The Radium-225 Experiment

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For the Ra EDM Collaboration

EDM SECTORS

d_e C_S C_T $g_\pi^{(0)}$ $g_\pi^{(1)}$ đ_n

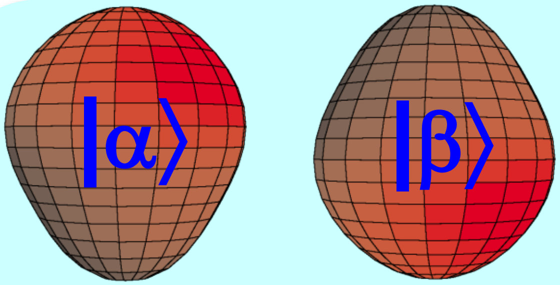
Paramagnetic — Diamagnetic — Neutrons

ThO, YbF, Cs, Tl, Fr…

Hg, Ra, Xe, TlF

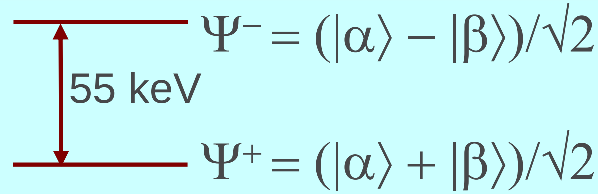
Sector	Exp Limit (e-cm)	Location	Method	Standard Model
Electron	9×10^{-29}	Harvard-Yale	ThO molecules in a beam	10^{-38}
Neutron	3×10^{-26}	ILL	UCN in a bottle	10^{-31}
Nuclear	7×10^{-30}	U. Washington	^{199}Hg atoms in a cell	10^{-33}

RADIUM EDM



A large quadrupole and octupole deformation results In an enhanced Schiff moment
– Auerbach, Flambaum & Spevak (1996)

Relativistic atomic structure weakens the Schiff theorem, resulting in a strong enhancement with increasing Z
($^{225}Ra/^{199}Hg$ ~ 3)
– Dzuba, Flambaum, Ginges, Kozlov (2002)



A closely spaced parity doublet enhances the appearance of parity violating terms in the underlying Hamiltonian
– Haxton & Henley (1983)

$$S \propto \sum_{i \neq 0} \frac{\left\langle \psi_0 \middle| \hat{S}_z \middle| \psi_i \right\rangle \left\langle \psi_i \middle| \hat{H}_{PT} \middle| \psi_0 \right\rangle}{E_i - E_0} + c.c.$$

	C_T	g(0)	g(1)
Ra/Hg	2	430	833
Ra/Xe	38	4200	23000
Ra/n	∞	.1	20

J. Engel et al., Progress in Particle and Nuclear Phys. (2013)

RADIUM SETUP

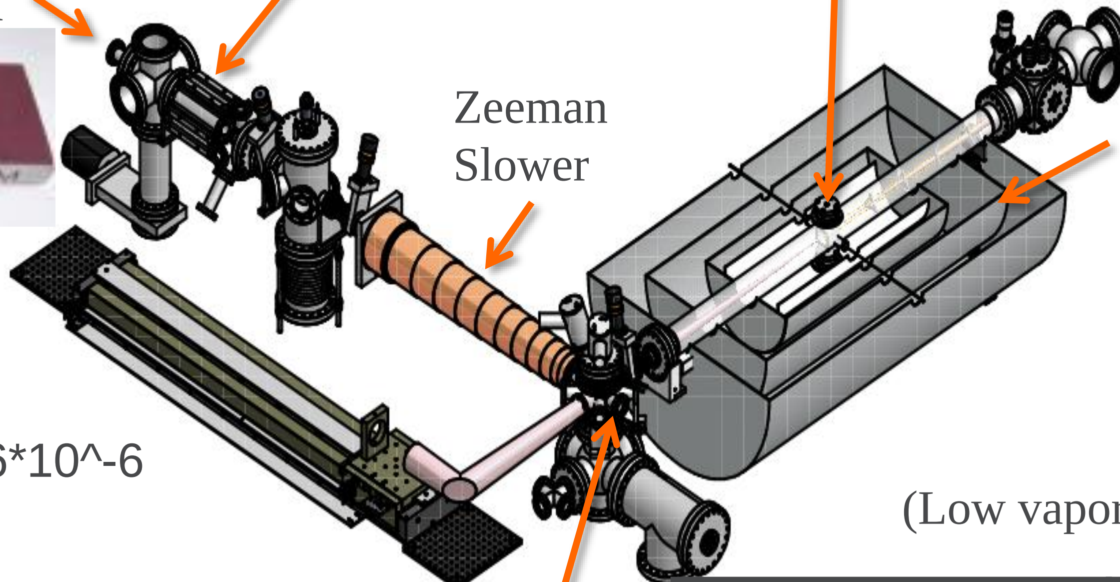
$Ra(NO_3)_2$+Ba Oven

Transverse Cooling

HV Electrodes

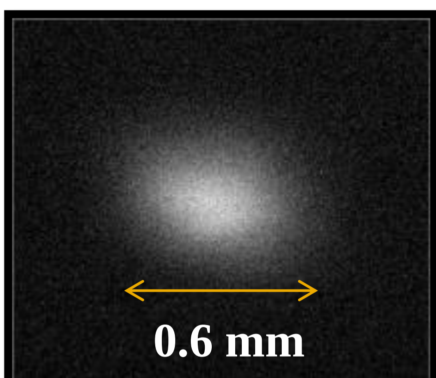
Zeeman Slower

Magnetic Shielding & Magnet Coils



η ~ 1.6*10^-6

(Low vapor pressure)

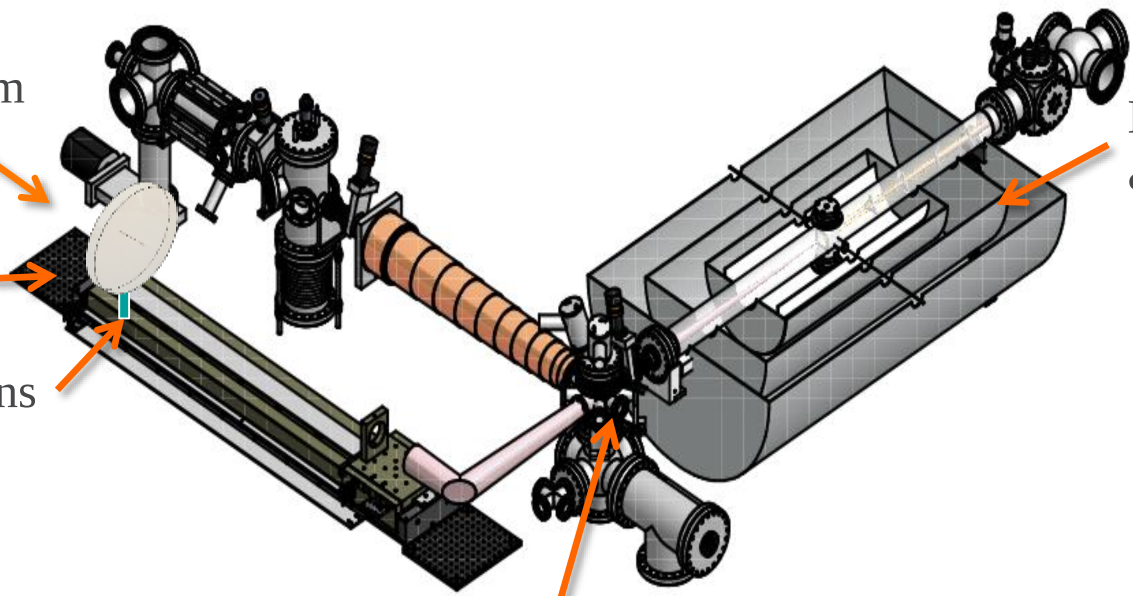


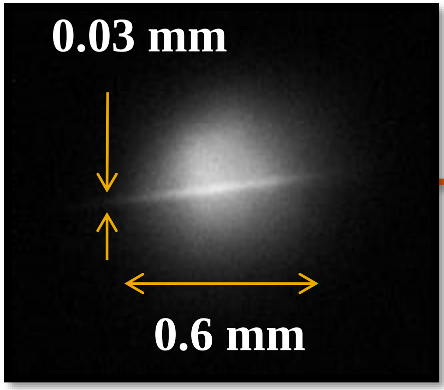
^{226}Ra MOT
200,000 atoms
40 μK

For EDM:	For Testing:
Ra-225	Ra-226
I = 1/2, J = 0	I = 0, J = 0
$t_{1/2}$ = 15 days	$t_{1/2}$ = 1600 yrs

