The Ongoing Radium EDM Experiment

Matt R. Dietrich

Physics Division

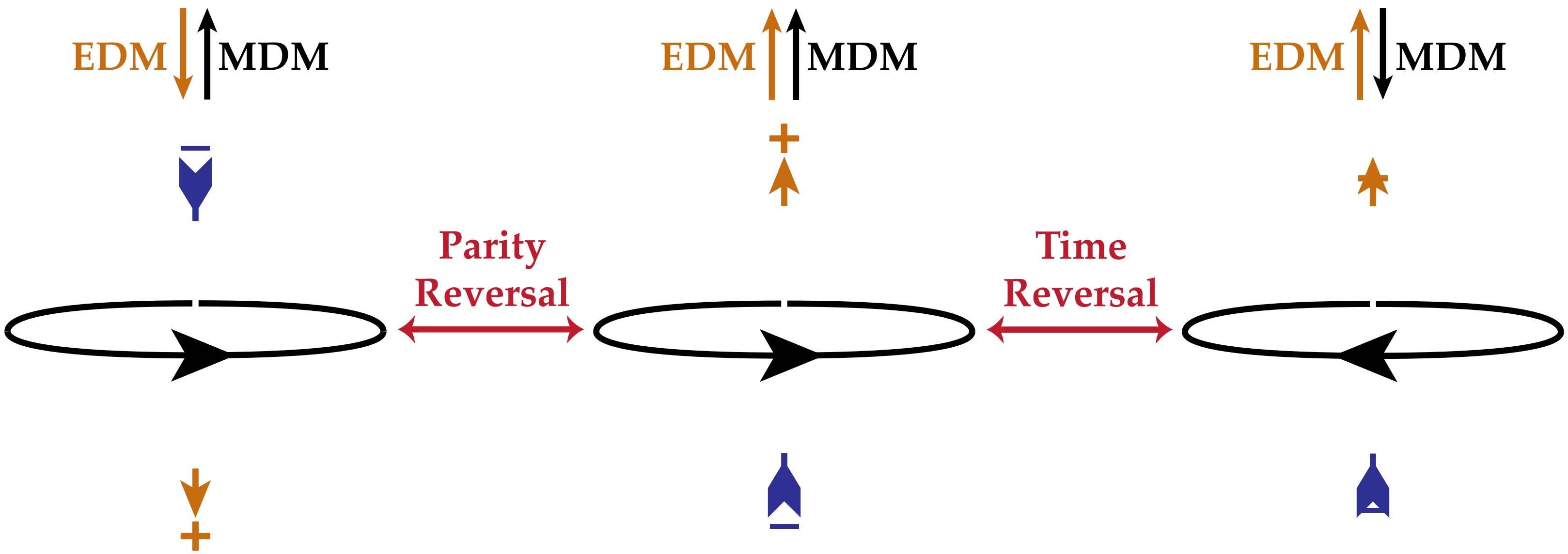
Argonne National Lab

Supported by DOE Office of Nuclear Physics

Electric Dipole Moments and Discrete Symmetries

Electric dipole moment (EDM):

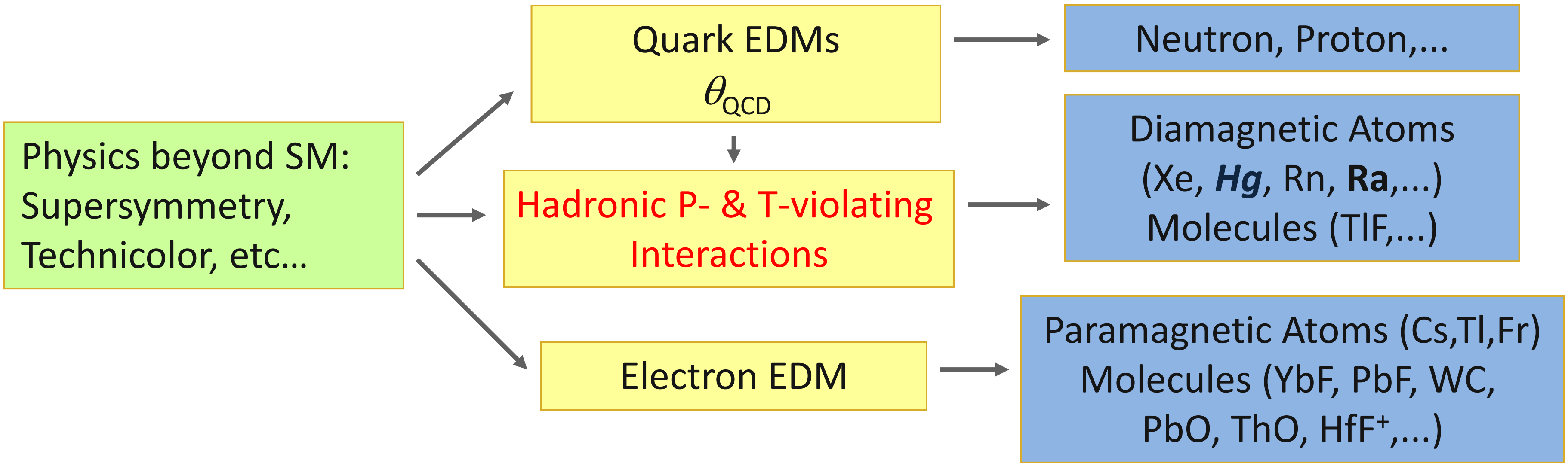
* displacement vector from a particle's center of mass to its center of charge.
* violates both *P*-parity (spatial inversion) and *T*-time reversal symmetries:



Assuming the combination of *C*-charge conjugation (particle <-> antiparticle), *P*, and *T* is conserved:

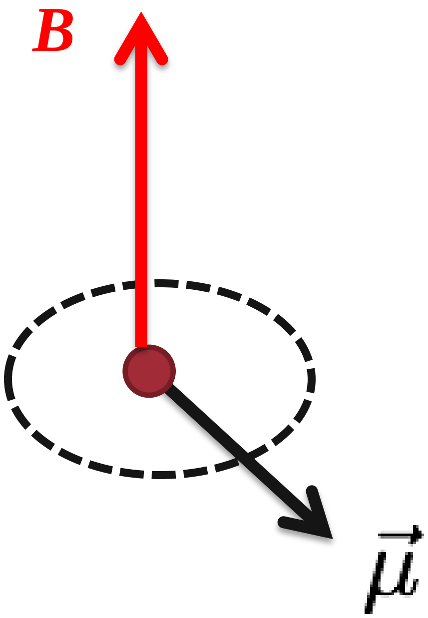
* *T*-violation implies *CP*-violation
* EDMs are a very sensitive probe of *CP*-violation

EDM Sectors



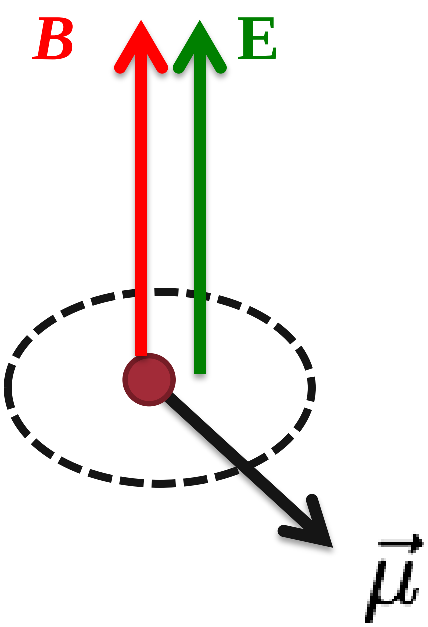
Sector	Exp Limit (e-cm)	Location	Method	Standard Model
Electron	1×10^{-27}	Imperial College	YbF molecules in a beam	10^{-38}
	9×10^{-29}	Harvard	ThO molecules in a beam	
Neutron	3×10^{-26}	ILL	UCN in a bottle	10^{-31}
Nuclear	3×10^{-29}	U. Washington	^{199}Hg atoms in a cell	10^{-33}

EDM Measurements



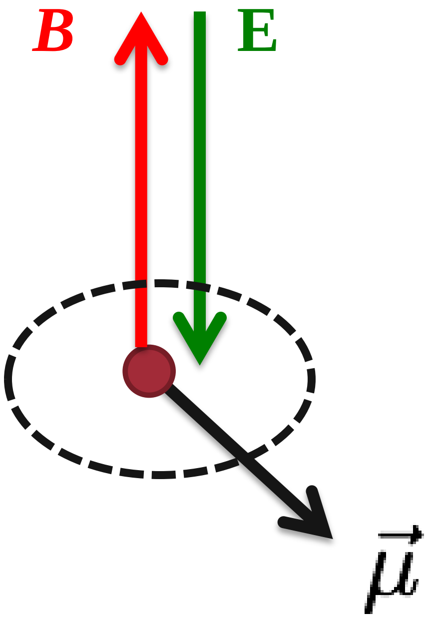
$$h\nu = \frac{\mu B}{S}$$

EDM Measurements



$$h\nu_+ = \frac{\mu B + dE}{S}$$

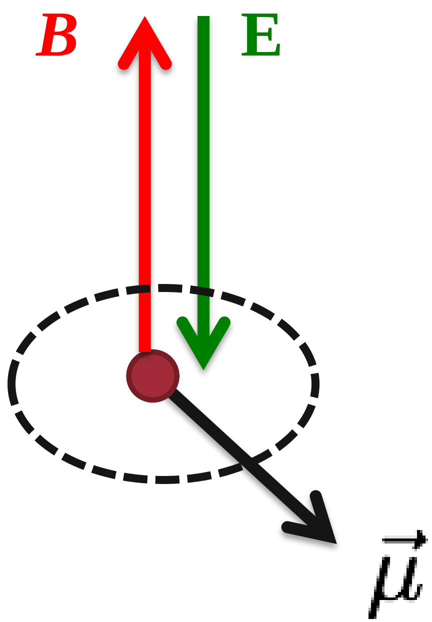
EDM Measurements



$$h\nu_+ = \frac{\mu B + dE}{S}$$

$$h\nu_- = \frac{\mu B - dE}{S}$$

EDM Measurements

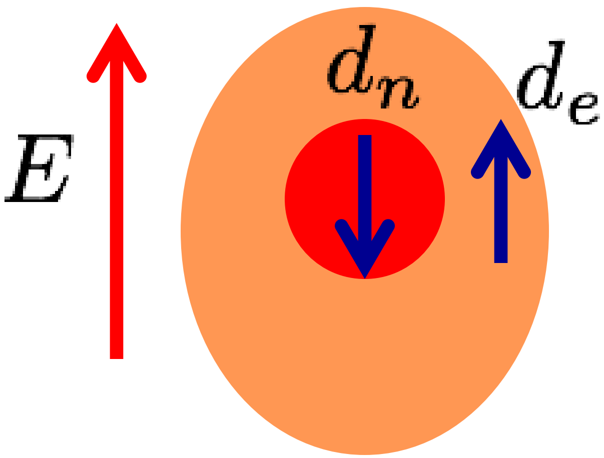


$$h\nu_+ = \frac{\mu B + dE}{S}$$

$$h\nu_- = \frac{\mu B - dE}{S}$$

$$\nu_+ - \nu_- = \frac{2dE}{hS}$$

Schiff Moments and EDMs



Schiff Moment

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

Schiff Theorem (1963):

* Any permanent dipole moment of the nucleus is perfectly shielded by its electron cloud

* True for point-like nuclei, non-relativistic electrons

However, the "Schiff moment" is not shielded by this effect

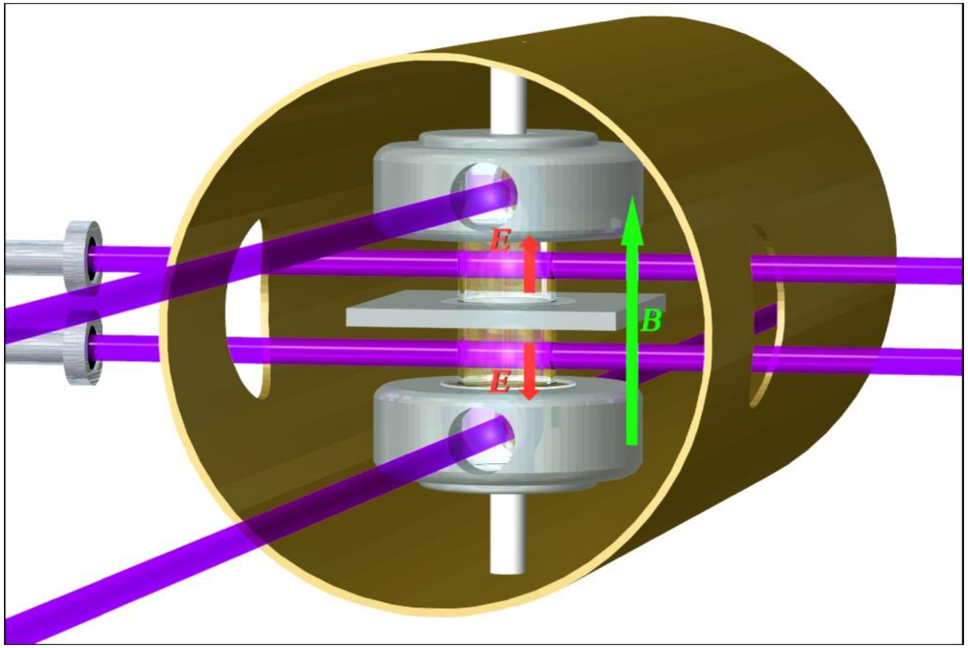
* Zero for point-like, spherical nuclei

* Arises from deformations in the nucleus or its constituent nucleons

* Very large in nuclei with both a quadrupole and octupole deformation

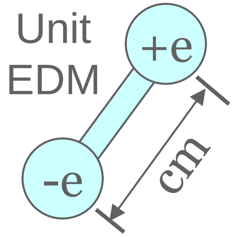
Look for heavy nuclei with large quadrupole and octupole deformations!

The Seattle EDM Experiment



Properties of Hg-199 and experiment

- Stable
- Spin I=½ nucleus (no quadrupole moment)
- Nuclear T2 ~ 100-200 seconds
- High Vapor Pressure, 4*10^13 cm^{-3} at room temperature
- High Z=80
- Nearly spherical nucleus
- Glass cell limits E field to 10 kV/cm
- Leakage current through cell is leading systematic

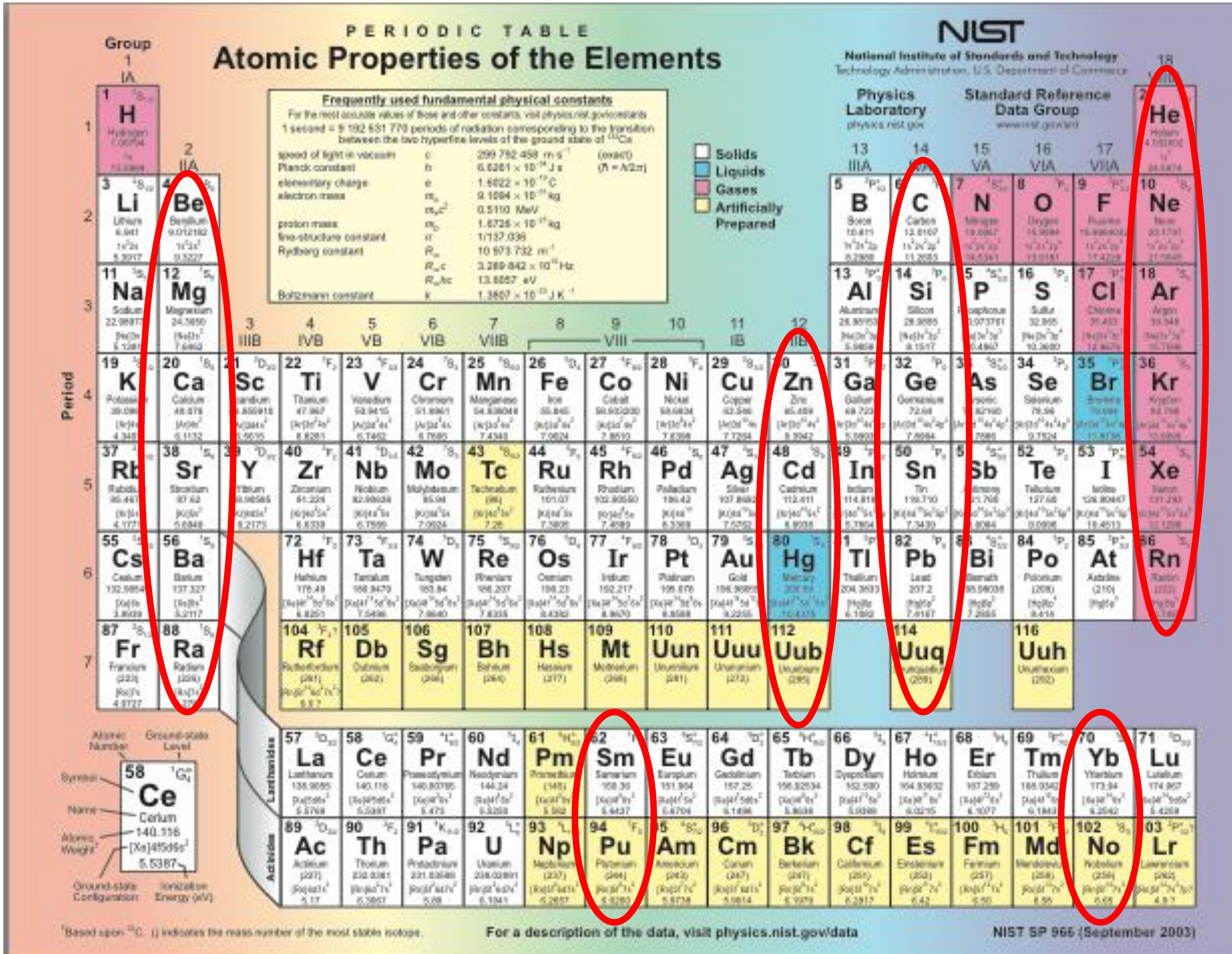


EDM(Hg-199) < 3 x 10^-29 e cm

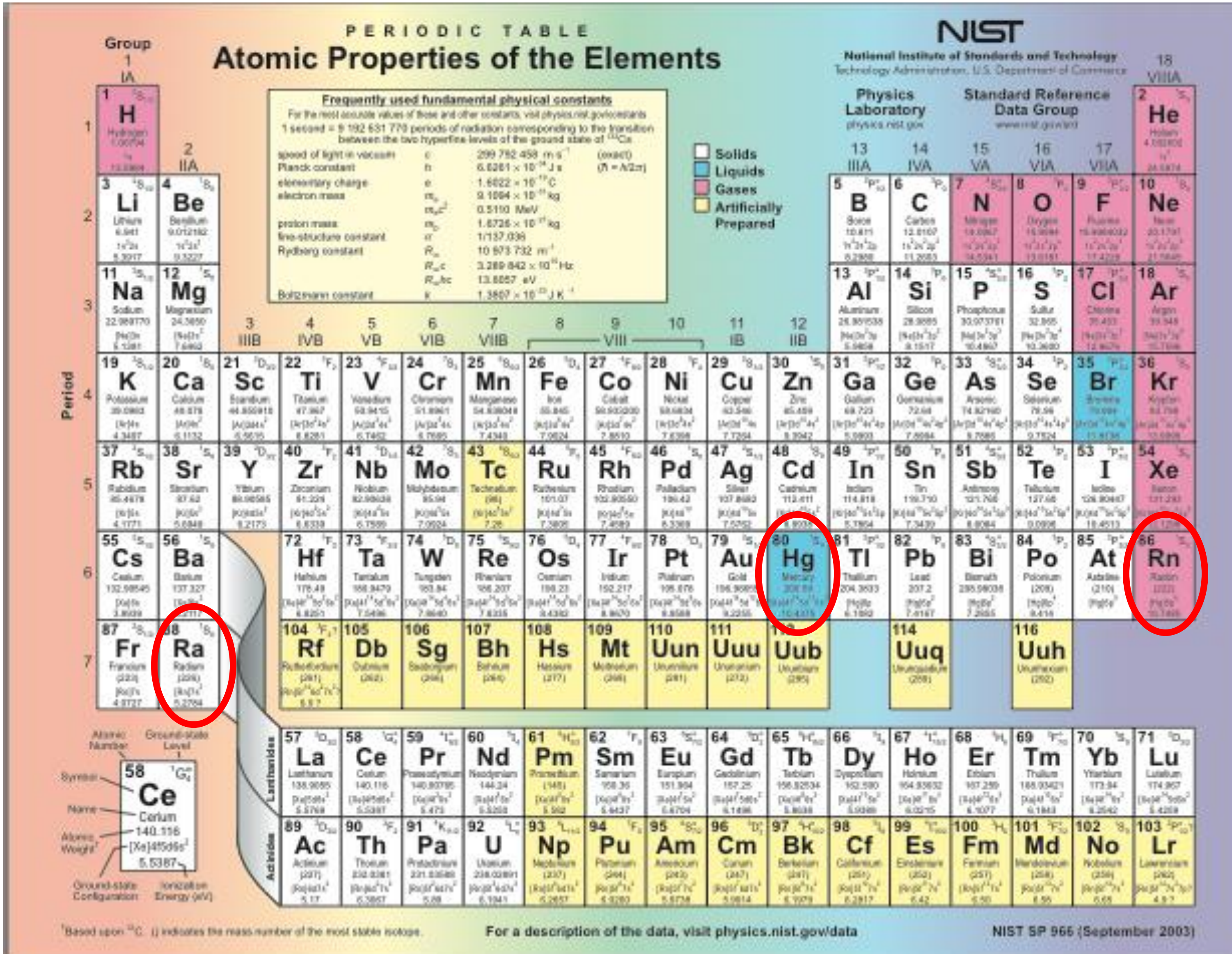
If Hg nucleus is size of earth, then this is two charges separated by 220 pm

