

Proposed experiment for the anapole measurement in francium

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UNIVERSITY OF
MARYLAND

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Sprouse, Y. Zhao At TRIUMF

Supported by NSF.

Current members at UMD:

Adrian Perez Galvan

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Past members at Stony Brook:

2005 Dr. Eduardo Gomez (Universidad Autonoma de San Luis Potosi)

2003 Dr. Seth Aubin (William and Mary)

2001 Dr. Joshua Grossman (St. Mary University)

1998 Dr. John E. Simsarian (Bell Labs)

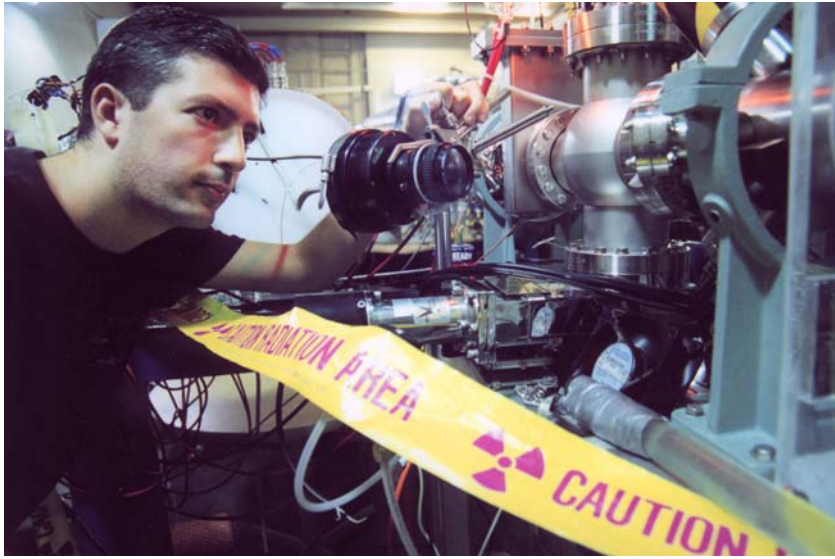
1995 Dr. Gerald Gwinner (U. Manitoba)

Dr. Paul Voytas (Wittenberg University)

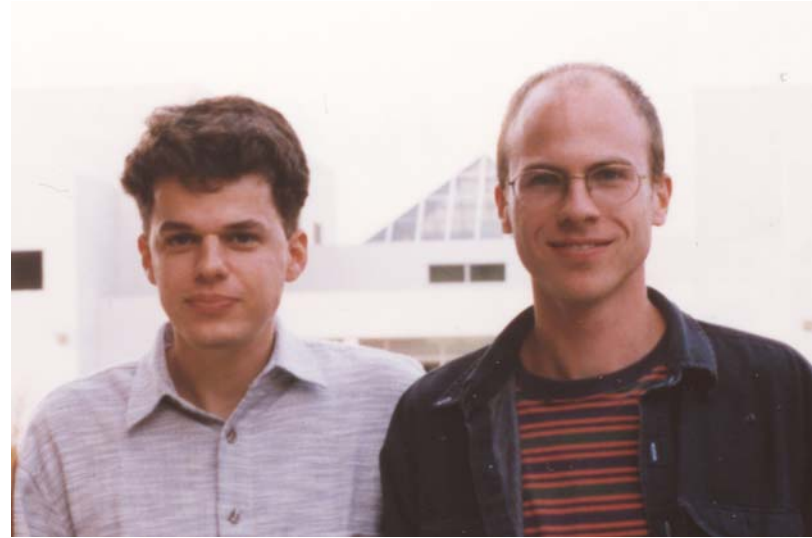
Dr. John Behr (TRIUMF)

Dr. Matthew Pearson (TRIUMF)

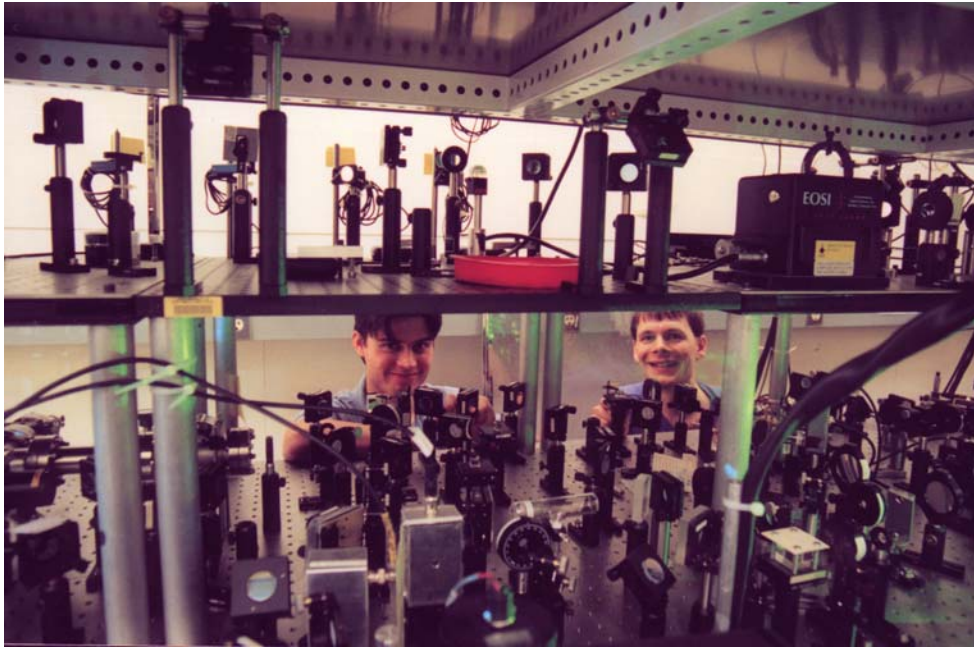
Collaboration from David DeMille (Yale)