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

TRANSFER ATOMS FROM MOT TO "BUS" ODT



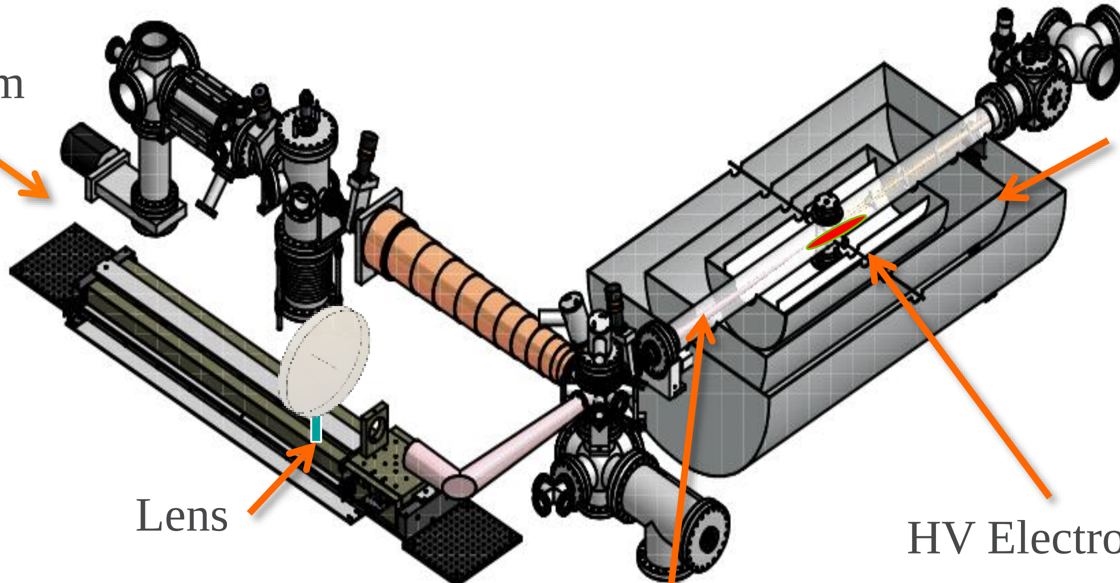


MOT + ODT
80% Efficiency

Argonne NATIONAL LABORATORY

TRANSFER ATOMS FROM “BUS” TO “HOLDING” ODT

“Bus” ODT
50 W 1550 nm

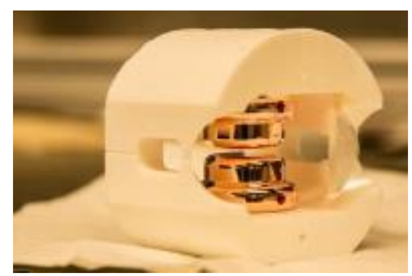


Magnetic Shielding