Griffith *et al.*, Phys Rev Lett (2009)

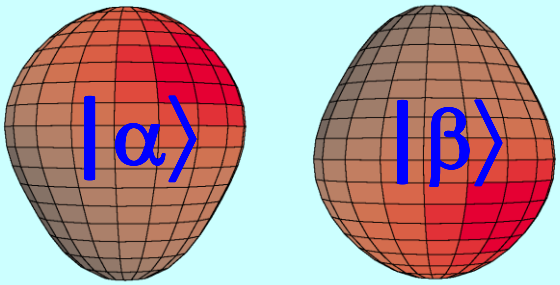
Candidate Nuclei



Candidate Nuclei



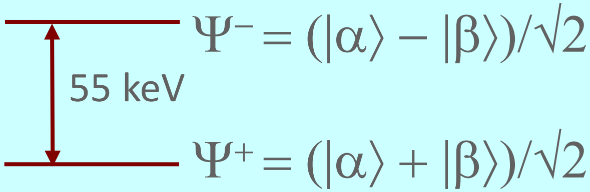
Enhanced EDM Sensitivity in Ra-225



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)

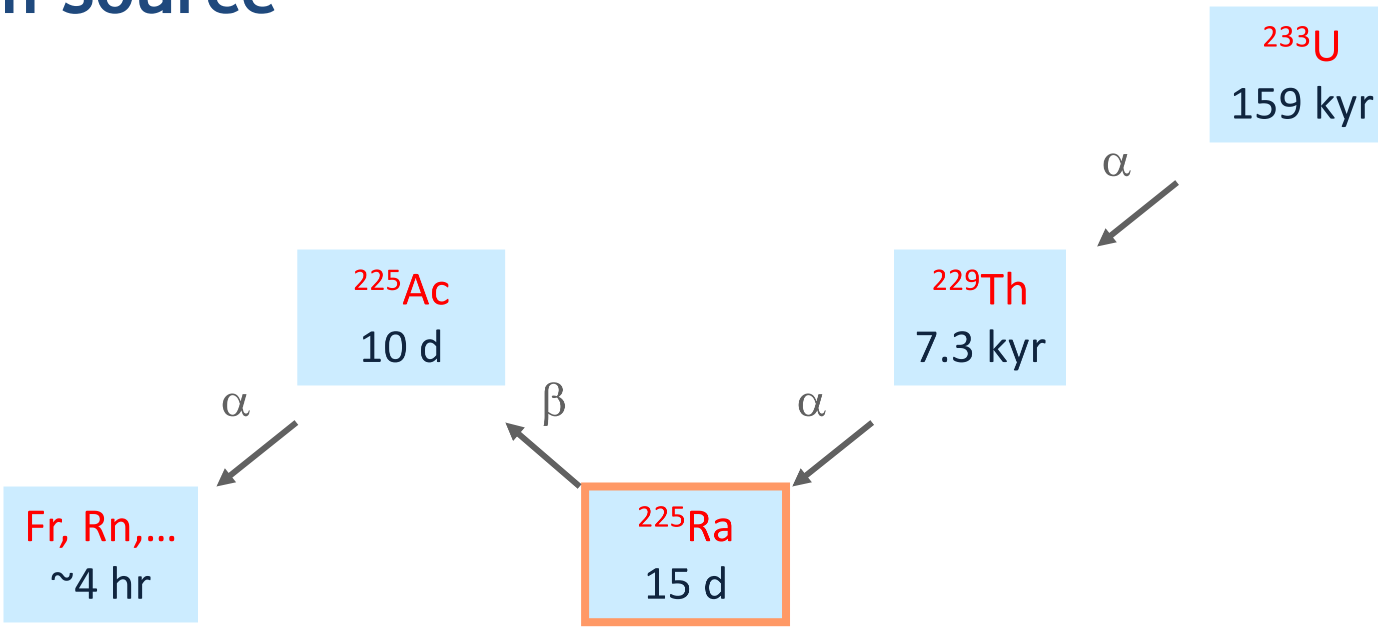
$$S \propto \sum_{i\neq 0} \frac{\left\langle \psi_0 \middle| \hat{S}_z \middle| \psi_i \right\rangle \left\langle \psi_i \middle| \hat{H}_{PT} \middle| \psi_0 \right\rangle}{E_i - E_0} + c.c.$$

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

Skyrme Model	Isoscalar	Isovector	Isotensor
SIII	300	4000	700
SkM*	300	2000	500
SLy4	700	8000	1000

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

Radium Source

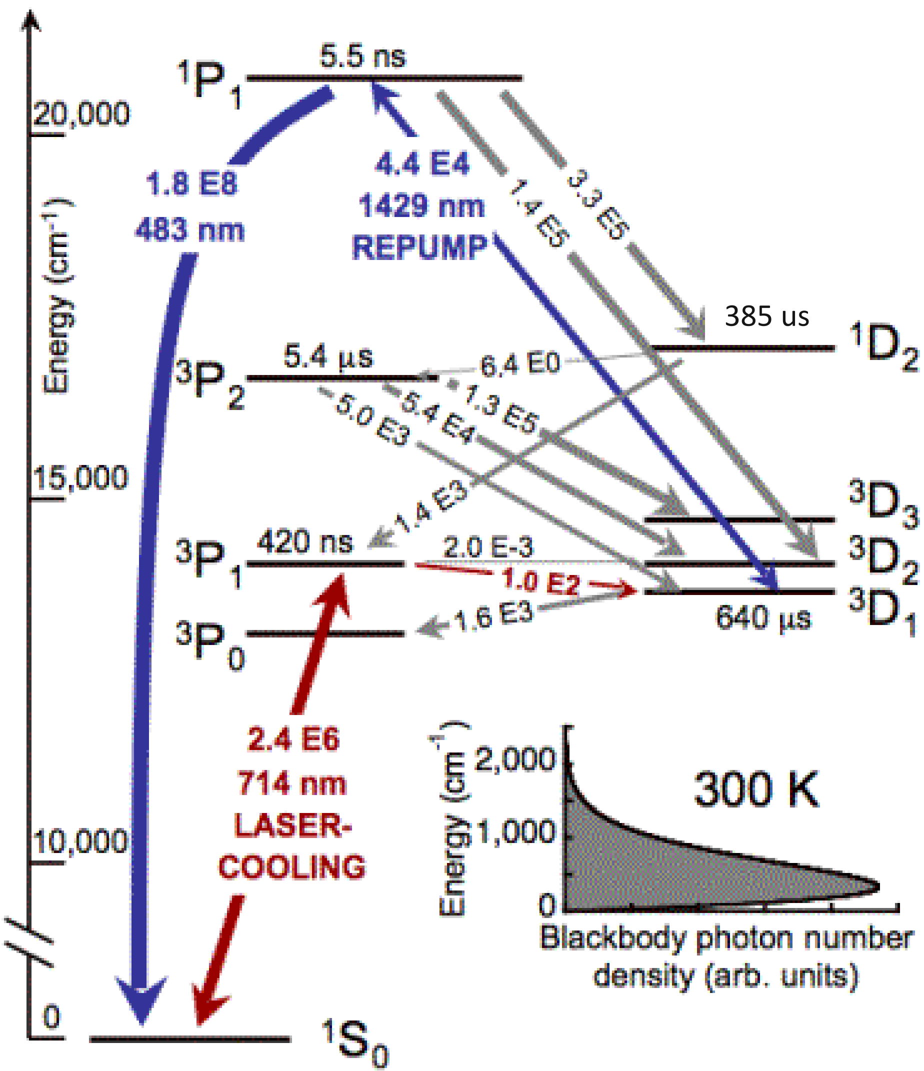


- Up to 30 mCi (750 ng, 2*10^15 atoms) ^{225}Ra sources from:

  National Isotope Development Center (Oak Ridge, TN)

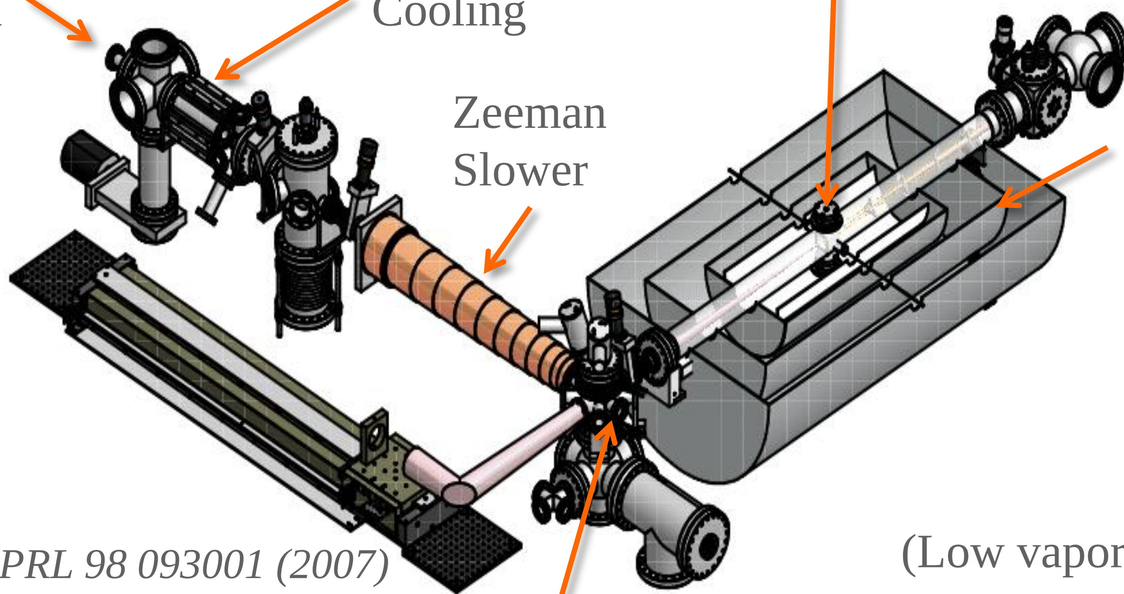
- Test source: 5 μCi (5 μg, 1.3*10^16 atoms) ^{226}Ra
- Integrated Atomic Beam Flux ~ 10^9/s ^{226}Ra, 10^7 – 10^8/s ^{225}Ra
- Special Thanks: John Greene, Angel Garcia, Dave Fieramosca
- Vapor pressure 10^13 cm^{-3}… at 450C

Basic Radium Energy Level Diagram



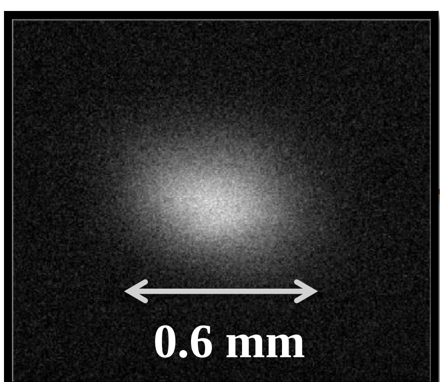
- Level scheme similar to Sr, Yb
- 1P1 state leaky to metastable D states
- Operate instead on intercombination line at 714 nm
- 900 mW 714 nm provided by Ti:Saph, 300 mW 1429 nm provided by pigtailed diode
- Blackbody repumping
- Tremendous DC Stark shift (10^5 a.u)

Collect Atoms in MOT



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

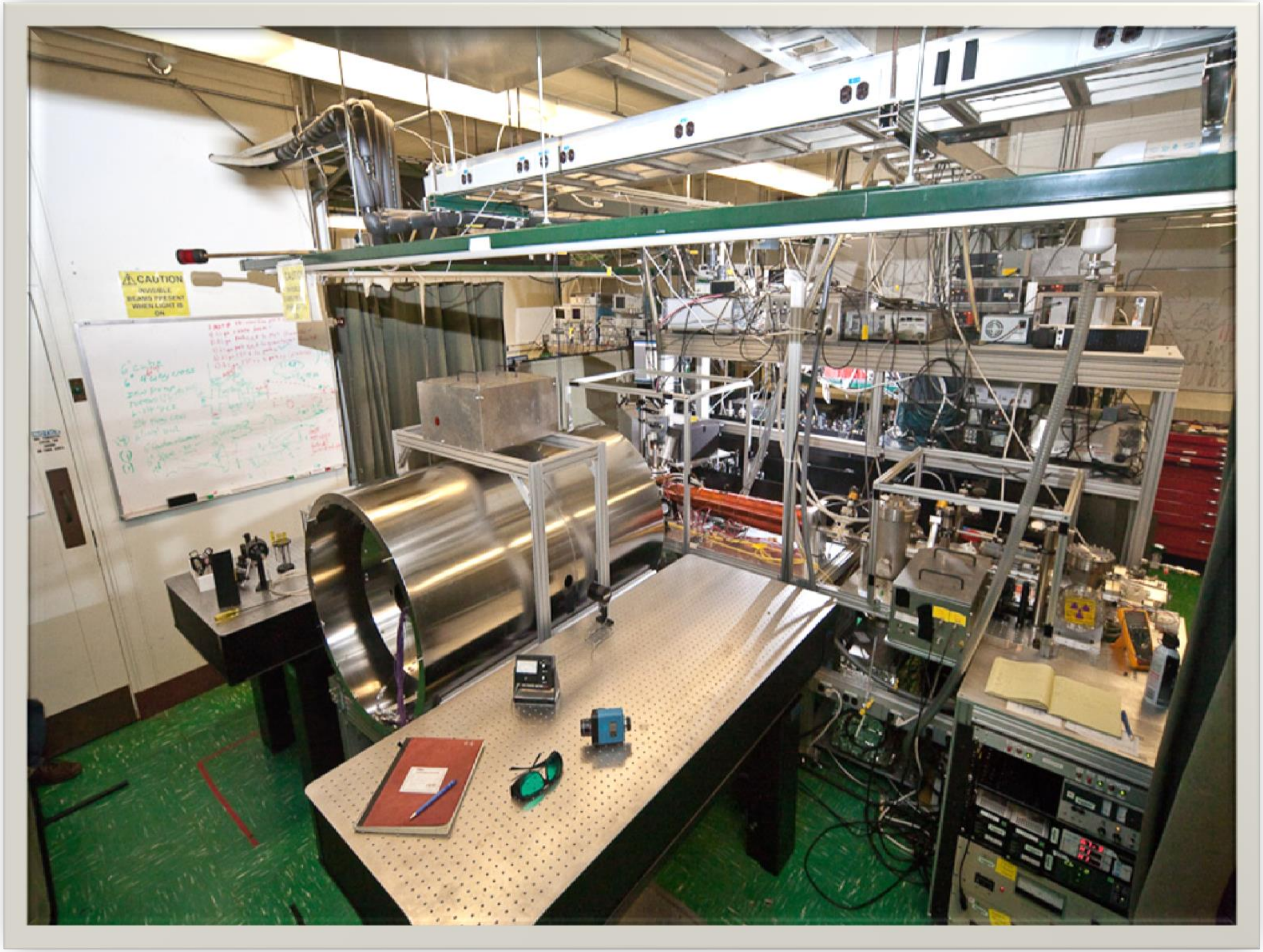
(Low vapor pressure)