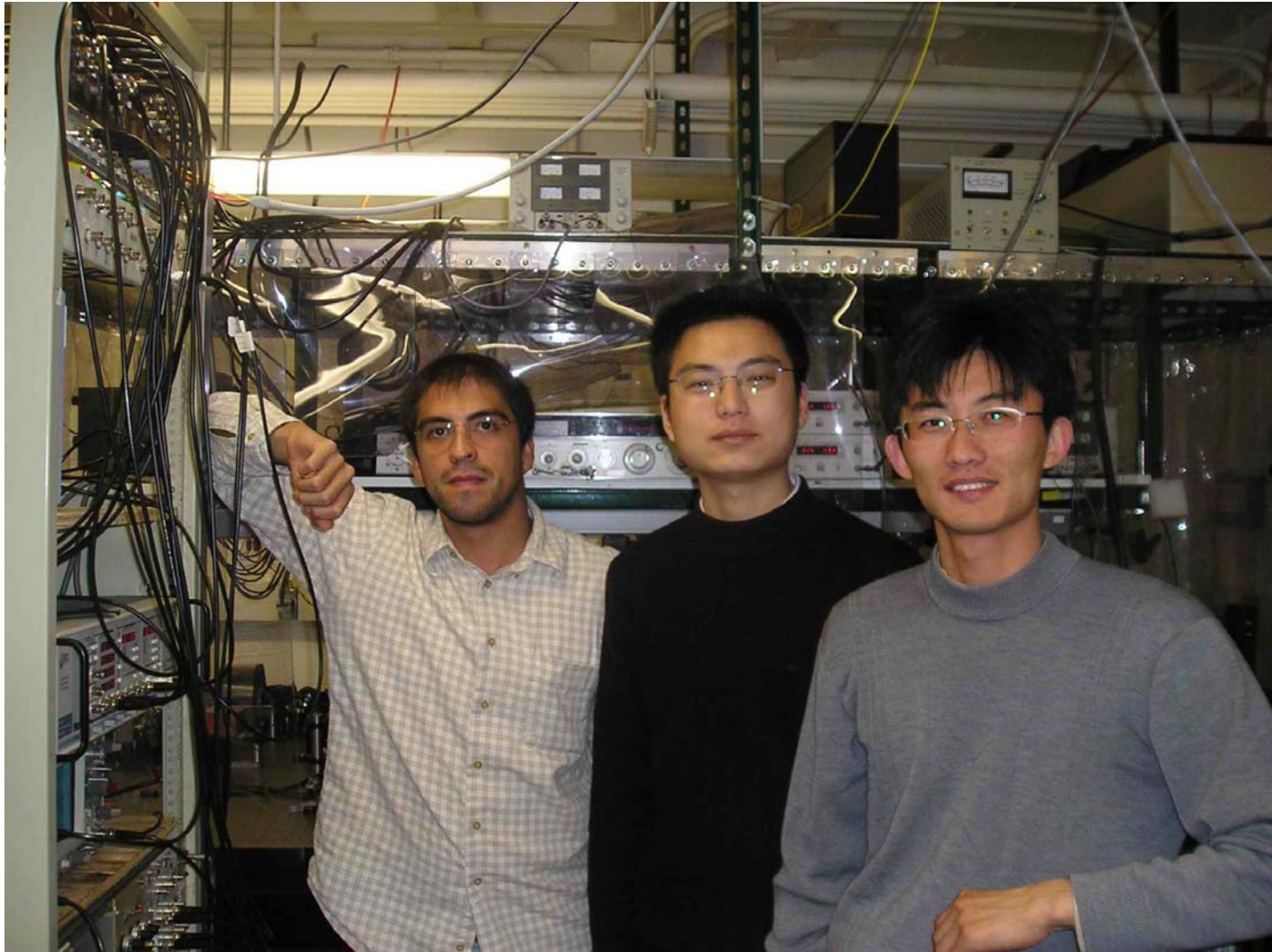
Josh



Gerald and Jesse



Eduardo and Seth



Adrian, Dong y Yanting

	IA																	0
1	1 H	IIA																2 He
2	3 Li	4 Be										5 B	6 C	7 N	8 O	9 F	10 Ne	
3	11 Na	12 Mg	III B	IV B	V B	VI B	VII B	VIII VII			IB	IB	13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	*La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	+Ac	104 Rf	105 Ha	106	107	108	109	110	111	112						

Naming conventions of new elements

* Lanthanide Series

+ Actinide Series

58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

A Brief History of Francium at Stony Brook

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

1995: Produced and Trapped Francium in a MOT.

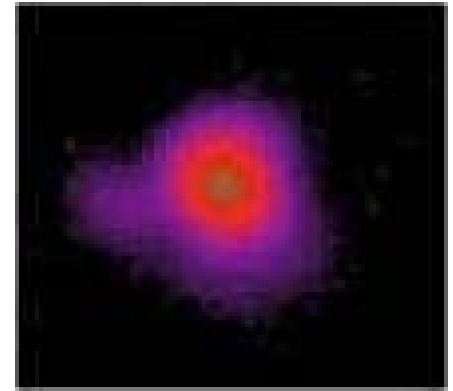
1996-2000: Laser spectroscopy of Francium ($8S_{1/2}$, $7P_{1/2}$, $7D_{5/2}$, $7D_{3/2}$, hyperfine anomaly).

2000-2002: High efficiency trap.

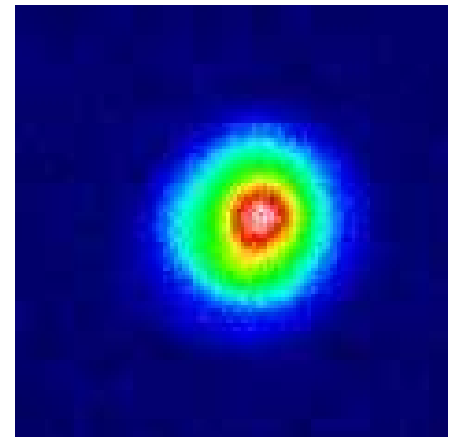
2003: Spectroscopy of $9S_{1/2}$ $8p$ levels,

2004: Study of $8s$ levels.

