Atomic parity non conservation; the francium project

SSP2012 June 2012

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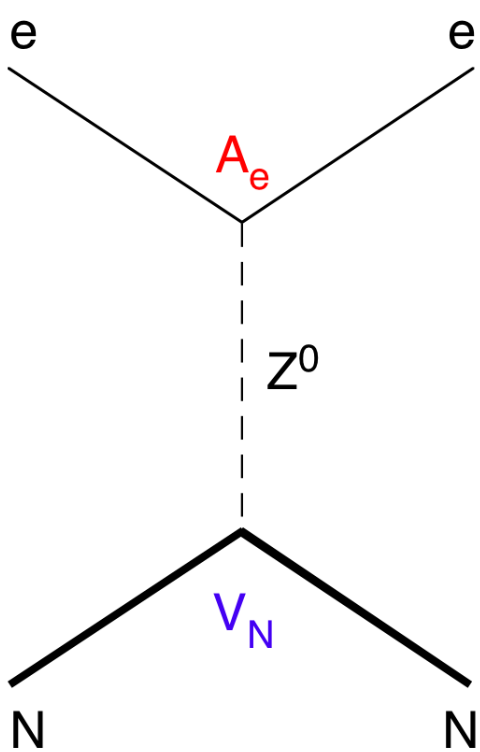
Thanks to:

Dima Budker (Berkeley)
Anne Marie Bouchiat (ENS Paris)
Roberto Calabrese (Ferrara)
Sidney Cahn (Yale)
David DeMille (Yale)
Andrei Derevianko (Reno)
Victor Flambaum (New South Wales)
Gerald Gwinner (Manitoba)
Klaus Jungmann (KVI)
Mariana Safranova (Delaware)

Atomic Parity Violation

Z-boson exchange between atomic electrons and the quarks in the nucleus

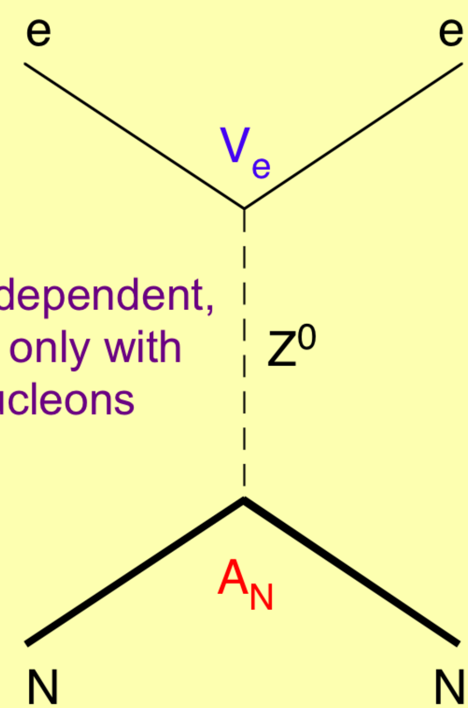


nucl. spin *independent* interaction:
coherent over all nucleons

H_{PNC} mixes electronic *s* & *p* states

$< n's' | H_{PNC} | np > \;\propto\; Z^3$

Drive s → s E1 transition!



nucl. spin dependent,
interaction only with
valence nucleons

Cs: 6s → 7s osc. strength f ≈ 10^{-22}

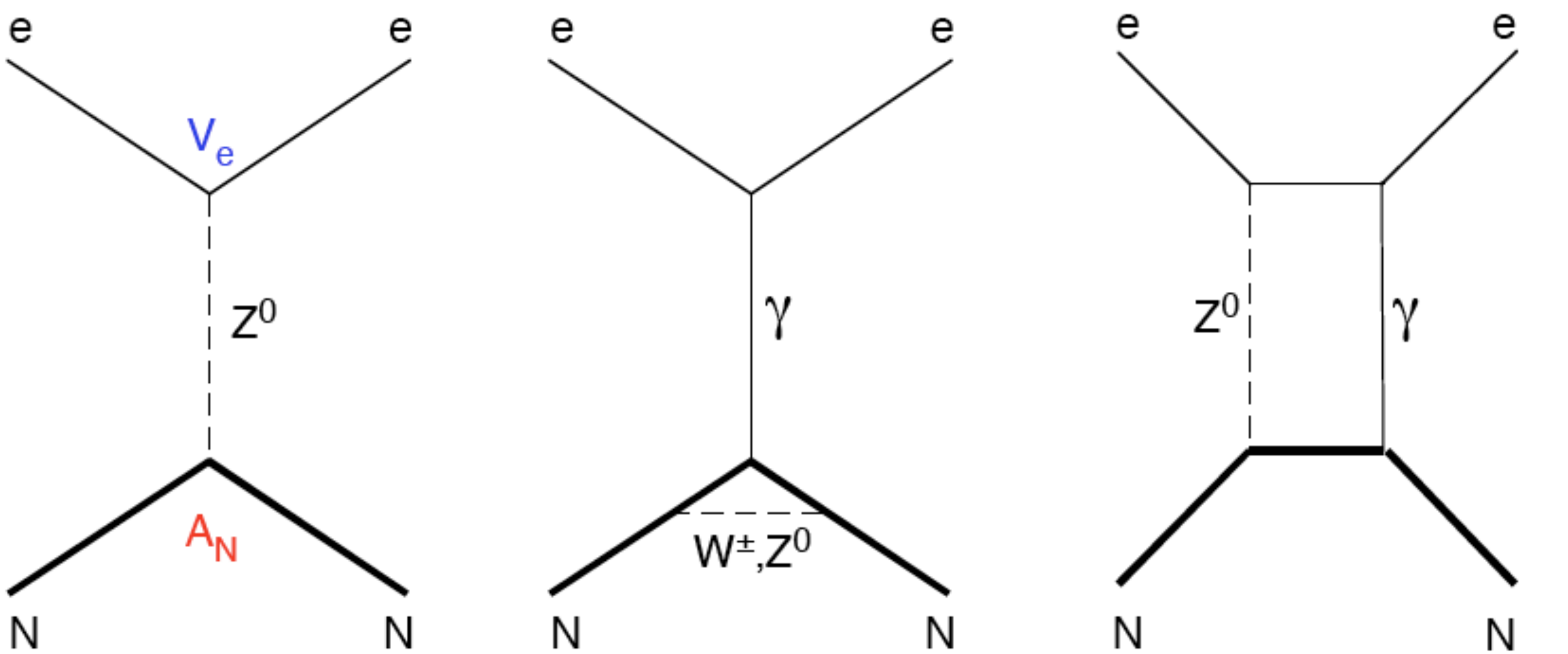
use interference:

$f \propto | A_{PC} + A_{PNC} |^2$

$\approx A_{PC}^2 + A_{PC} A_{PNC} \cos \varphi$

Gwinner

Nuclear spin dependent APNC



NSD Z-exchange

PV hadronic interactions
⇒ PV anapole moment
of the nucleus

hyperfine correction to
the weak neutral current

$$H_{\rm PNC} = \frac{G_F}{\sqrt{2}} \left(-\frac{Q_w}{2}\gamma_5 + \left(\frac{K}{I+1}\kappa_a + \kappa_2 + \kappa_{Q_w} \right) \frac{1}{I} \sigma_n \gamma_0 \vec{\gamma} \right) \rho(\vec{r})$$

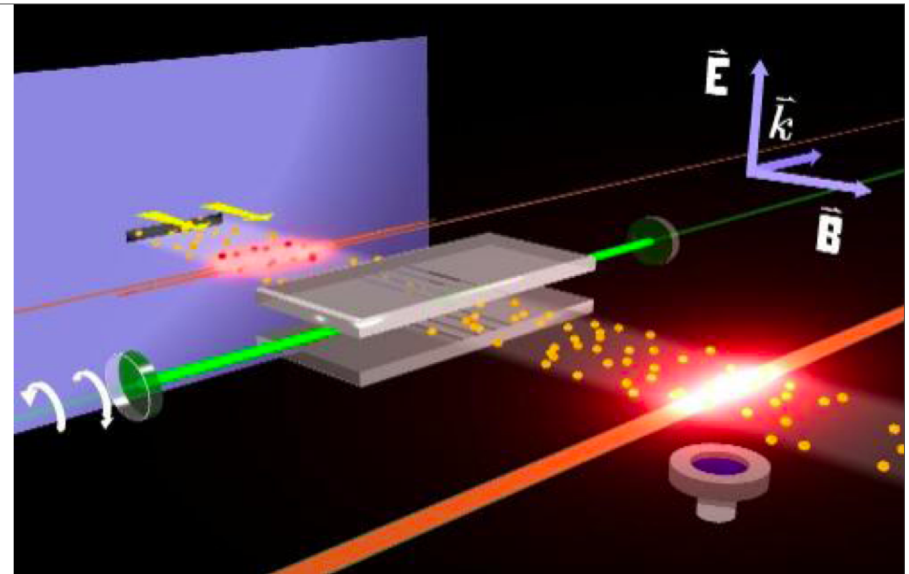
$|\kappa_2| \approx \mathcal{O}(1 - 4\sin^2\theta_w)$

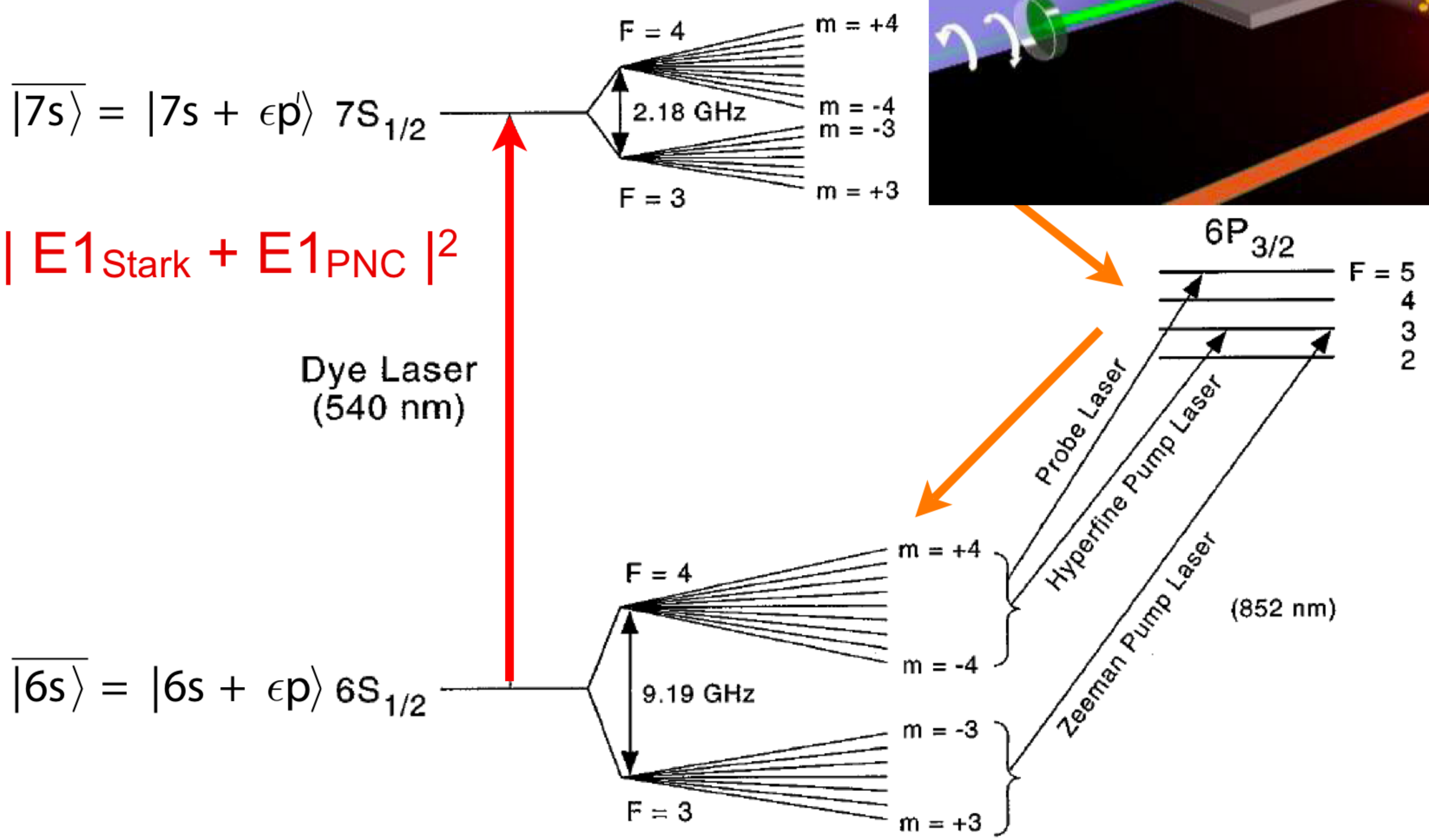
$K = (-)^{I+1/2-\ell}(I + 1/2)$
$g_p \approx 5 \quad g_n \approx -1$

Khriplovich and Flambaum (1980)
$\kappa_a \approx 1.15 \times 10^{-3} A^{2/3} \mu_n g_n$

Gwinner

The Boulder Cs Experiment (Wood, 1996)