& Magnet Coils

30 mG

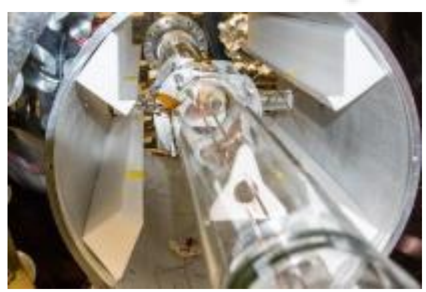
Lens

HV Electrodes

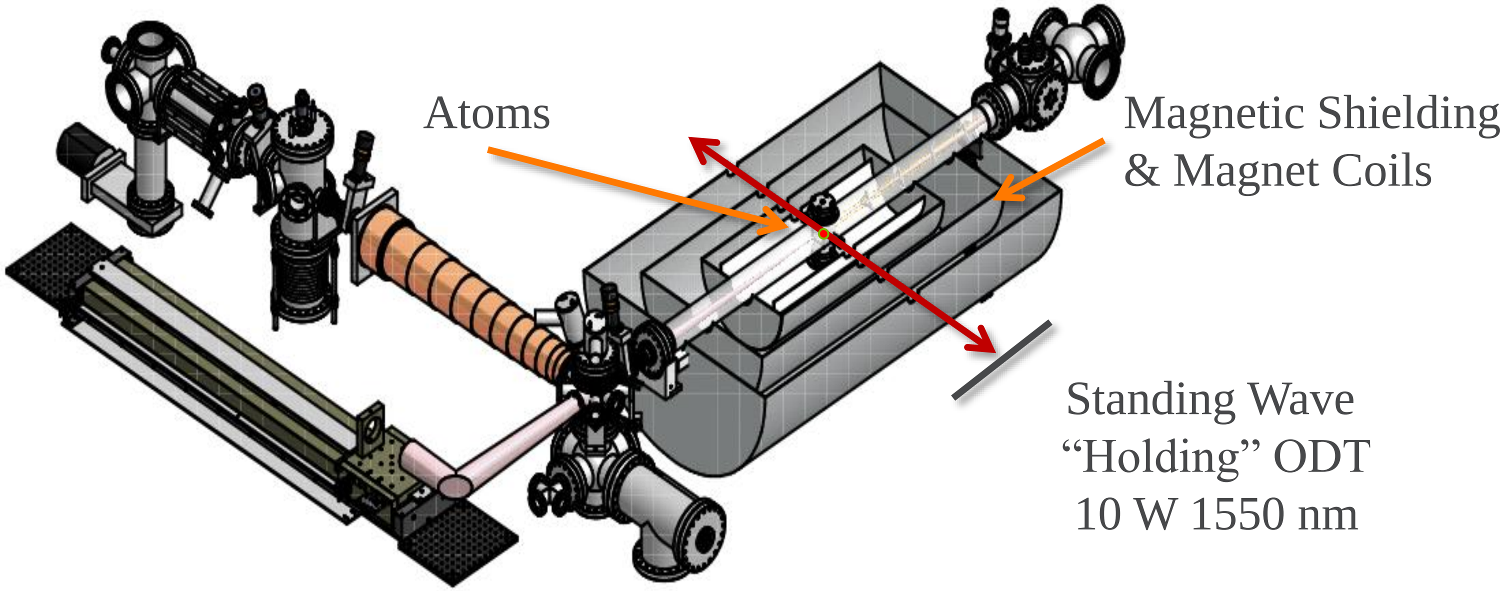


70 kV/cm

Glass Tube
Vacuum chamber
10^{-11} Torr

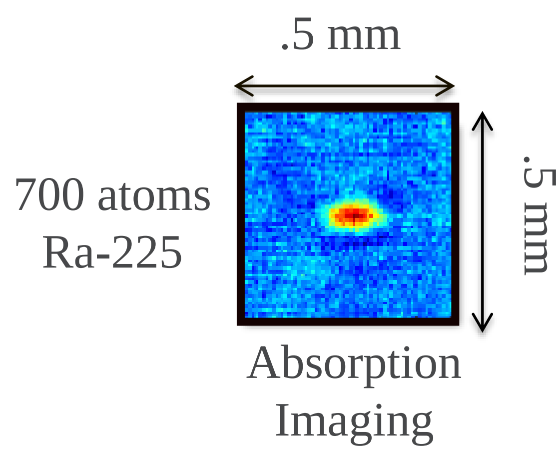


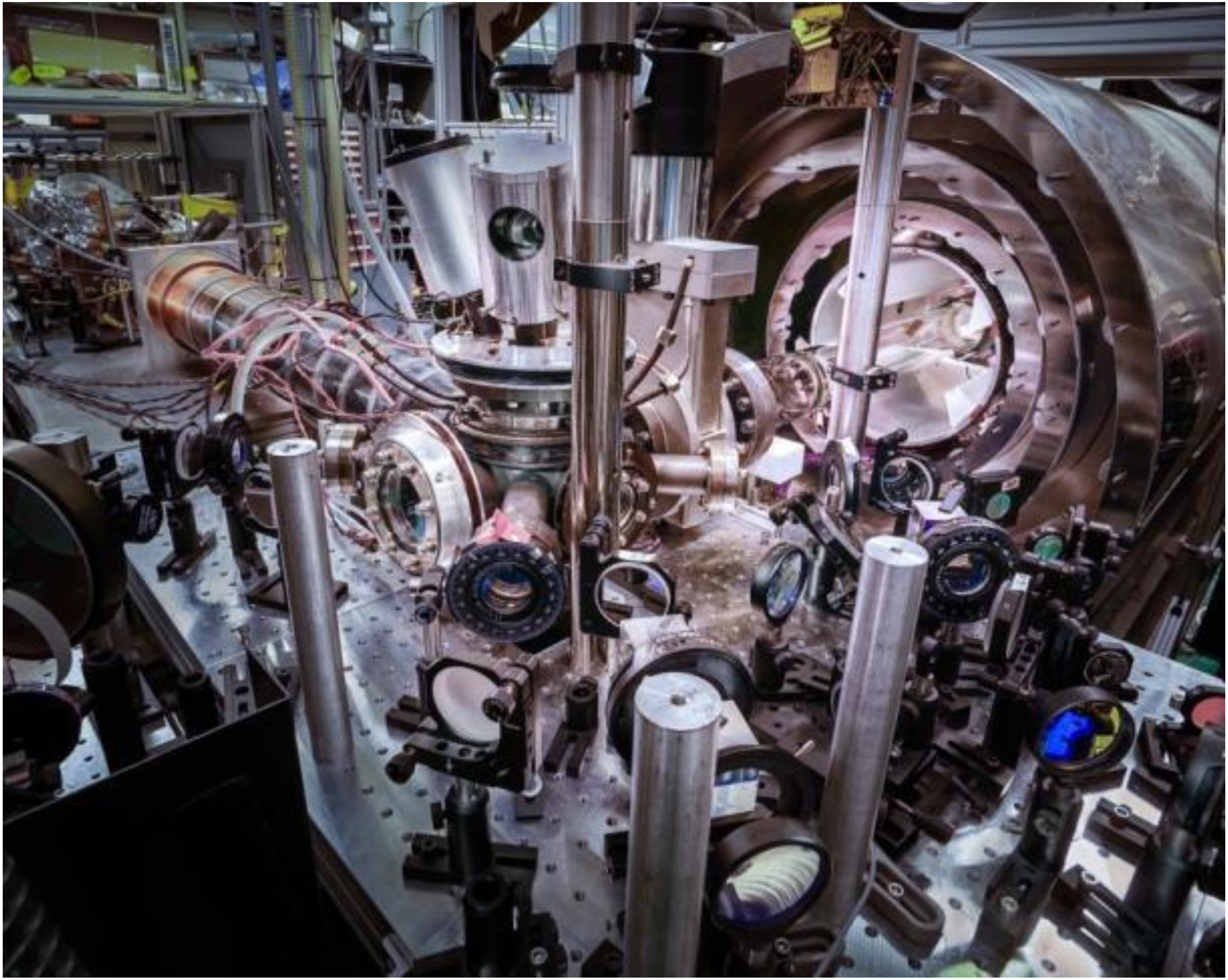
TRANSFER ATOMS FROM "BUS" TO "HOLDING" ODT