2007: Magnetic moment ^{210}Fr . (M. Safronova)

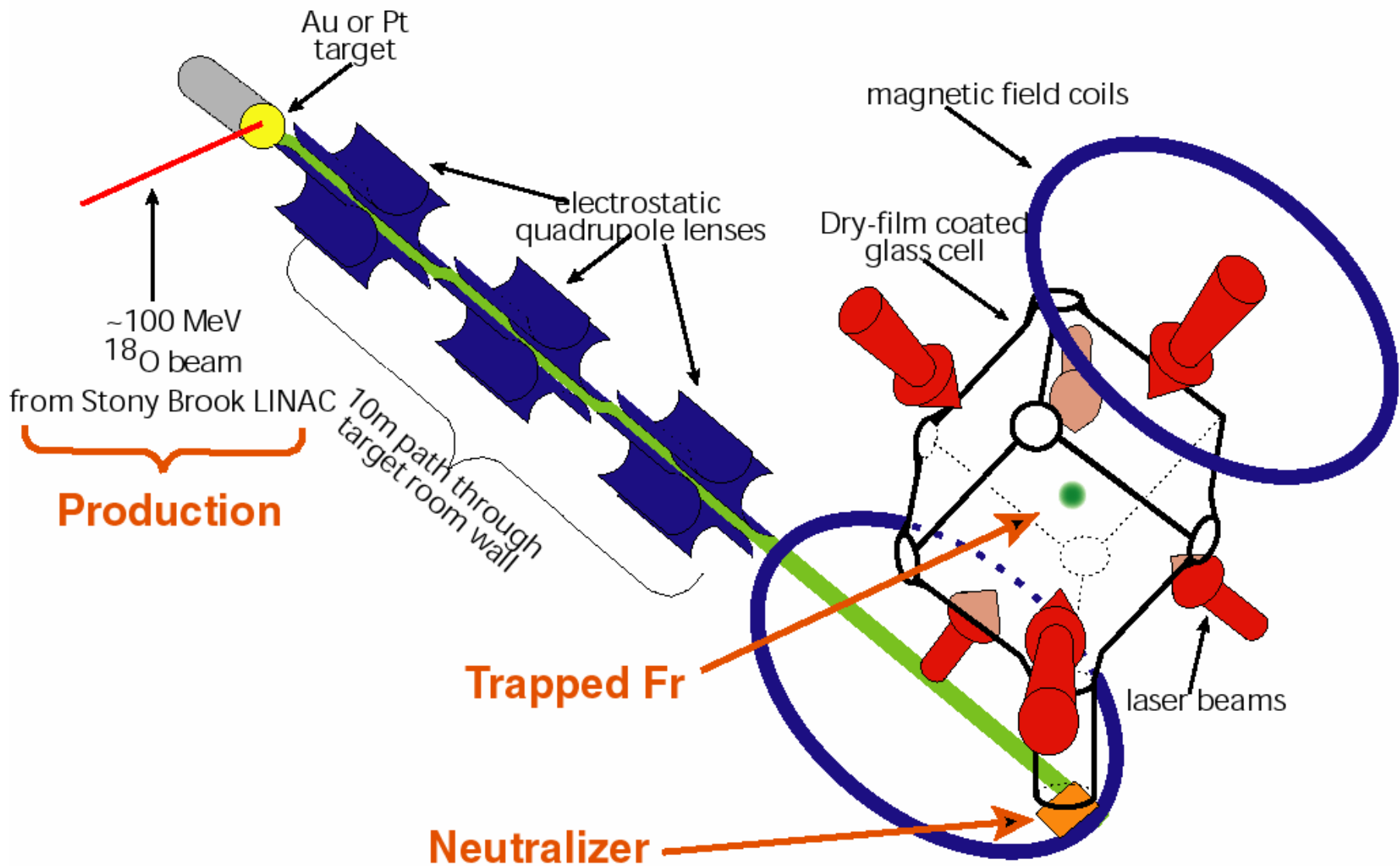


2,000 atom Fr
MOT

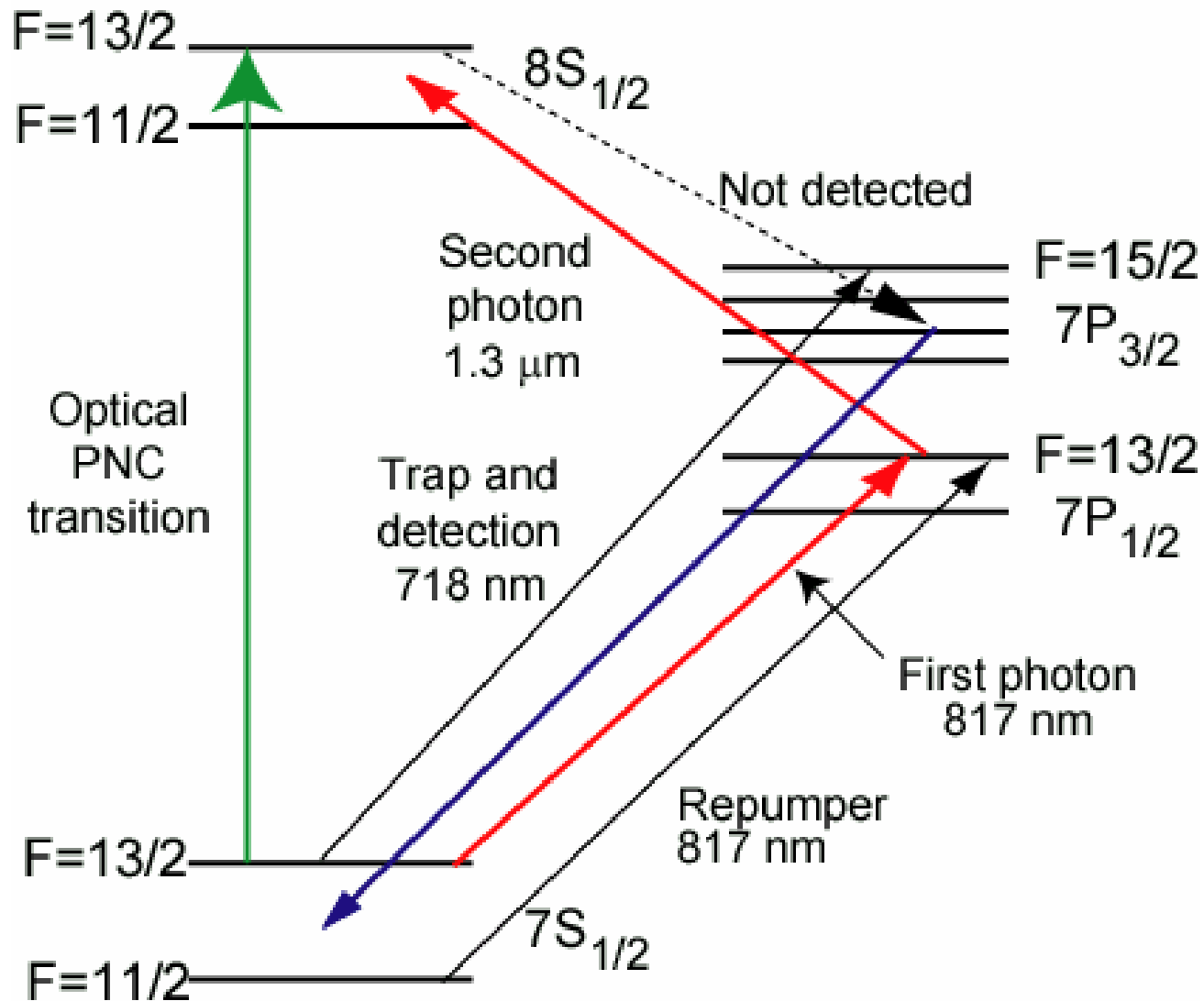