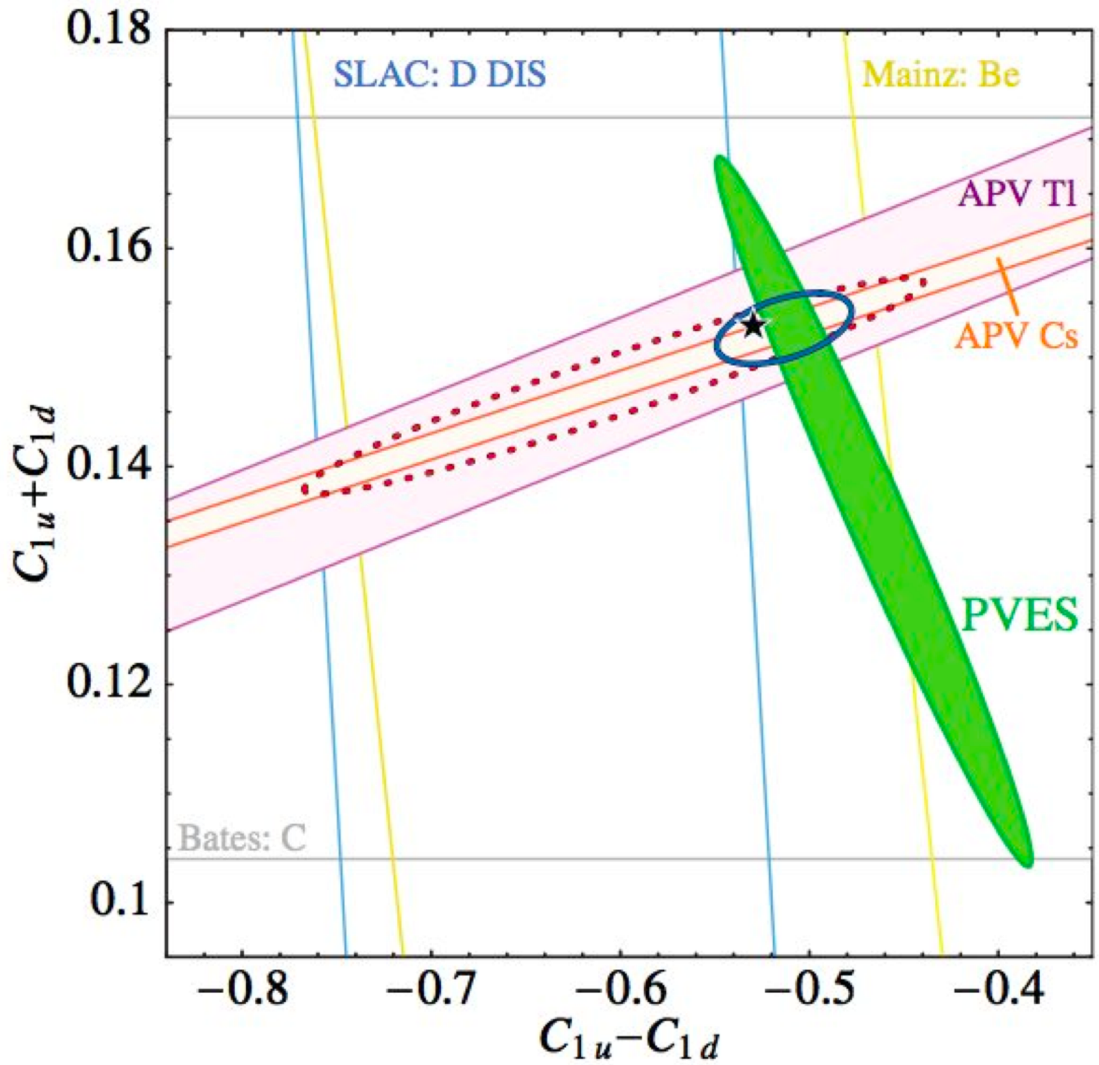


Gwinner

$$\frac{\mathrm{Im}(E\ 1_{PNC})}{\beta} = \begin{array}{llll} -1.5576(77) & \mathrm{mV/cm} & 6S\ F = 3 & 7S\ F' = 4 \\ -1.6349(80) & \mathrm{mV/cm} & 6S\ F = 4 & 7S\ F' = 3 \end{array}$$

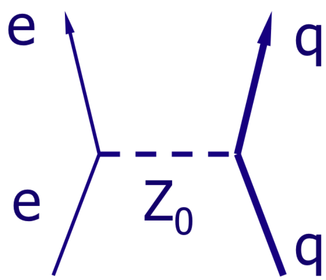
Young et al., PRL 2007: Dramatic recent progress from PV electron scattering for (C_{1u} - C_{1d})

APNC uniquely provides the orthogonal constraint (C_{1u} + C_{1d})



Gwinner

How to extract weak charge Q_w from Cs experiment?



Electron-quark parity violating interaction (exchange of virtual Z_0 boson)

$$H_W = \frac{G_F}{\sqrt{2}}\left(\bar{e}\gamma_\mu\gamma_5 e\right)\left\{C_{1u}\bar{u}\gamma^\mu u + C_{1d}\bar{d}\gamma^\mu d\right\} + \ldots$$

Neutron density function

Electronic sector: $H_{PNC}^{(1)} = \frac{G_F}{2\sqrt{2}} Q_W \gamma_5 \rho(r)$

Extraction of weak the charge:

Theoretical calculation of PNC amplitude

Measured value → $E_{PNC} = E_{PNC}^{theory} Q_W^{\text{inferred}}$

Safranova

Summary of the PNC amplitude calculations

Coulomb interaction		Porsev et al., PRL 102, 181601 (2009)
Main part, n = 6 - 9	0.8823(18)	
Tail	0.0175(18)	
Total	0.8998(25)	
Corrections		
Breit	-0.0054(5)	Derevianko, PRL 85, 1618 (2000)
QED	-0.0024(3)	Shabaev et al., PRL 94, 213002 (2005)
Neutron skin	-0.0017(5)	Derevianko, PRA 65, 012016 (2000)
e-e weak interactions	0.0003	Blundell et al., PRL 65, 1411 (1990)
Final	**0.8906(26)**	Porsev et al., PRL 102, 181601 (2009)

Units: $i|e|a_B(-Q_W/N)\times 10^{11}$

Safranova

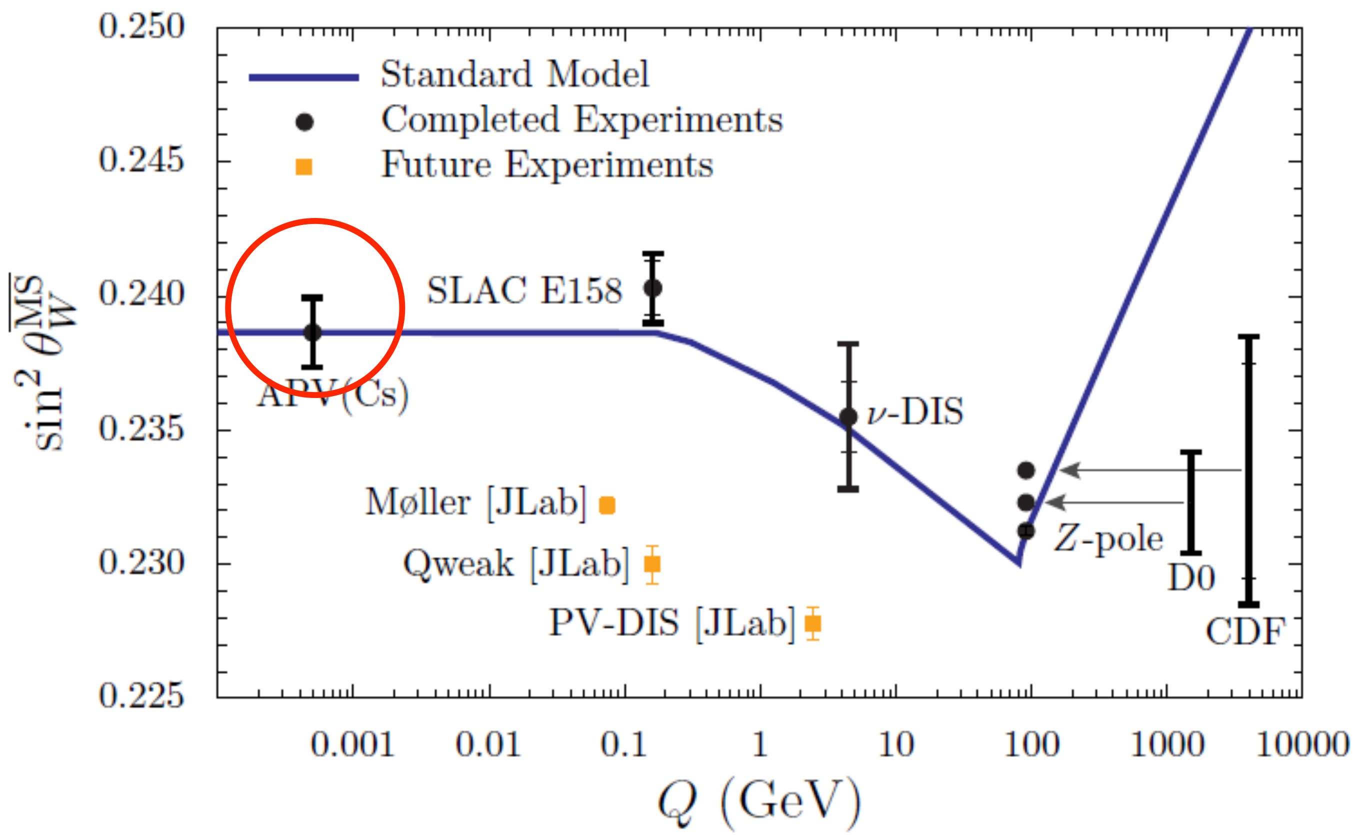
Weak charge of ^{133}Cs

Atomic experiment	E_{PV}	$\left.\begin{matrix} \\ \\ \end{matrix}\right\} \Rightarrow Q_W^{\mathrm{inferred}} = -73.16(29)_{\mathrm{expt}}(20)_{\mathrm{theor}}$
Atomic theory	E_{PV} / Q_W	
Standard Model		$Q_W^{\mathrm{SM}} = -73.16(3)$

Agreement with the Standard Model

Experiment: Wood *et al*. (1997); Bennett and Wieman (1999) (Boulder group)
Theory: S.G. Porsev, K. Beloy, A. Derevianko Phys. Rev. Lett. (2009)

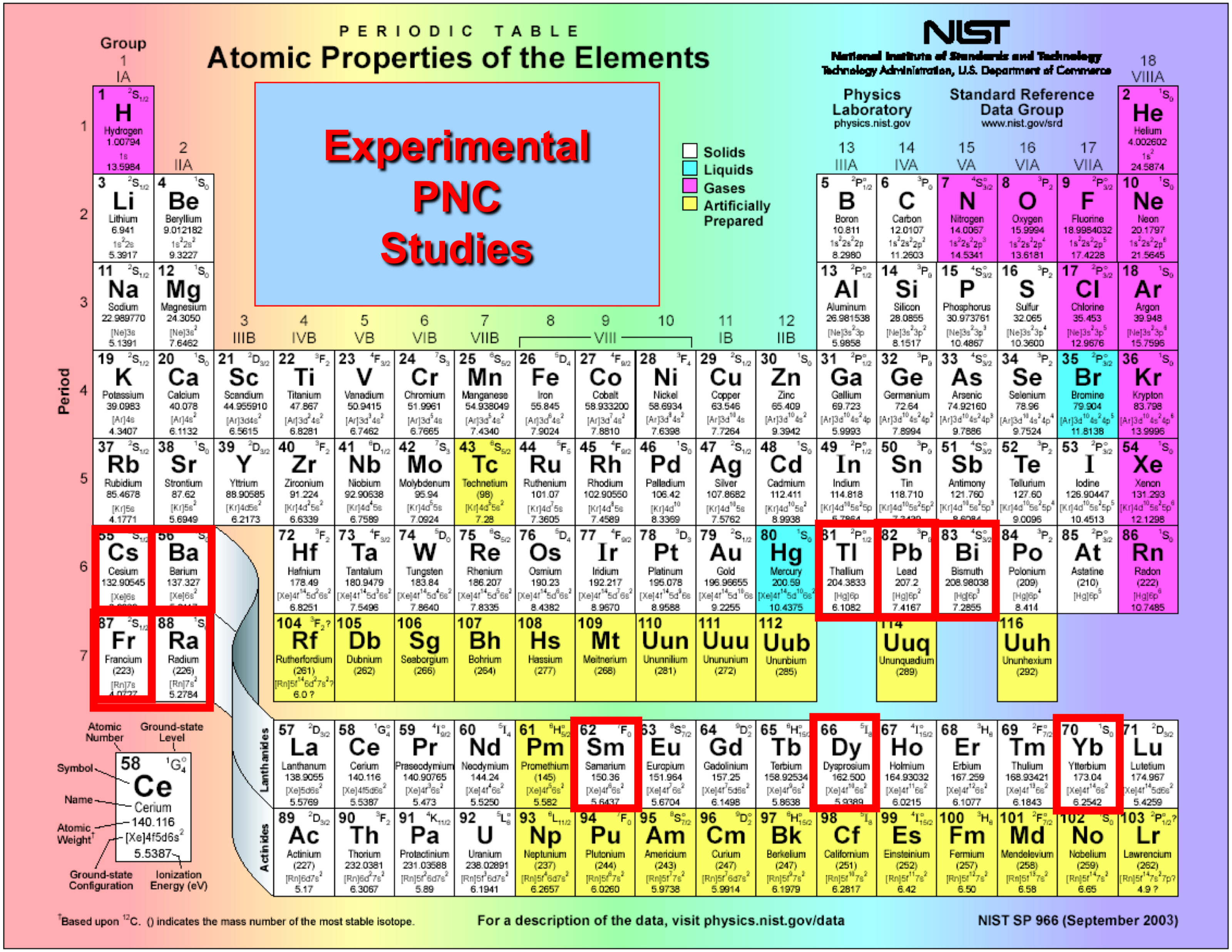
Bigger picture (running)