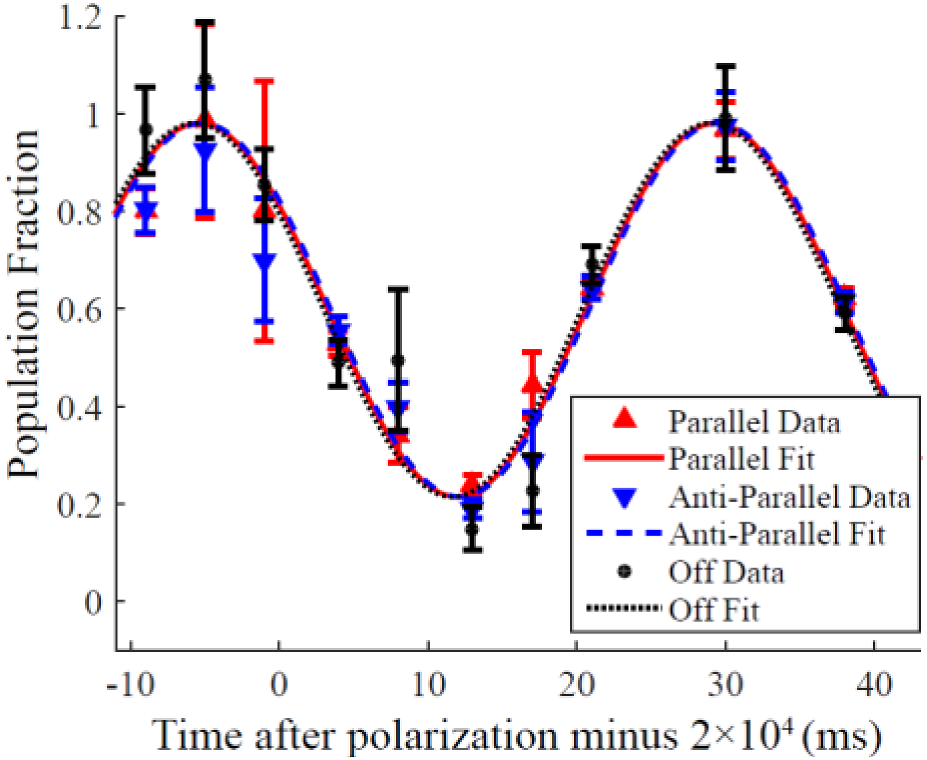
ODT→ODT Transfer: 70% Efficiency

R. H. Parker *et al.*, PRC **86**, 065503 (2012)





EDM RESULT



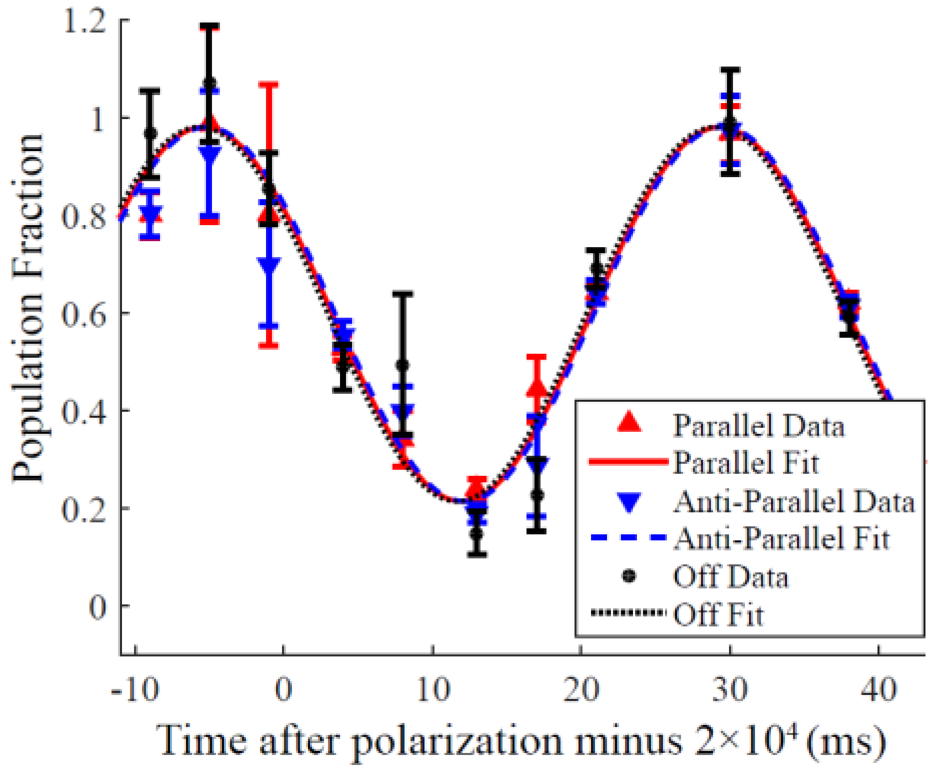
$\chi^2/25 = 1.4$

$$y_{\mathrm{E-field\,Off}} = \frac{A}{1+P}\left[1 - P\cos(\omega t)\right]$$

$$y_{\mathrm{Parallel,\,Anti-Parallel}} = \frac{A}{1+P}\left[1 - P\cos(\omega t + \theta \pm \Delta\phi/2)\right]$$

M. Bishof *et al.* PRC 94, 025501 (2016)

EDM RESULT



$\chi^2/25 = 1.4$

$d_{Ra\text{-}225} = (4 \pm 6_{stat} \pm 0.2_{syst}) \times 10^{-24}$ e-cm
$d_{Ra\text{-}225} < 1.4 \times 10^{-23}$ e-cm 95% C.L.

M. Bishof *et al.* PRC 94, 025501 (2016)

SYSTEMATICS

Effect (e-cm)	2016 Measurement	Improved Statstics	Co-magnetometer
E-squared Effects	1×10^{-25}	7×10^{-29}	7×10^{-31}
B-field Correlations	1×10^{-25}	5×10^{-27}	3×10^{-29}
ODT Power Corr.	6×10^{-26}	9×10^{-30}	9×10^{-32}
Stark Interference	6×10^{-26}	2×10^{-27}	3×10^{-29}
Blue Power Corr.	7×10^{-28}	1×10^{-31}	1×10^{-31}
Blue Freq. Corr.	4×10^{-28}	8×10^{-30}	8×10^{-30}
E x v Effects	4×10^{-28}	7×10^{-30}	-
Leakage Current	3×10^{-28}	9×10^{-29}	-
E-field Ramping	9×10^{-28}	2×10^{-29}	-
Geometric Phase	3×10^{-31}	7×10^{-30}	5×10^{-33}
Total	$\mathbf{2\times10^{-25}}$	$\mathbf{5\times10^{-27}}$	$\mathbf{4\times10^{-29}}$

M. Bishof *et al.* PRC 94, 025501 (2016)

EDM LIMITS

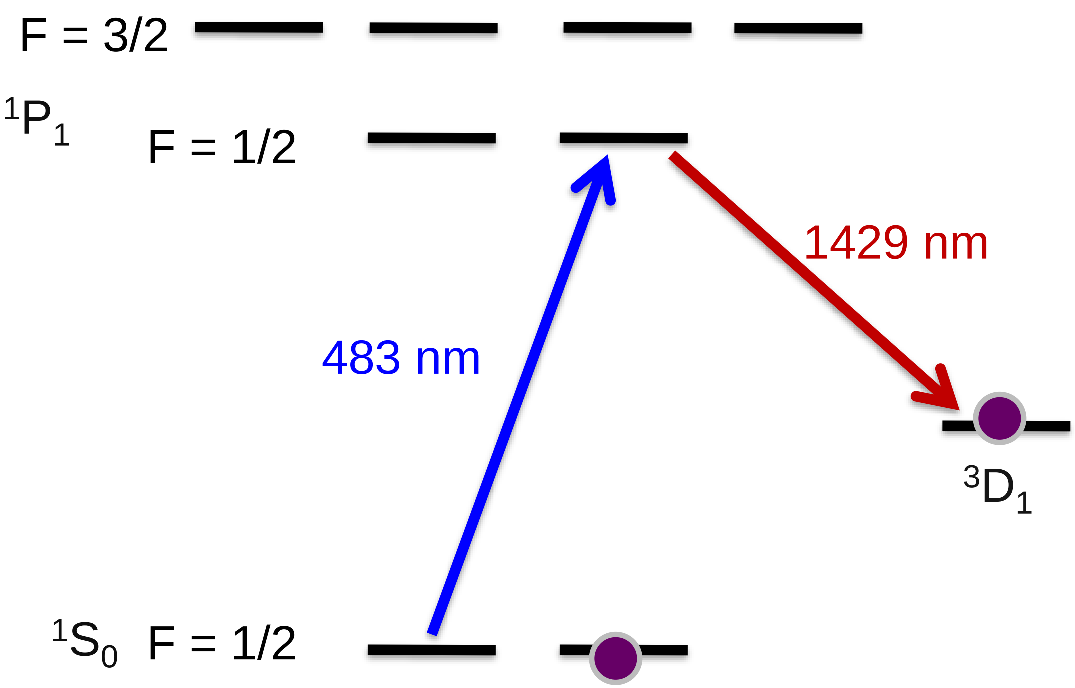
$$d = \frac{\hbar S \Delta\phi}{2ET}$$

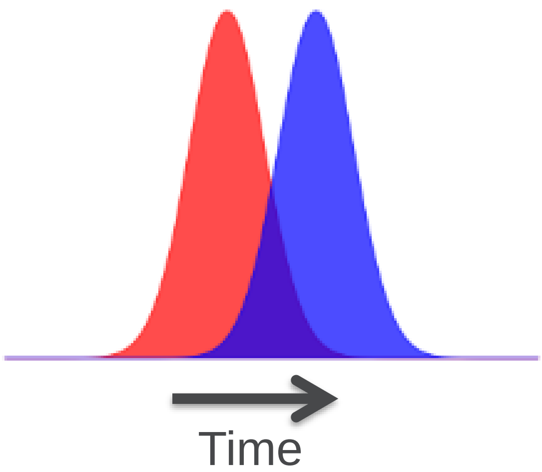
$$\sigma_{\Delta\phi} = \frac{1}{\sqrt{n} \times \mathrm{SNR}}$$

