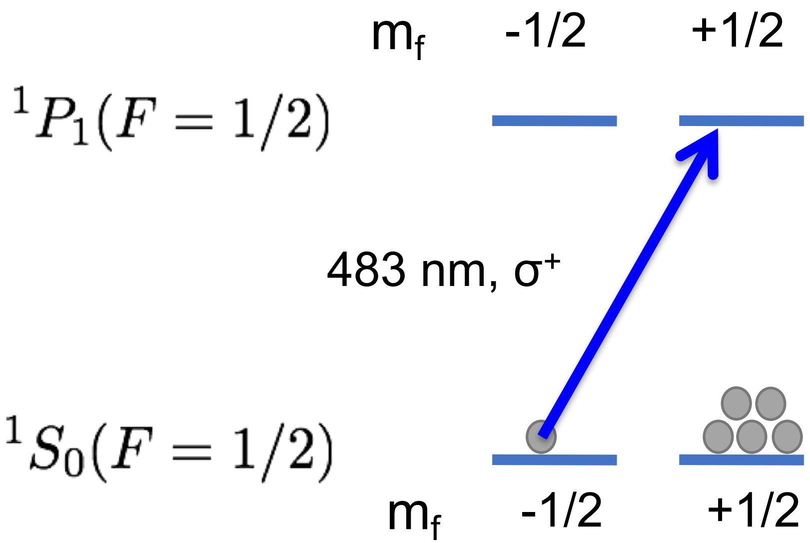


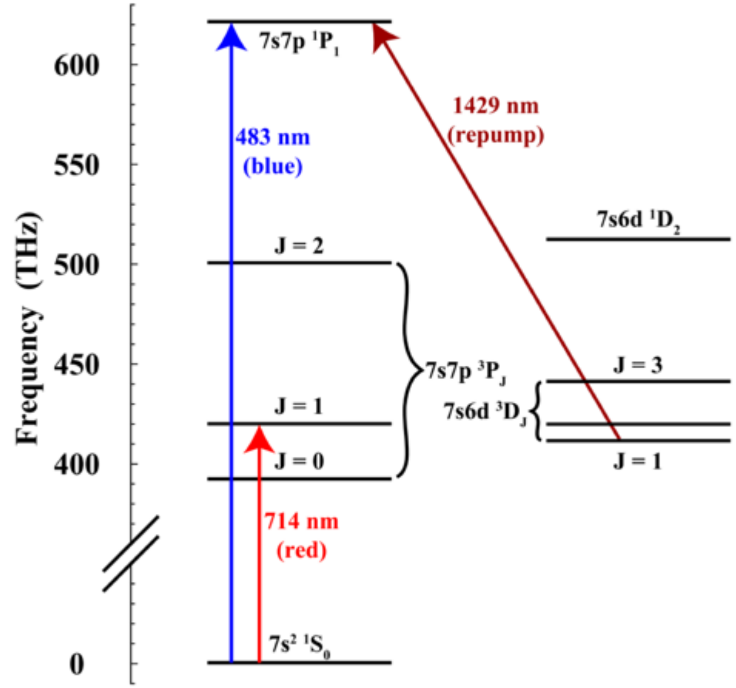




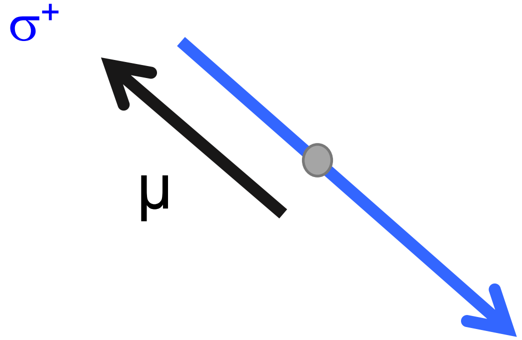
The Ra experiment: optical pumping and state detection

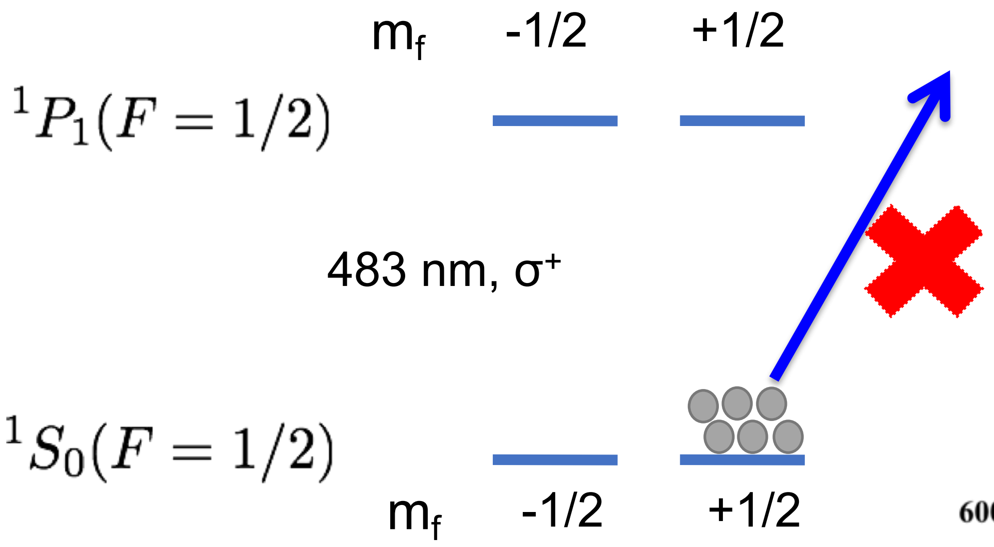


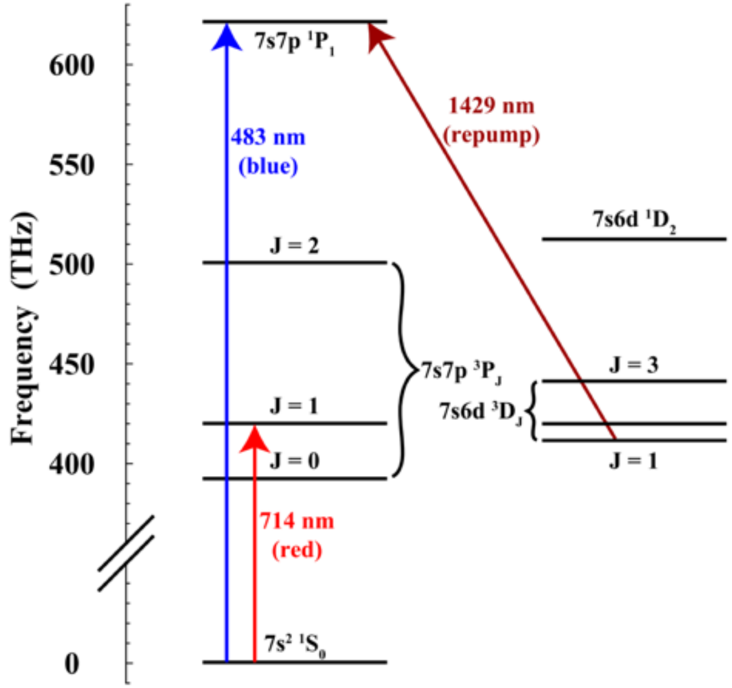




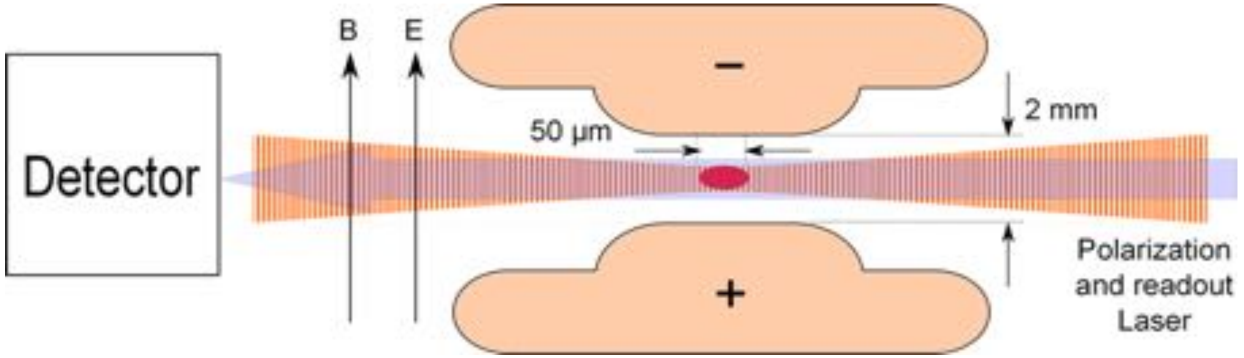
The Ra experiment: optical pumping and state detection