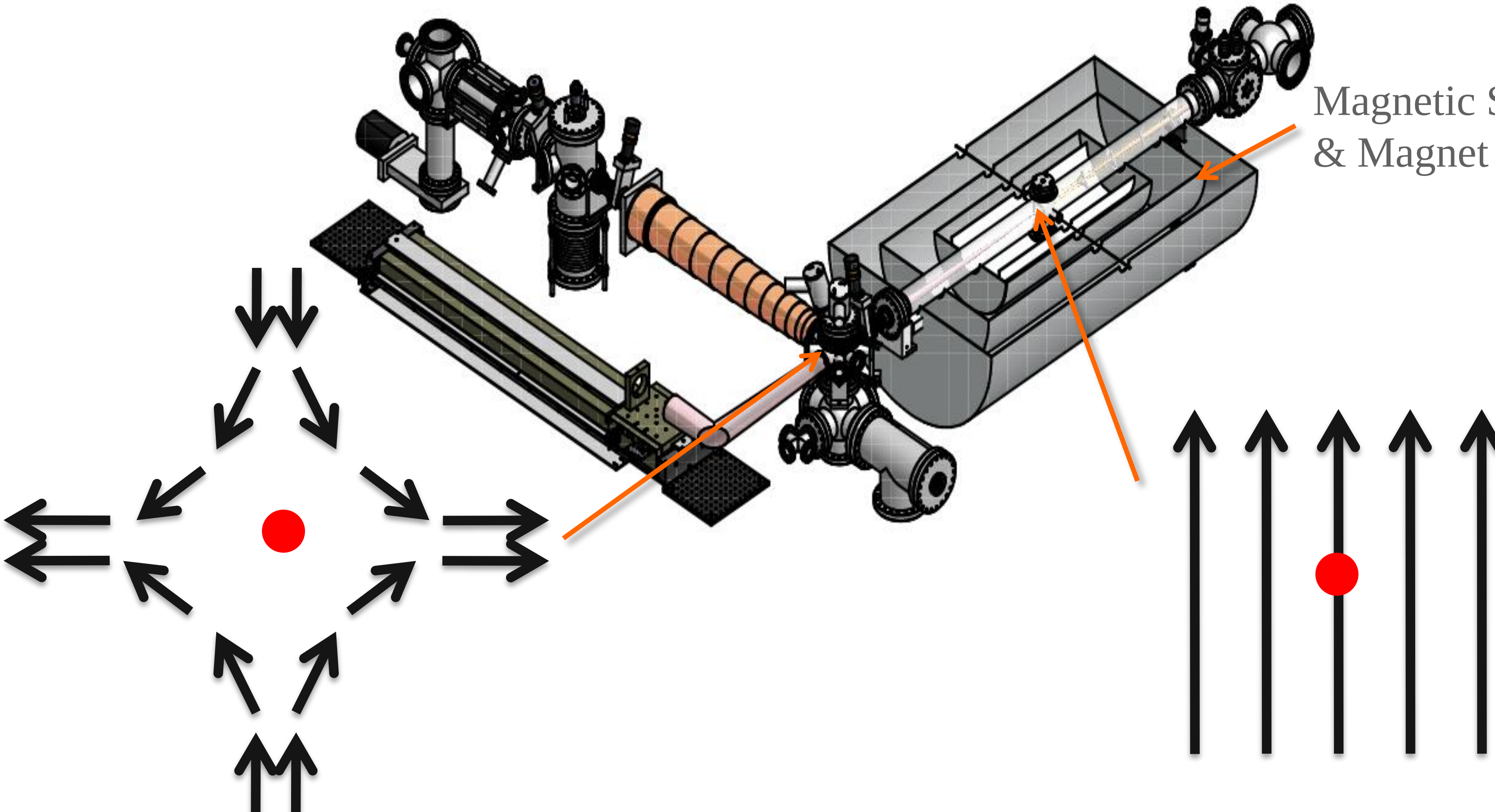
^{226}Ra MOT
20,000 atoms

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

Apparatus



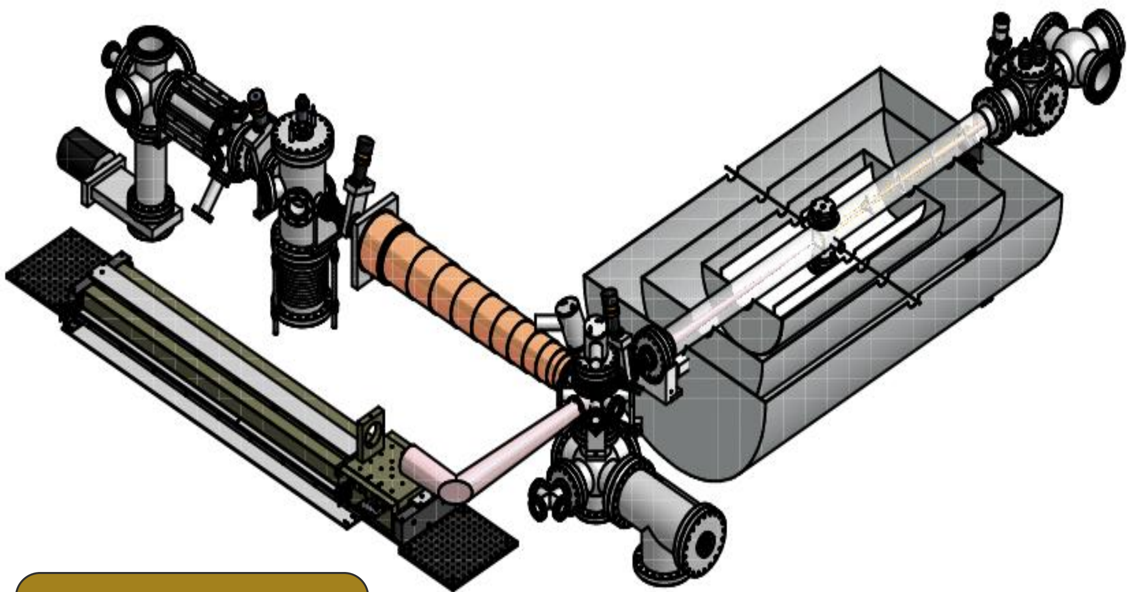
Contradicting Requirements

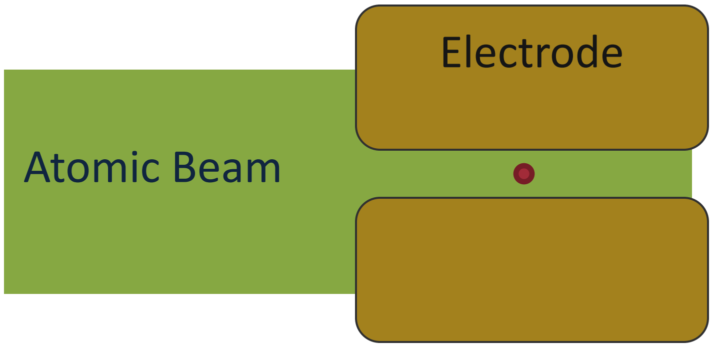


B Field in an EDM Experiment

B Field in a MOT

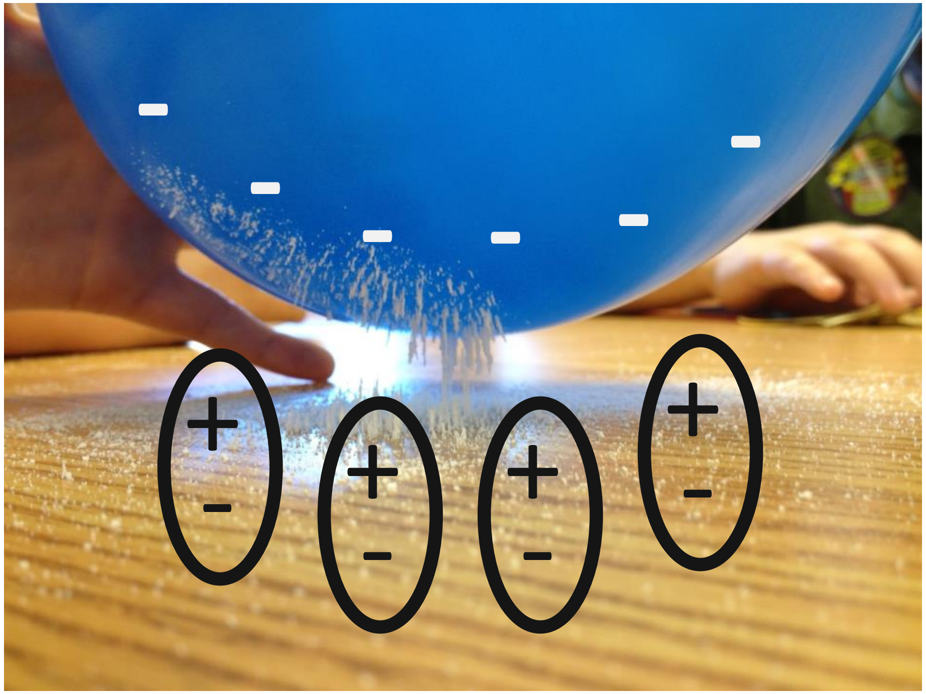
Contradicting Requirements





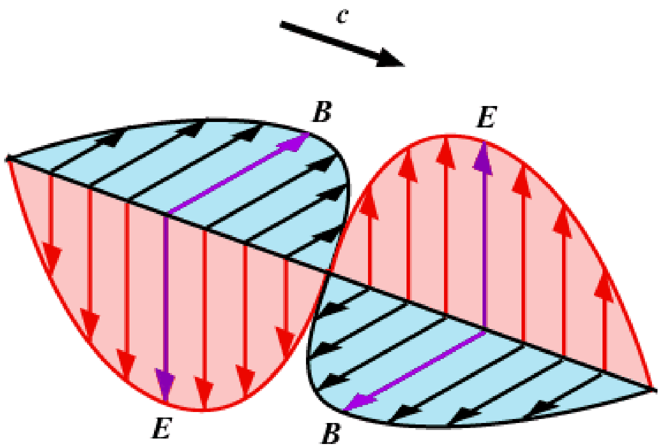
Optical Dipole Traps

Optical Dipole Traps



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

Optical Dipole Traps

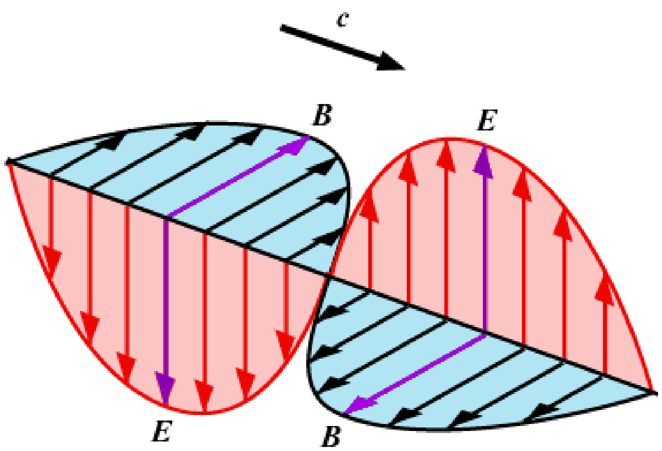


$$U = -\frac{1}{2}\alpha E^2$$

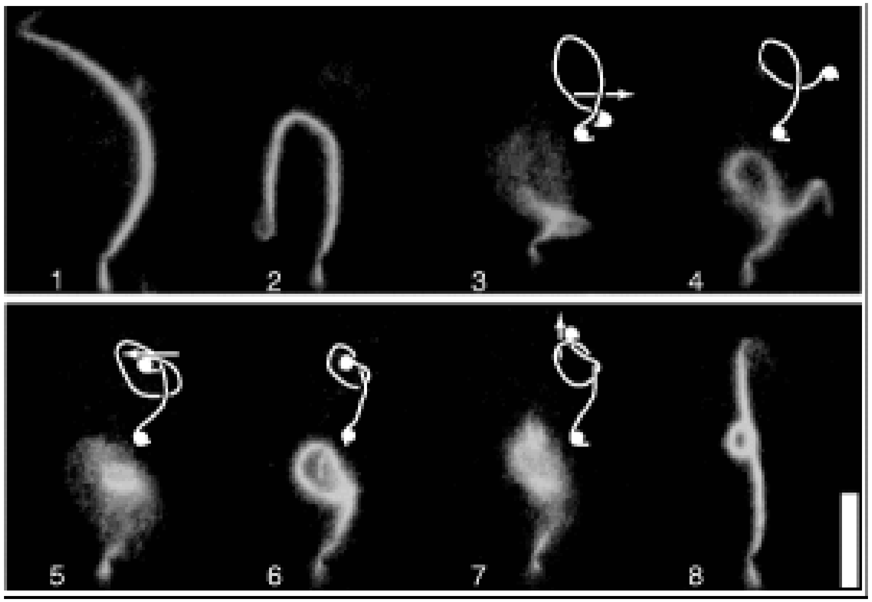
$$= -\frac{1}{2}\alpha \left\langle E^2 \right\rangle$$

$$\propto -I$$

Optical Dipole Traps

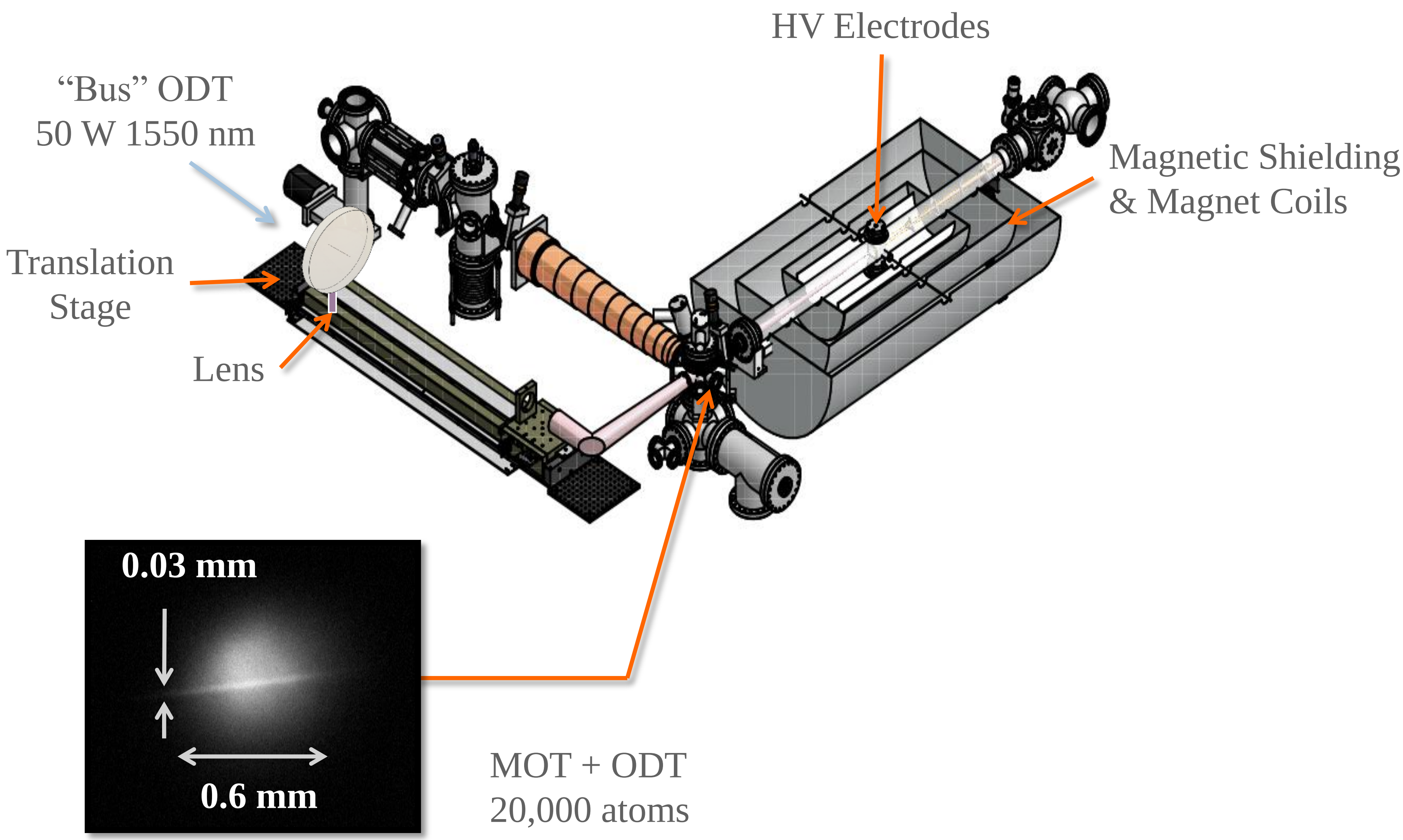


$$U = -\frac{1}{2}\alpha E^2$$
$$= -\frac{1}{2}\alpha \left\langle E^2 \right\rangle$$
$$\propto -I$$



Y. Arai et al., Nature 399, 446 [1999]

Transfer Atoms from MOT to “Bus” ODT



“Bus” ODT Atom Transport to Science Chamber

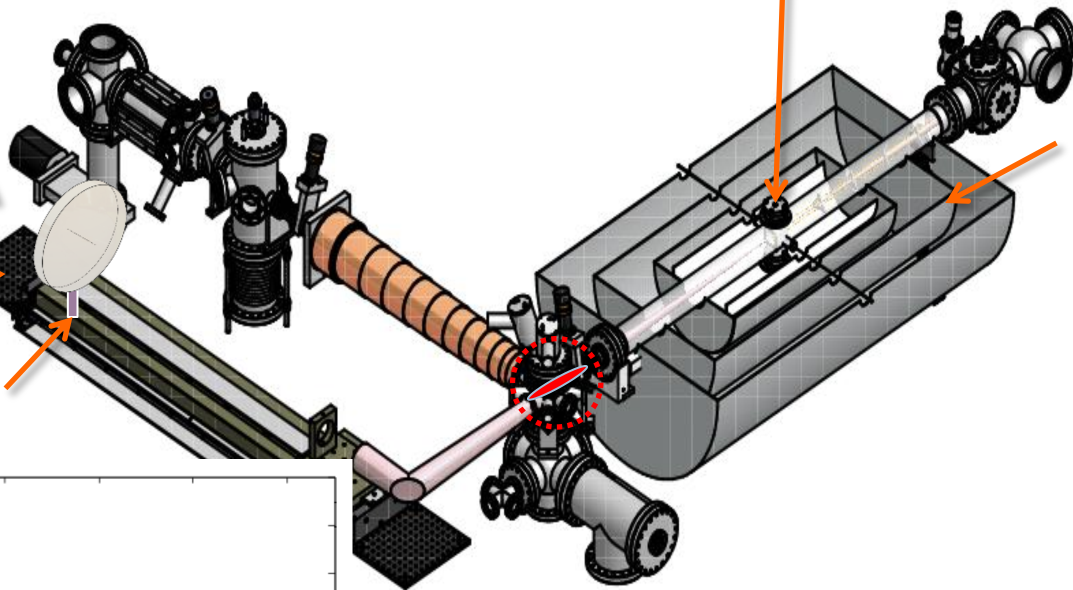
“Bus” ODT
50 W 1550 nm

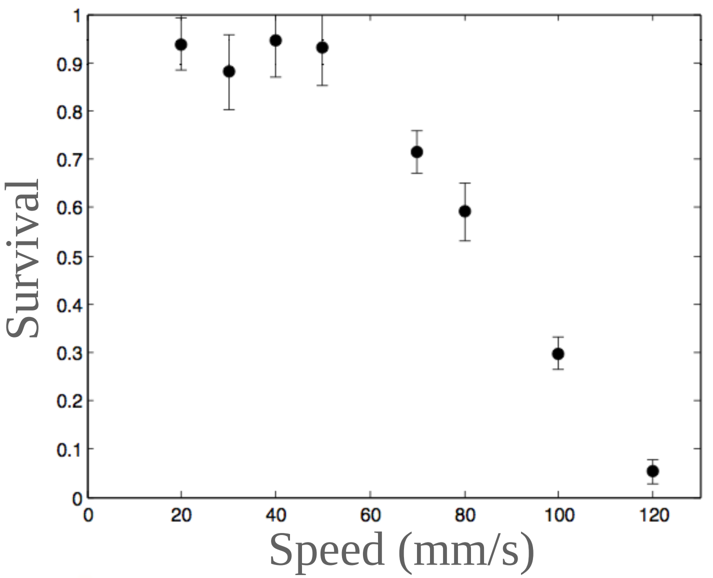
Translation Stage

Lens

HV Electrodes

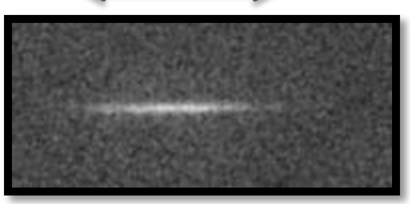
Magnetic Shielding & Magnet Coils





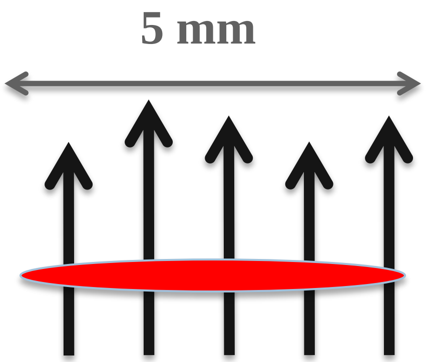
5 mm

6000 atoms

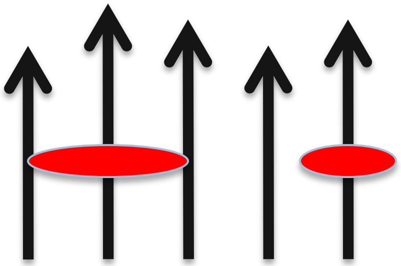


0.03 mm

Unsuitability of Traveling Wave ODT

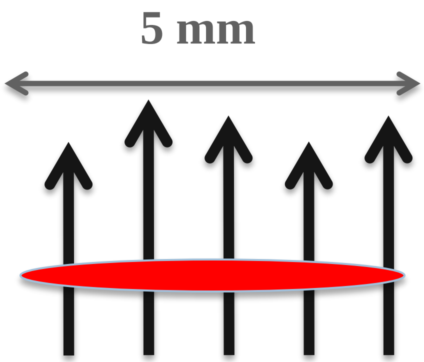


B Field inhomogeneities
Reduced Coherence

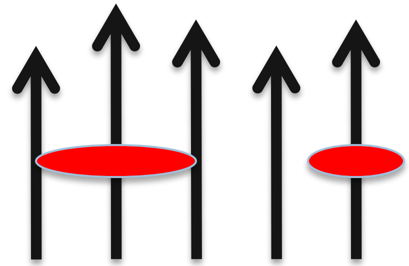


DC Stark Shift
Atom Clumping/Shifting

Unsuitability of Traveling Wave ODT



B Field inhomogeneities
Reduced Coherence



DC Stark Shift
Atom Clumping/Shifting

ϵ ODT E Field Polarization

b ODT B Field Polarization

E Static E Field

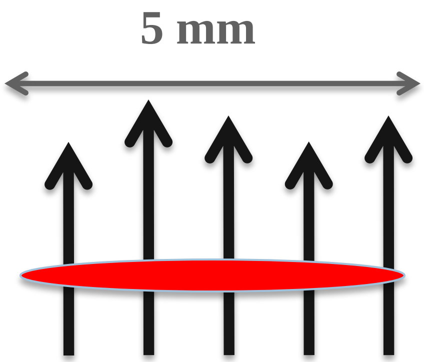
σ Atom Spin

$$(\epsilon \cdot \sigma)(E \cdot b)$$
$$(E \cdot \epsilon)(b \cdot \sigma)$$

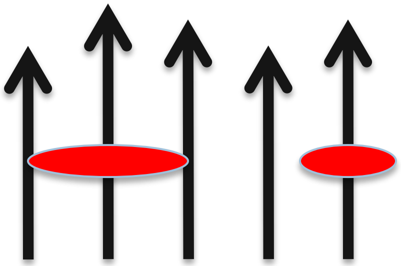
Stark Interference

- ODT electric field interferes with the static E field to produce an EDM like signal
- Effect is suppressed with standing wave
- *M. V. Romalis and N. Fortson, PRA 59, 6 4547 (1999)*