$$\boxed{\sigma_d = \frac{\hbar}{4ET\sqrt{n} \times \mathrm{SNR}}}$$

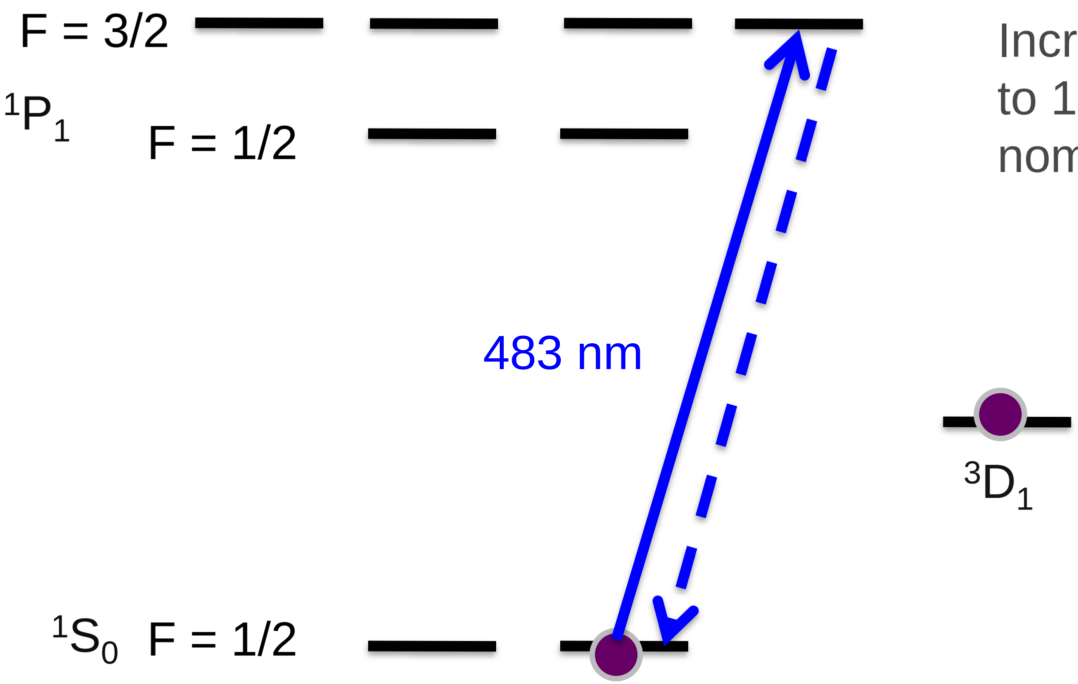
- SNR/shot = .2-.4 in current experiment
- Atom shot noise limit is 12. How do we get there?

IMPROVED DETECTION



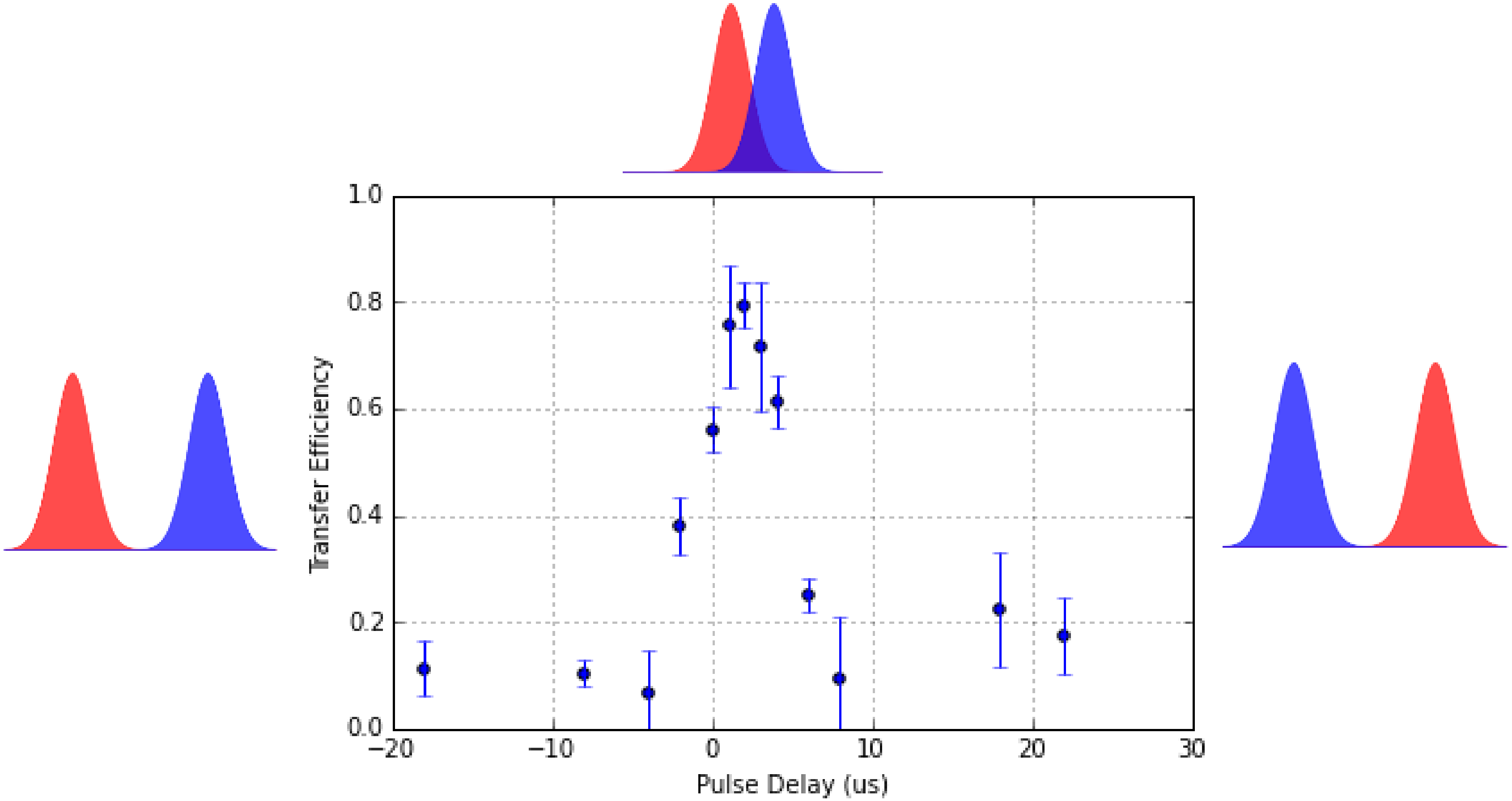


IMPROVED DETECTION



Increase from 2.1 photons per atom to 1000 photons per atom, for a nominal SNR improvement of 20.