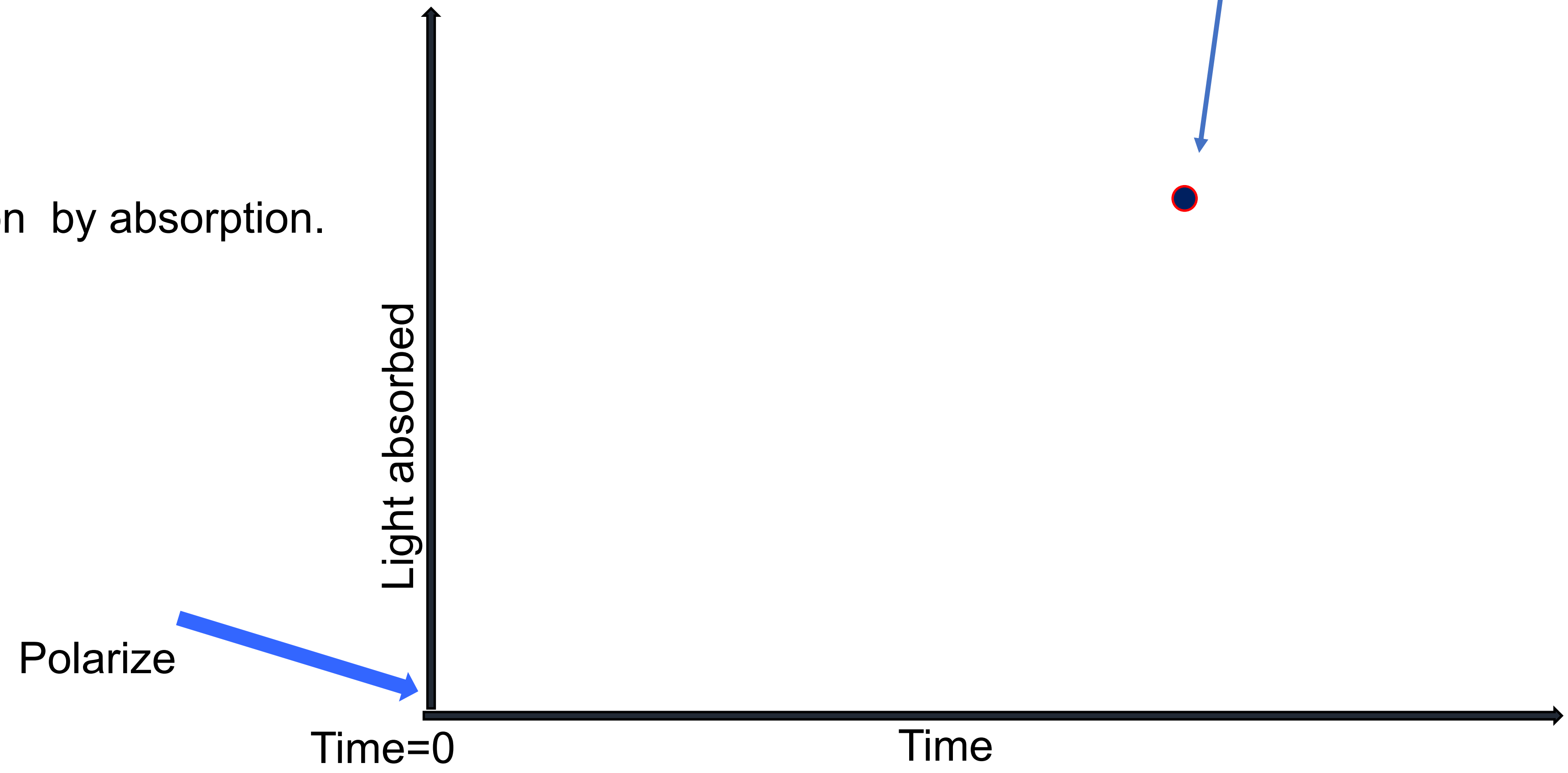




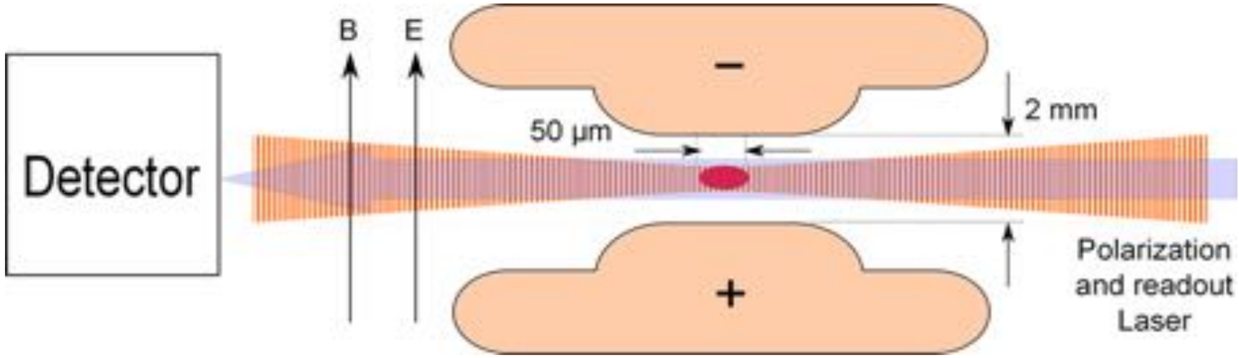
The Ra experiment: the way we do the EDM measurement



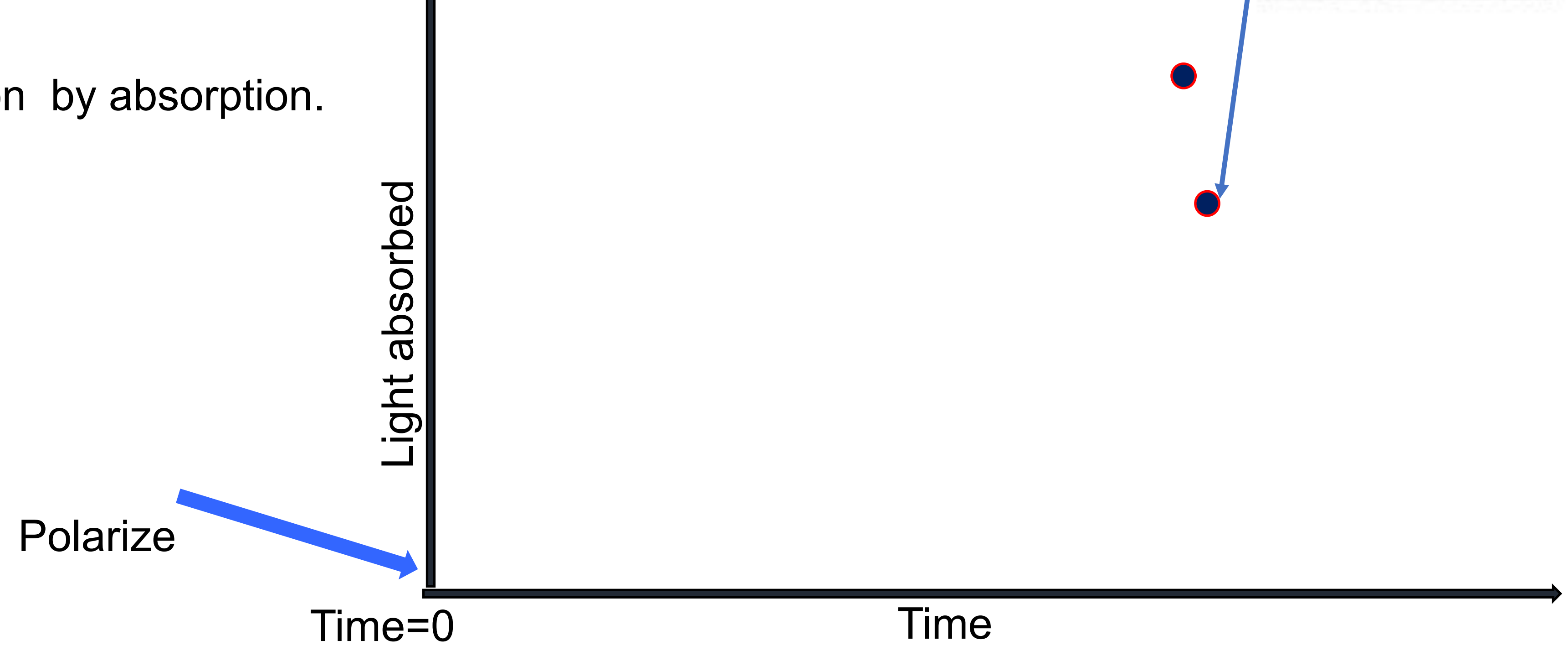
- Polarize.
- Allow to precess.
- Detect the polarization by absorption.
- BKG subtraction.
- 50 s duration.