Unsuitability of Traveling Wave ODT



B Field inhomogeneities
Reduced Coherence



DC Stark Shift
Atom Clumping/Shifting

ϵ ODT E Field Polarization

b ODT B Field Polarization

E Static E Field

σ Atom Spin

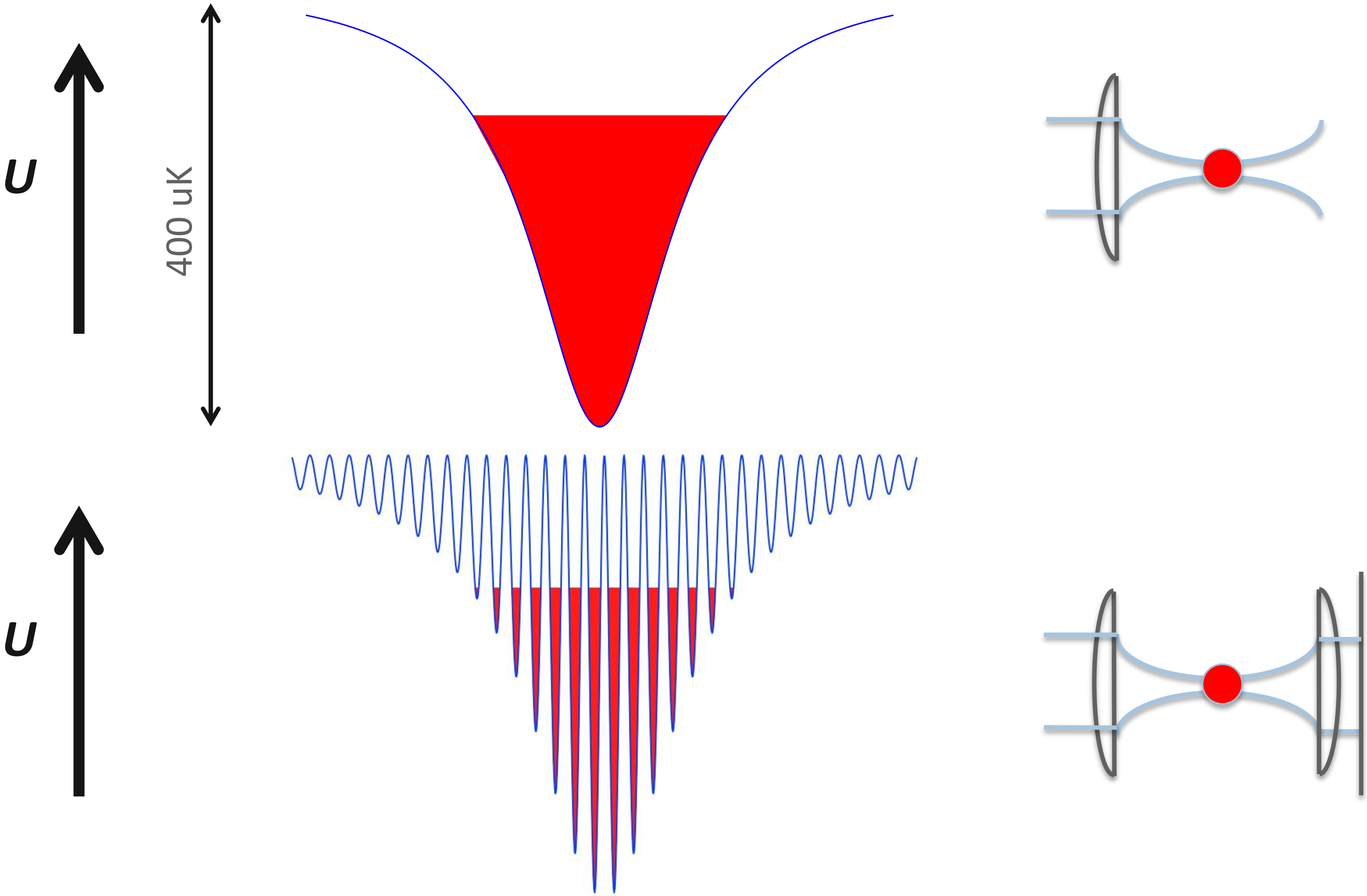
$$(\epsilon \cdot \sigma)(E \cdot b)$$
$$(E \cdot \epsilon)(b \cdot \sigma)$$

Stark Interference

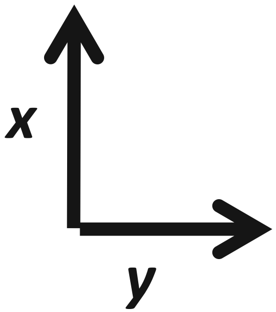
- ODT electric field interferes with the static E field to produce an EDM like signal
- Effect is suppressed with standing wave
- *M. V. Romalis and N. Fortson, PRA 59, 6 4547 (1999)*