S. G. Porsev, K. Beloy and A. Derevianko, *Phys. Rev. Lett.* ***102**, 181601 (2009)*

S. G. Porsev, K. Beloy and A. Derevianko, *Phys. Rev. D* ***82**, 036008 (2010)*

Derevianko

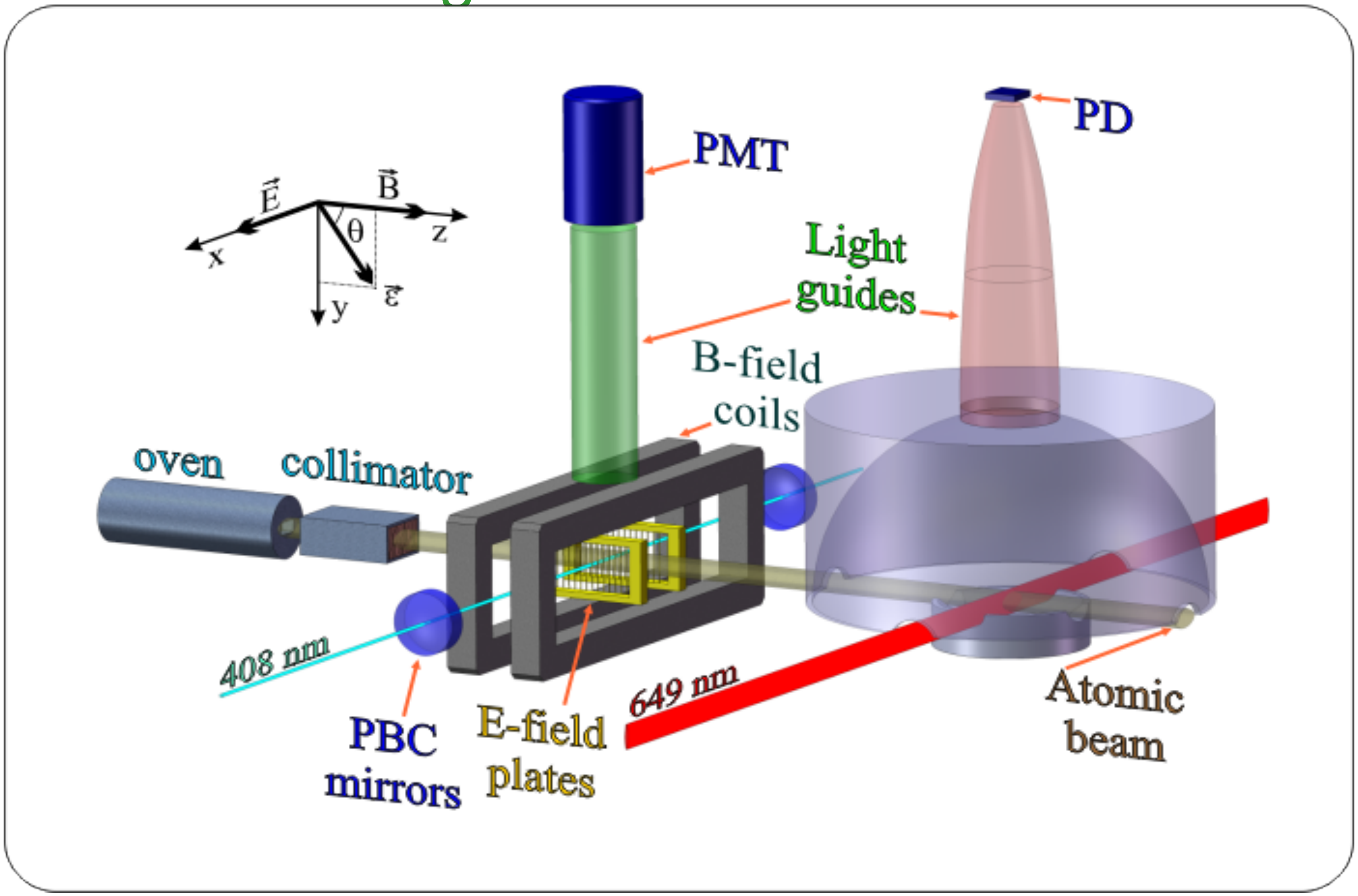


PERIODIC TABLE
Atomic Properties of the Elements
NIST
National Institute of Standards and Technology
Technology Administration, U.S. Department of Commerce
Physics Laboratory
physics.nist.gov
Standard Reference Data Group
www.nist.gov/srd
Experimental
PNC
Studies
Solids
Liquids
Gases
Artificially Prepared
Group
Period
Lanthanides
Actinides
Atomic Number
Ground-state Level
Symbol
Name
Atomic Weight
Ground-state Configuration
Ionization Energy (eV)
Based upon 12C. () indicates the mass number of the most stable isotope.
For a description of the data, visit physics.nist.gov/data
NIST SP 966 (September 2003)

Safranova

The Yb PV Experiment

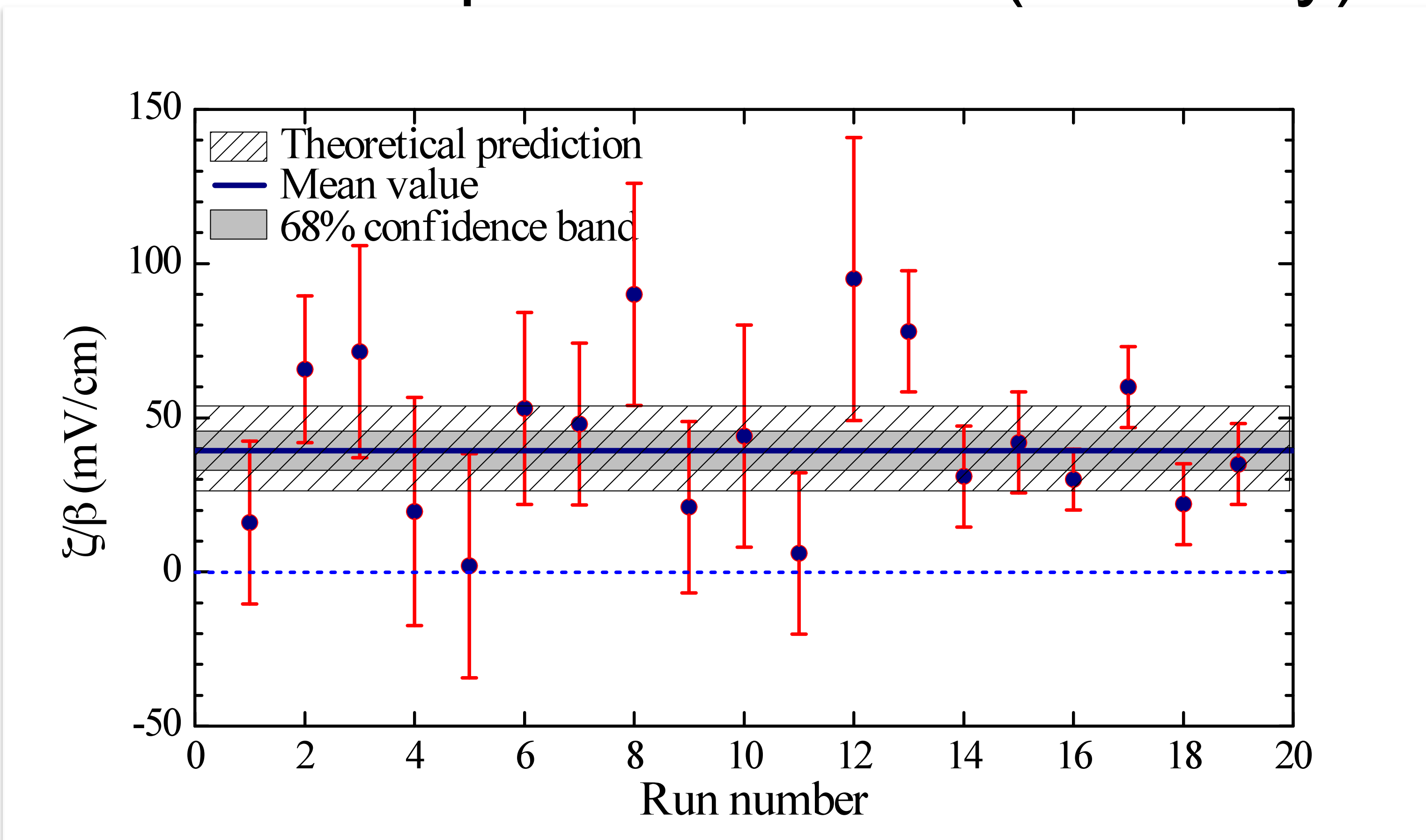
Electric and magnetic fields define **handedness**



Rotational Invariant: $\left(\vec{\varepsilon}\cdot\vec{B}\right)\left(\vec{E}\times\vec{\varepsilon}\cdot\vec{B}\right)$

Budker

Yb PV Amplitude Results (Berkeley)

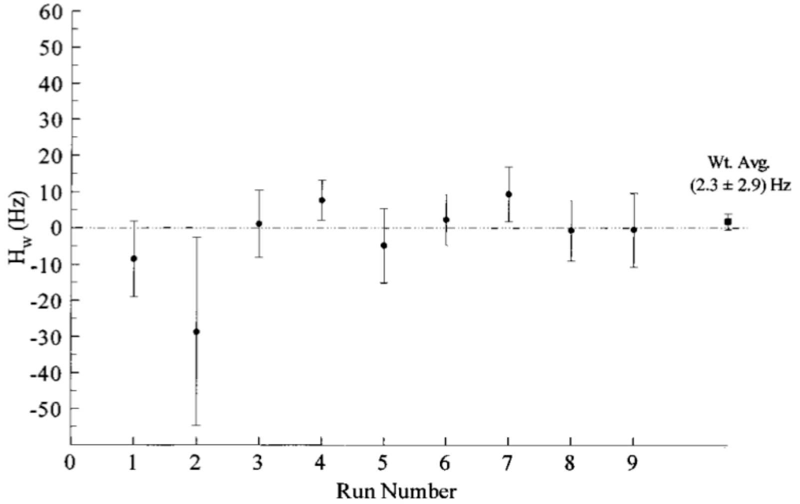


$\zeta/\beta = 39(4)_{stat.}(5)_{syst.}$ mV/cm $\Rightarrow |\zeta| = (8.7 \pm 1.4) \times 10^{-10}\ ea_0$

Accuracy is affected by HV-amplifier noise, fluctuations of stray fields, and laser drifts → improved for the next phase

Budker

Parity Nonconservation in Dy



- Theory (1994):
  - $H_w = 70 \pm 40$ Hz
    - V. A. Dzuba *et al.* Phys. Rev. A **50**, 3812 (1994)
- Experiment (1997):
  - $|H_w| = |\, 2.3 \pm 2.9$ (statistical) $\pm\, 0.7$ (systematic) $|$
    - A. T. Nguyen *et. al*. Phys. Rev. A **56**, 3453 (1997)
- Improved theory (2010):
  - $H_w \approx 2$ Hz
    - V. Dzuba and V. Flambaum (http://arxiv.org/abs/1001.1184)

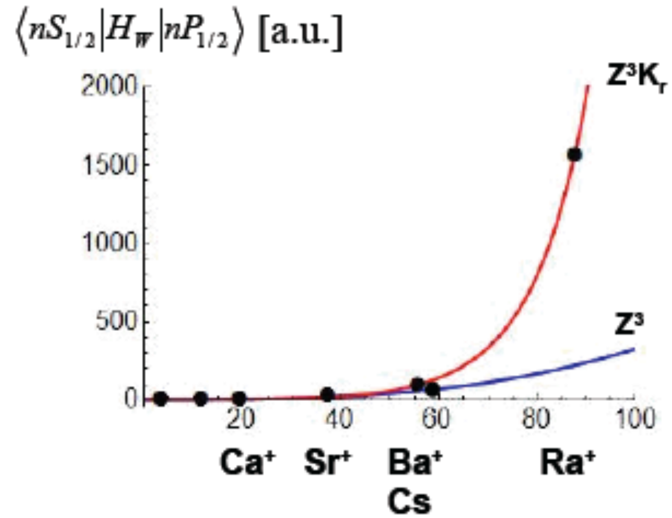
Budker

Single ion work in Ra^+ at KVI

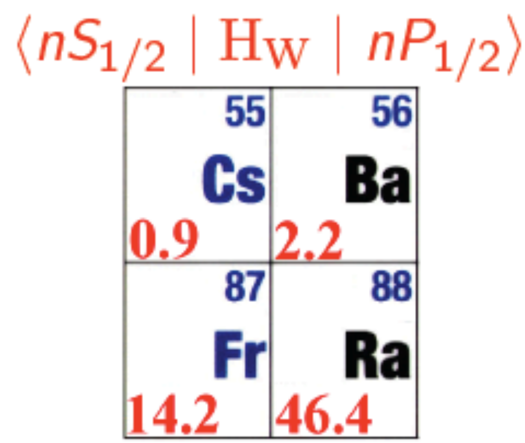
Ra^+: An Ideal Candidate

Advantages

- Heavy: APV signal $\gtrsim Z^3$
- Atomic theory is tractable
- Easy lasers (semiconductor diodes)
- Different isotopes available @ TRIμP



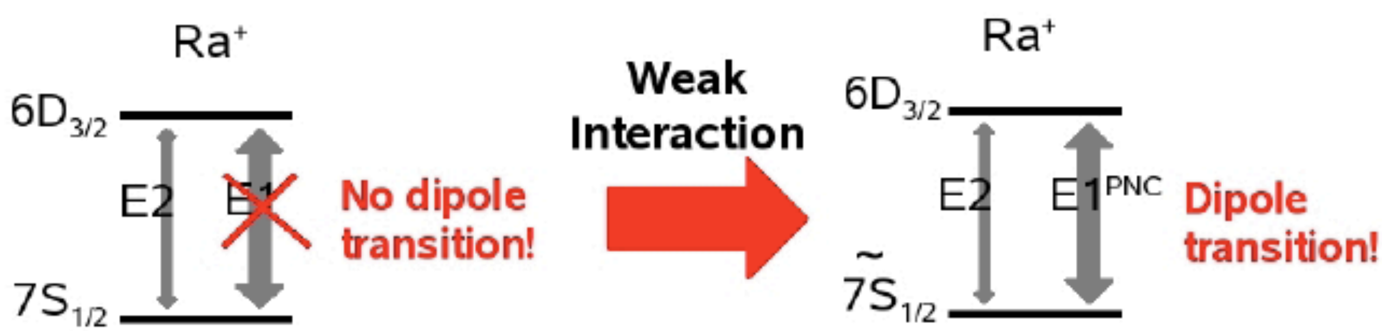
Isotope	Lifetime (S)	Nuclear Spin
209	4.6(2)	5/2
210	3.7	0
211	13(2)	5/2
212	13(2)	0
213	164.4(3.6)	1/2
214	2.46(3)	0



Jungmann

APV in Ra^+

Weak interaction mixes states of opposite parity



$$|\,7S_{1/2}\rangle \rightarrow |\,7\tilde{S}_{1/2}\rangle = |\,7S_{1/2}\rangle + \varepsilon\,|\,nP_{1/2}\rangle$$