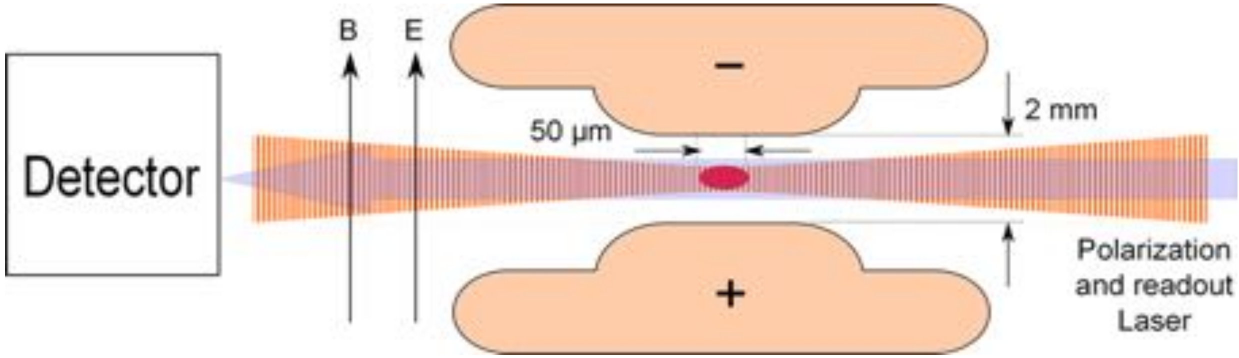
The Ra experiment: the way we do the EDM measurement



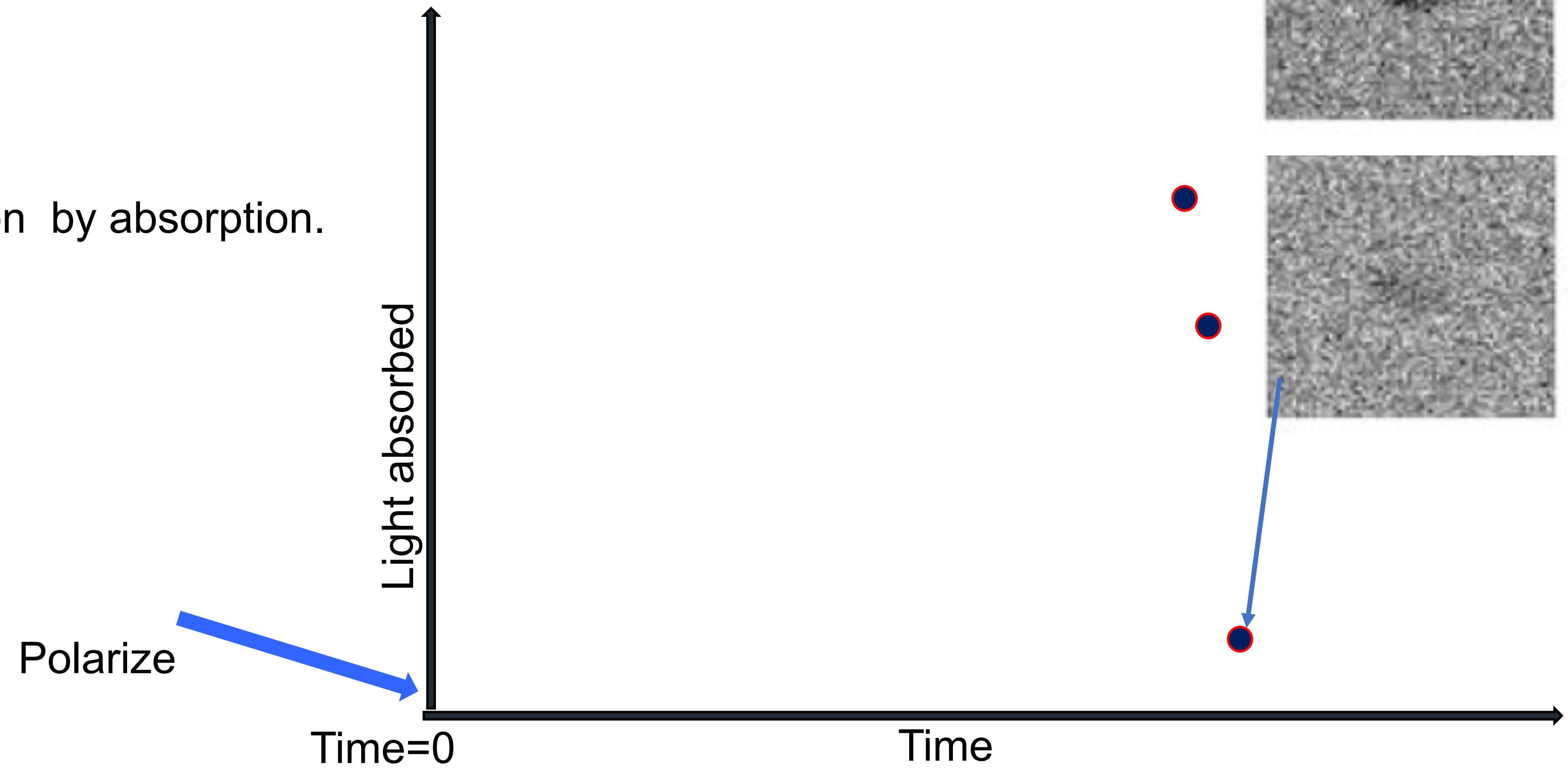
- ❑ Polarize.
- ❑ Allow to precess.
- ❑ Detect the polarization by absorption.
- ❑ BKG subtraction.
- ❑ 50 s duration.



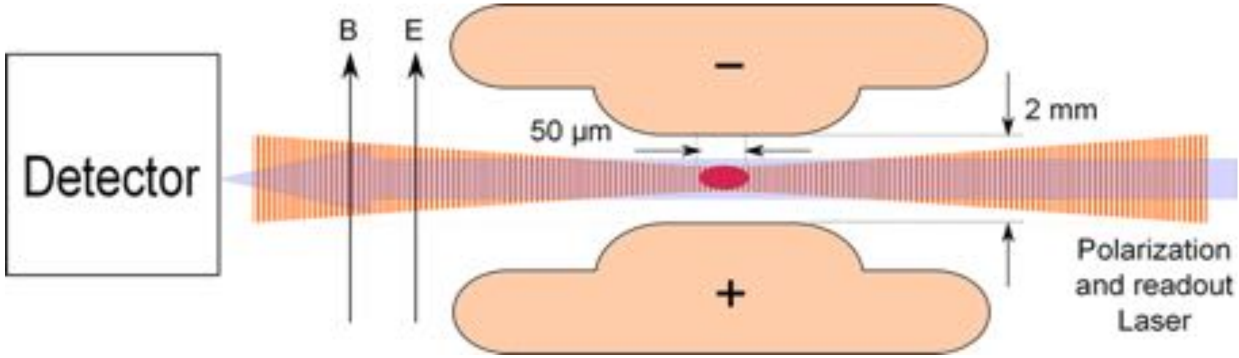
The Ra experiment: the way we do the EDM measurement