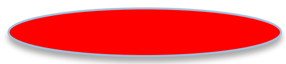
Solution: Standing Wave ODT

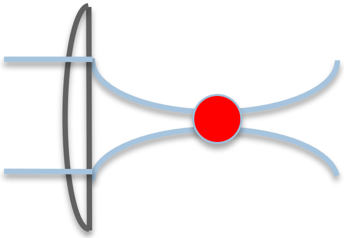
Standing and Traveling Wave

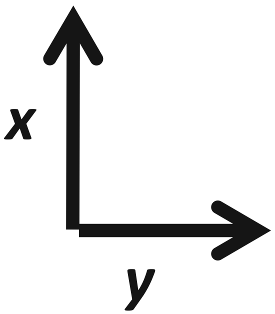


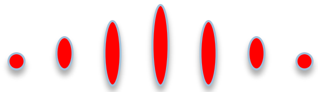
Standing and Traveling Wave

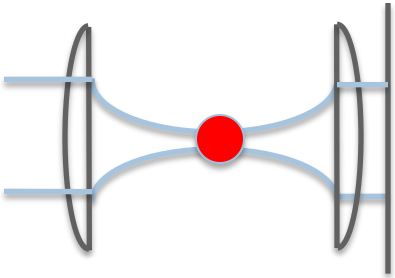








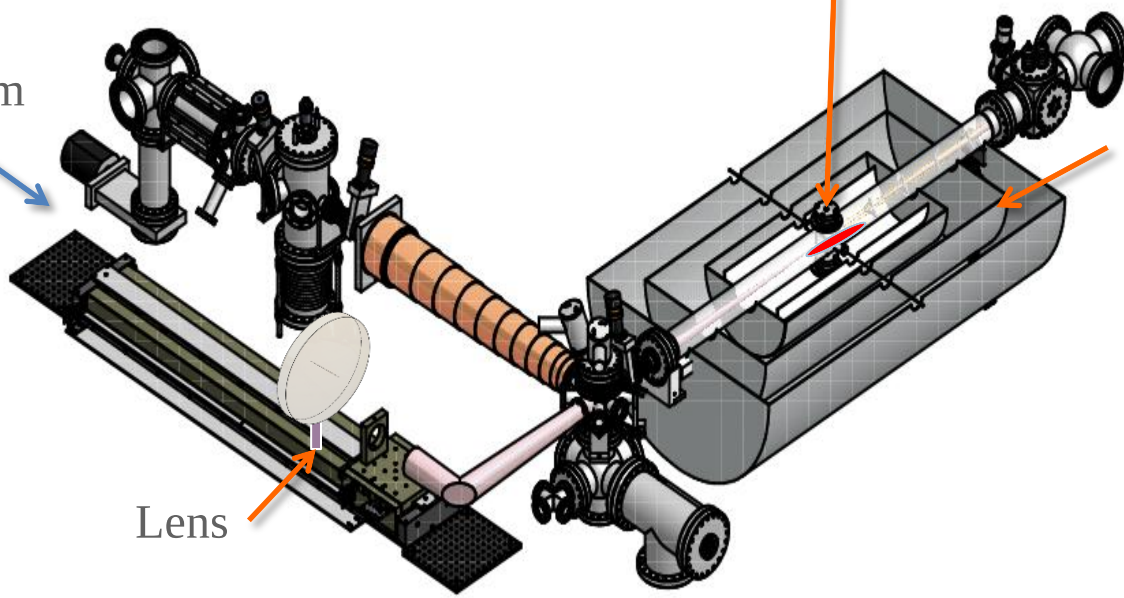




Transfer Atoms from “Bus” to “Holding” ODT

HV Electrodes

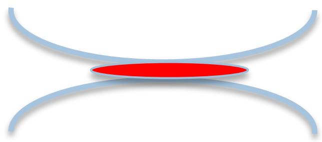
“Bus” ODT
50 W 1550 nm



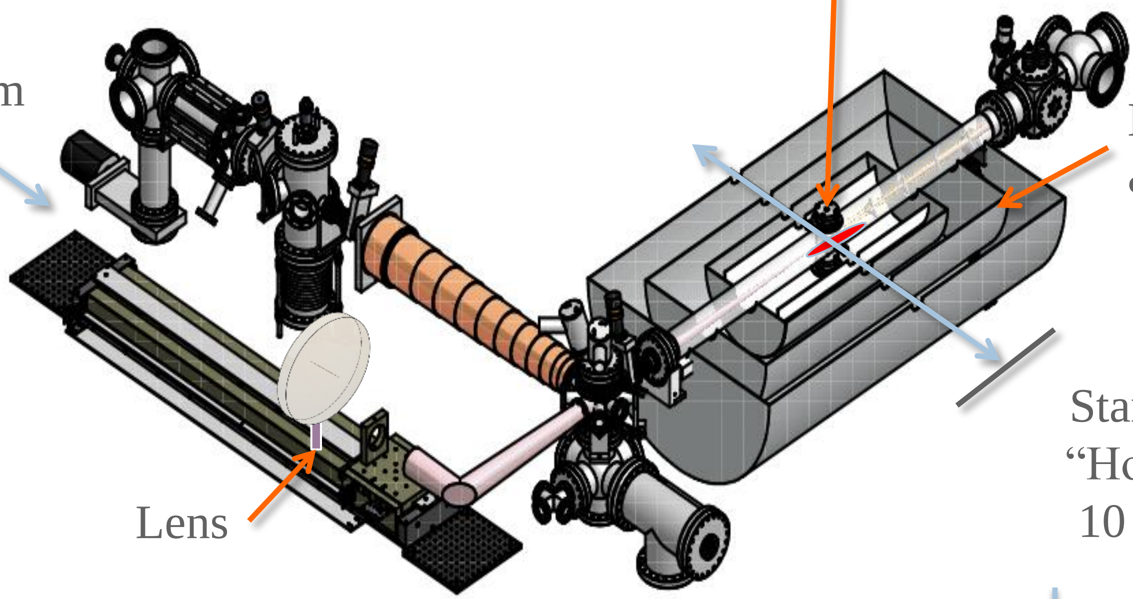
Magnetic Shielding
& Magnet Coils

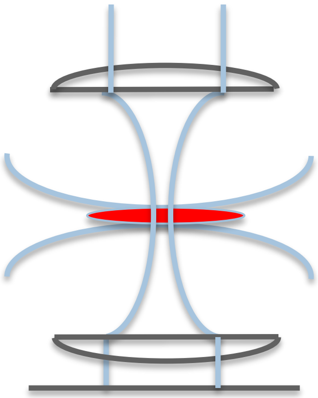
Lens

Traveling Wave
“Bus” ODT

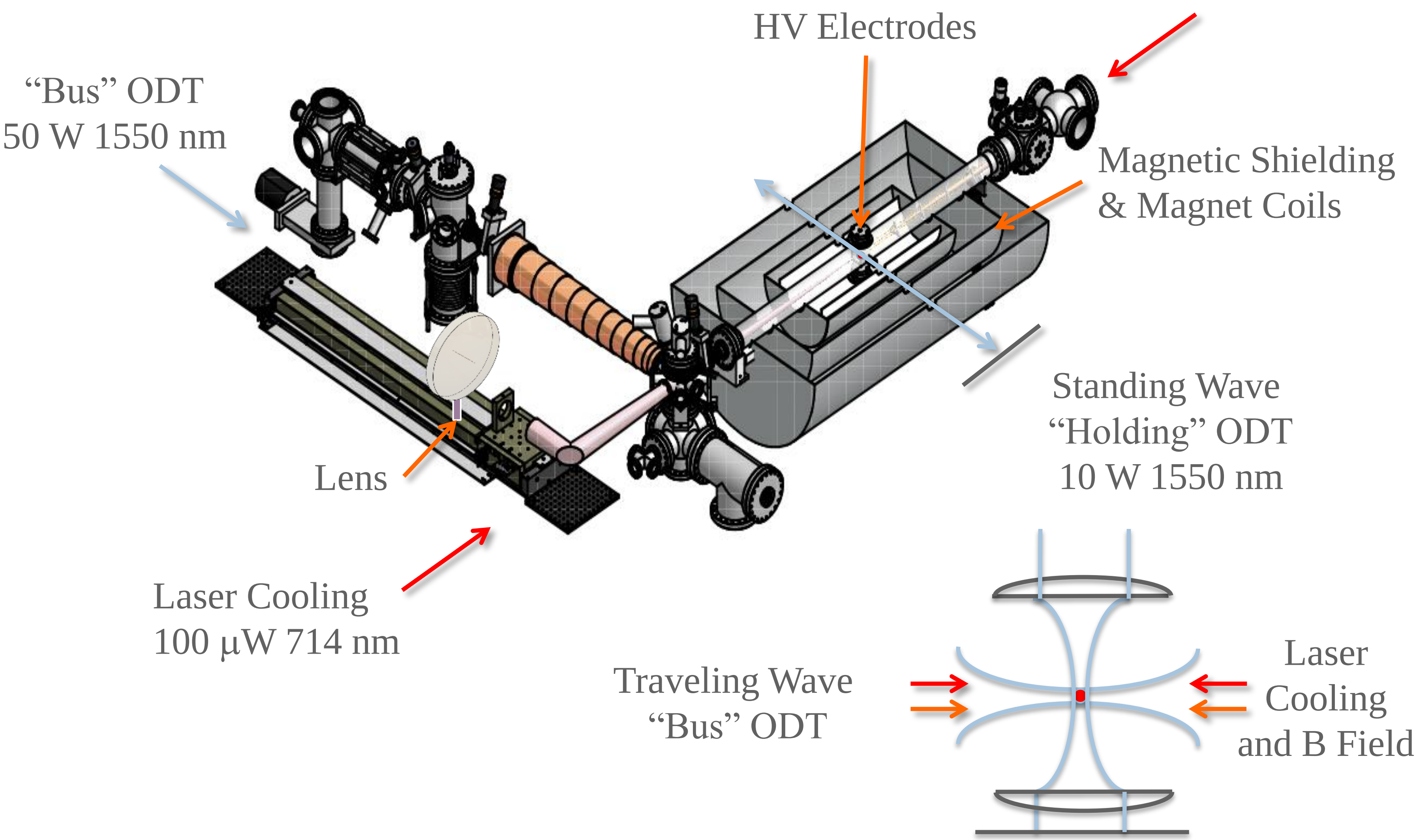


Transfer Atoms from "Bus" to "Holding" ODT

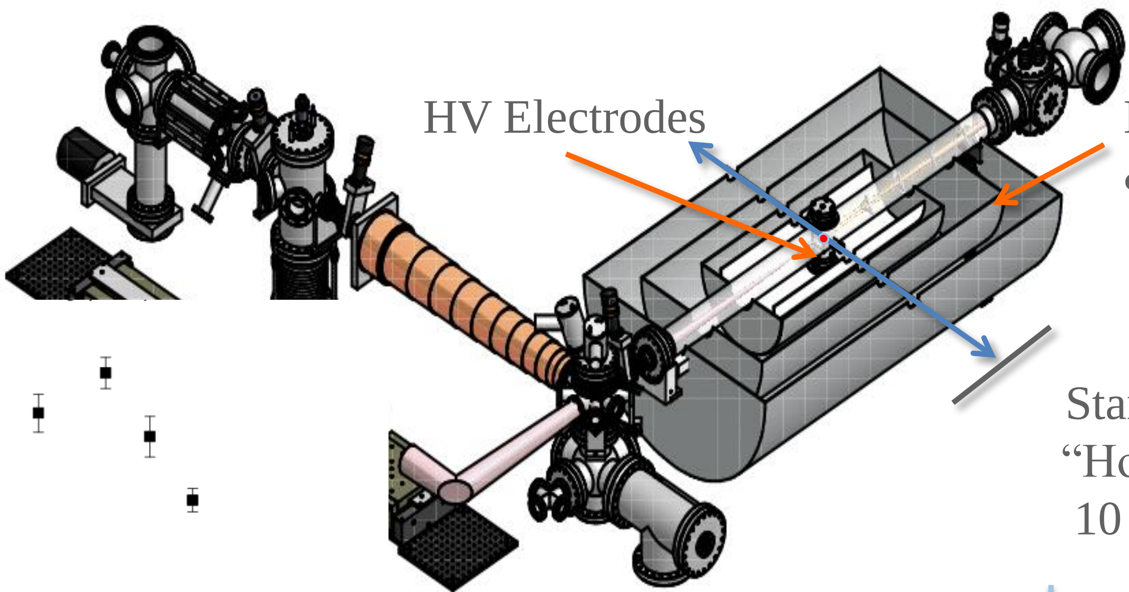


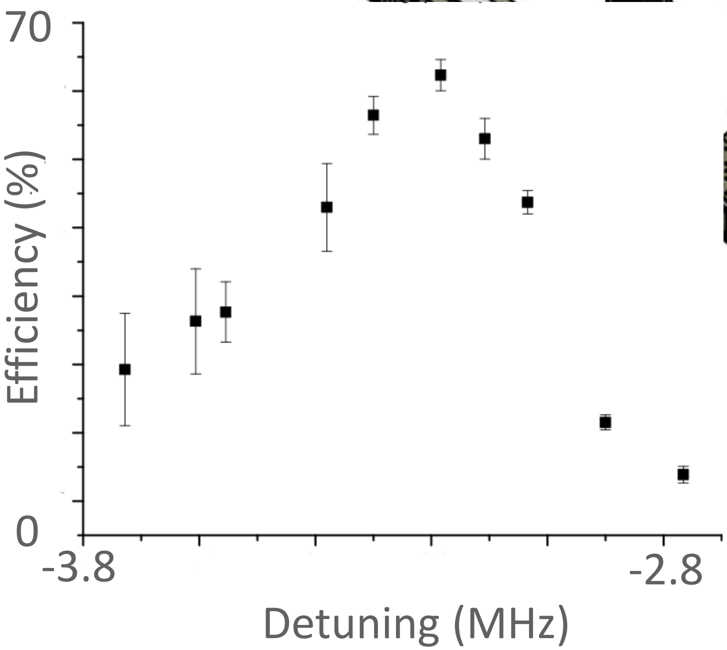


Transfer Atoms from “Bus” to “Holding” ODT

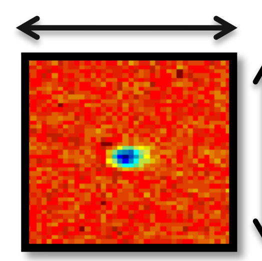


Transfer Atoms from “Bus” to “Holding” ODT



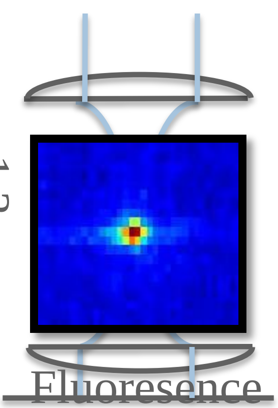


R. H. Parker *et al.*, PRC **86**, 065503



700 atoms
1.4% abs

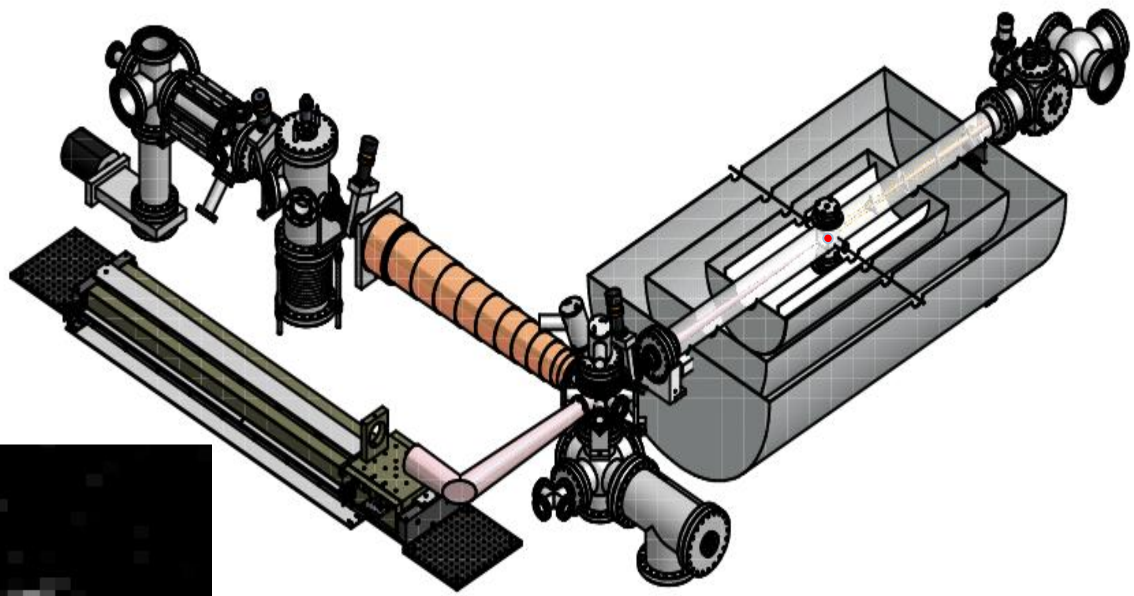
Absorption
Imaging

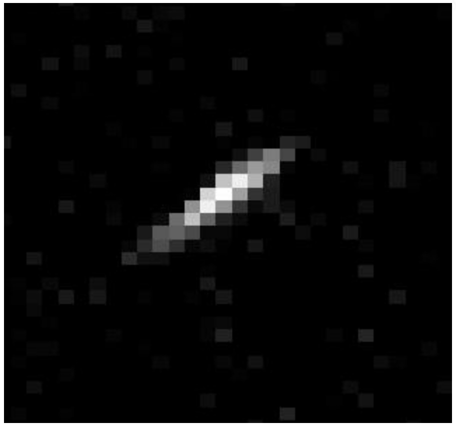


3000
atoms
10^{10} cm^{-3}

Fluoresence
Imaging

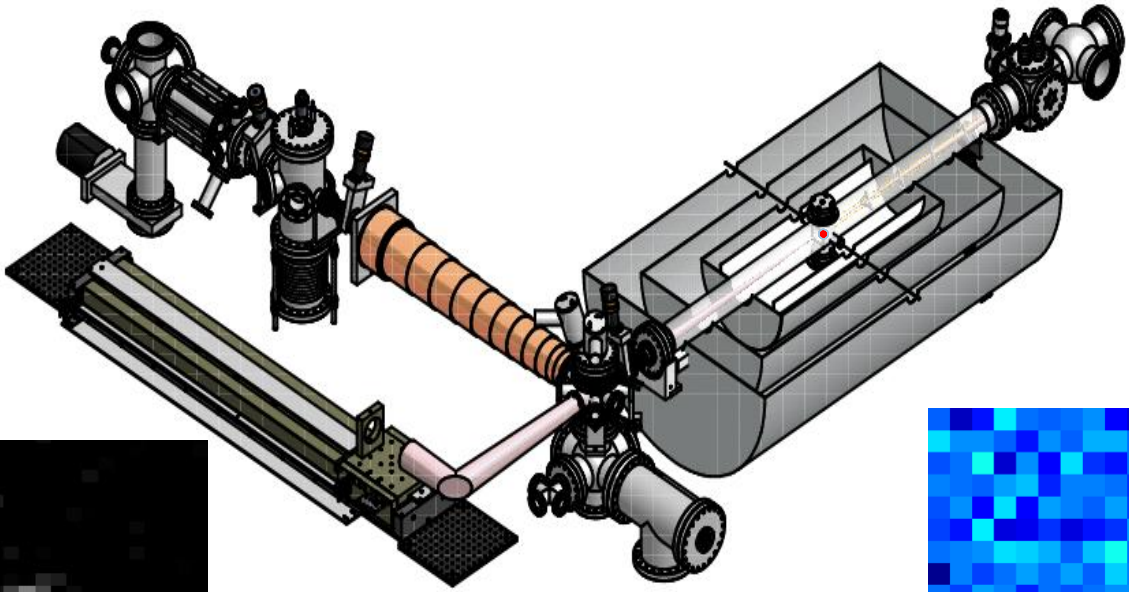
Ra-225 Trapping and Transport

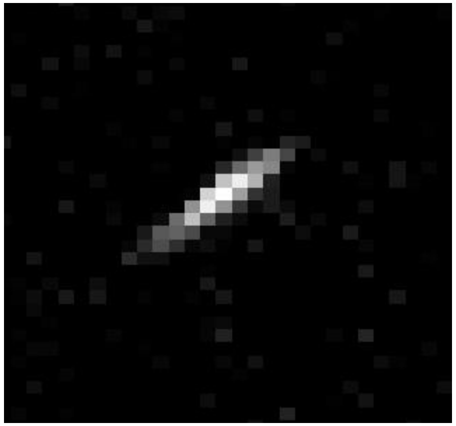




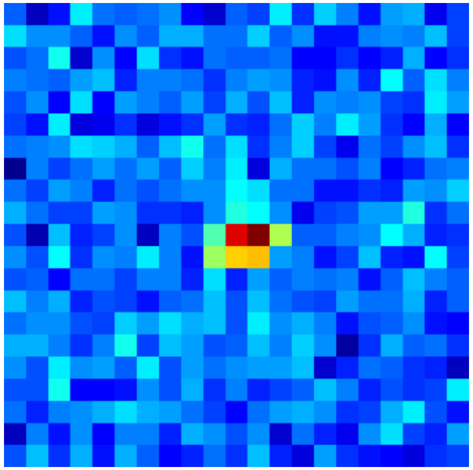
~100-200 Ra-225 Atoms in Bus ODT

Ra-225 Trapping and Transport



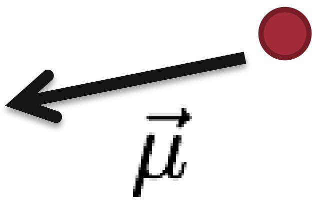


~100-200 Ra-225 Atoms in Bus ODT

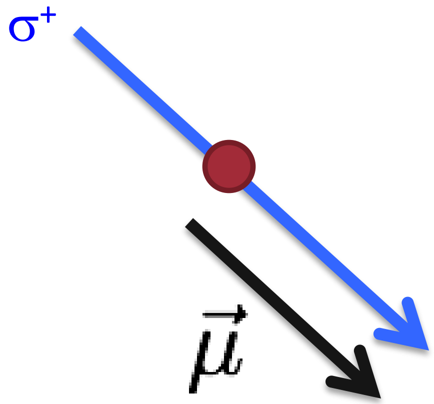


~50-100 Ra-225 Atoms in Holding ODT

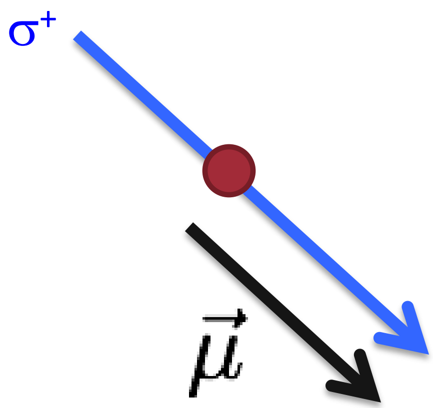
Optical Pumping

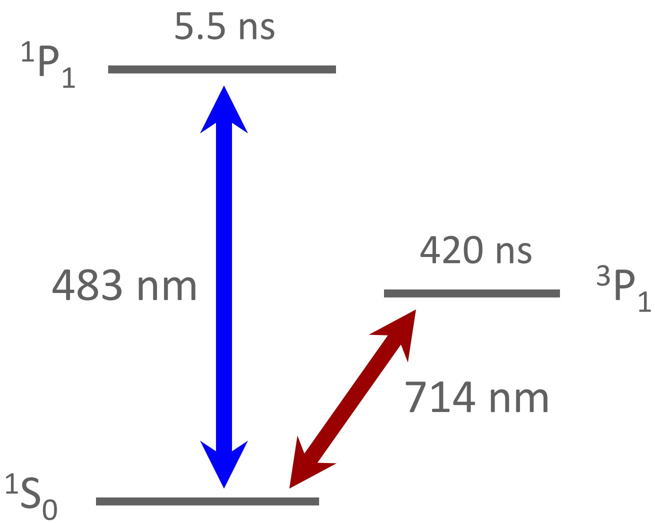


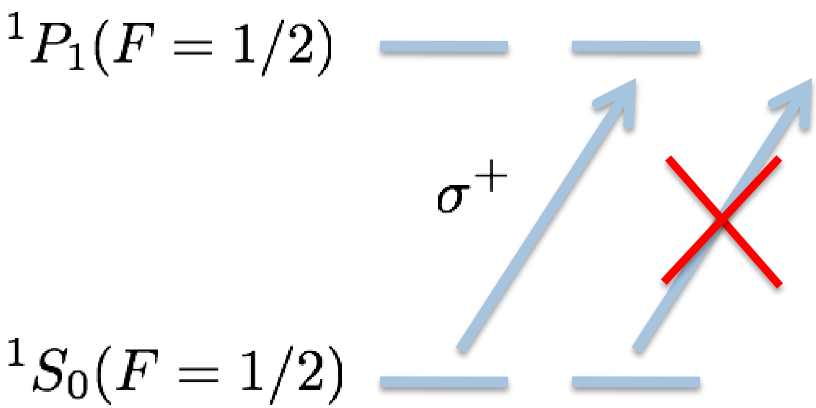
Optical Pumping



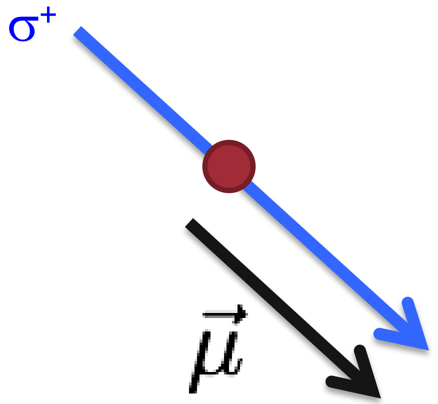
Optical Pumping

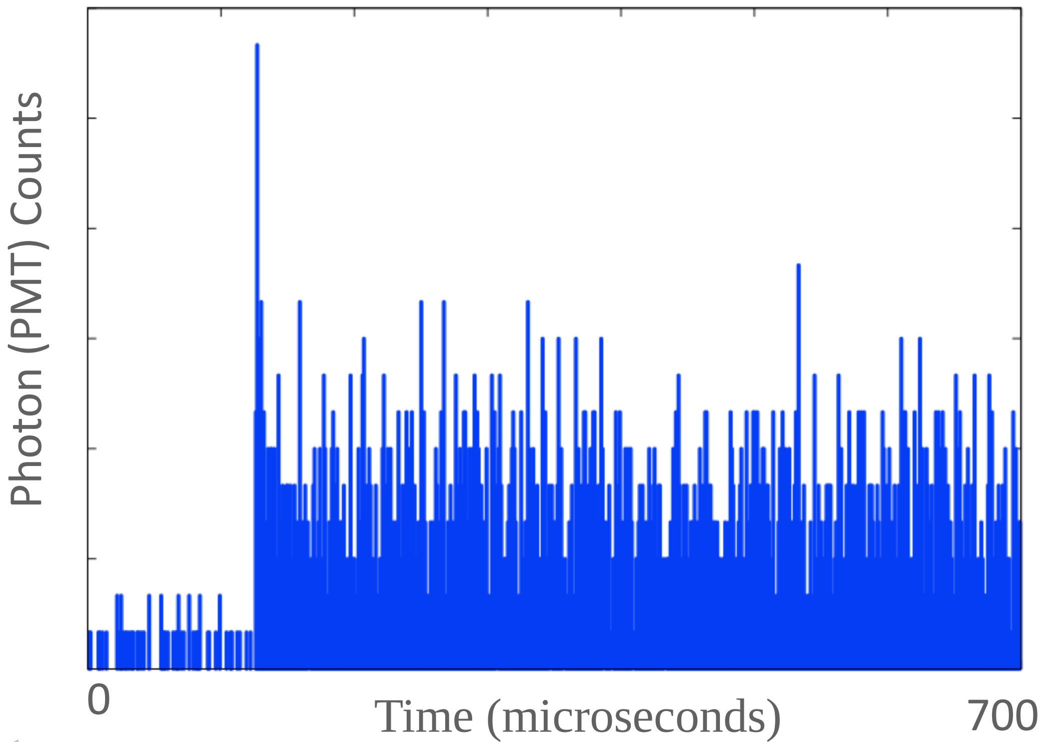