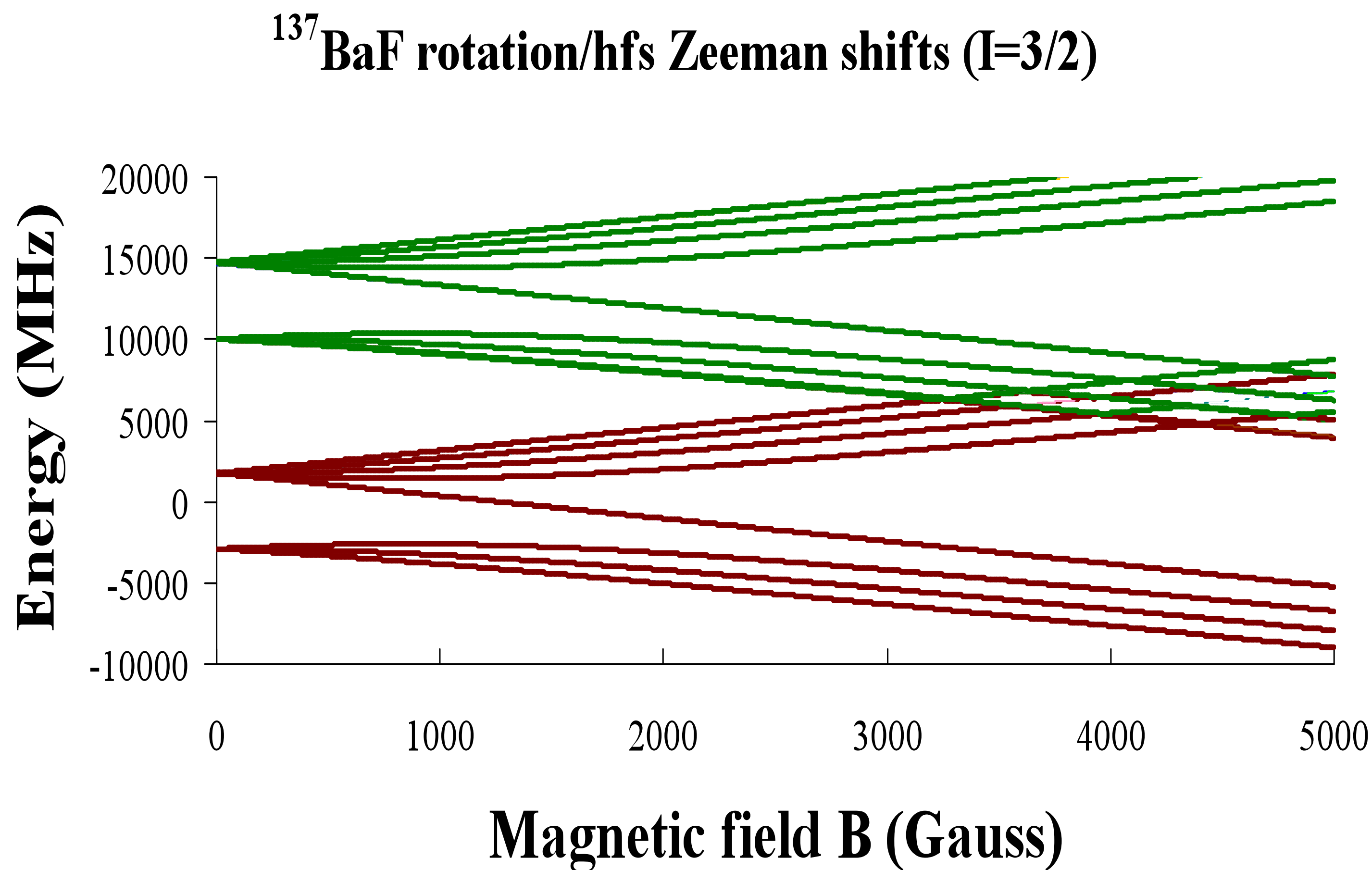
$$|\,6D_{3/2}\rangle \rightarrow |\,6\tilde{D}_{3/2}\rangle = |\,6D_{3/2}\rangle + \varepsilon\,|\,nP_{3/2}\rangle$$

$$E1^{PNC} = \langle 6\tilde{D}_{3/2}\,|\,D\,|\,7\tilde{S}_{1/2}\rangle = Q_w k$$

Jungmann

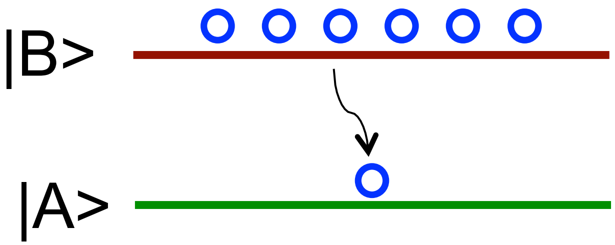
Using molecules to get at NSD-PNC

- Diatomic molecules *systematically* have close rotation+hyperfine levels of opposite parity--B-field tuning can give $\Delta E \sim 10^{-11}$ eV!
  [Sushkov, Flambaum, Sov. Phys. JETP 48, 608 (1978), Flambaum, Khriplovich, Phys. Lett. A 110, 121 (1985) Kozlov, Labzowsky, & Mitruschenkov, JETP **73**, 415 (1991)]]



Cahn, DeMille

Strategy to detect PNC in near-degenerate levels



$$H = \begin{array}{c} \\ \langle A| \\ \langle B| \end{array} \begin{array}{cc} |A\rangle & |B\rangle \\ \left(\begin{array}{c} 0 \\ -iH_W + dE \end{array} \right. & \left. \begin{array}{c} iH_W + dE \\ \Delta \end{array} \right) \end{array}$$

$$E = E_0 \sin(\omega t); \quad dE_0 \ll \omega; \quad \Delta \ll \omega$$

$$\left| \langle A | \psi(T) \rangle \right|^2 = 4 \sin^2\left(\frac{\Delta T}{2}\right) \left[(1 or 2) \frac{H_W}{\Delta} \frac{dE_0}{\omega} + \left(\frac{dE_0}{\omega}\right)^2 \right]$$

Weak Term
Odd in E

Stark Term
Even in E

D. DeMille, S.B. Cahn, D. Murphree, D.A. Rahmlow, and M.G. Kozlov
Using molecules to measure nuclear spin-dependent parity violation
Phys. Rev. Lett. **100,** 023003 (2008)

Cahn

FrPNC Collaboration

Approved experiments at TRIUMF S1010, S1065, S1218

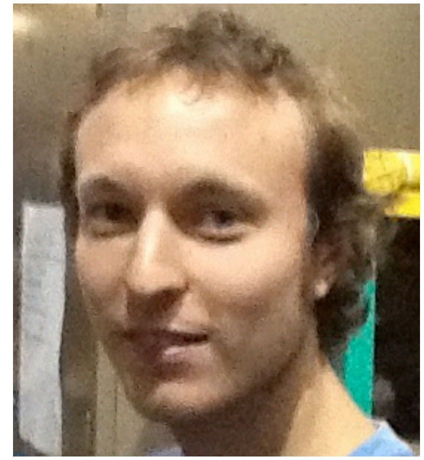
Seth Aubin; College of William and Mary, USA.
John A. Behr, K. Peter Jackson, Matt R. Pearson, Michael Tandecki; TRIUMF, Canada.
Victor V. Flambaum; University of New South Wales, Australia.
Eduardo Gómez, Maricarmen Ruiz; Universidad Autónoma de San Luis Potosí, México.
Gerald Gwinner SPOEKESPERSON Robert Collister, Andrew Senchuk; University of Manitoba, Canada.
Dan Melconian; Texas A&M, USA.
Luis A. Orozco, Jiehang Zhang, Young Shing, Gary Cheng; University of Maryland, USA.
Gene D. Sprouse; SUNY Stony Brook, USA.
Yanting Zhao; Shanxi University, Taijuan, China.

Work supported by NSERC from Canada, DOE, and NSF from the USA.

TRIUMF:

John Behr

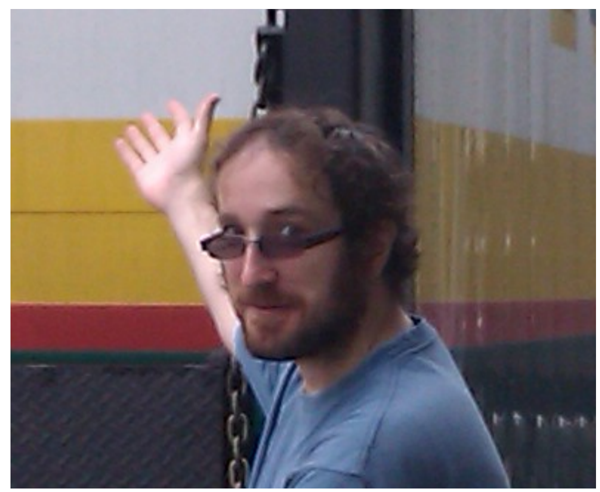
Matthew Pearson



Michael Tandecki

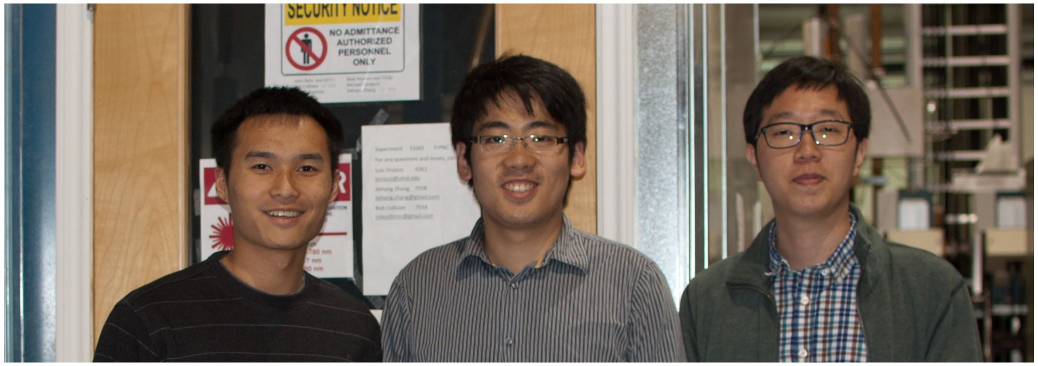
University of Manitoba

Gerald Gwinner



Robert Collister

University of Maryland

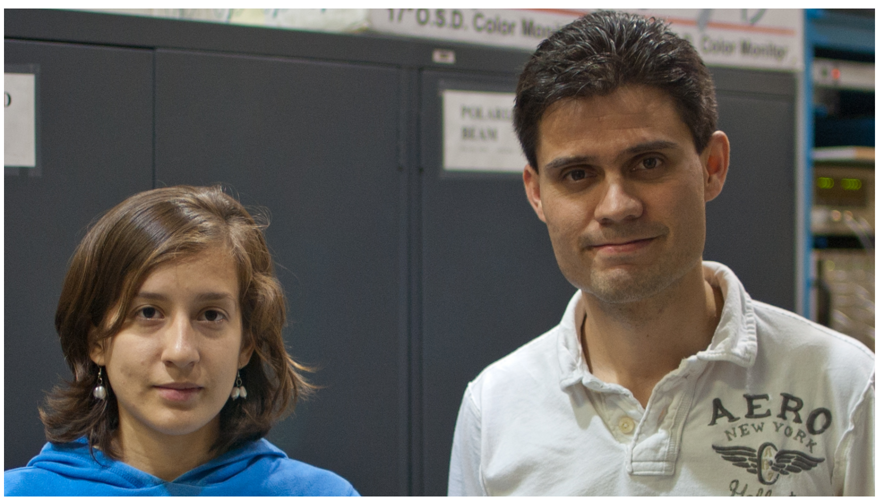


Gary Cheng, Jiehang Zhang, and Young Shing

William and Mary

Seth Aubin

San Luis Potosi

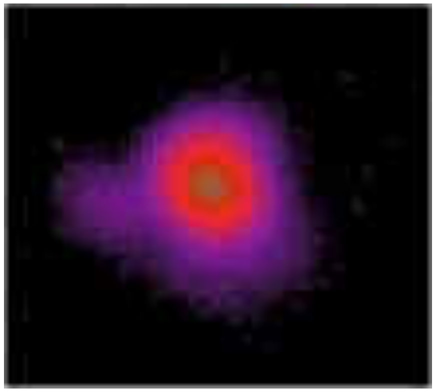


Maricarmen Ruiz, Eduardo Gomez

Texas A&M

Dan Melconian

A Brief History of Francium at Stony Brook

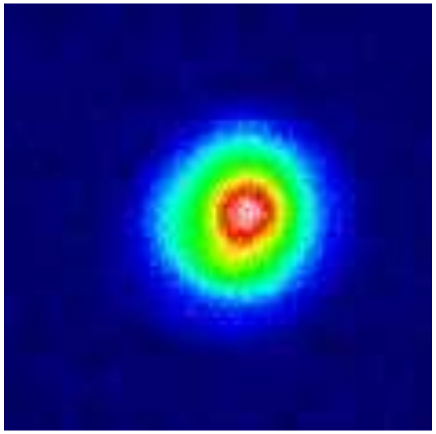


2,000 atoms
Fr MOT

1991-94: Construction of 1st production and trapping apparatus.

1995: Produced and Trapped Francium in a MOT.

1996-2000: Laser spectroscopy of Francium ($8S_{1/2}$, $7P_{1/2}$,$7D_{5/2}$,$7D_{3/2}$, hyperfine anomaly).



250,000 atoms
Fr MOT

2000-2002: High efficiency trap.

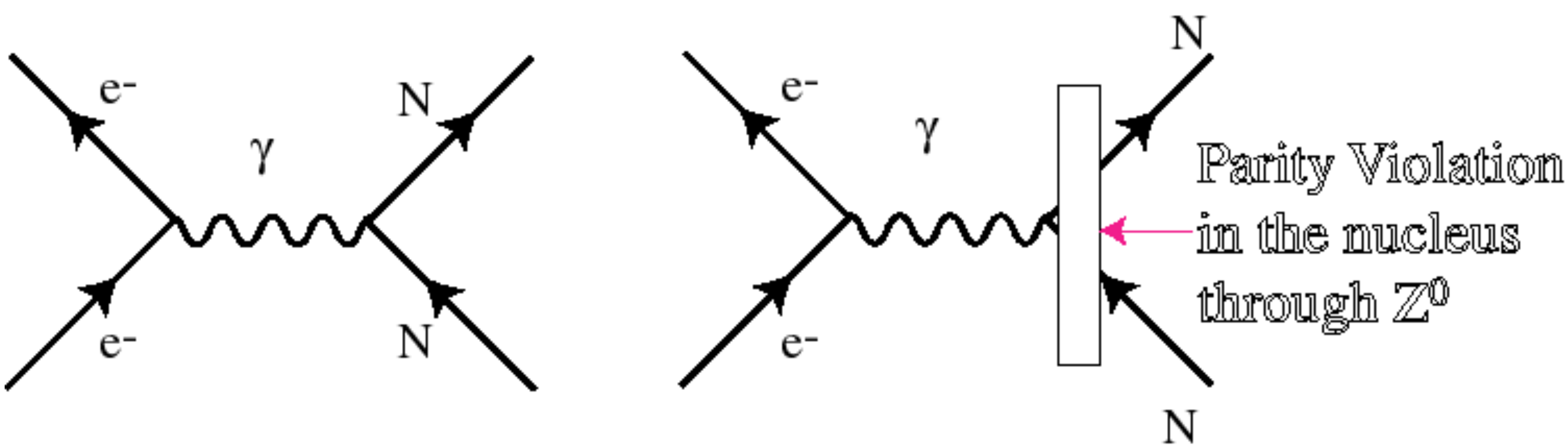
2003: Spectroscopy of $9S_{1/2}$,$8P_{1/2}$,$8P_{3/2}$ levels,