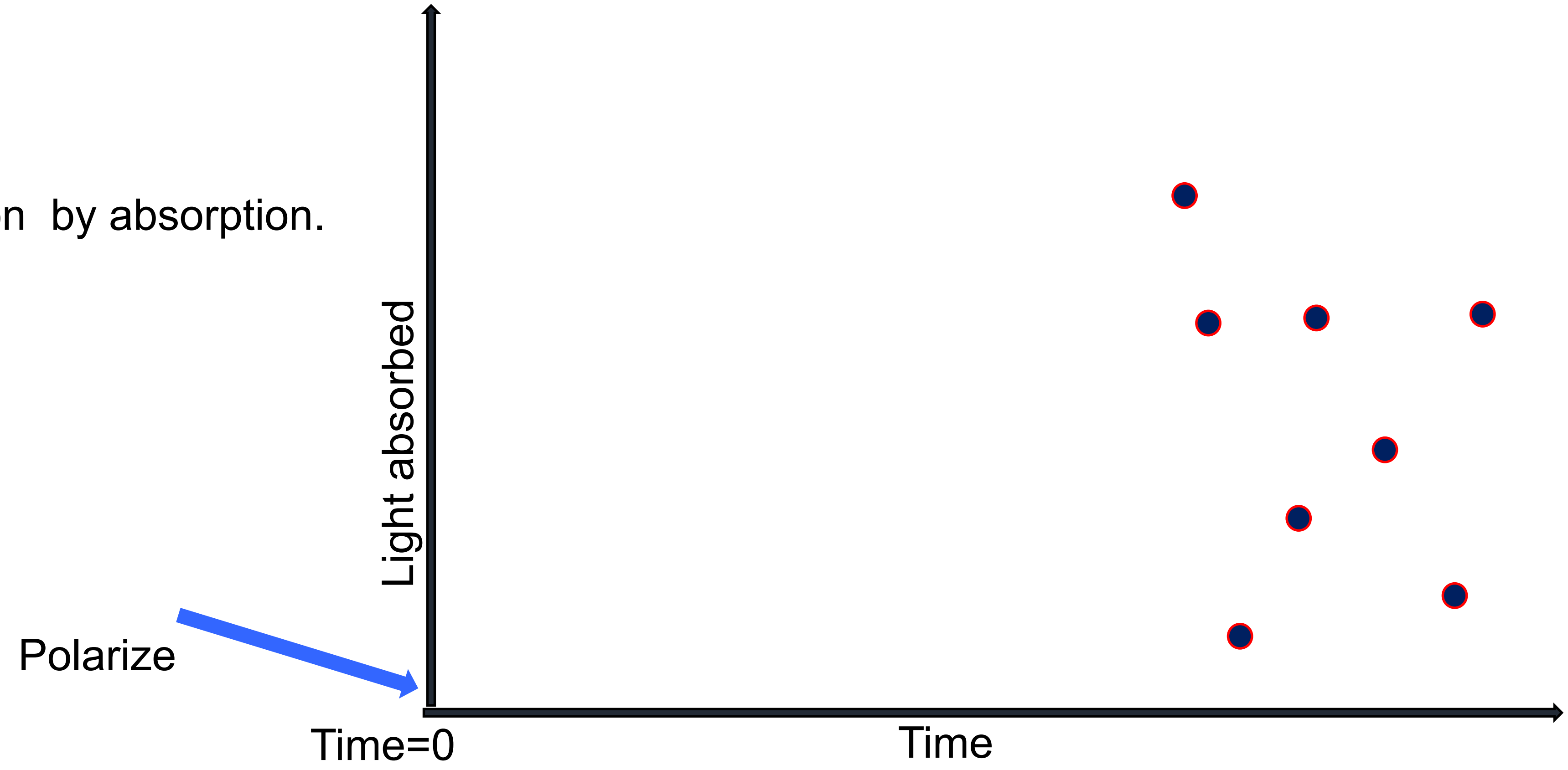
- ❑ Polarize.
- ❑ Allow to precess.
- ❑ Detect the polarization by absorption.
- ❑ BKG subtraction.
- ❑ 50 s duration.



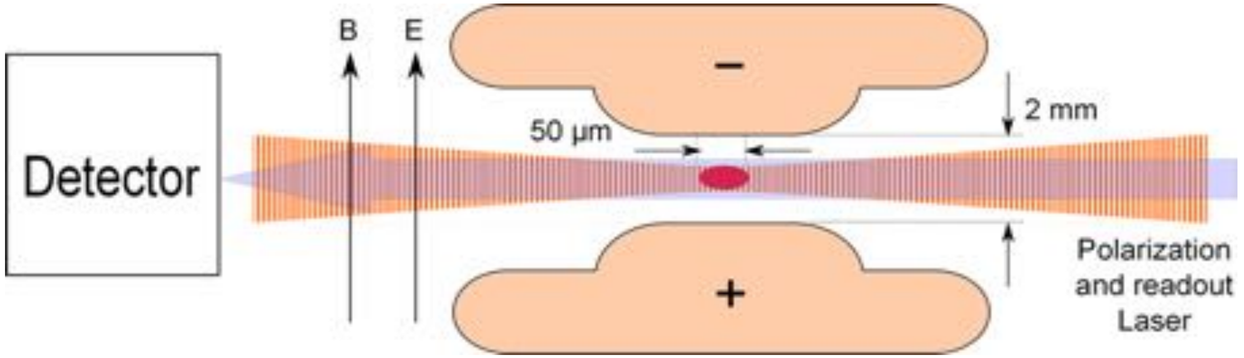
The Ra experiment: the way we do the EDM measurement



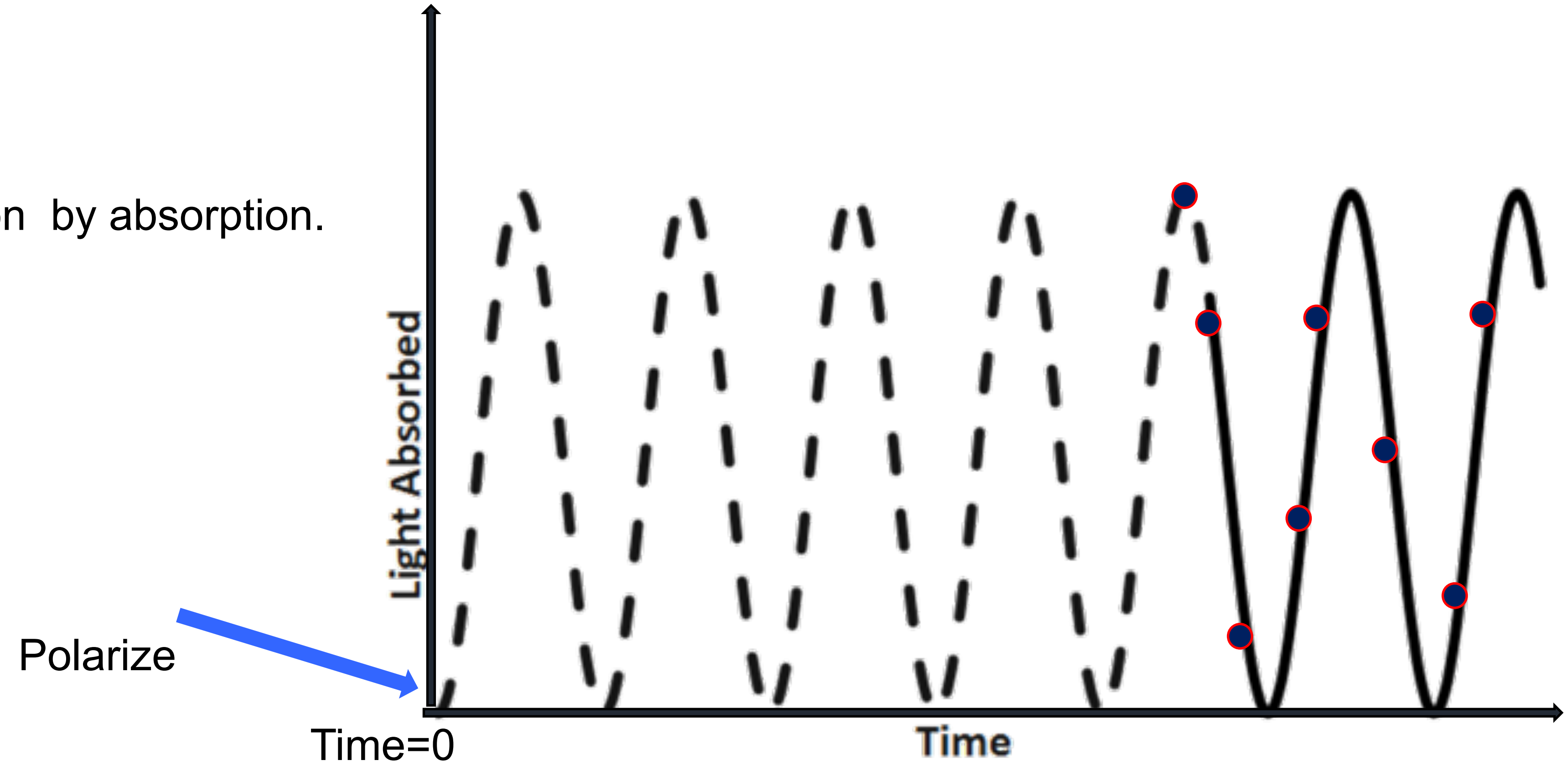
- ❑ Polarize.
- ❑ Allow to precess.
- ❑ Detect the polarization by absorption.
- ❑ BKG subtraction.
- ❑ 50 s duration.