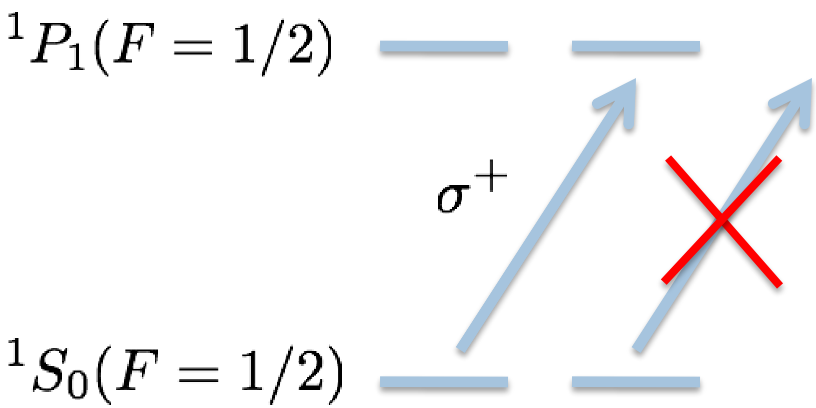




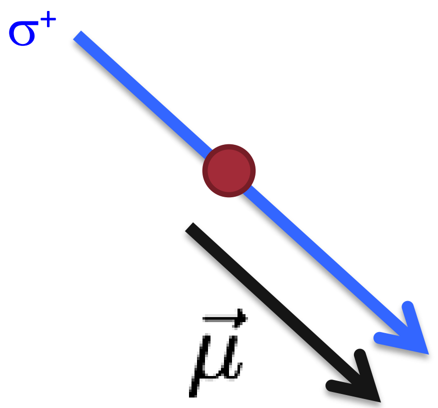
Optical Pumping

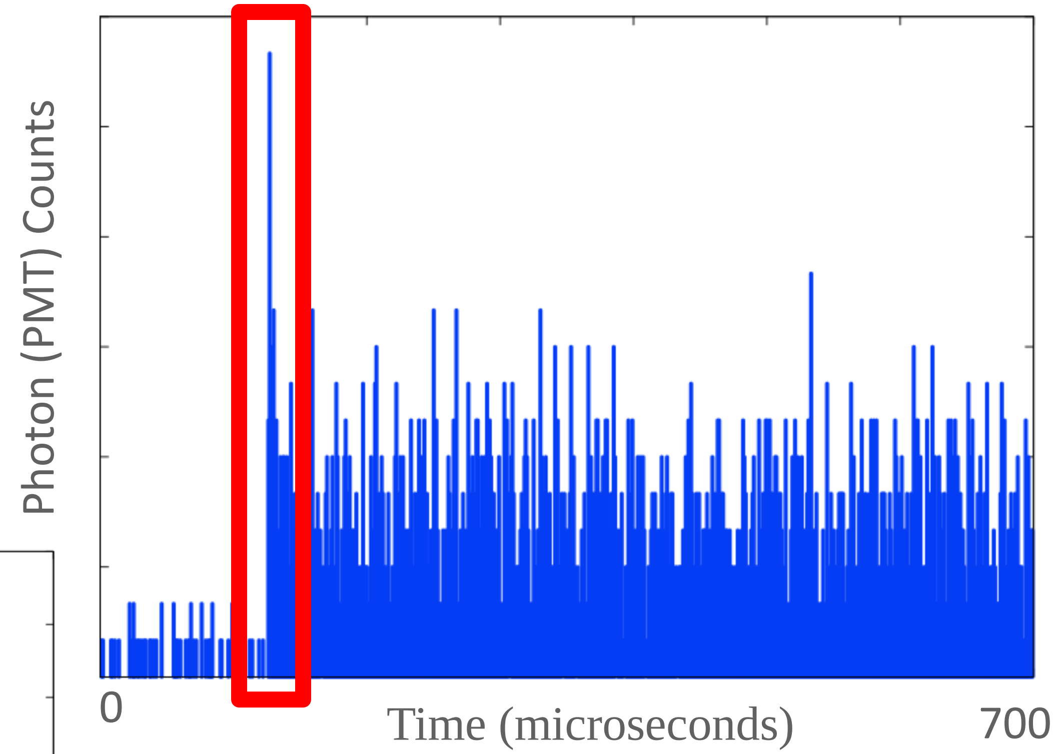


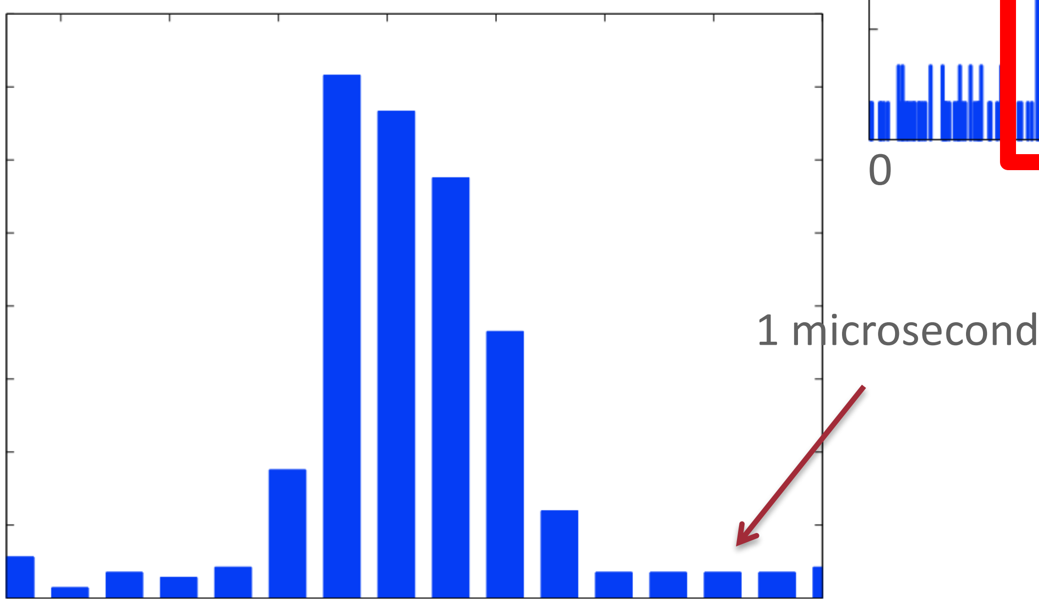




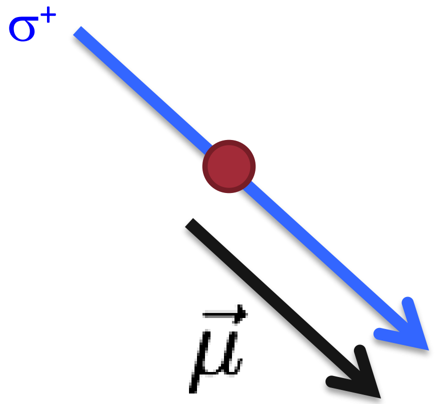
Optical Pumping

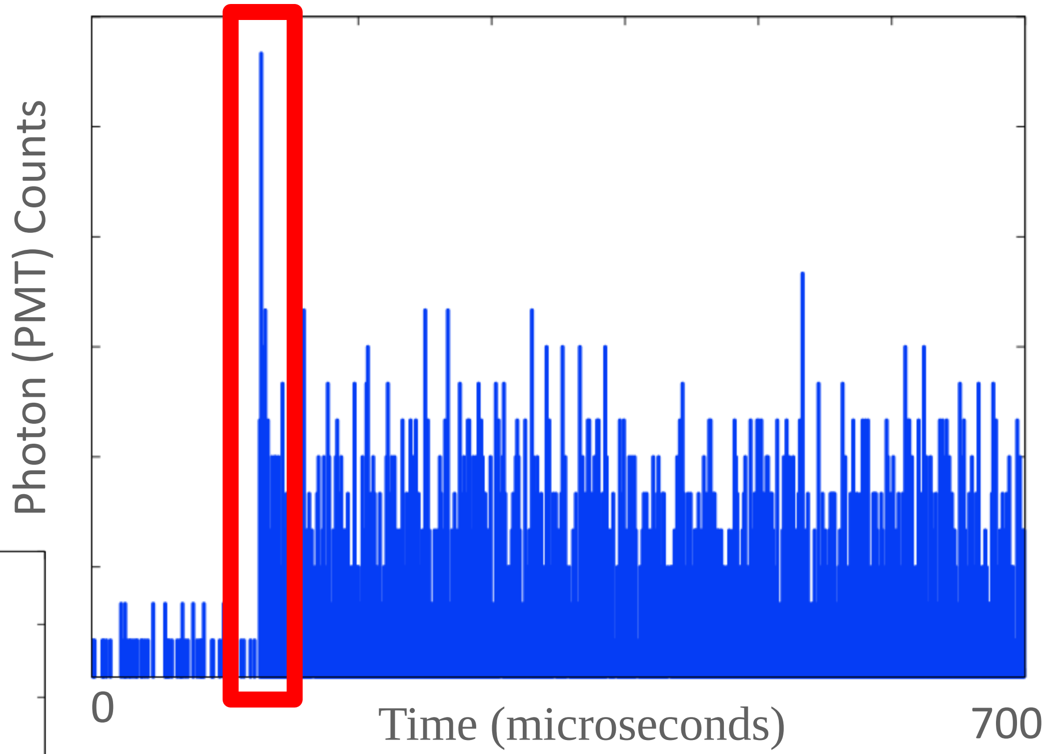


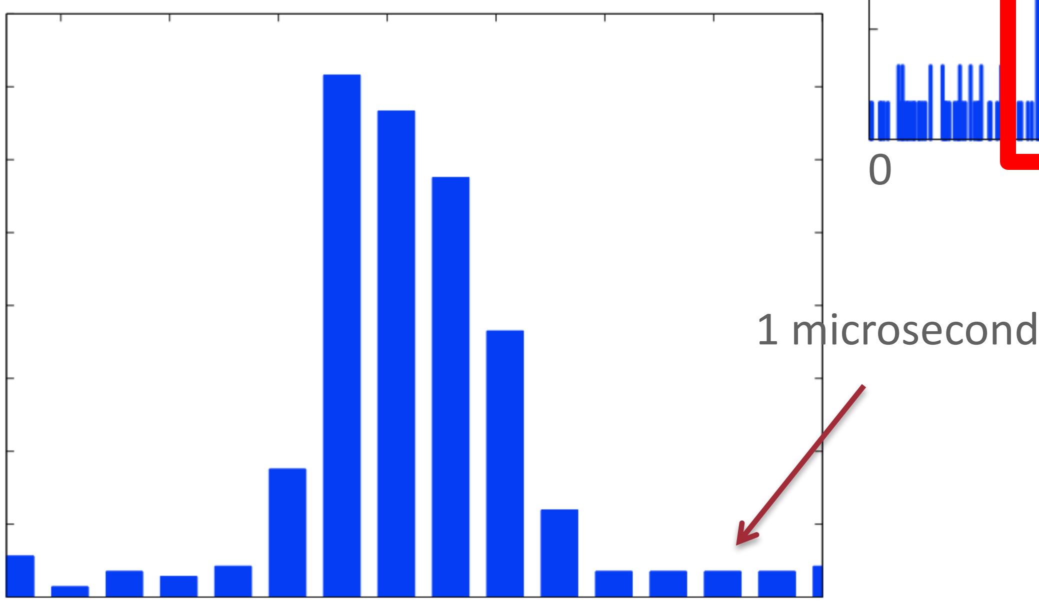


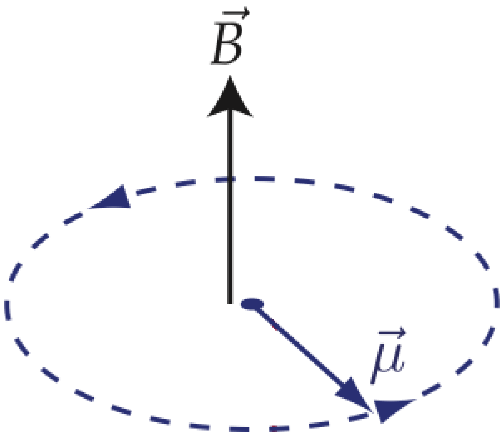


Optical Pumping

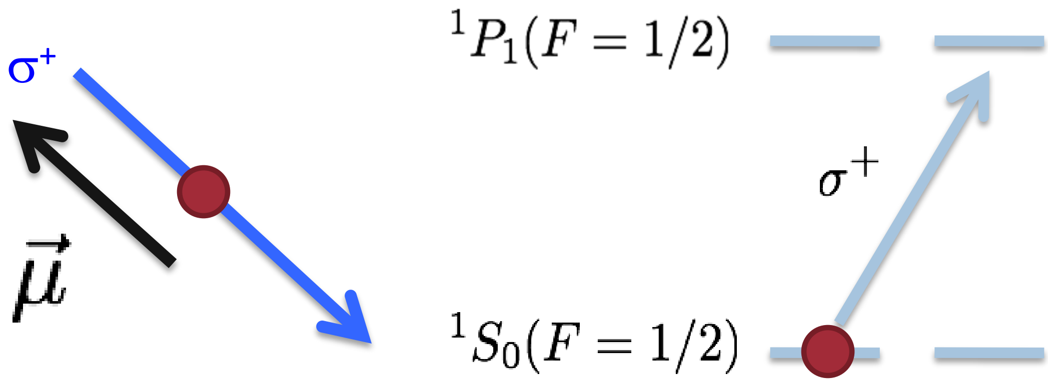


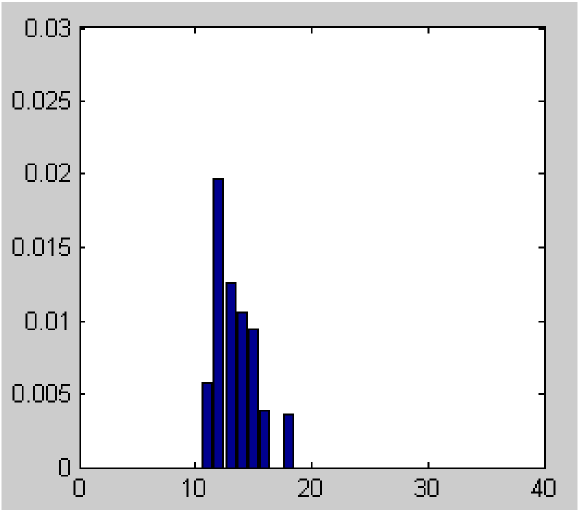




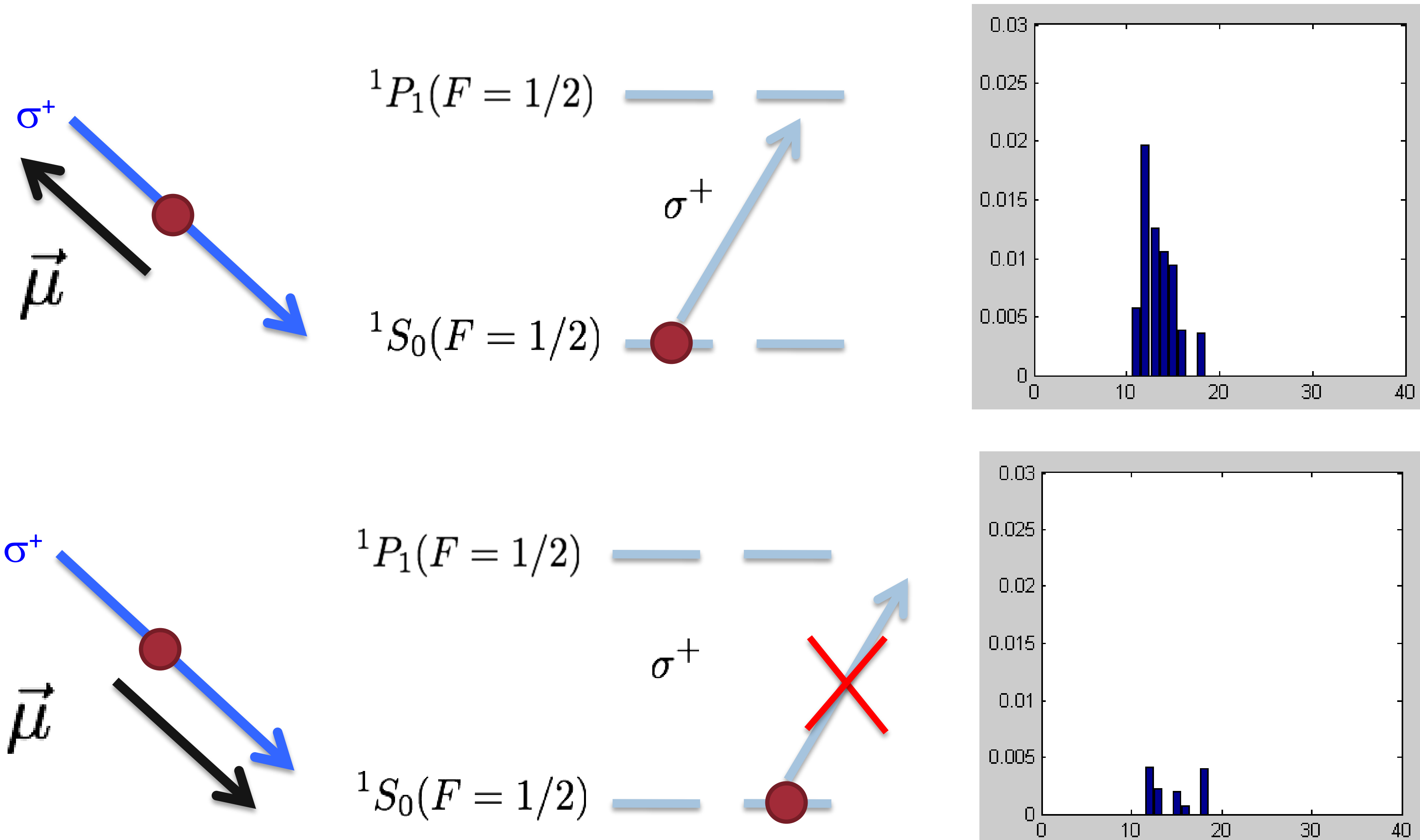


Optical Pumping and State Detection



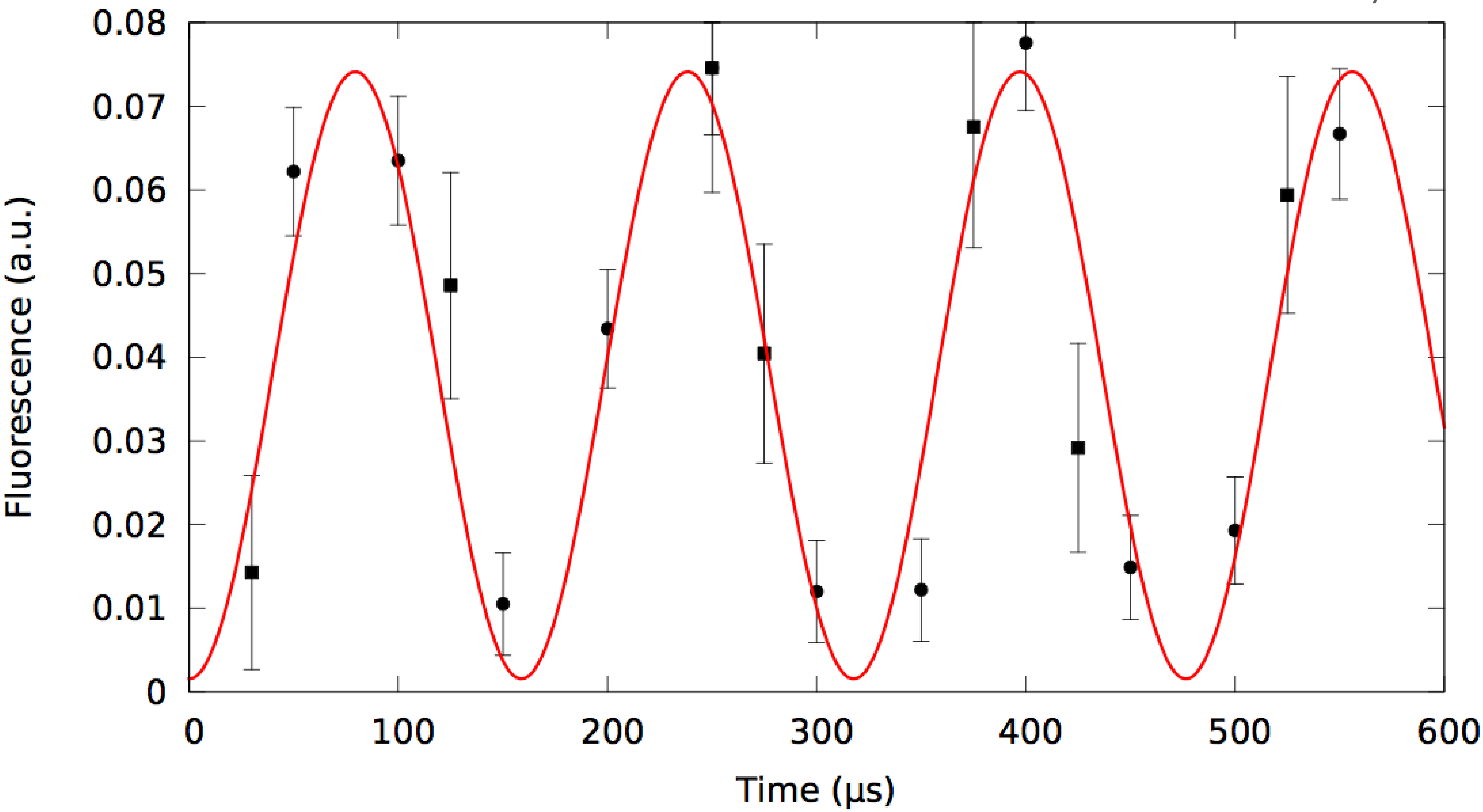


Optical Pumping and State Detection

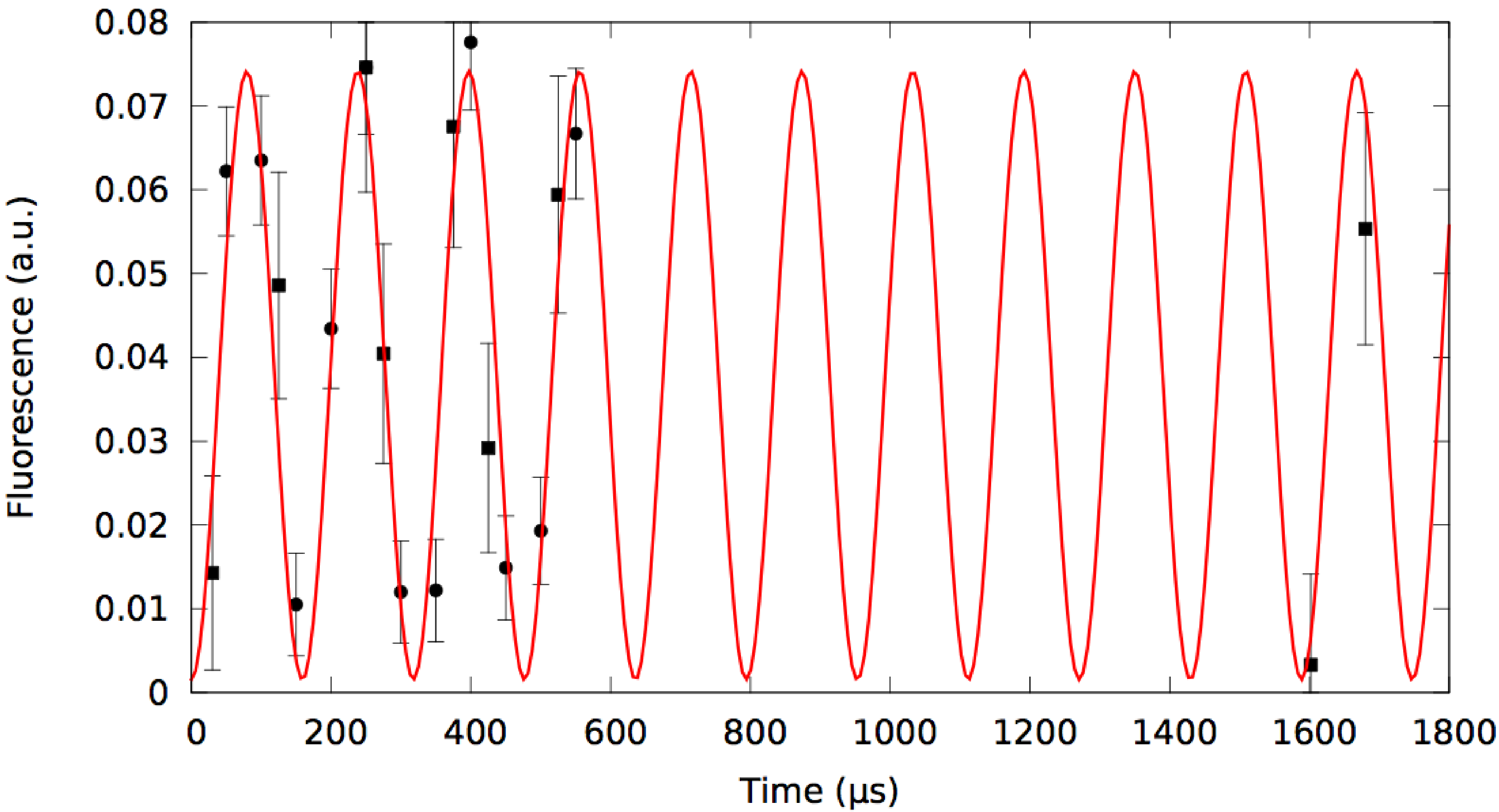


Precession of Radium 225

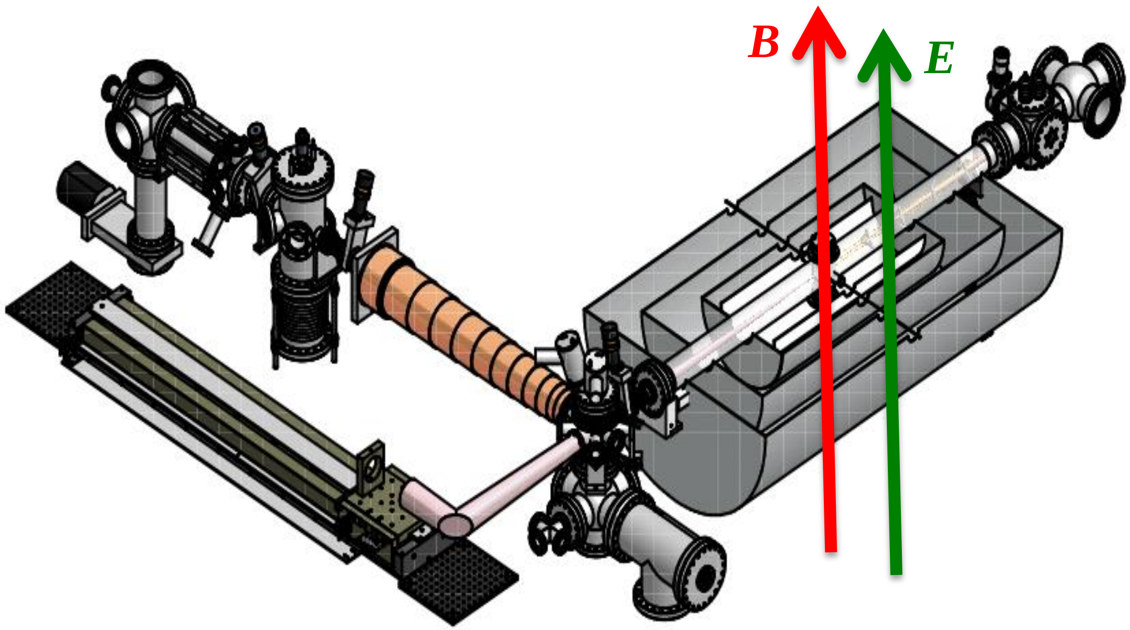
Polarization 96(10)%
Frequency 6.30(4) kHz
Reduced Chi2 19.0/15

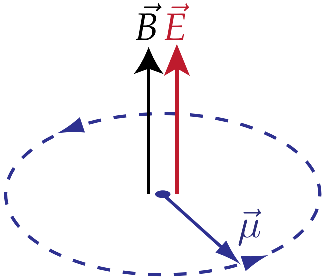


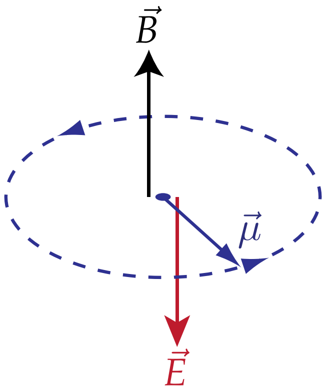
Precession of Radium 225



And for our final trick…







$$h\nu_{\pm} = \frac{\mu B \pm dE}{S}$$

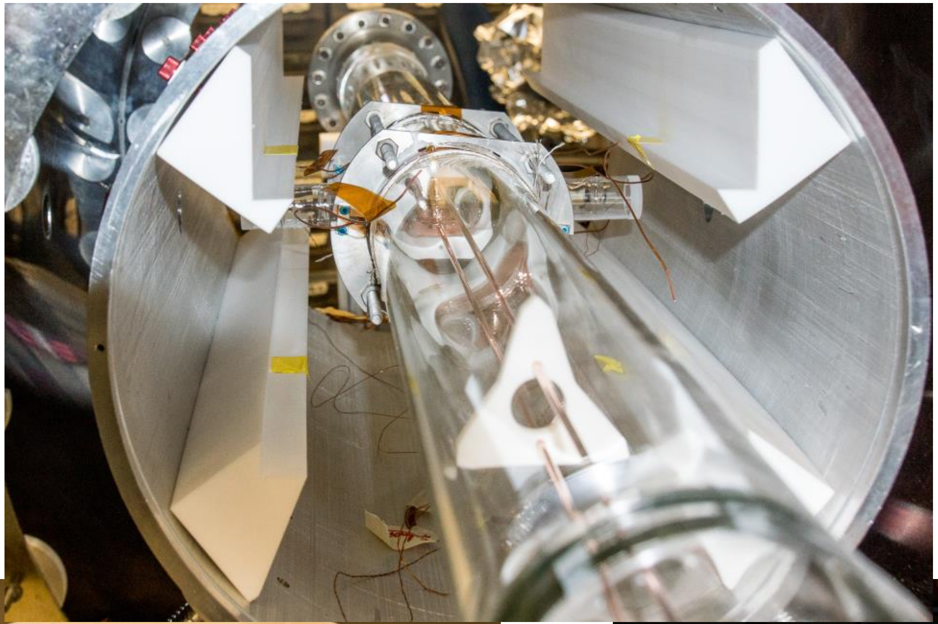
Status at Time of Precession

$$\sigma_d^{\text{stat}} \geq \frac{\hbar}{2E\sqrt{\varepsilon N \tau T}}$$

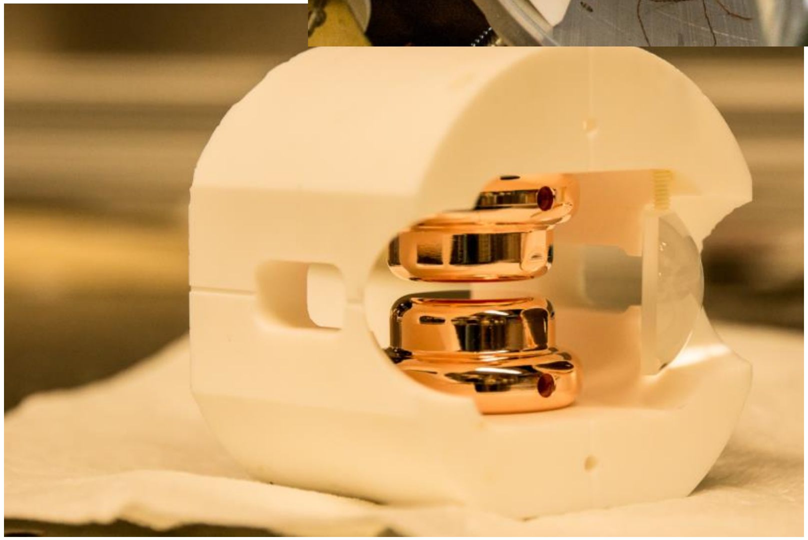
parameter	During last Ra-225 Run	near term goal for Ra-225	comments
E, electric field (kV/cm)	0	100	Install Completed HV System
τ, storage time (s)	7	100	Vacuum Upgrade
N, # of atoms	10^2	10^3	Vacuum upgrade, increased activity, extra repump
ε, efficiency	~0.003	0.1	STIRAP, increased atom number
T, integration time (days)	~3	10	Improve data collection procedures

Phase 1 goal of 3×10^{-26} *e* cm (1σ) is competitive with the best limits from Hg-199

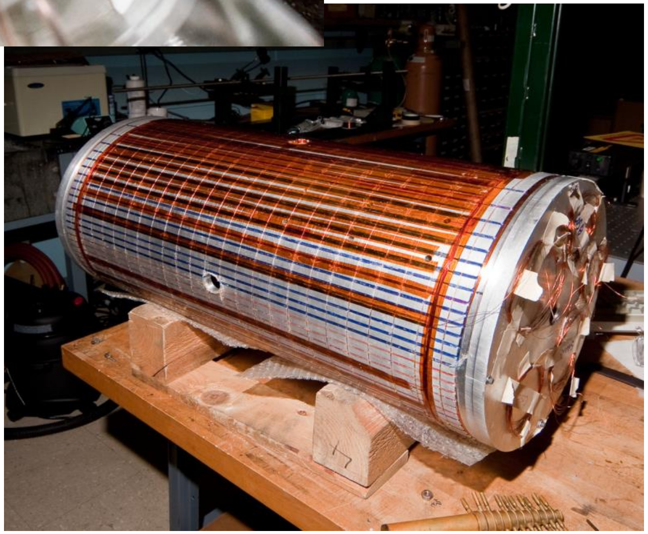
Vacuum Upgrade



~ 5 x 10^-11 Torr



100 kV/cm



B gradient < 10 μG/cm

Present Status

$$\sigma_d^{\text{stat}} \geq \frac{\hbar}{2E\sqrt{\varepsilon N \tau T}}$$