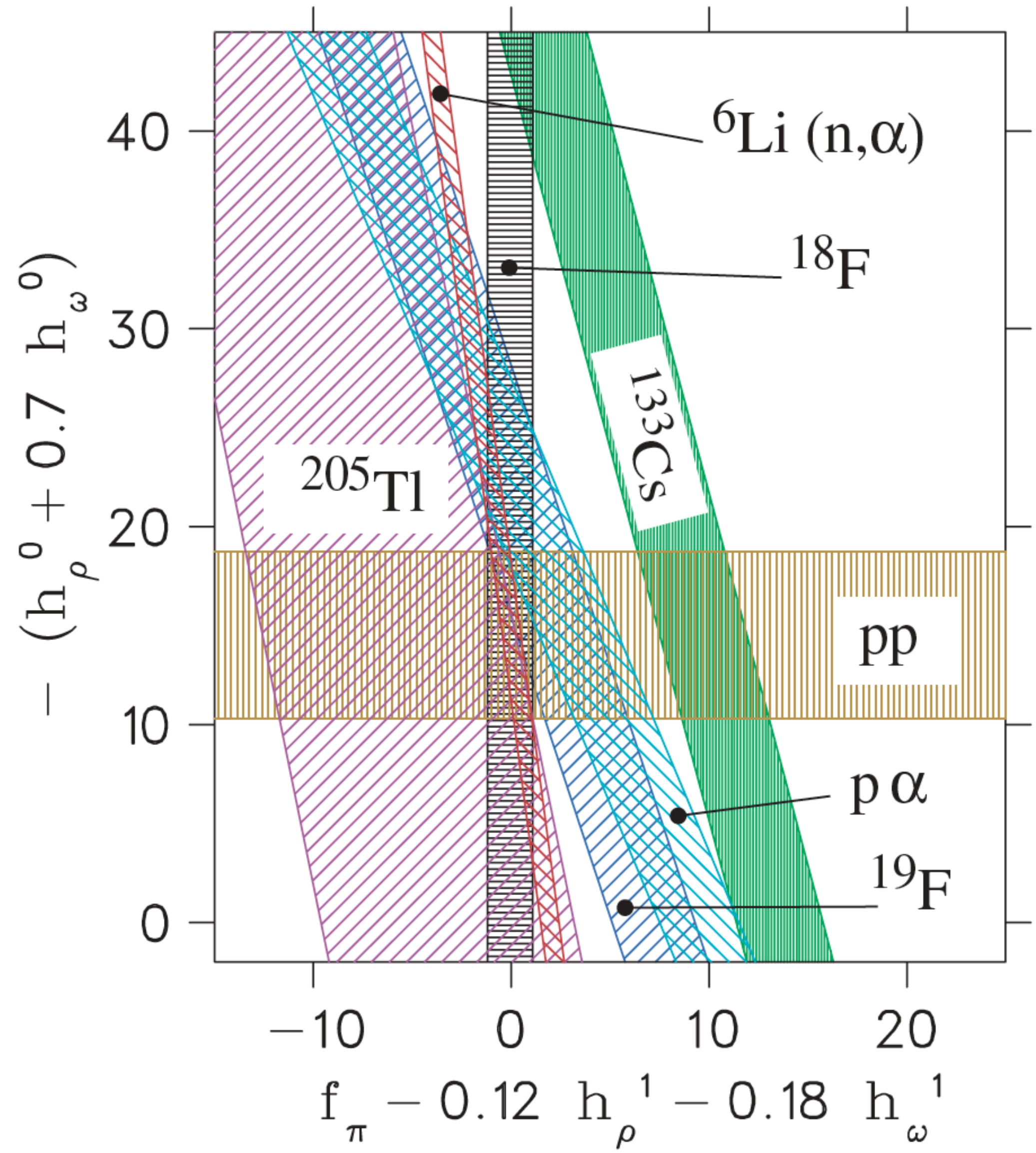
2004: Lifetime of 8S level.

2007: Magnetic moment ^{210}Fr based on $9S_{1/2}$.

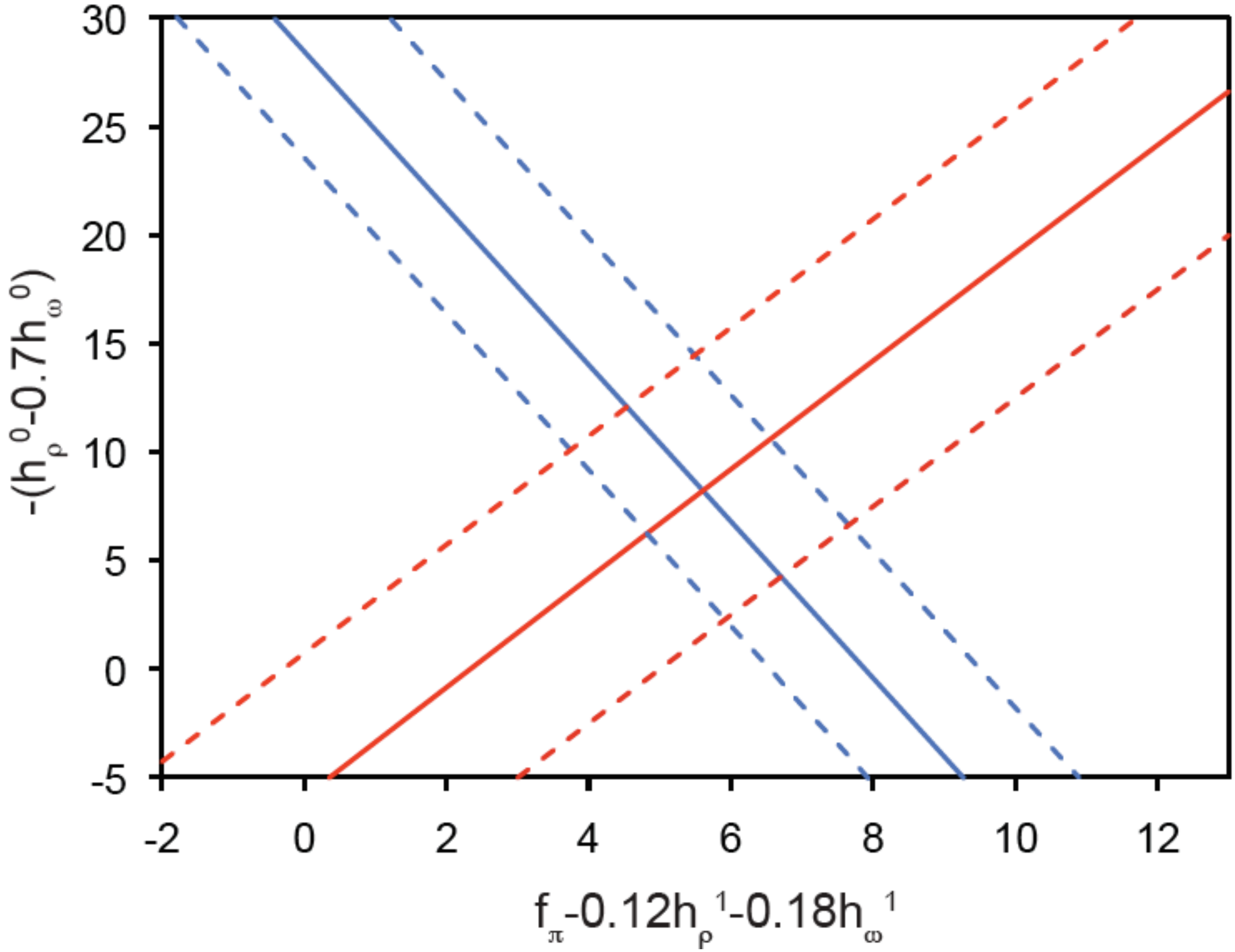
The Anapole Moment History

1958 Zel'dovich, Vaks
1980 Khriplovich, Flambaum
1984 Khriplovich, Flambaum, Shuskov
1995 Fortson (Seattle) bound from an experiment Thallium
1997 Wieman (Boulder) 15% measurement from an experiment Cesium





Constraints of the isovector and isoscalar meson couplings (10^7). The error bands are one standard deviation. The illustrated region contains all of the DDH "reasonable ranges" for the indicated parameters (Behr, based on Haxton and Wieman).



Constraints of couplings (10^7) from future measurements of two francium isotopes (even and odd isotopes) based on the calculations of Flambaum and Murray.

the FrPNC?

• Tested system with Rb at UMD and shipped to TRIUMF.

Now:

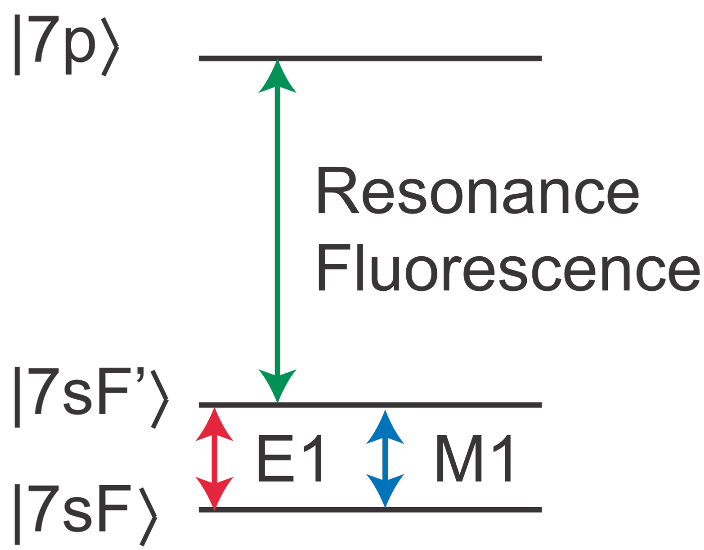
• Construct laboratory at ISAC in TRIUMF and trap Fr

Next

• Measurement of the anapole moment of a chain of Fr isotopes through the *E1* forbidden hyperfine transition. Shot noise limited signal-to-noise better than 1 $(Hz)^{-1/2}$. Extract weak coupling constants in the nucleus.

• The apparatus also works for Optical PNC to measure the spin independent part (Weak charge).

Anapole Measurement



Expected signal with 450 V/m

$$A_{E1}/\hbar = 0.01\, rad/s$$

1.- Define handedness of the apparatus by the coordinate system

$$(iE_{RF} \times B_{M1} \cdot B_{DC})$$

2.- Create superposition to interfere and enhance PNC signal:

$$A_{total} = A_{M1}^{PC} \pm A_{E1}^{PNC}$$

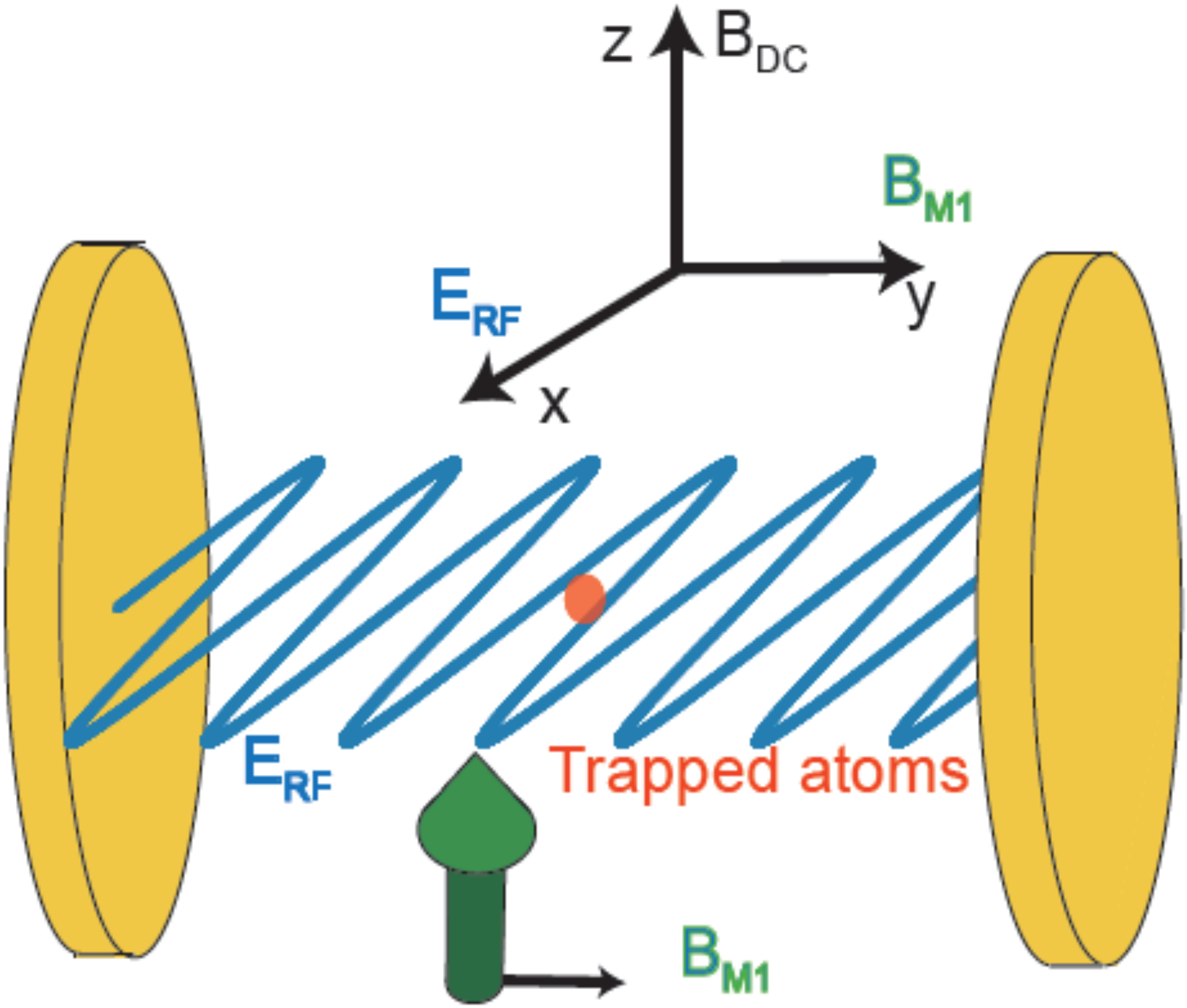
3.- Measure rate of transition through resonance fluorescence.