250,000 atom
Fr MOT

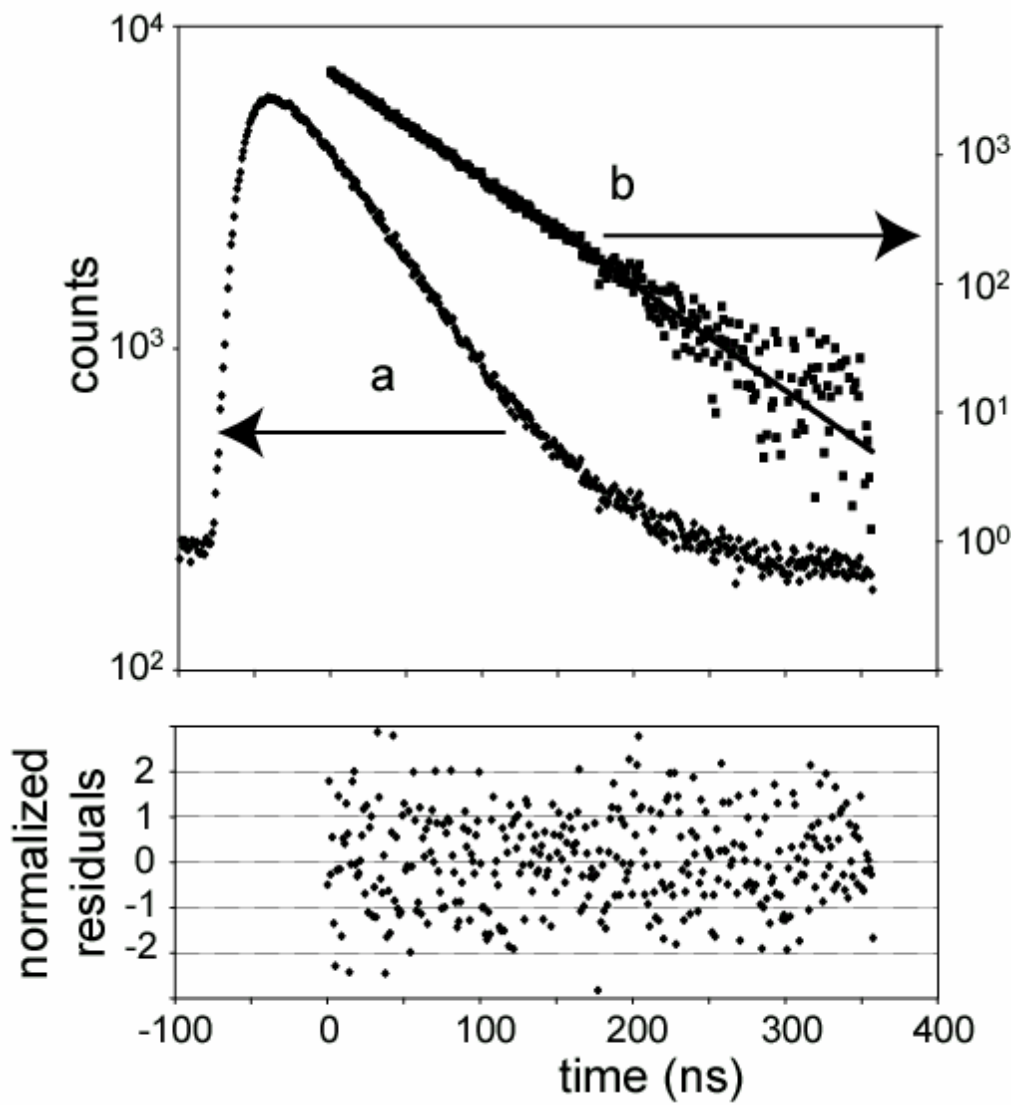
Apparatus for Production and Trapping of Francium