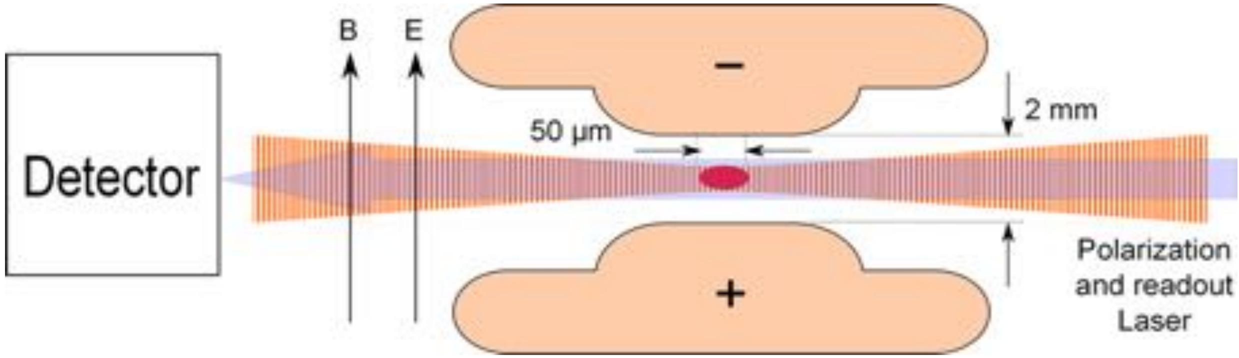
The Ra experiment: the way we do the EDM measurement

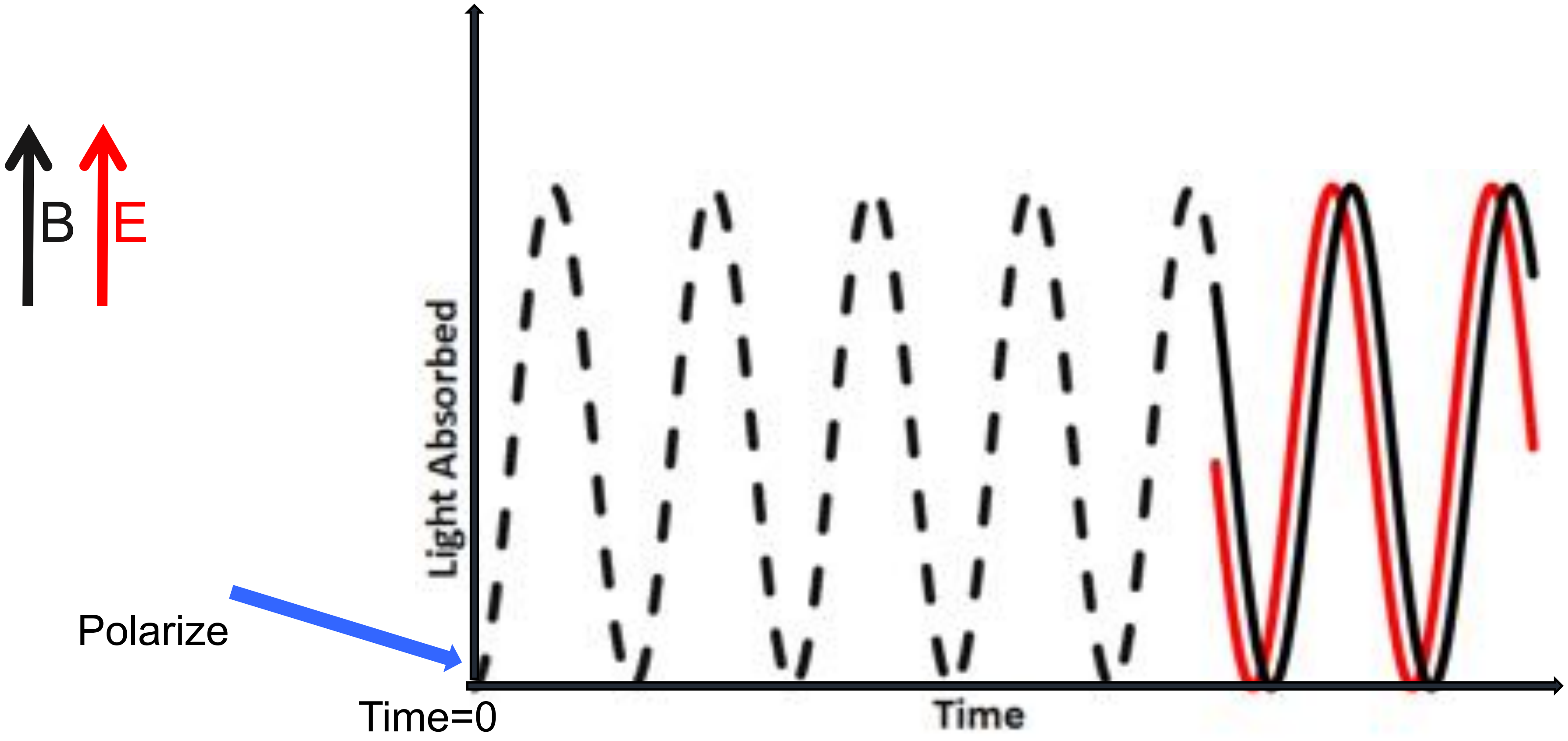


- ❑ Polarize.
- ❑ Allow to precess.
- ❑ Detect the polarization by absorption.
- ❑ BKG subtraction.
- ❑ 50 s duration.