$$Rate \propto \left|A_{total}\right|^2$$

4.- Change handedness of apparatus

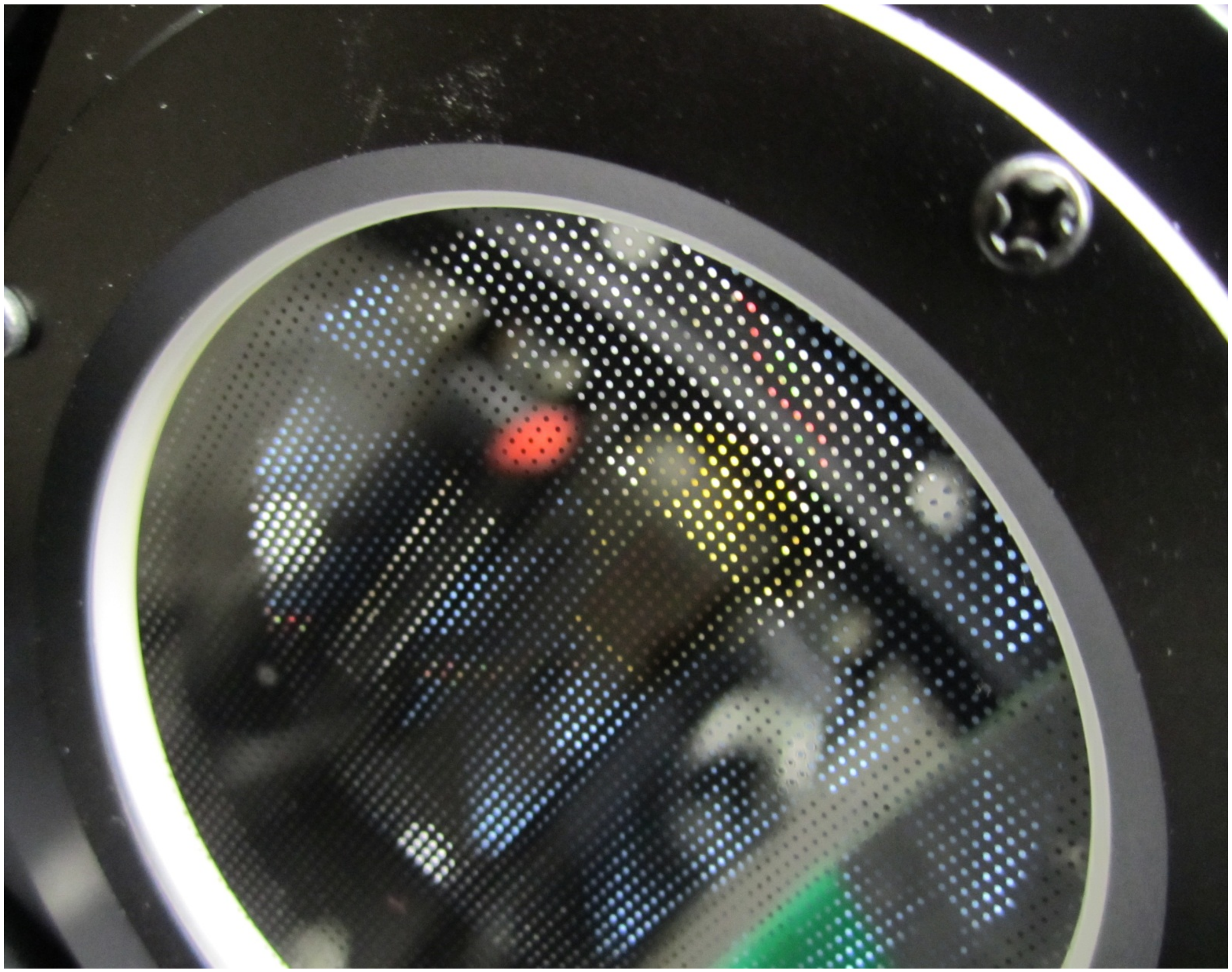
$$Signal \propto \left|A_{total}^{+}\right|^2 - \left|A_{total}^{-}\right|^2$$

5.- Repeat.



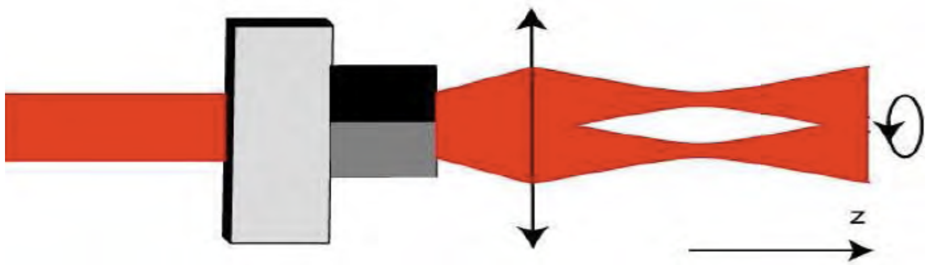
z
B_DC
B_M1
E_RF
y
x
E_RF
Trapped atoms
B_M1

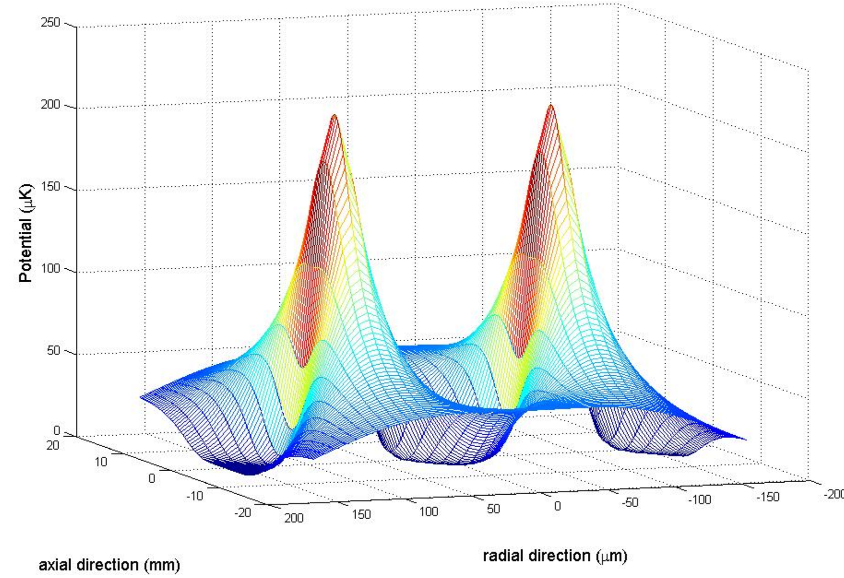
Manufactured Microwave Mirror



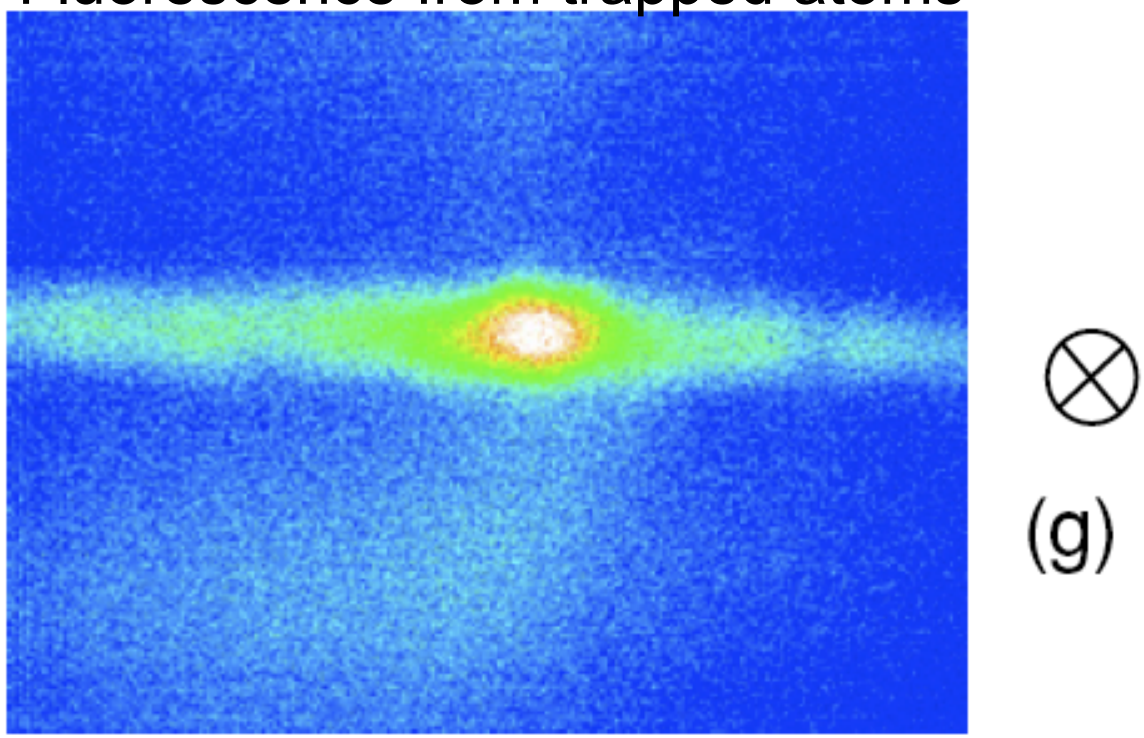
Perforated Hole array mirror fabricated in UMD FabLab.

Blue detuned trap



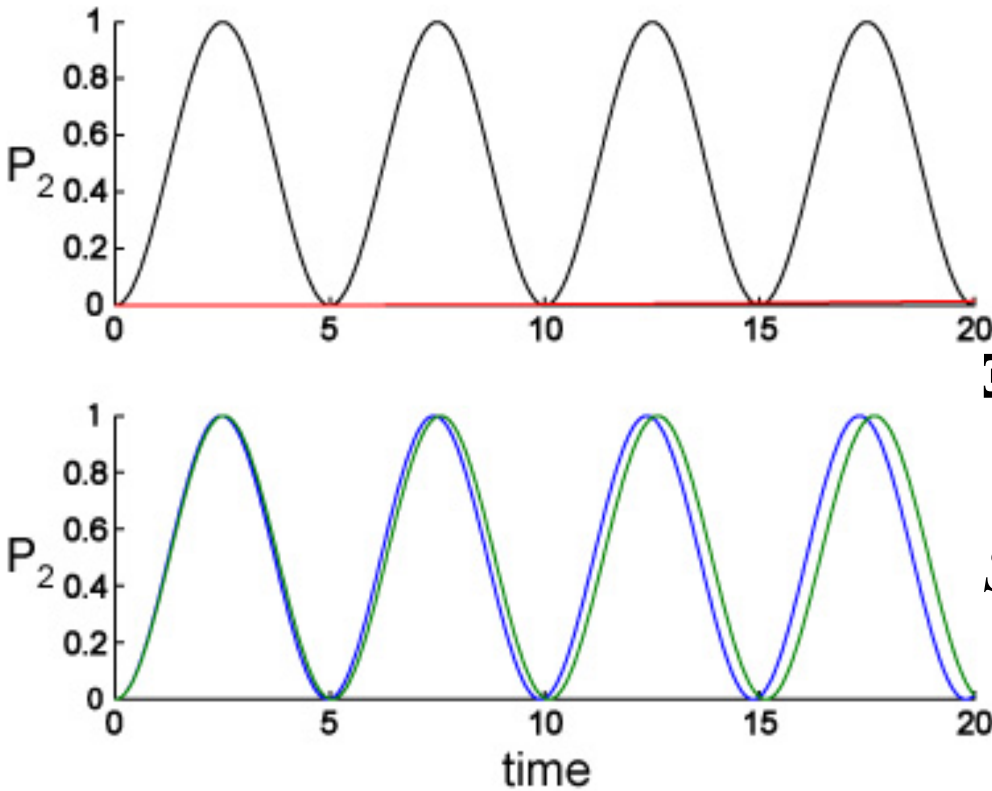


Fluorescence from trapped atoms



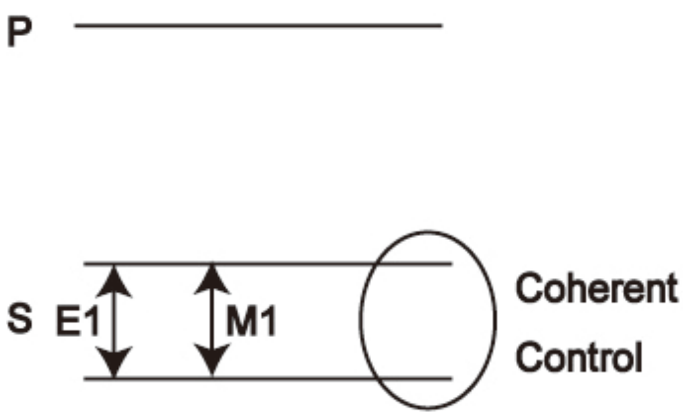
(g)

Principle of the measurement



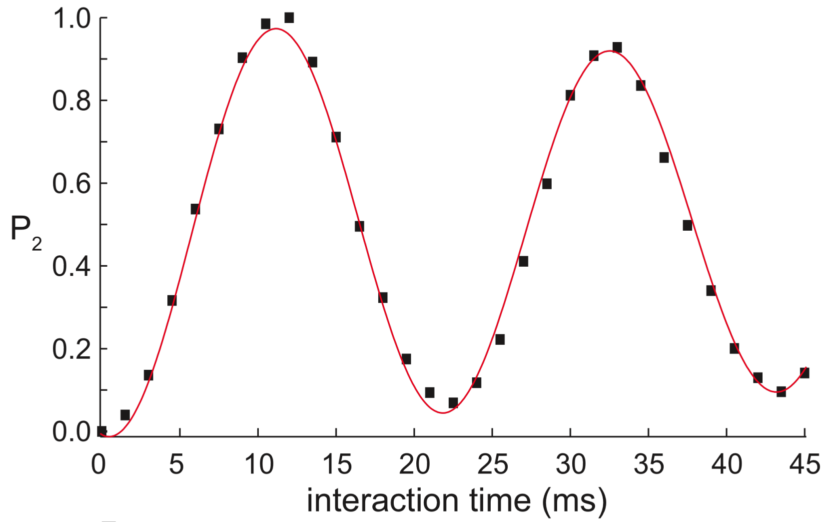
$$\Xi_{\pm} = N \sin^2\left(\frac{(A_{M1} \pm A_{E1})t_c}{2\hbar}\right)$$

$$S = \Xi_{+} - \Xi_{-} \cong N \sin\left(\frac{A_{M1}t_c}{2\hbar}\right)\left(\frac{A_{E1}t_c}{2\hbar}\right)$$

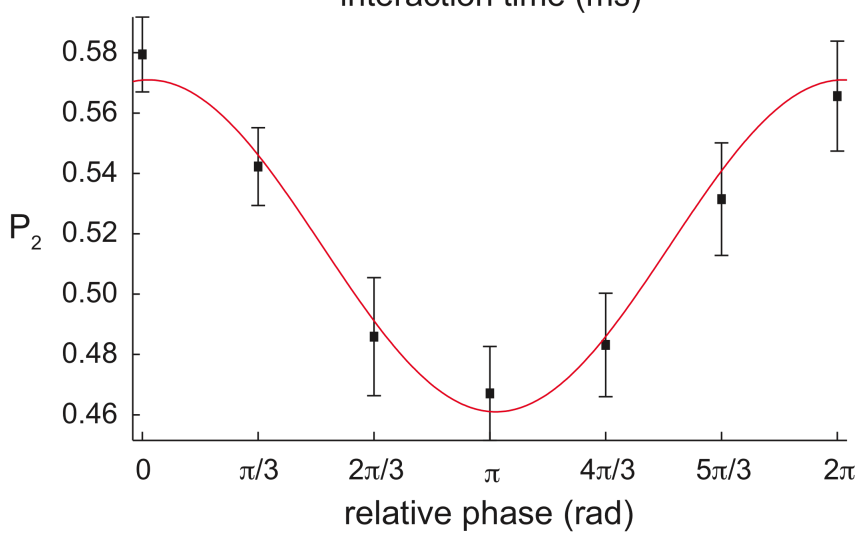


Control phase of different interactions
Ground state hyperfine splitting
Fr ~46 GHz, Z=87
Rb ~6.834 GHz, Z=37

Oscillations and sensitivity test



M1 Rabi oscillations (50 Hz) with 10^5 Rb atoms in blue detuned (20 nm) dipole trap. Decoherence time 180 ms.