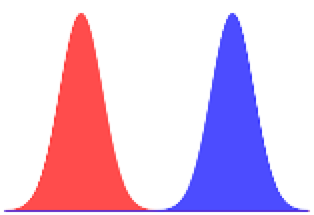
STIRAP SIGNAL

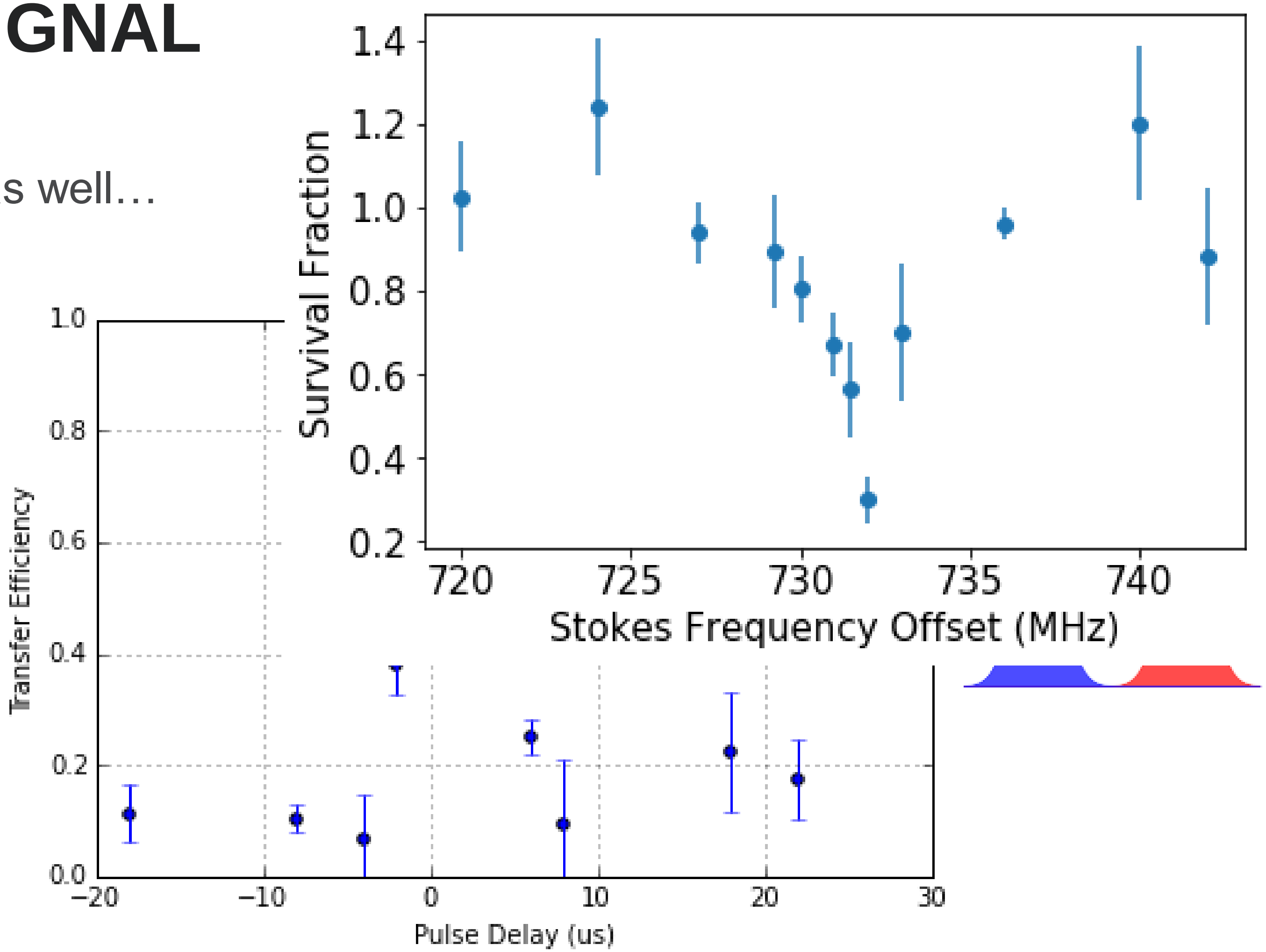


Consistent with an SNR factor improvement of 17

STIRAP SIGNAL

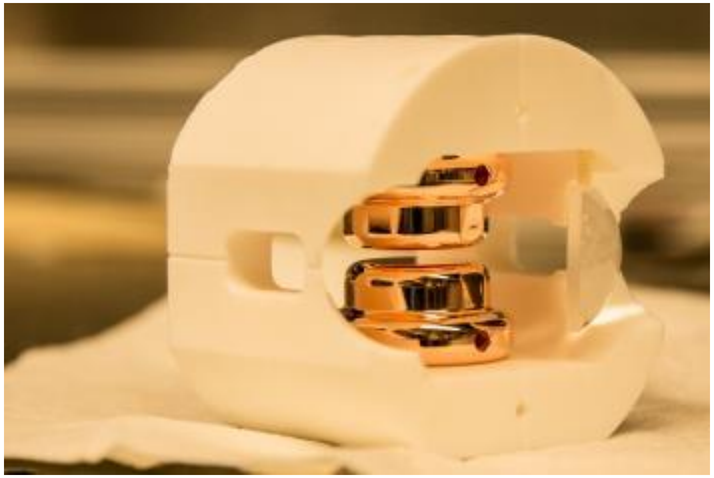
In Ra-225 as well…





Consistent with an SNR factor improvement of 17

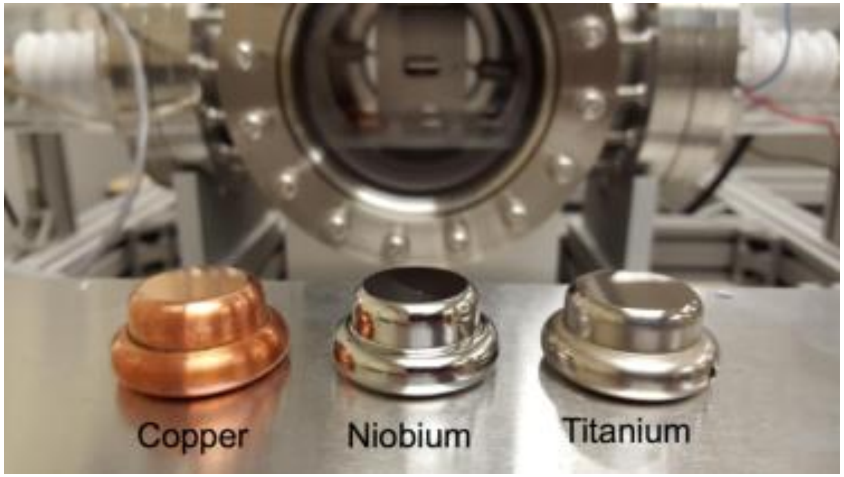
INCREASED FIELD



Present: Copper Electrodes, E = 70 kV/cm

Niobium electrodes newly installed:
>300 kV/cm demonstrated
(J. Singh/MSU, M. Kelly, T. Reid/ANL, M. Poelker/Jlab)

Phys. Rev. Spec. Top. – Acc. and Beams, **15**, 083502 (2012)



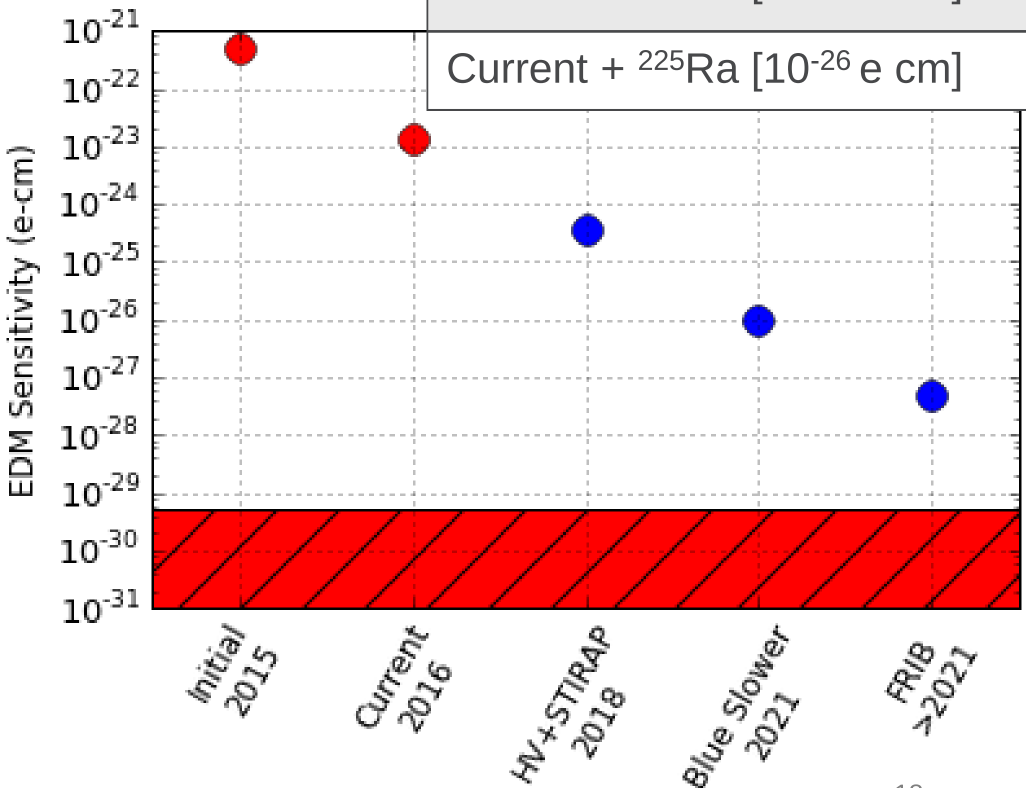
Factor of 4-5 increase in EDM Sensitivity