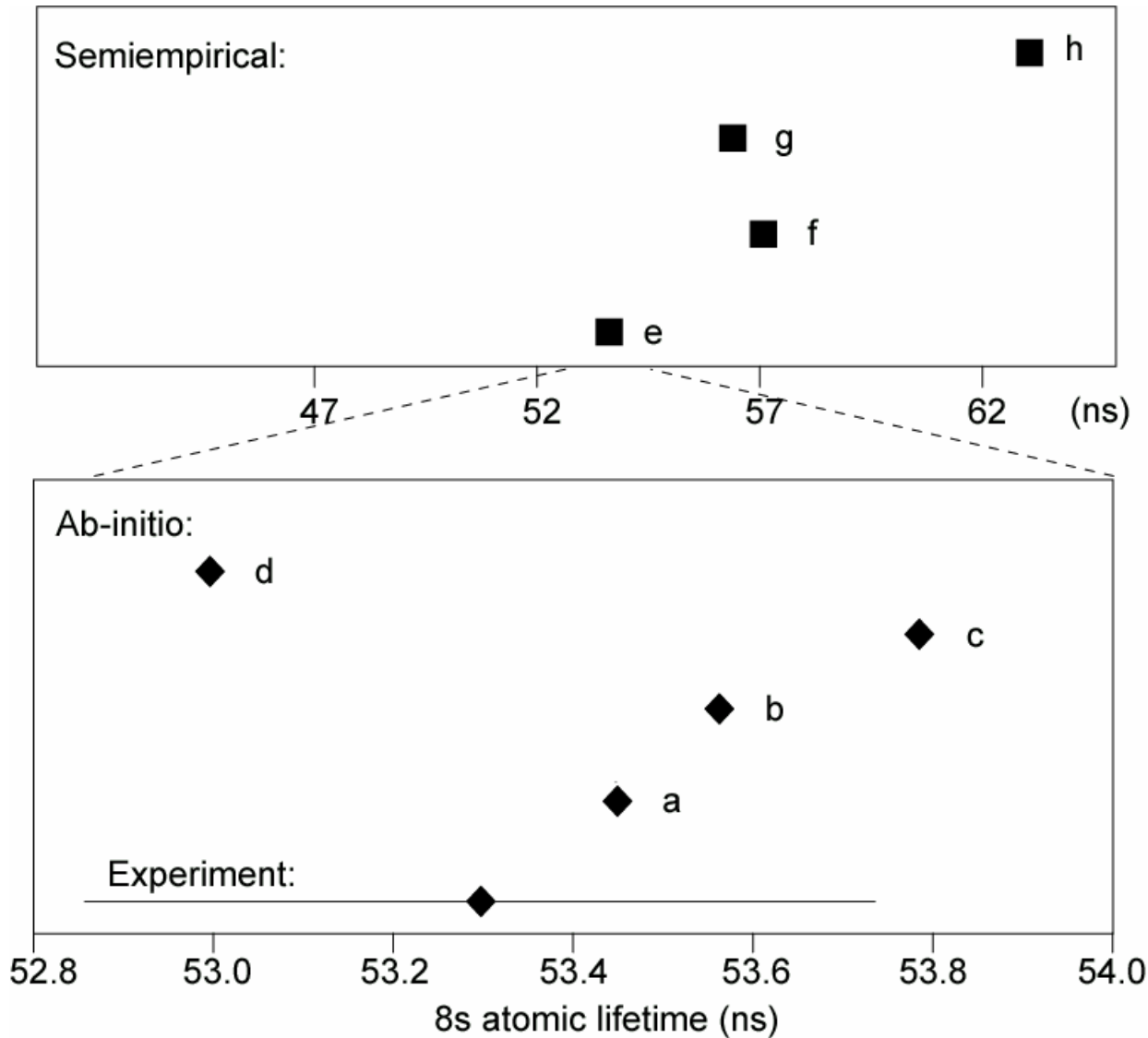
Lifetime of the 8s level



8s decay

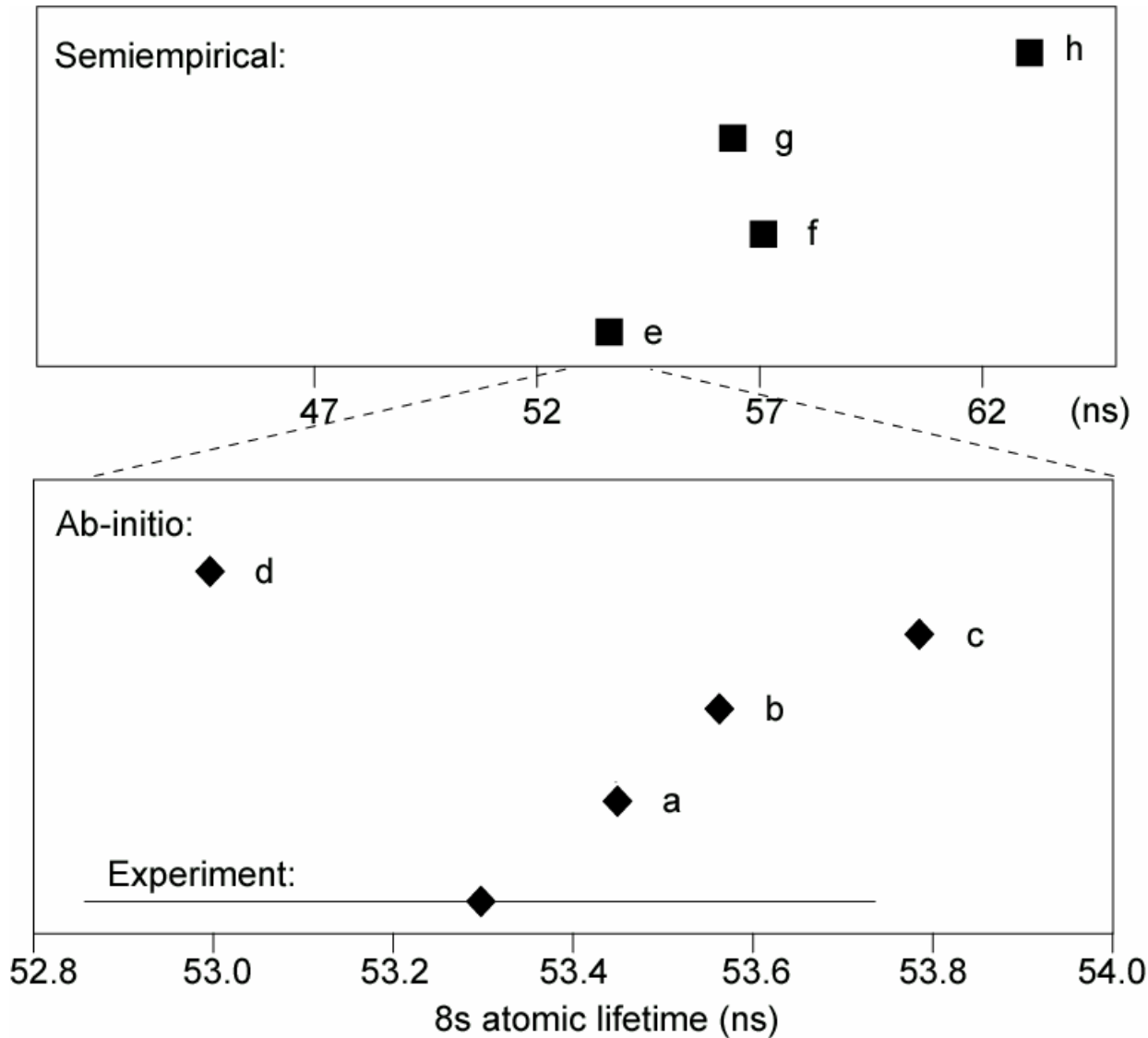


Comparison with theory



- a) Safronova *et.al.*
- b) Dzuba *et.al.*
- c) Johnson *et.al.*
- d) Dzuba *et.al.*
- e) Marinescu *et.al.*
- f) Theodosiou *et.al.*
- g) Biemont *et.al.*
- h) Van Wijngaarden *et.al.*