parameter	During last Ra-225 Run	near term goal for Ra-225	comments
E, electric field (kV/cm)	0 → 100	100	Install Completed HV System
τ, storage time (s)	7 → >50 s MOT	100	Vacuum Upgrade
N, # of atoms	10^2 → x8 gain	10^3	Vacuum upgrade, increased activity, extra repump
ε, efficiency	~0.003	0.1	STIRAP, increased atom number
T, integration time (days)	~3	10	Improve data collection procedures

Phase 1 goal of 3*10^{-26} *e* cm (1σ) is competitive with the best limits from Hg-199

Phase 0 Measurement

- Using current parameters, move ahead with a demonstration run in the next few months
- Likely to result in an EDM limit near 10^-24 e cm
- Due to synergy with other experiments, even measurements in the 10^-25 to 10^-24 e cm range puts pressure on some regions of phase space (T. Chupp)
- After this, implement upgrades to reach Phase I goals

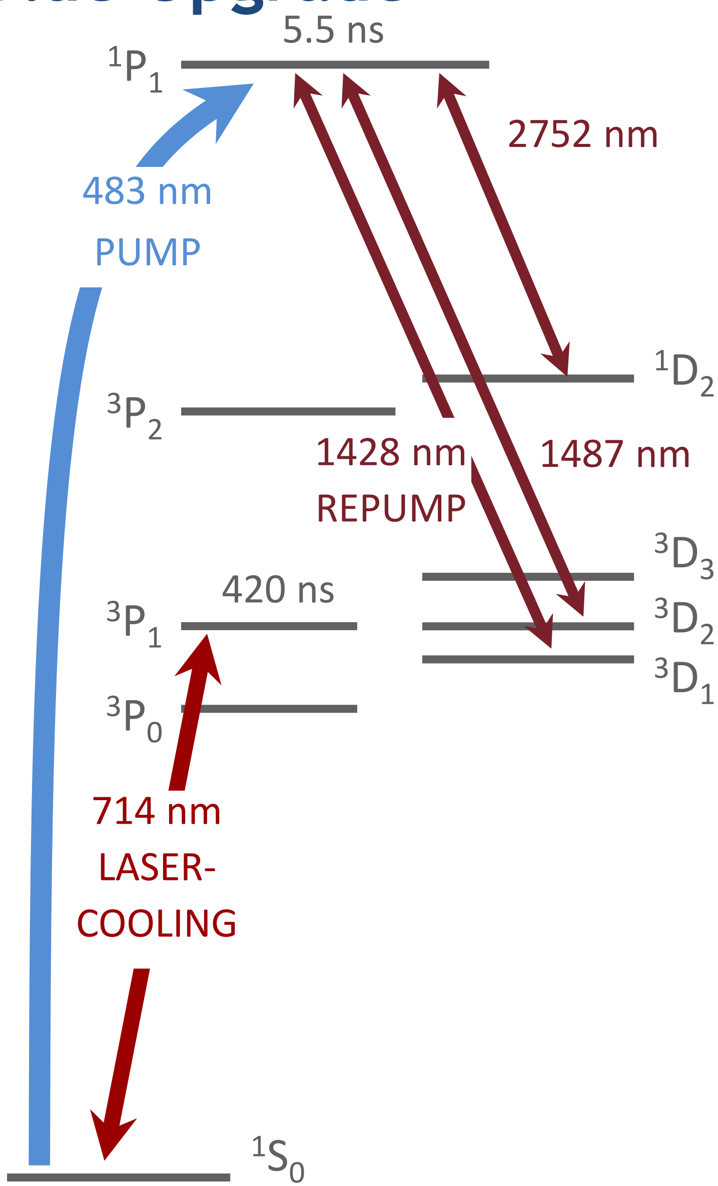
	Phase 0	Phase I	Phase II
Goal (e cm)	10^-24 (?)	3*10^-26	10^-27

Projections

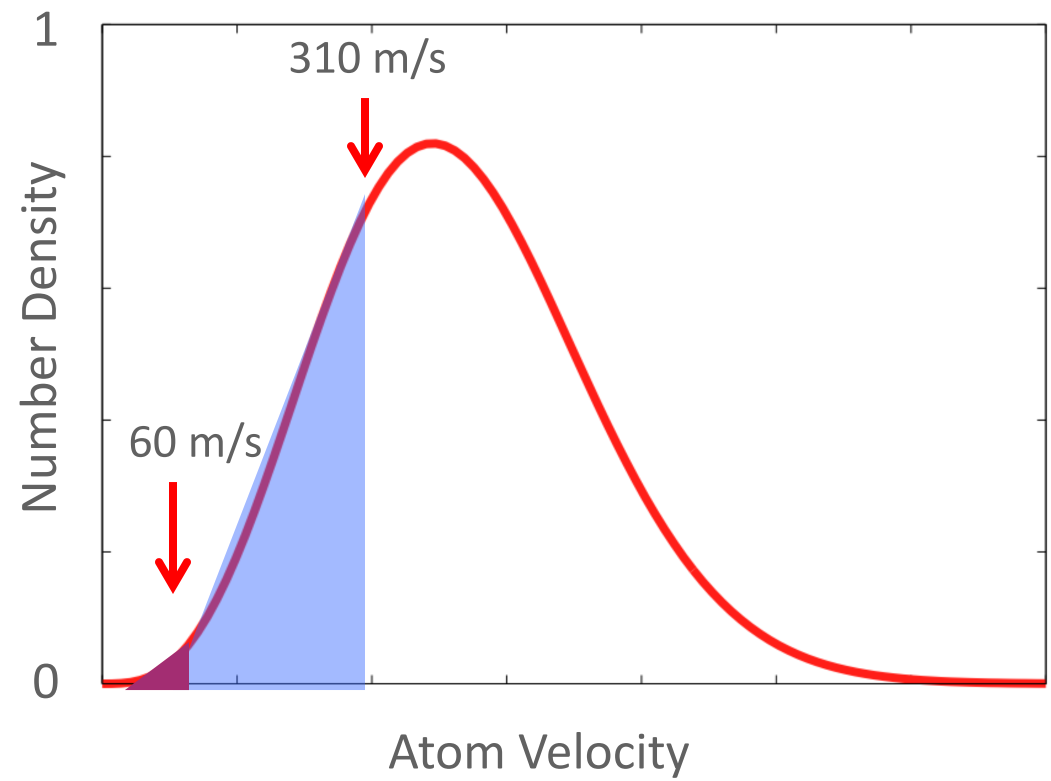
Limiting Effect	Phase I (e cm)	Phase II w/Comagnetometer (e cm)
Statistics	3*10^-26	10^-27
Leakage Current (10 pA)	3*10^-27	5*10^-30
Stark Interference	5*10^-27	5*10^-30
Exv Effects	< 2*10^-27	5*10^-30
Geometric Phase	10^-35	10^-35

Blue Upgrade

$$\sigma_d^{\mathrm{stat}} \geq \frac{\hbar}{2E\sqrt{\varepsilon N \tau T}}$$



x30 – x100 Atom Capture Efficiency



Project X

I.C. Gomes, J. Nolen et al.
Project X workshop, July 2012

Protons on thorium target: 1 mA x 1000 MeV = 1 MW

Predicted yields of some important isotopes:

Radon: $^{211}Rn > 10^{13}$ $^{223}Rn \sim 10^{11}$ /s

Francium: $^{213}Fr > 10^{13}$ $^{221}Fr > 10^{14}$ $^{223}Fr > 10^{12}$ /s

Radium: $^{223}Ra > 10^{13}$ $^{225}Ra > 10^{13}$ /s

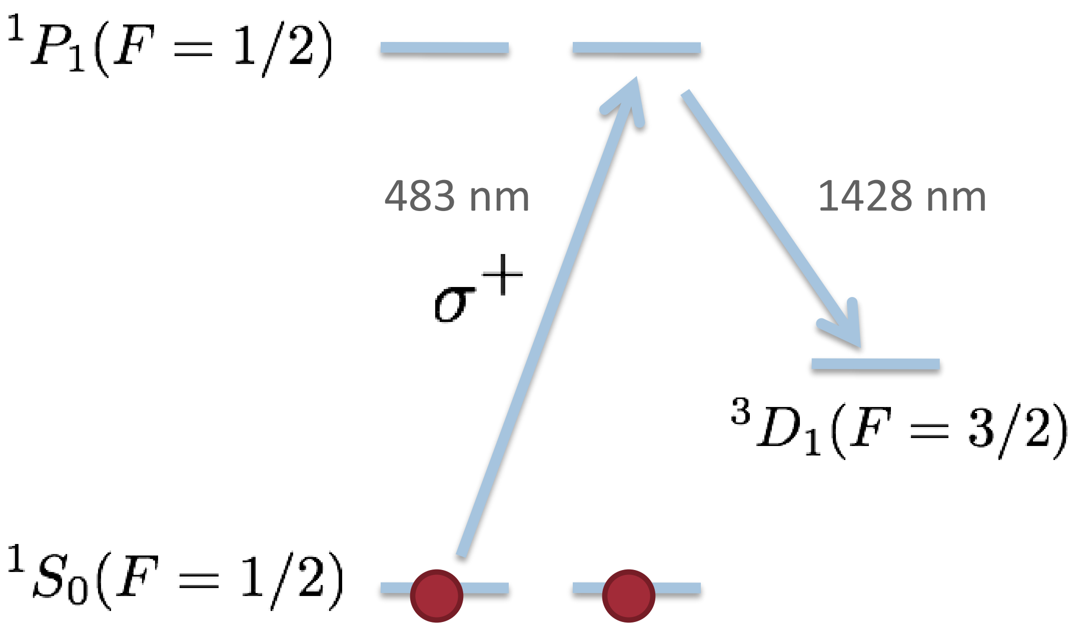
Actinium: $^{225\text{-}229}Ac > 10^{14}$ /s