Together, a factor of ~100 increase, bringing us to high 10^{-26} or low 10^{-25} e-cm level

EFFECT ON STANDARD MODEL EXTENSIONS

BSM parameter	C_T	$g_p^{(0)}$	$g_p^{(1)}$	$\bar{d}_n$ (e cm)
Current limits (95% CL)	2×10^{-6}	8×10^{-9}	1.2×10^{-9}	1.2×10^{-22}
Improvement Factor (over current limit)				
Current + ^{225}Ra [10^{-25} e cm]	40	2	1.2	20
Current + ^{225}Ra [10^{-26} e cm]	200	8	4	60

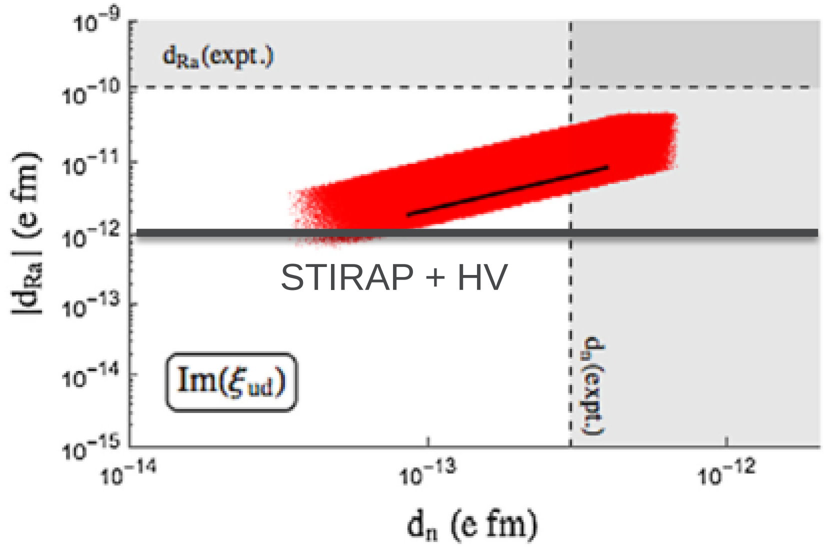
T. Chupp and M. Ramsey-Musolf, PRC 91, 035502 (2015)

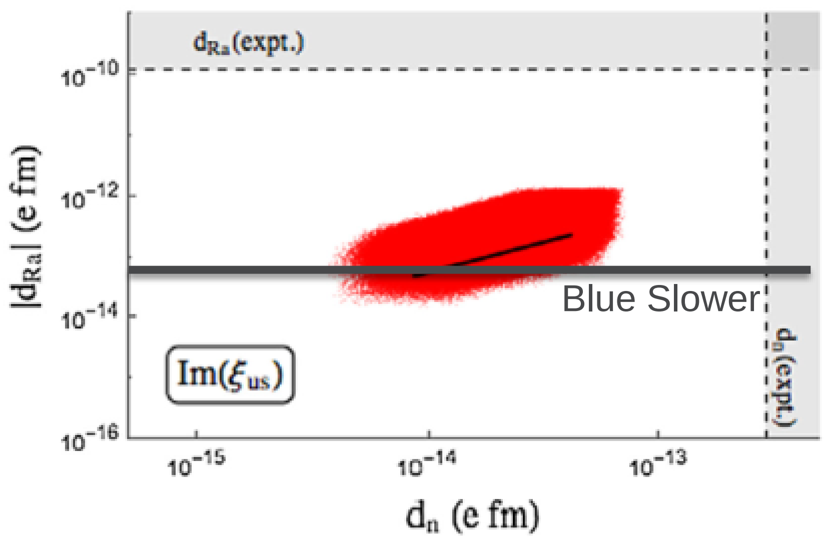


At the level available with those upgrades, radium will improve significantly on the global sensitivity for all parameters

RIGHT-HANDED CHARGED CURRENTS

- Apparent tension in CP-violating parameters from Kaon decays could be explained by a right-handed charged weak current, which would be detectible with Hadronic EDM experiments
- Due to large theoretical uncertainties in Hg, present constraints on such a model are very weak
- The upcoming radium measurement will be sensitive to this possibility





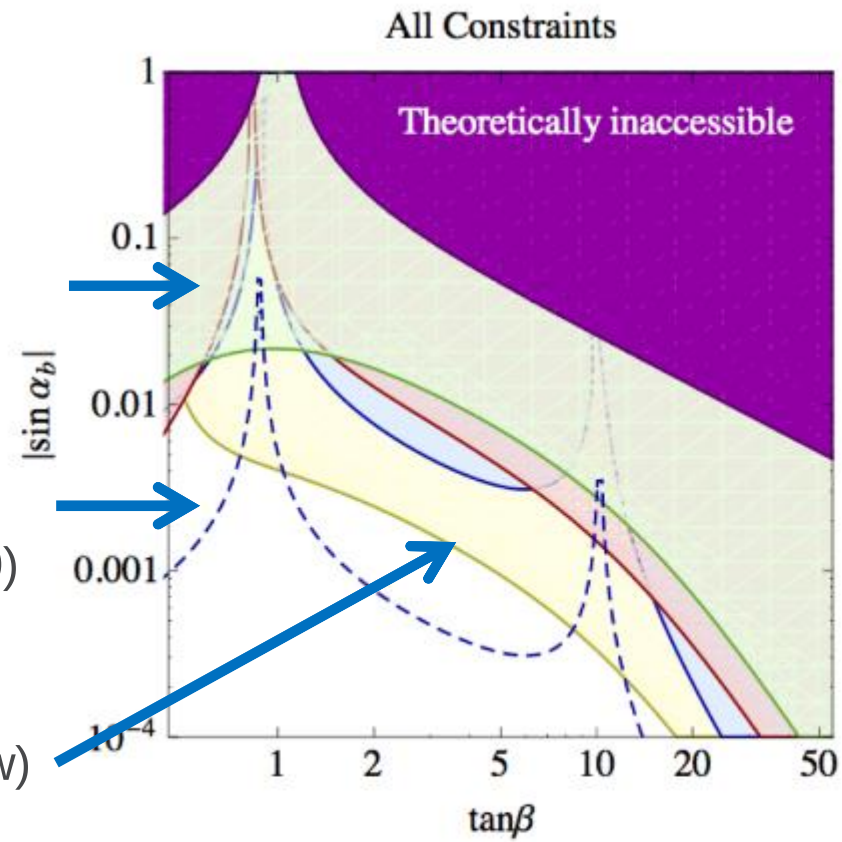
V. Cirigliano, W. Dekens, J. de Vries, and E. Mereghetti, Phys. Lett. B 767, 1 (2017)
arXiv:1708.00797v2

TWO-HIGGS DOUBLET

LANL neutron EDM (Green)

Future electron EDM (blue, x10)

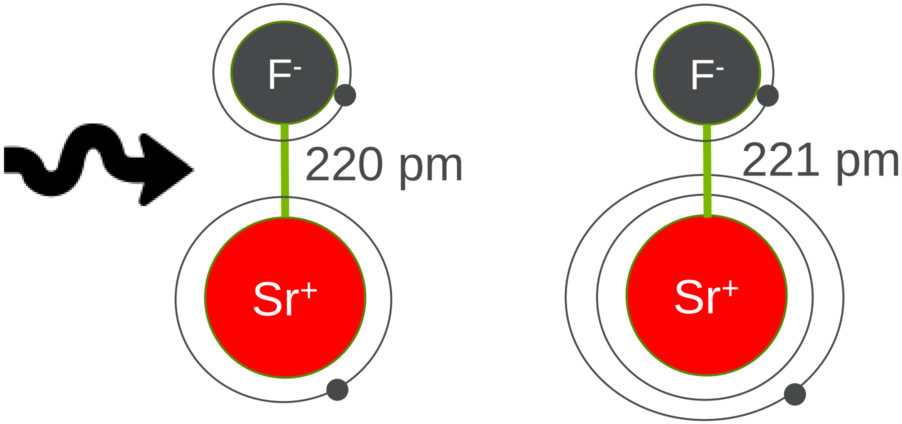
Radium Blue Slower (yellow) 10^-27 e-cm



- 2HDM is a simple extension to the SM allowing for CP-violation and natural mechanisms for baryogenesis
- Radium has strong sensitivity to 2HDM, in spite of electroweak nature of theory
- Complementary to electron EDM, which exhibits interference