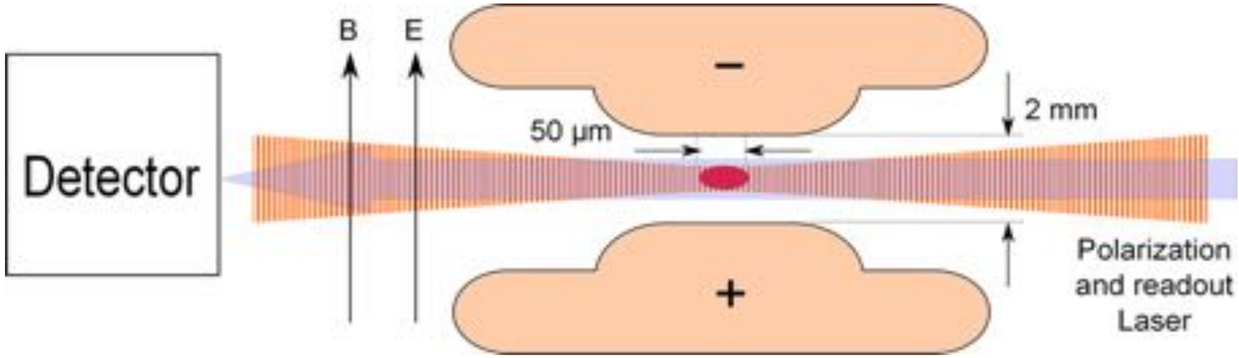


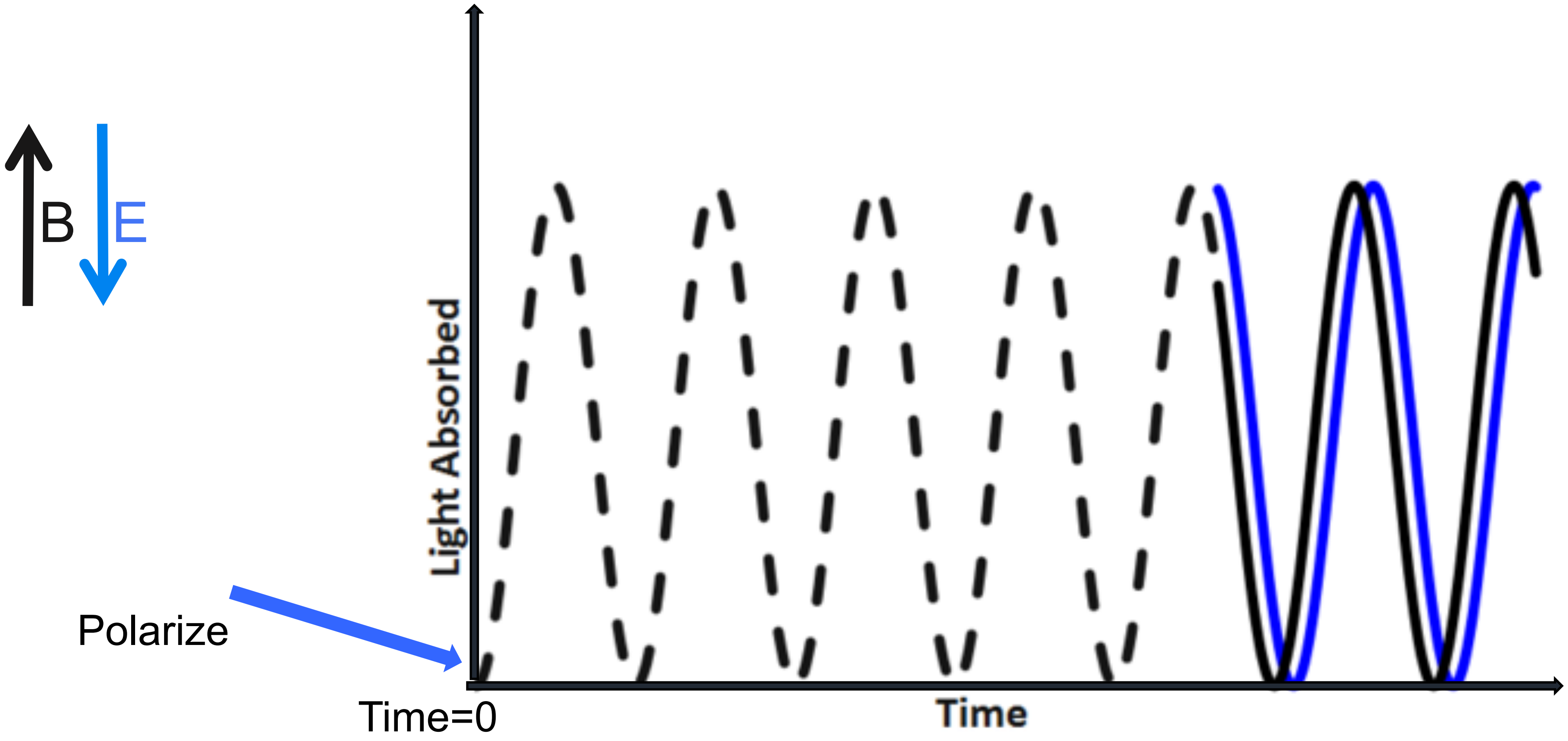
The Ra experiment: the way we do the EDM measurement