While sitting at 37.5 ms, add a second microwave source with 10^4 attenuation, change of the phase and see the signal increase and decrease.

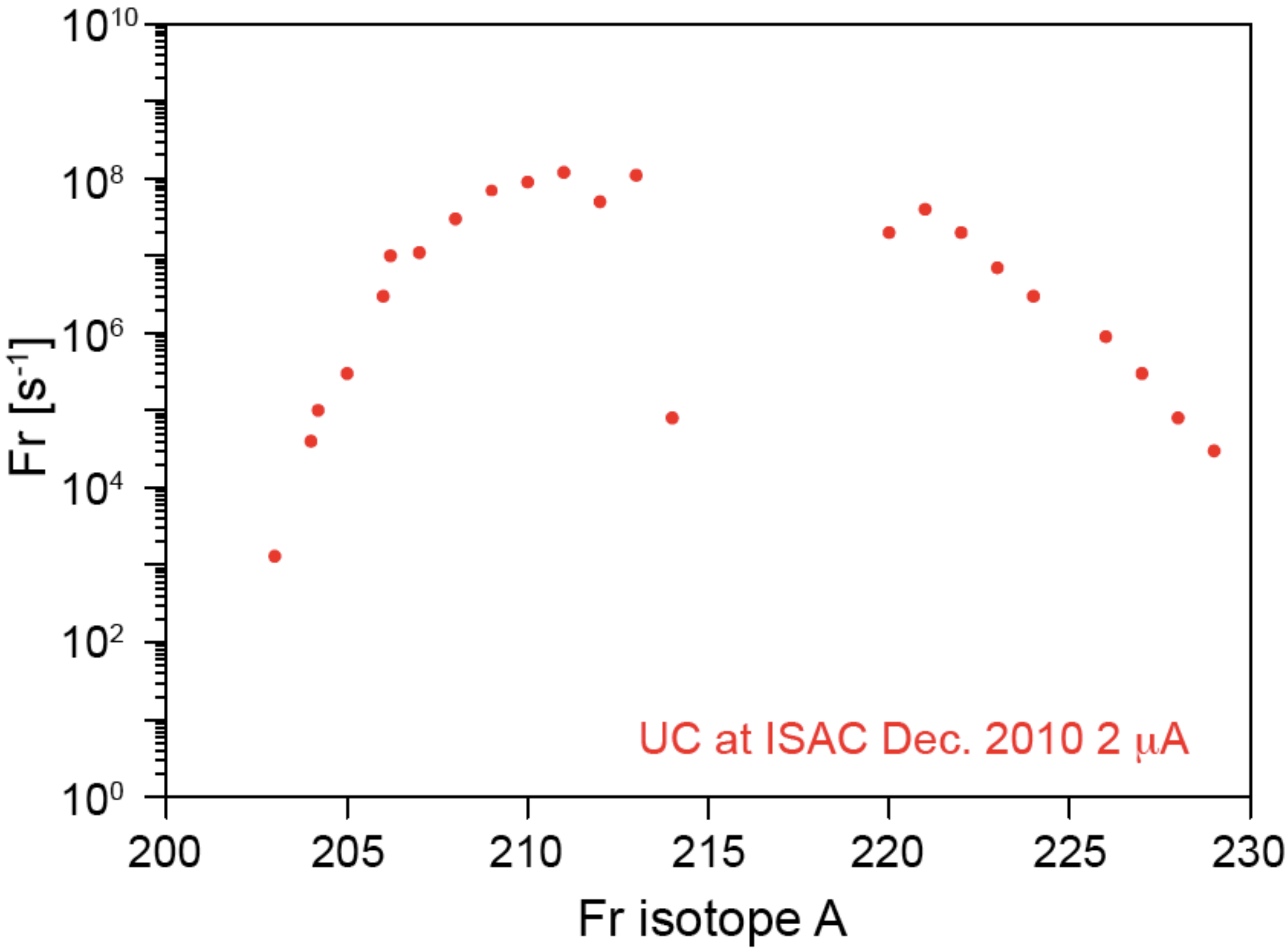
$$\frac{Signal}{Noise} = 2\Omega_{E1}\Delta t\sqrt{N} = 2$$

Number of atoms = $N \sim 10^6$

$\Omega_{E1} \sim 10$ mrad

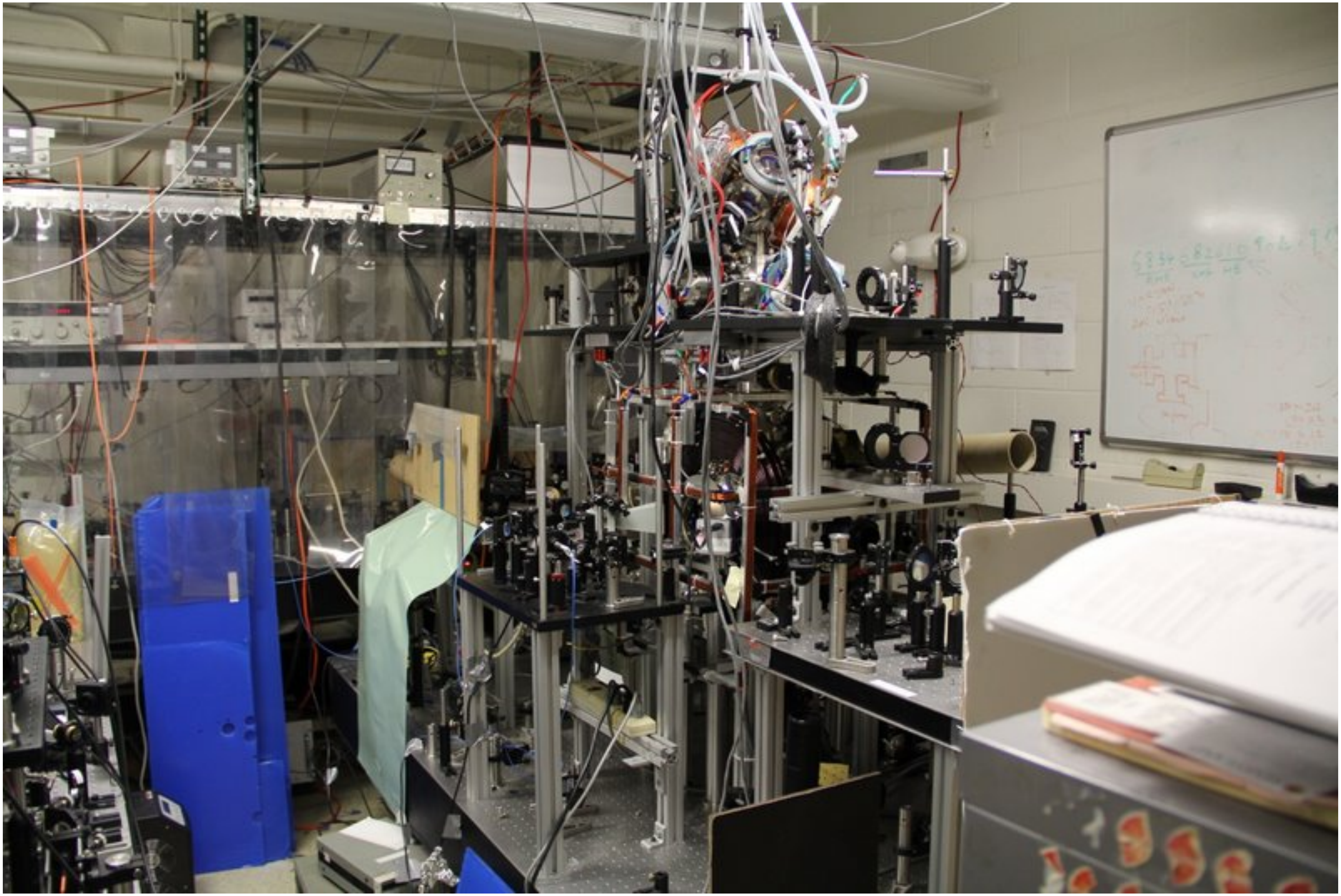
Interaction time = $\Delta\tau \sim 0.1$s

December 2010 results actinite target



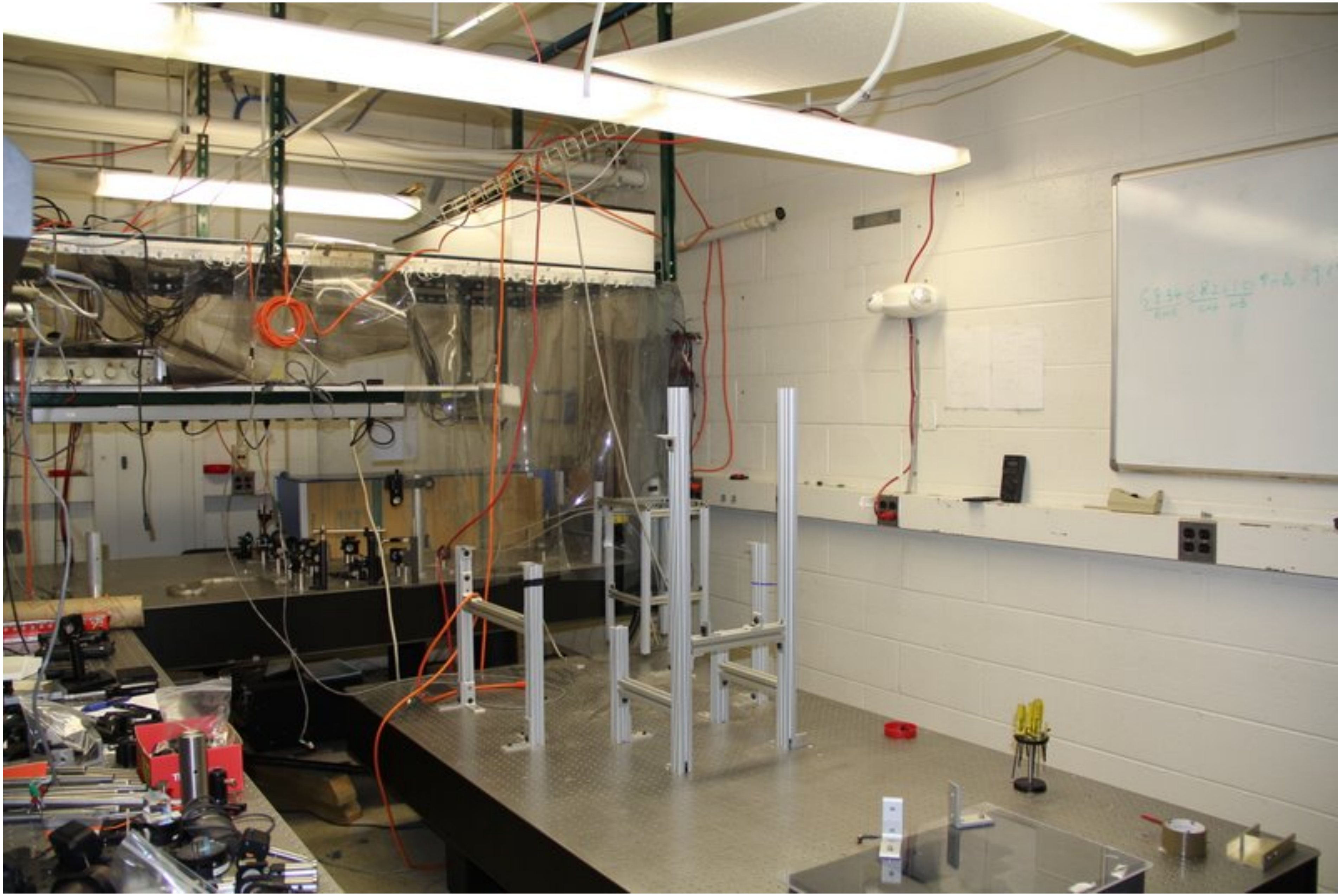
ISAC facility @ TRIUMF500 MeV protons (2 μA) on UC (30 g/cm2).