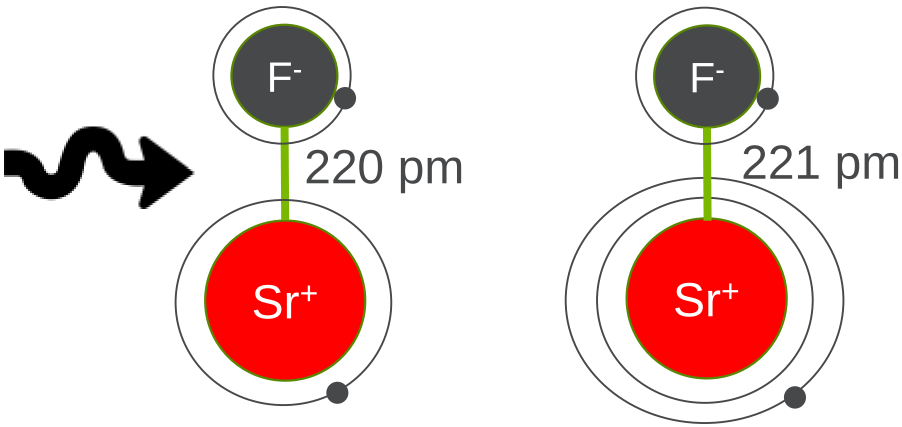
S. Inoue, M. J. Ramsey-Musolf, Y. Zhang Phys. Rev. D 89, 115023 (2014)
C.-Y Chen, H.-L Li, M. J. Ramsey-Musolf, Phys. Rev. D 97, 015020 (2018)

RADIUM MOLECULES



- Because of its high degree of polarization, the ground and excited states of SrF have about the same bond length
- Which makes vibrational modes difficult to excite
- This makes SrF one of the (rare) laser-coolable molecules

RADIUM MOLECULES



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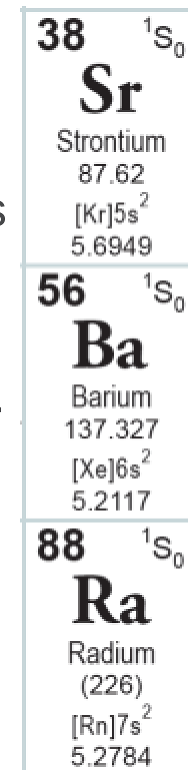
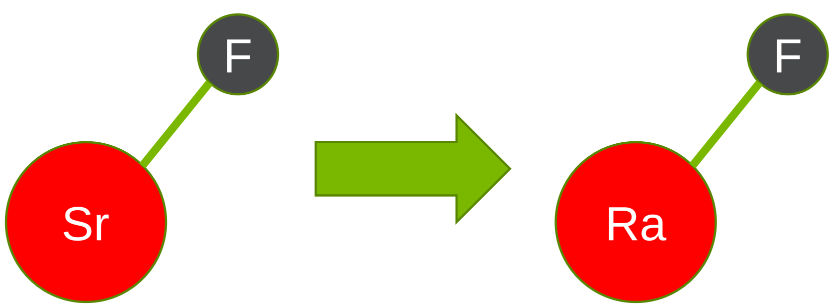


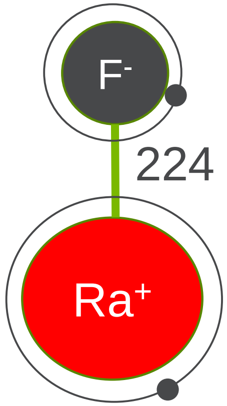
Guess who is similar to strontium…



RaF is also thought to be laser coolable

Phys. Rev. A 82, 052521
arXiv: atom-ph/1302.5682

MOLECULES AND EDMS

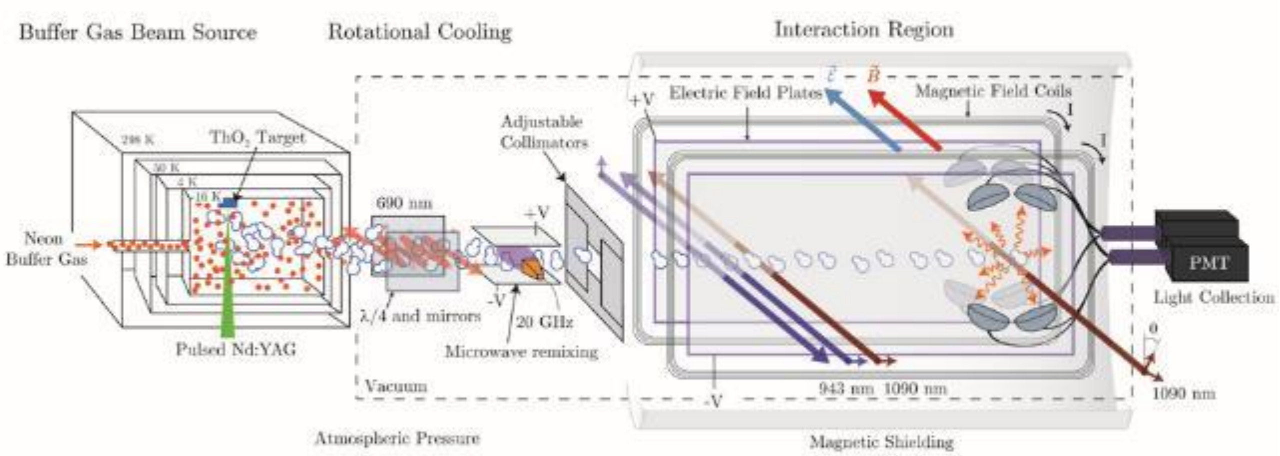


$$E \approx k_e \frac{e}{r^2} \approx 290 \text{ MV/cm}$$

A more careful analysis tells us that a measurement in RaF with a given sensitivity is just as good as one in neutral radium with a field of ***130 MV/cm***

Phys. Rev. A 90, 052513 (2014)

Compare with 250 kV/cm in the new generation of electrodes



Electron EDM experiments have been taking advantage of molecules in beams for many years (courtesy ACME experiment)

MOLECULES AND EDMS

- However the lifetime in beam experiments is very short
  - ThO: **1.8 ms**
  - Radium Atom Trap Experiment: **40 s**
- Atom trap experiments have a significant advantage in lifetime, even more than the molecule enhancement alone
- A RaF trapped-atom experiment would posses octupole, molecule, and lifetime enhancements
- Assuming
  - 1% production and extraction efficiency
  - .01% trapping efficiency
  - Current transfer and detection efficiencies
  - 1 Ci Ra-225
- Gives 1-sigma sensitivity 4×10^{-31} e-cm equivalent Ra EDM sensitivity
- Standard model background for radium between 7×10^{-32} e-cm and 1×10^{-30} e-cm
  - *J. of High Energy Phys.*, 2016, 67 (2016)

ATOM TRAPPERS @ ARGONNE

U.S. DEPARTMENT OF ENERGY

Office of Science

DOE Office of Nuclear Physics