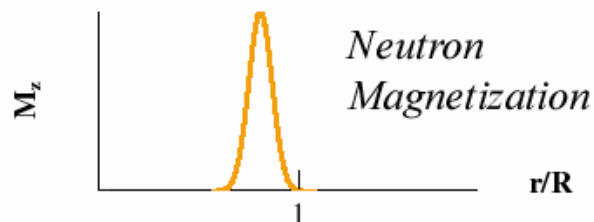
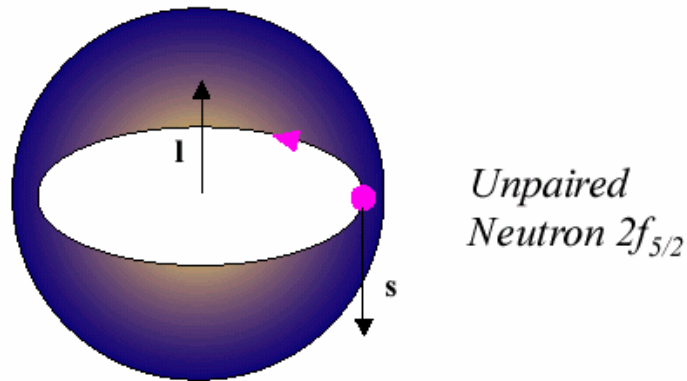
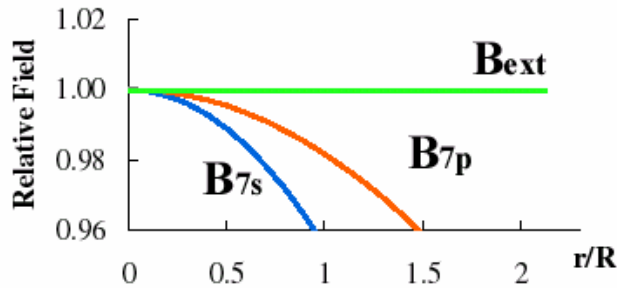
Comparison with theory



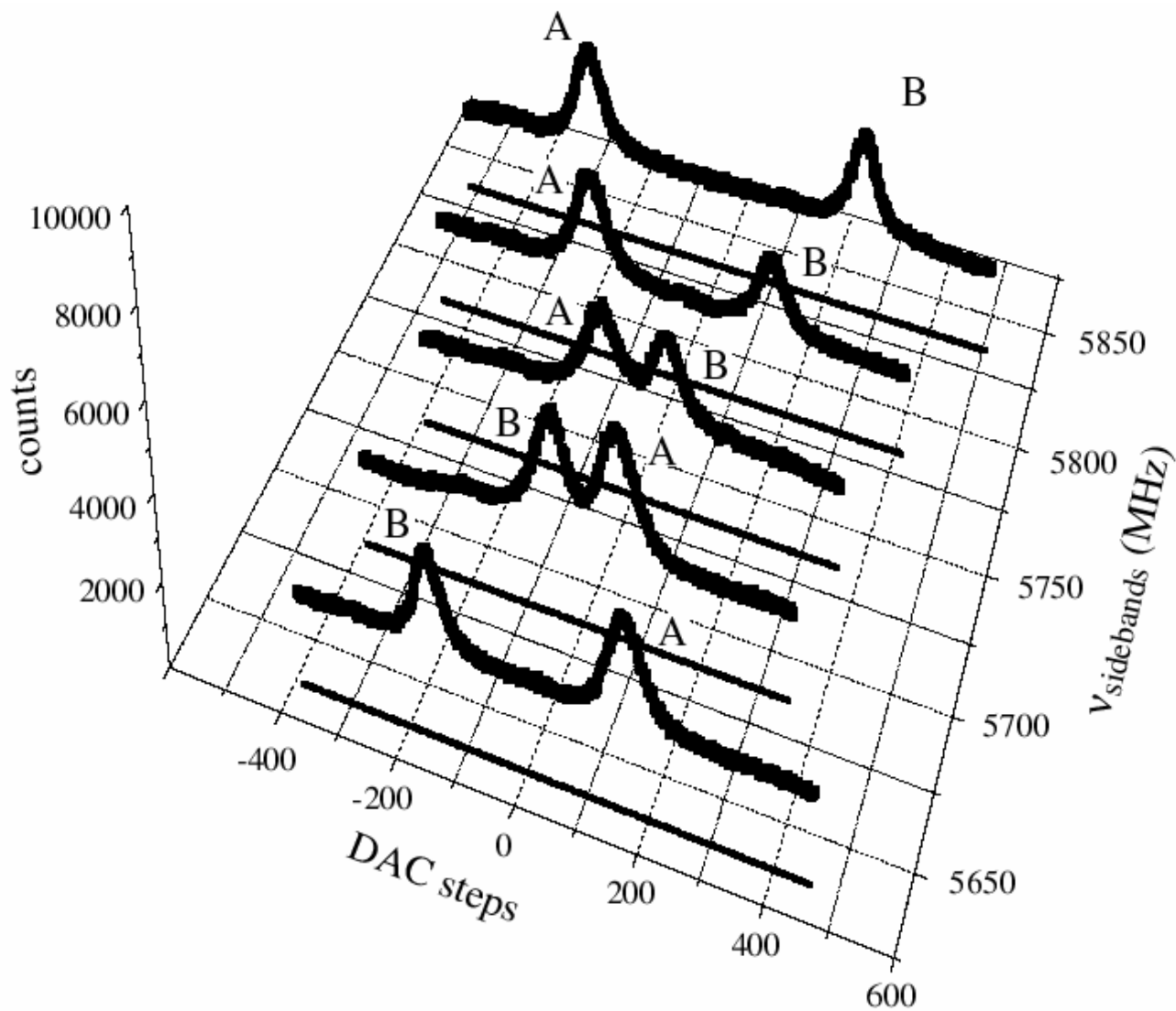
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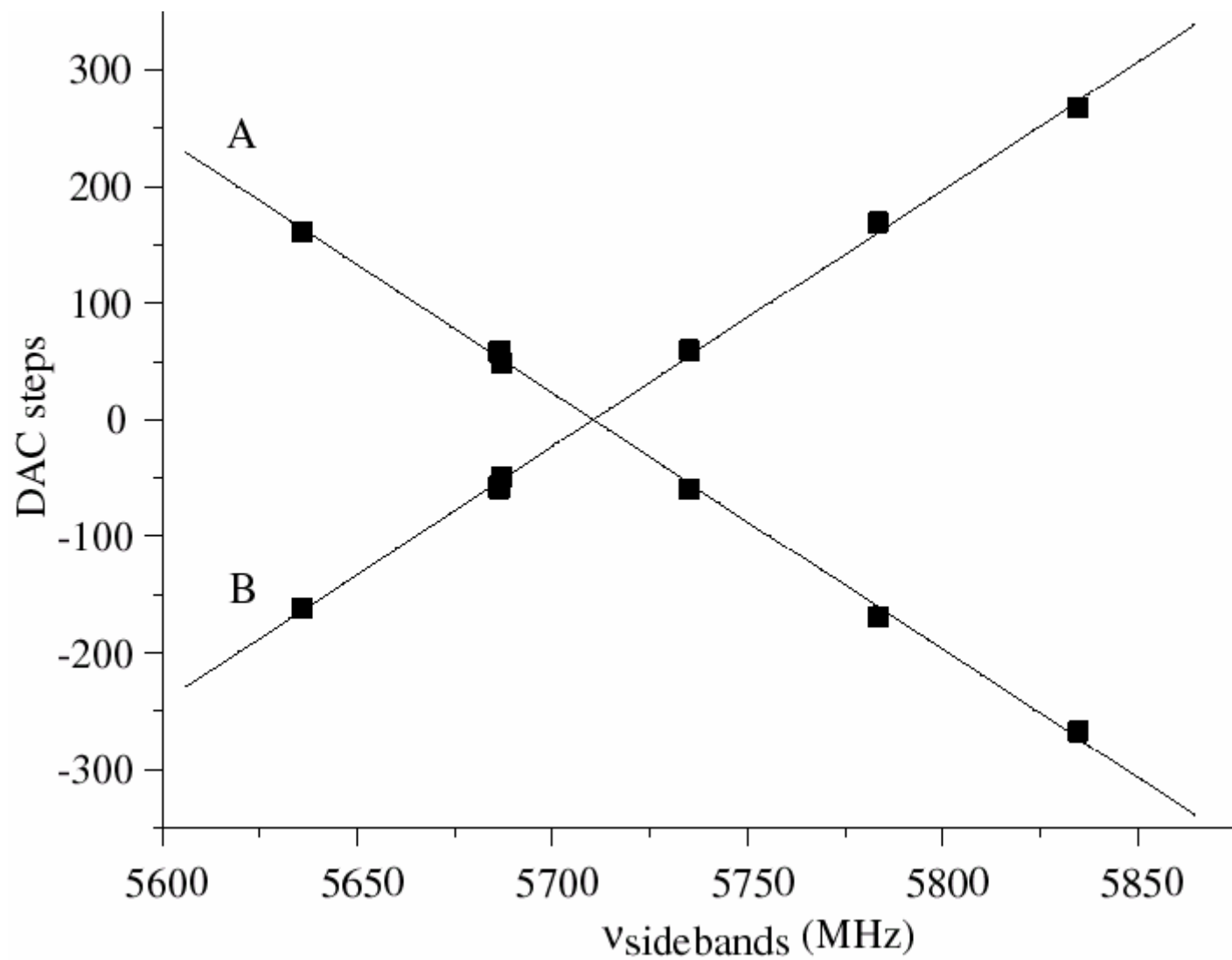
Example of studies of Francium linked to nuclear structure