Compare 10^8 /s Today

Atoms Trappers @ Argonne

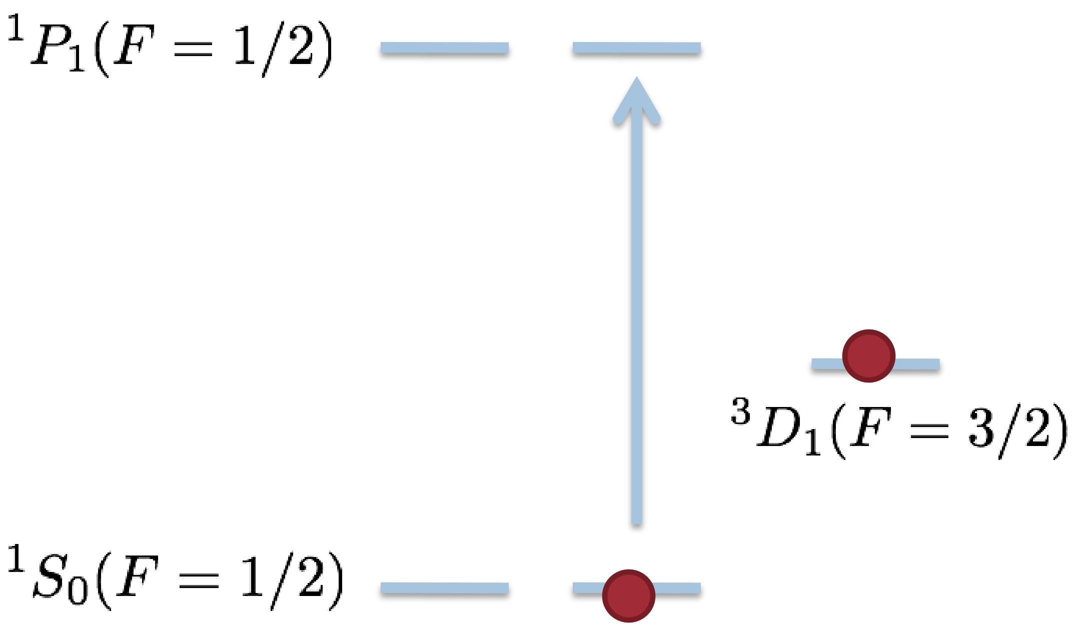
STIRAP

- For an EDM measurement, the free precession time is 100 seconds, and so the data cycle is very long. Thus our statistics need to be dramatically improved.
- Electron shelving technique allows us to increase number of photons from 3 to 1000 per atom, thereby overcoming this limitation

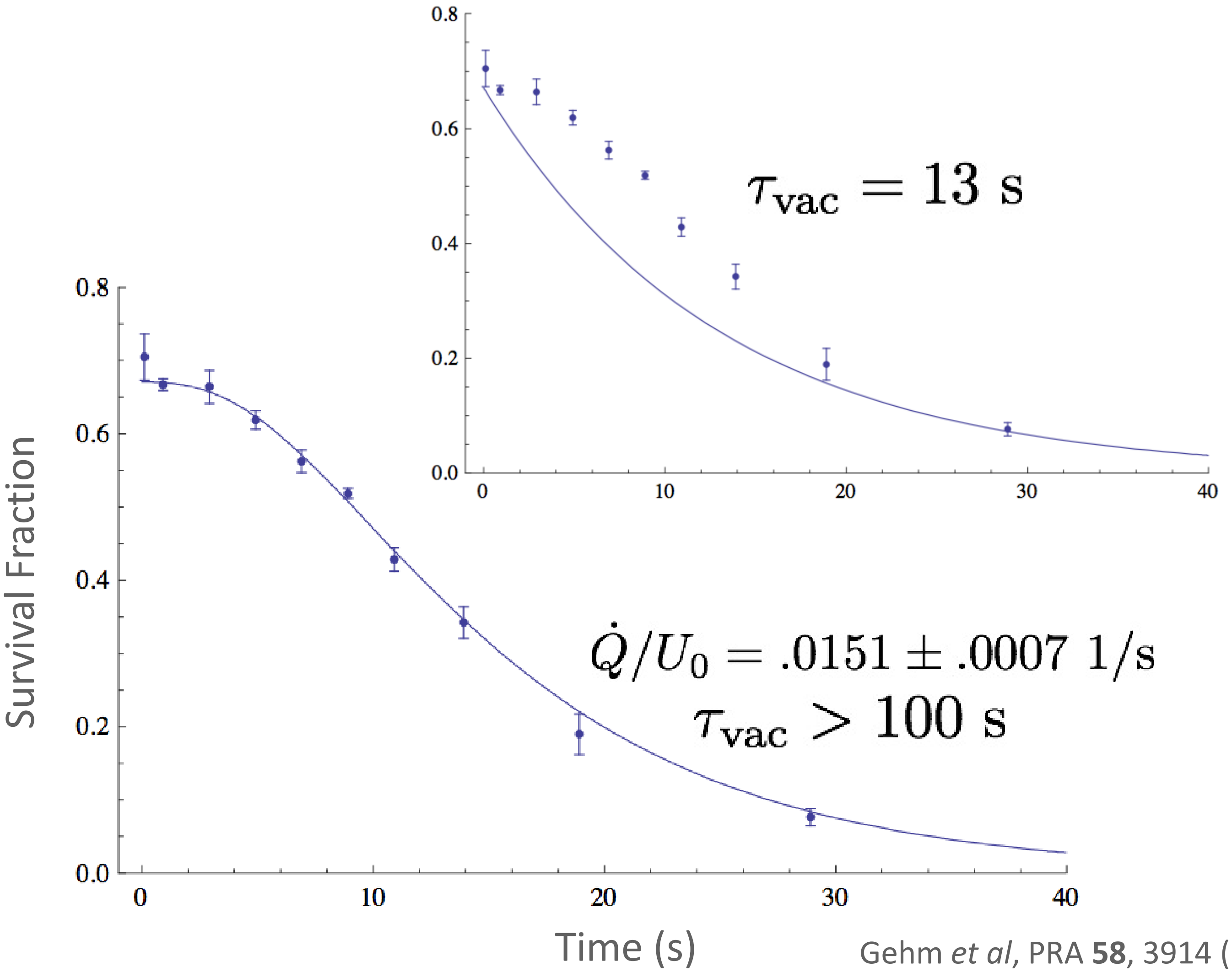


STIRAP

- For an EDM measurement, the free precession time is 100 seconds, and so the data cycle is very long. Thus our statistics need to be dramatically improved.
- Electron shelving technique allows us to increase number of photons from 3 to 1000 per atom, thereby overcoming this limitation



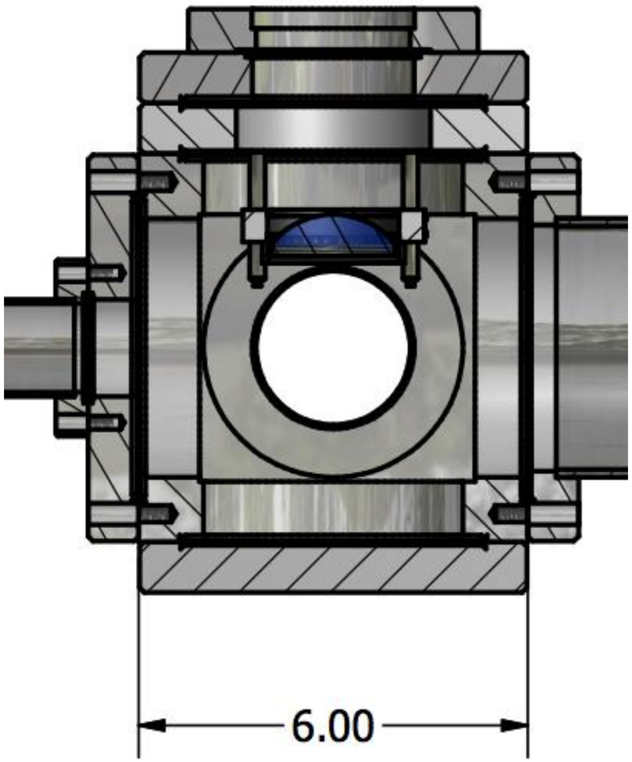
ODT Lifetime

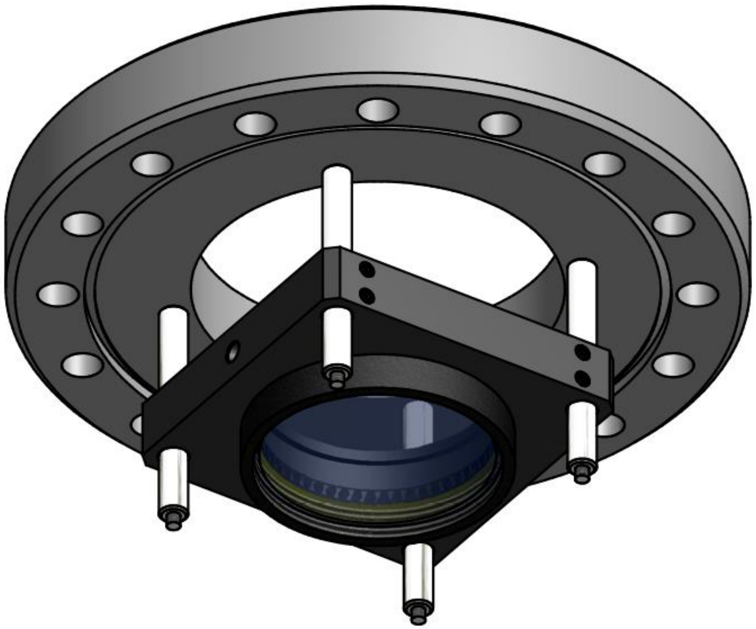


Gehm *et al*, PRA **58**, 3914 (1998)

- Our ODT lifetime now seems to be limited by laser noise, rather than vacuum
- May need to stabilize ODT power to achieve design lifetimes

Fluorescence Collection System for Precession Measurement



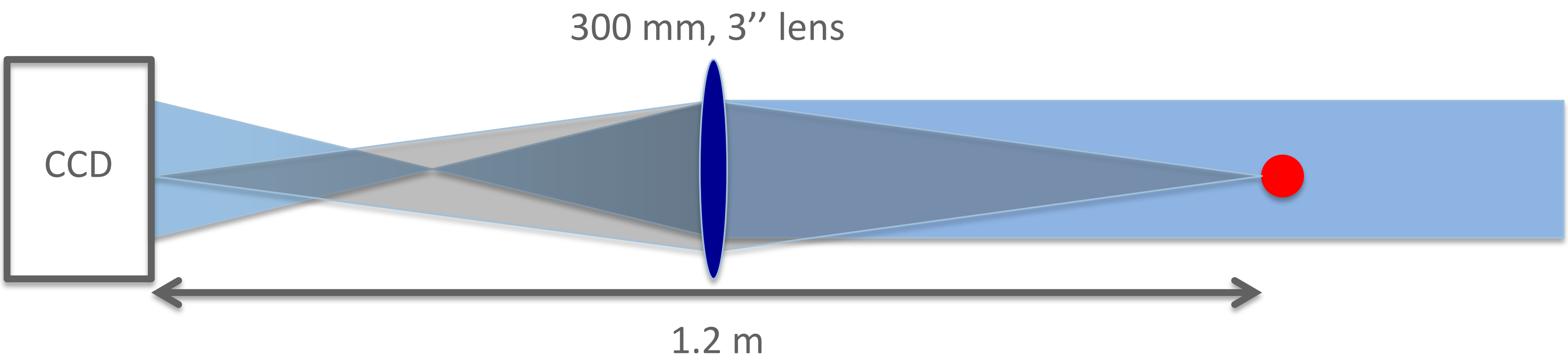


- 60 mm focal length, 2’’ diameter singlet
- Solid Angle 4%
- Total Efficiency: 1e-3 (later 3e-4)

Shadow Imaging

$$\mathrm{SNR} \approx \mathrm{N}^{1/2} \left(\frac{\sigma}{\mathrm{A}}\right)^{1/2} \frac{\mathrm{n}}{\sqrt{\mathrm{s}+1}}$$

- Achieve shot noise limit by careful background subtraction, not careful stabilization
- Effective collection efficiency at 1000 atoms: 1%



Yields of Enhancer Isotopes: Ra, Rn, Fr

Presently available

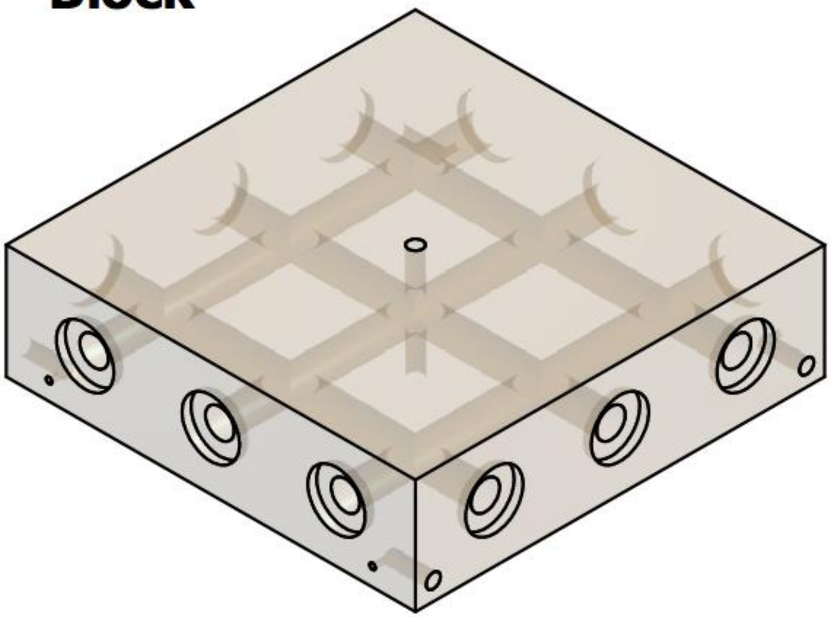
- Decay daughters of ^{229}Th, National Isotope Development Center, ORNL
  - ^{225}Ra: 10^8 /s

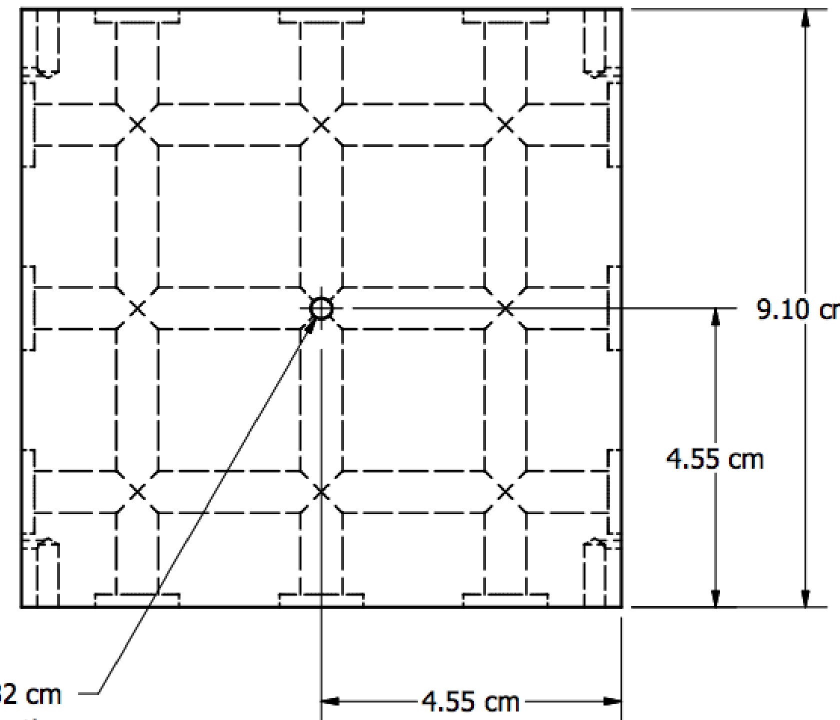
Projected rates at FRIB (B. Sherrill, MSU)

- Beam dump recovery with a ^{238}U beam
  - Parasitic operation, available ~ 150 days per year
  - ^{225}Ra: 6 x 10^9 /s ; ^{223}Rn: 8 x 10^7 /s; $^{208\text{-}220}$Fr: 10^9 -10^{10} /s.
- Dedicated running with a ^{232}Th beam
  - ^{225}Ra: 5 x 10^{10} /s ; ^{223}Rn: 1 x 10^9 /s; $^{208\text{-}220}$Fr: 10^{10} /s;

FRIB will produce isotopes with enhanced sensitivity to fundamental symmetries, and provide opportunities for discovering physics beyond the Standard Model.

Zerodur Cavity Block

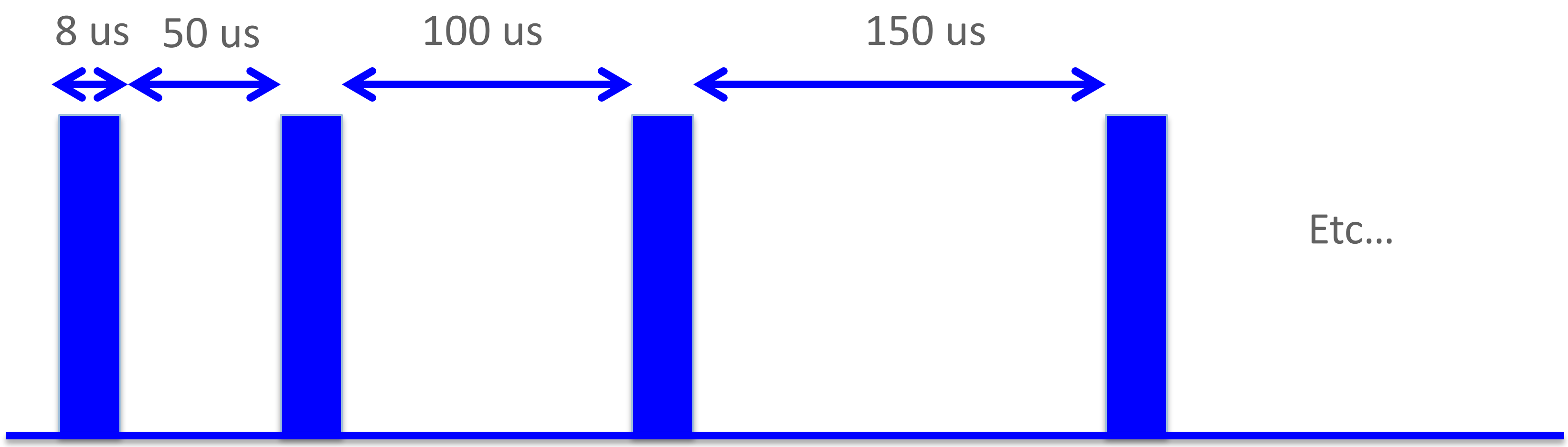




- Expected 1 MHz/K temperature drift
- Lock up to 6 lasers
- Suspended in standard 5 way cross with dowel pins

Rapid Interrogation Scheme

- Each detection pulse is also a state preparation pulse
- Therefore, a rapid sequence of pulses can be used to collect many data points from a single batch of atoms
- Requires a high magnetic field, set precession frequency to ~ 6 kHz
- Increase data collection rate by x40



Basic Radium Energy Level Diagram