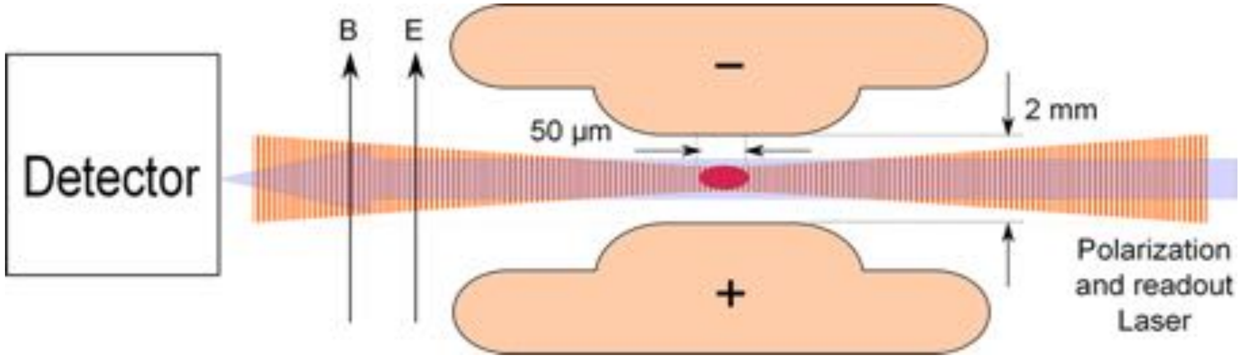


The Ra experiment: the way we do the EDM measurement

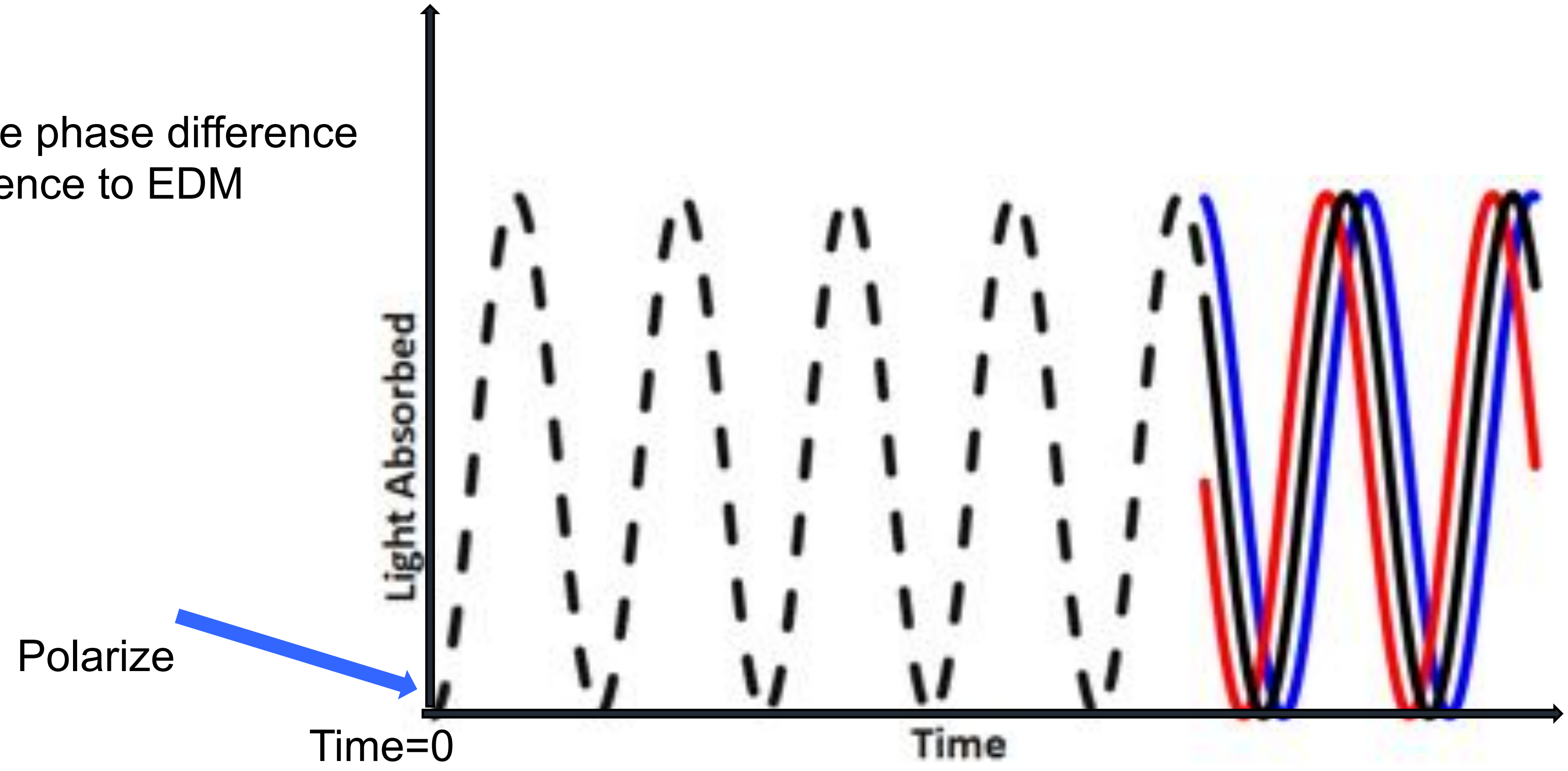




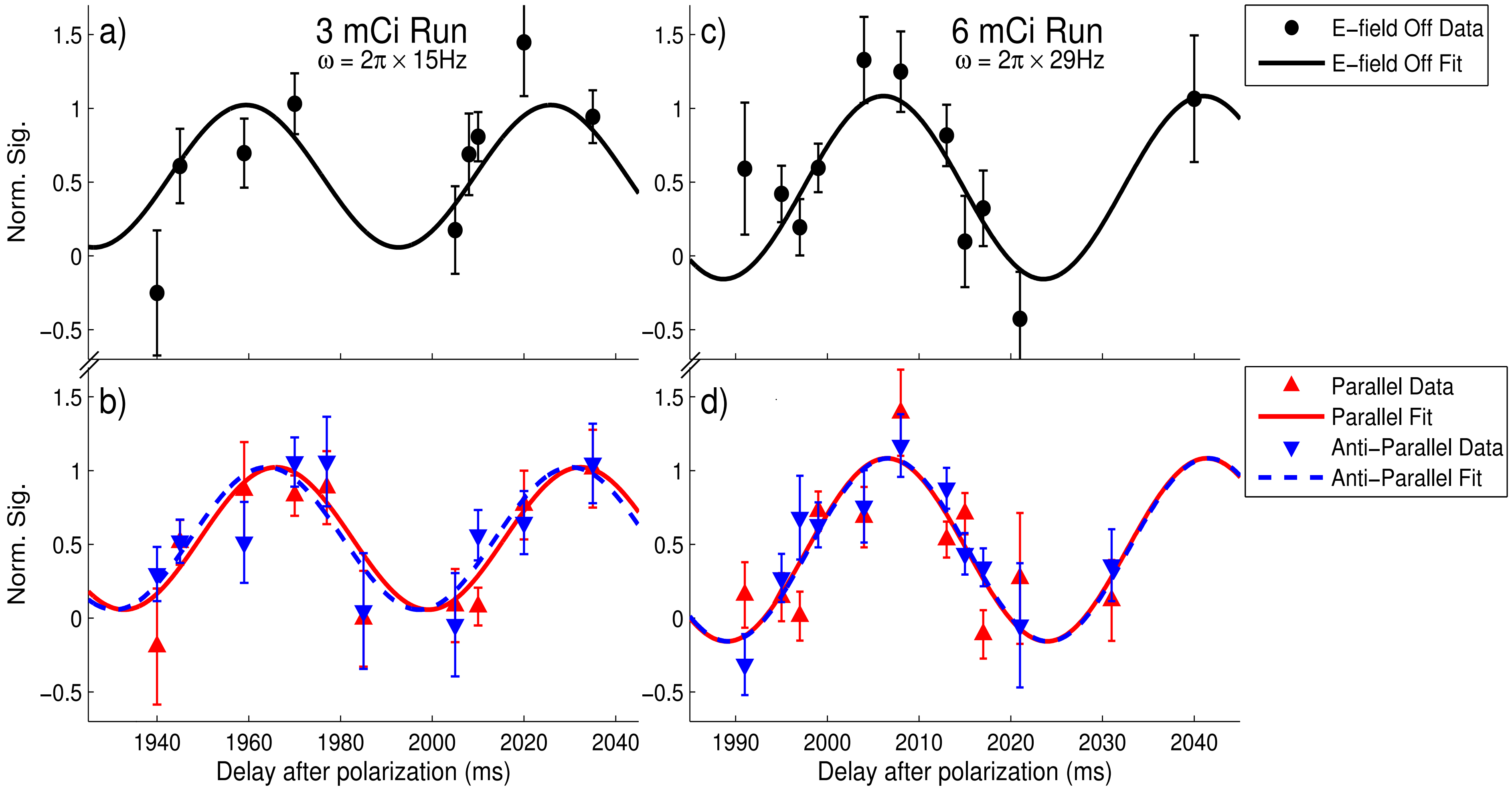
The Ra experiment: the way we do the EDM measurement



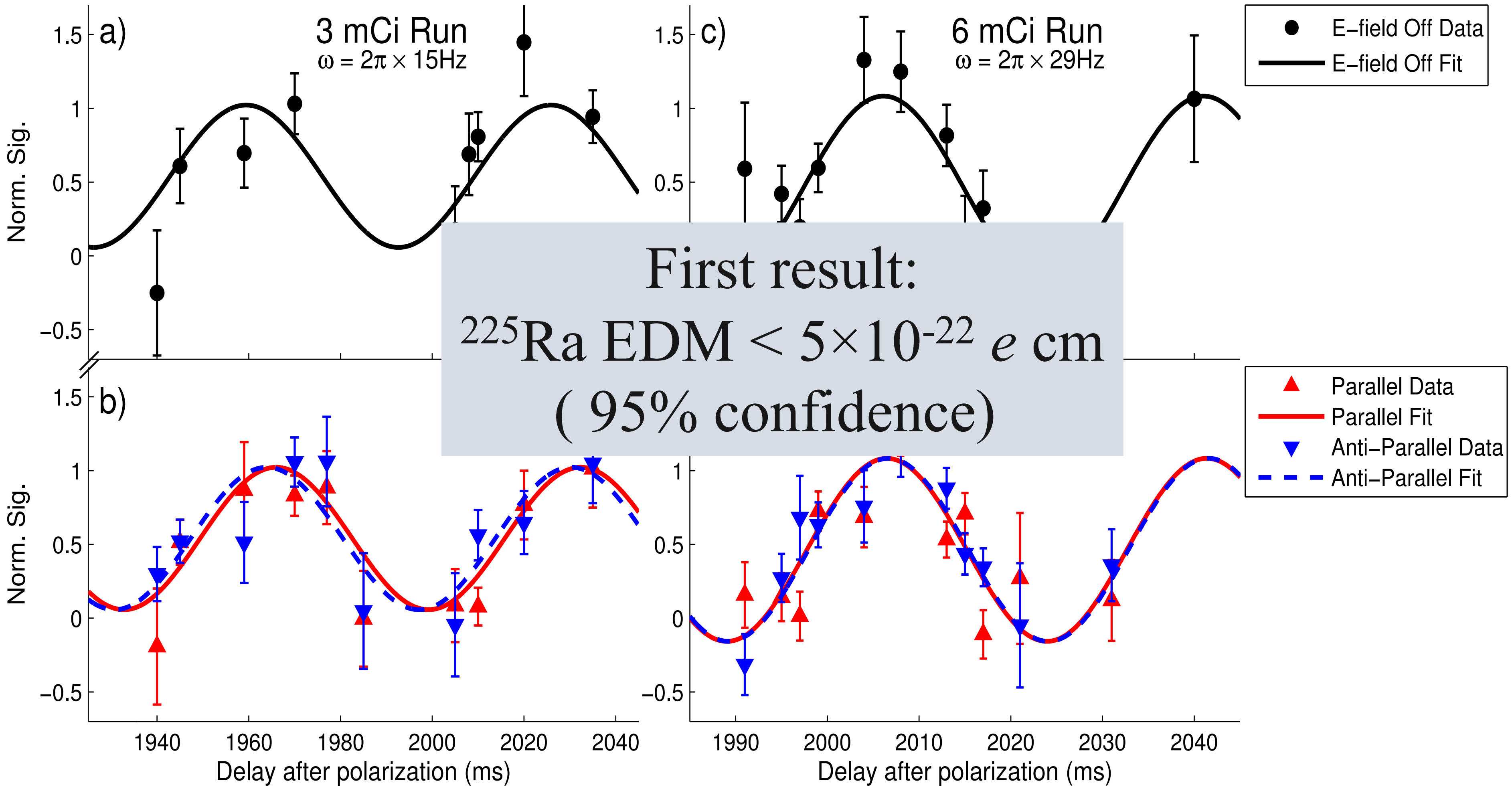
- ❑ From the fit obtain the phase difference
- ❑ Convert phase difference to EDM



The Ra experiment: EDM data



The Ra experiment: EDM data



First result:

^{225}Ra EDM < 5×10^{-22} *e* cm

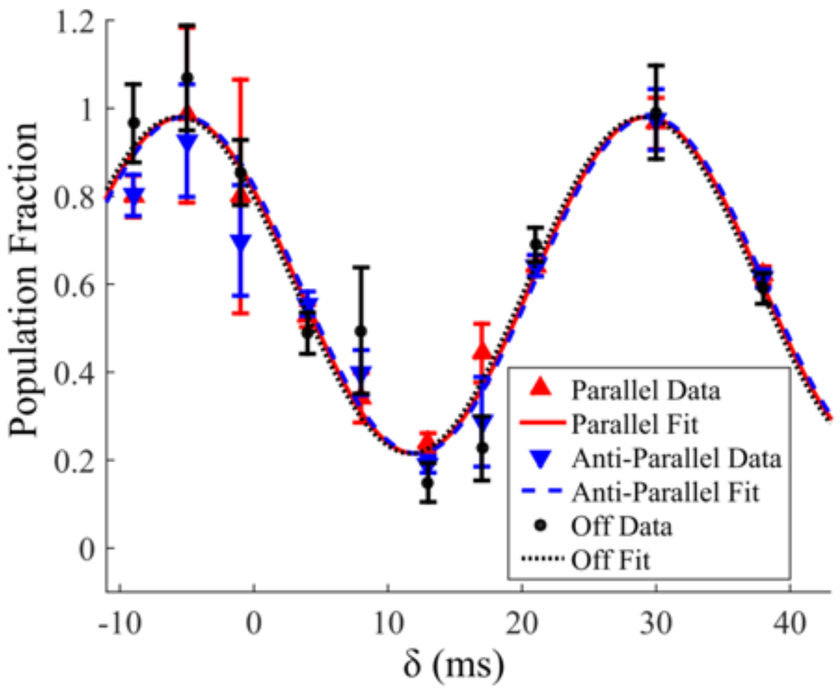
(95% confidence)

R. H. Parker et al., PRL ***114****, 233002 (2015)*

The Ra experiment: EDM data

Upgrades:

- ❑ Improved vacuum
- ❑ New ODT geometry
- ❑ ODT lifetime > **40 s** Vs 10 s.
- ❑ Precession time w/ E-field is **20 s** Vs 1.2 s.