The magnetic hyperfine structure is from the interaction of nuclear magnetic moment and the magnetic field of electrons at the nucleus. A depends upon $\mathbf{B} \cdot \boldsymbol{\mu}_I$, the ratio A_{7s} / A_{7p} is isotope dependent.

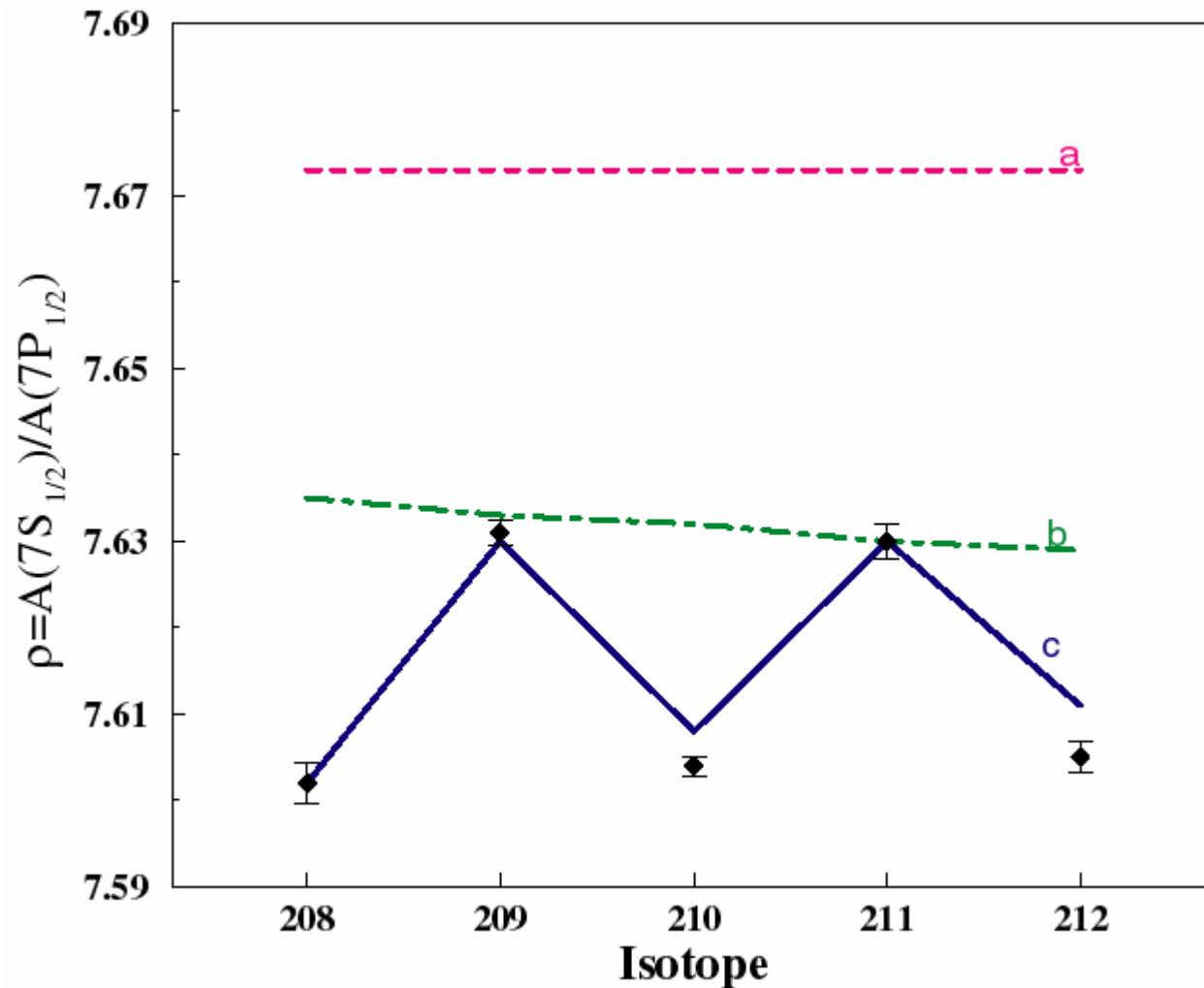


Fluorescence from the two $7P_{1/2}$ hyperfine states excited with FM sidebands





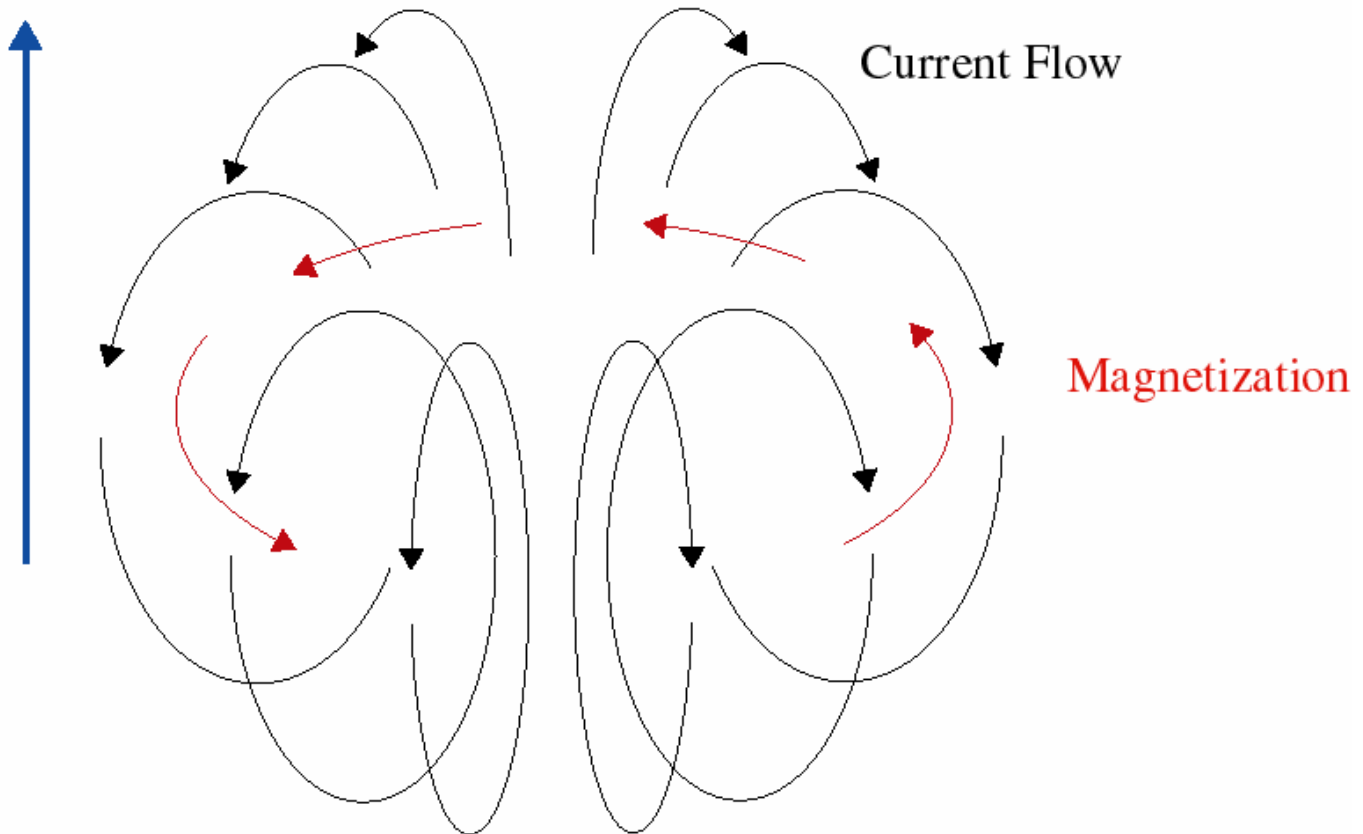
Hyperfine Anomaly



- a: point nucleus
- b: $\langle rc \rangle = \langle rm \rangle$
- c: shell model

The anapole moment

Nuclear Spin



$$H = \frac{G}{\sqrt{2}} (\kappa_{1i} \gamma_5 - \kappa_{nsd,i} \boldsymbol{\sigma}_n \cdot \boldsymbol{\alpha}) \delta(\mathbf{r}),$$

The nuclear spin dependent contribution has three parts:

An electron interacts weakly with a single valence nucleon (nucleon axial-vector current $A_n V_e$)

The nuclear chiral current created by weak interactions between nucleons (anapole moment).

The combined action of the hyperfine interaction and the spin-independent Z^0 exchange interaction from nucleon vector currents ($V_n A_e$).