University of Maryland



September 6, 2011

University of Maryland

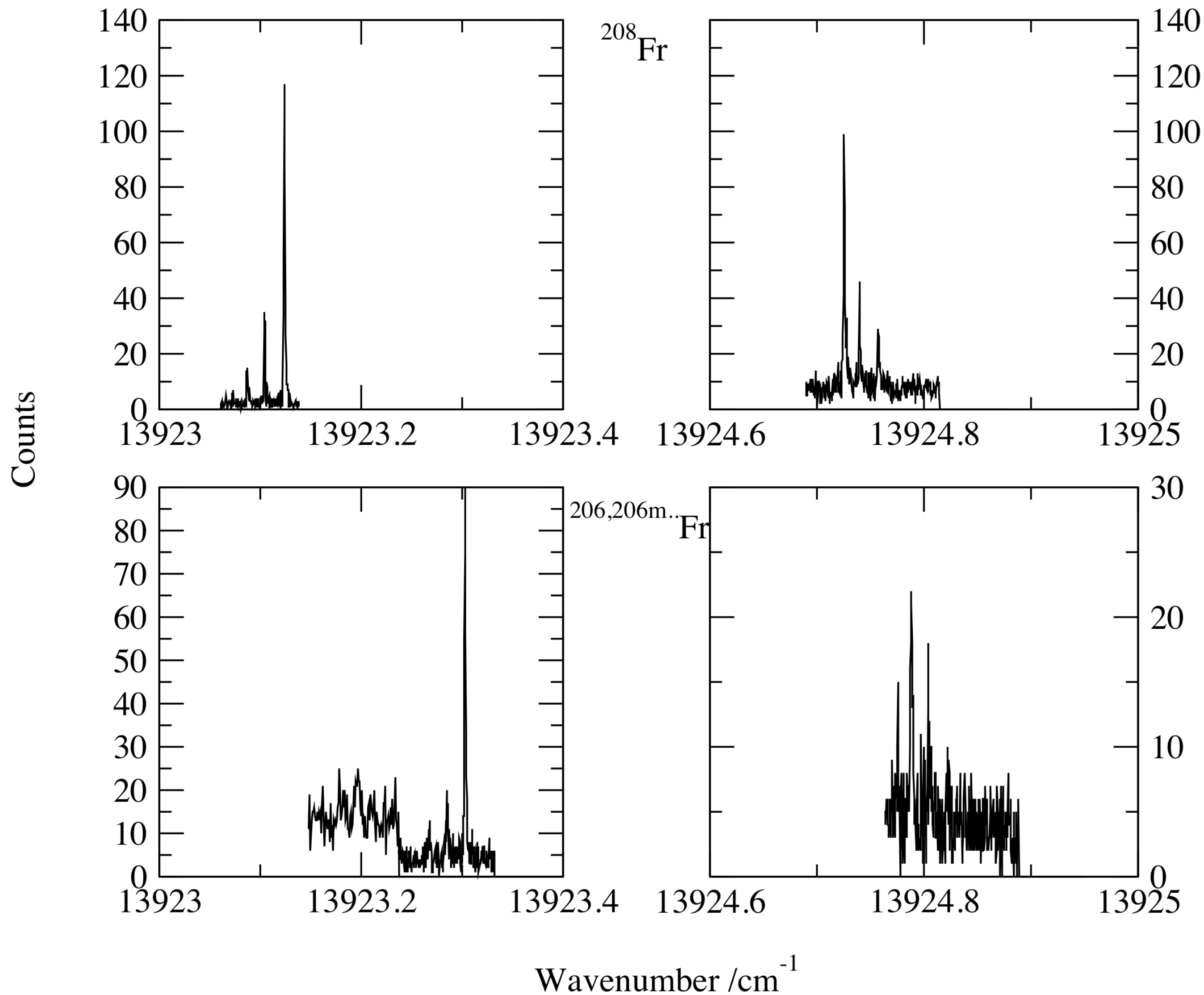


September 8, 2011

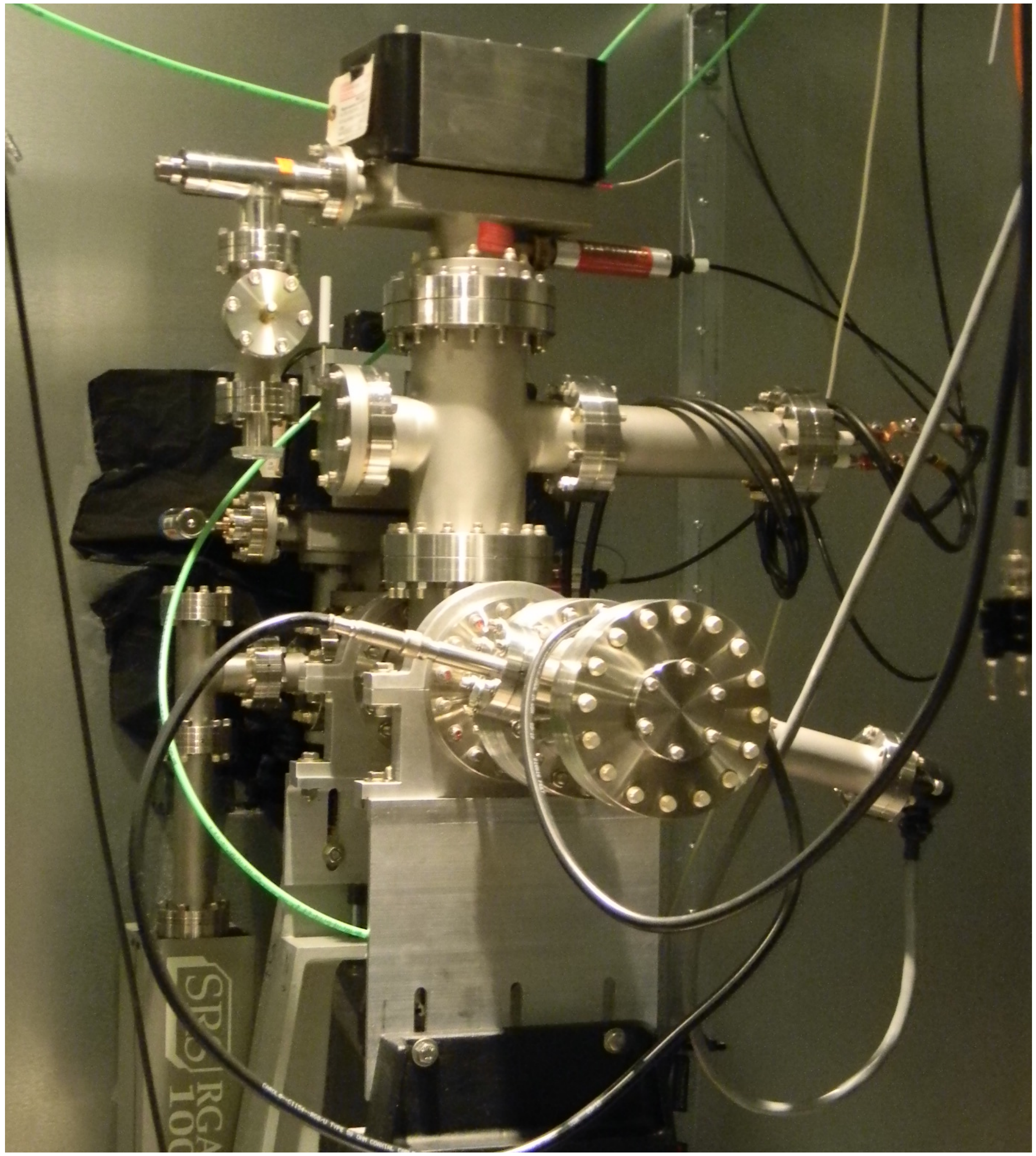
ISAC I hall at TRIUMF, new home of FrPNC

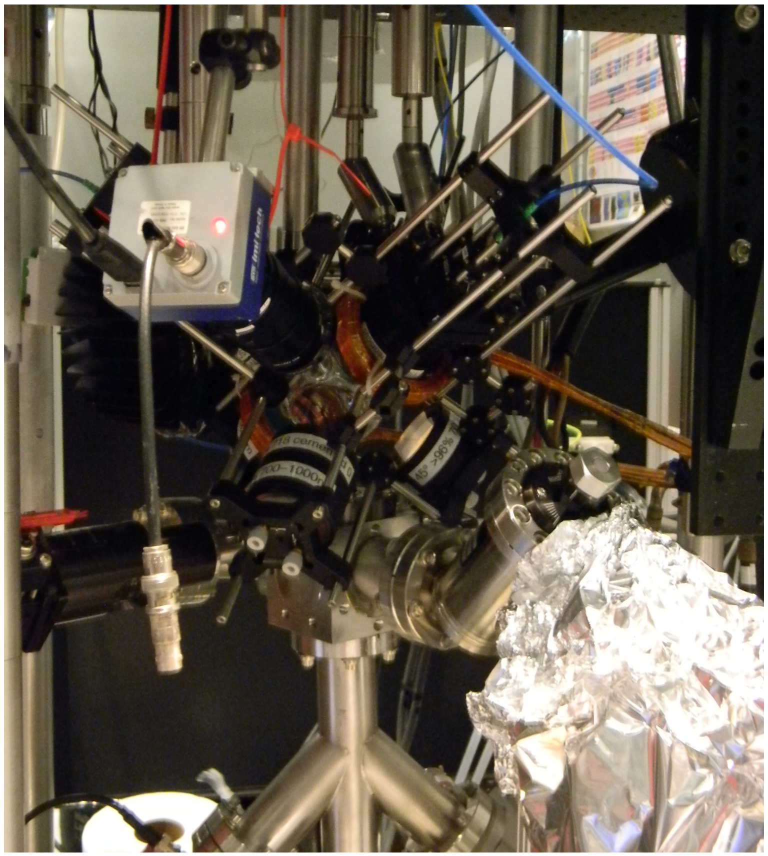
Collinear spectroscopy looking for ^{206}Fr in September 2011

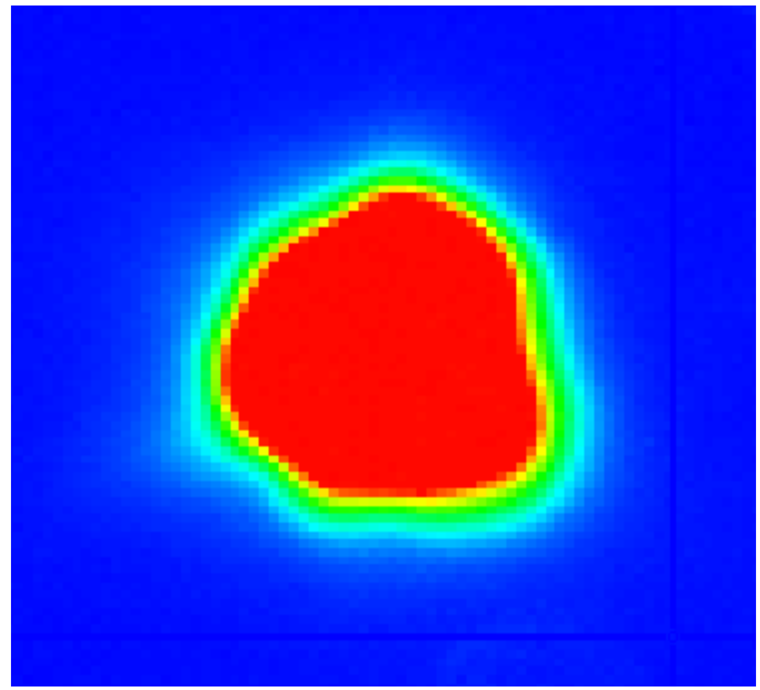
Preliminary results: observed the ground state 206 isotope and found its isomer



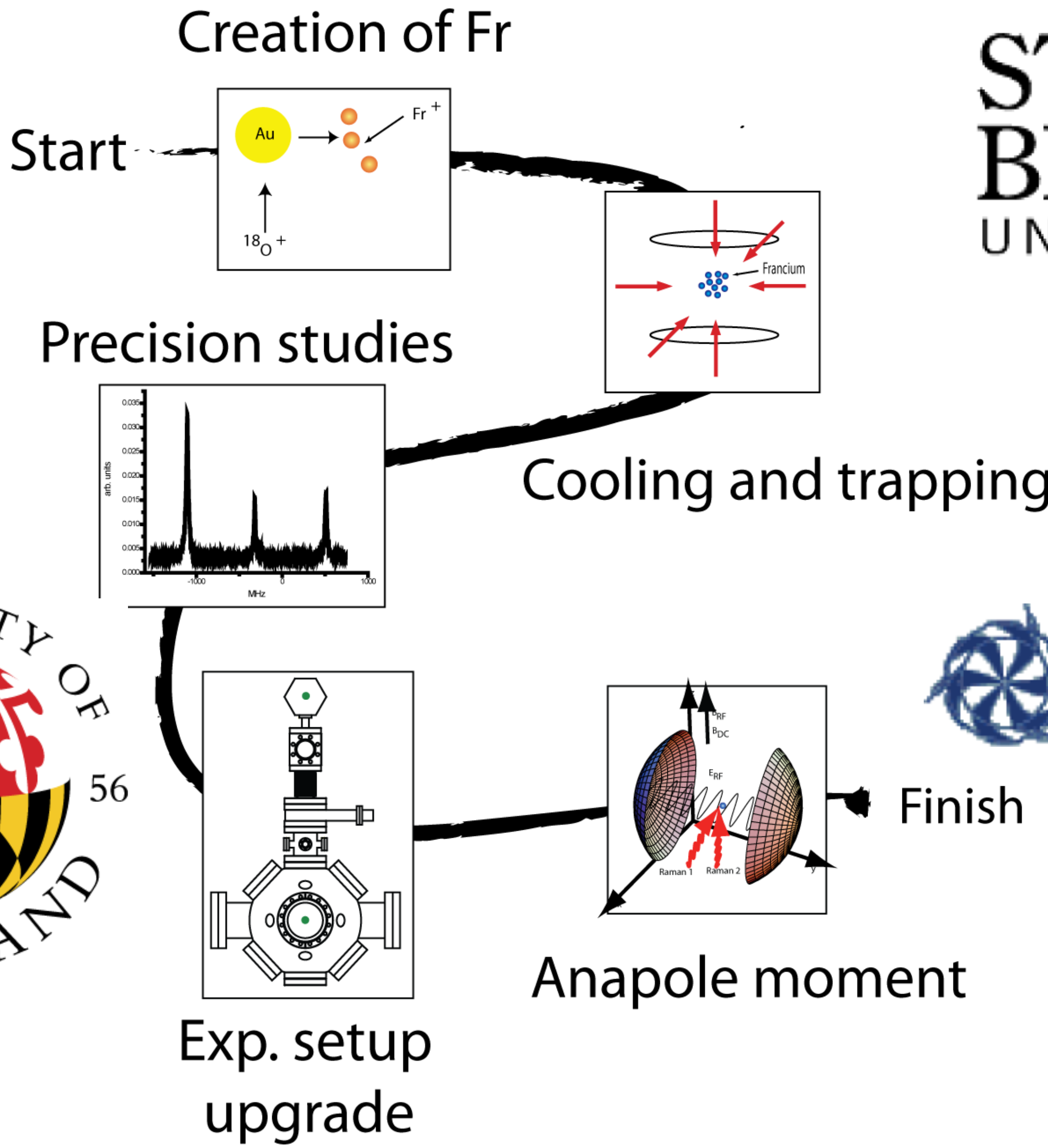

SECURITY NOTICE
DANGER


RGA





Rb Trap at Fr Trapping Facility



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UNIVERSITY OF MARYLAND 1856

THANKS!