Latest result: ^{225}Ra EDM < 1.4 × 10^{-23} *e* cm (95% confidence)

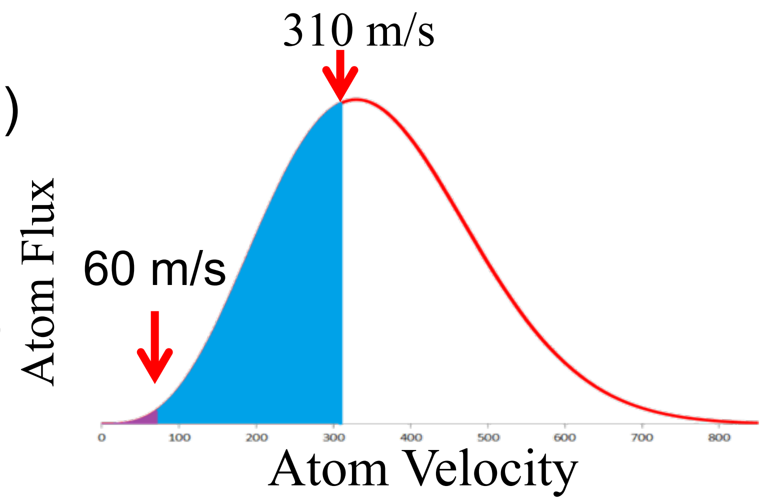
Systematic Effect	Δd_{225Ra} (e cm)
Imperfect E field reversal	< 1 × 10^{-25}
External B-field correlations	< 1 × 10^{-25}
Holding ODT power correlations	< 6 × 10^{-26}
E-field ramping	< 9 × 10^{-28}
Blue laser power correlations	< 7 × 10^{-28}
Blue laser frequency correlations	< 4 × 10^{-28}
E × v effects	< 4 × 10^{-28}
Leakage current	< 3 × 10^{-28}
Geometric phase	< 1 × 10^{-31}
Total	< 2 × 10^{-25}

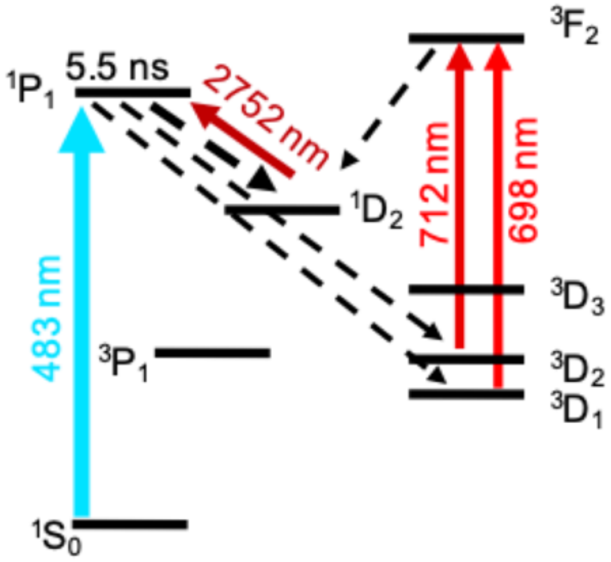
M. Bishof et. al., Phys. Rev. C ***94****,025501,(2016)*

The Ra experiment: EDM data

Upgrades being undertaken:

- ❑ Improved E field (Nb,150 kV/cm)
- ❑ Detection efficiency (STIRAP)
- ❑ Loading efficiency (New slower)
- ❑ Available atoms



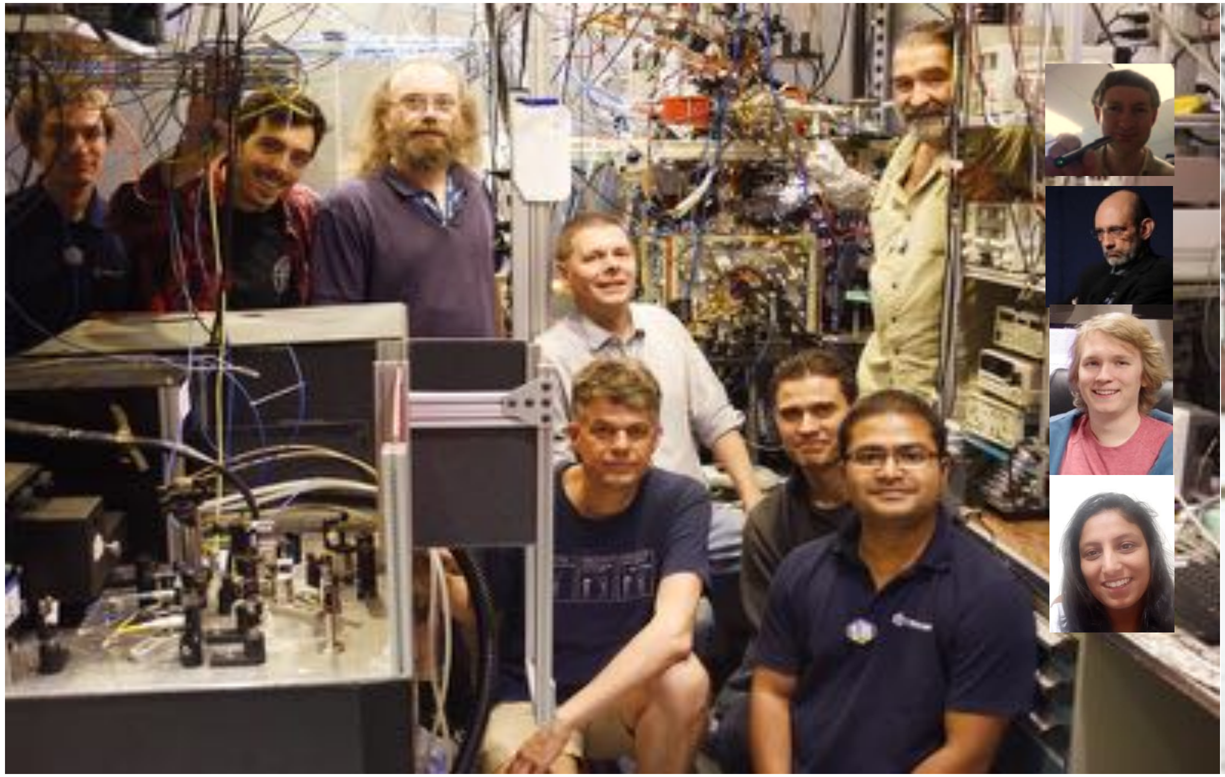


Projected

- ❑ FRIB (B. Sherrill, MSU)
  - ❑ Beam dump recovery with a ^{238}U beam 6×10^{9} /s
  - ❑ Dedicated running with a ^{232}Th beam 5×10^{10} /s
- ❑ ISOL@FRIB (I.C. Gomes and J. Nolen, Argonne)
  - ❑ Deuterons on thorium target, 1 mA × 400 MeV = 400 kW, 10^{13} /s
- ❑ MSU K1200 (R. Ronningen and J. Nolen, Argonne)
  - ❑ Deuterons on thorium target, 10 μA × 400 MeV = 4 kW, 10^{11} /s

R. Ready et al. Abstract: P01.00002, APS March Meeting 2020 Vol. 65, Number 1
D. W. Booth et al., arXiv:1910.03047v1 [physics.atom-ph]

Fr team



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

Ra team

Kevin Bailey, Michael Bishof, John Greene, Roy Holt, Nathan Lemke, Zheng-Tian Lu, Peter Mueller, Tom O'Connor, Richard Parker, Matt Dietrich; Mukut Kalita, Wolfgang Korsch; Jaideep Singh, Tenzin Ragba, Roy Ready

Summary:

- Atoms and molecules are attractive systems for experimental tests of the SM and searching for physics beyond the SM.
- Some rare and radioactive systems have favorable atomic and nuclear properties for these kind of tests.
- I have showed two examples, first with francium and then with radium where we use laser cooling and trapping techniques to prepare the atoms for measurements.
- The radium experiment has demonstrated the feasibility for EDM experiment.
- The francium experiment is getting closer towards first demonstration of APV measurements.

Thank You