$$H_{PNC}^{nsd} = \frac{G}{\sqrt{2}} \frac{KI \cdot \alpha}{I(I+1)} \kappa_{nsd} \delta(r),$$

$$\kappa_{nsd} = \kappa_a - \frac{K - 1/2}{K} \kappa_2 + \frac{I + 1}{K} \kappa_{QW},$$

Flambaum et al predict:

$$\kappa_2 \sim -0.05 \quad \text{in } {}^{209}\text{Fr}, \quad \kappa_a / \kappa_{QW} \simeq 15.$$

$$K = (I + 1/2)(-1)^{I+1/2-l}$$

$$\kappa_a = \frac{9}{10} g \frac{\alpha \mu}{m_p \tilde{r}_0} \mathcal{A}^{2/3},$$

$$\kappa_{Q_W} = -\frac{1}{3} Q_W \frac{\alpha \mu_N}{m_p \tilde{r}_0 \mathcal{A}} \mathcal{A}^{2/3},$$

$$g_p \sim 4$$

$0.2 < g_n < 1$ for neutrons

For the case of atoms with heavy nucleus dominated by an unpaired proton, the interaction is dominated by the anapole moment.

Flambaum and Murray give for ^{133}Cs the analytic result:

$$\kappa_a = \frac{9}{10} \frac{\alpha \mu}{m r_0} A^{2/3} g_p = 0.08 g_p$$

Flambaum and Murray show that the proton-nucleus; neutron nucleus constants are:

$$\begin{aligned}
 g_p = 2.0 \times 10^5 W_\rho & \left[176 \frac{W_\pi}{W_\rho} f_\pi - 19.5 h_\rho^0 - 4.7 h_\rho^1 + 1.3 h_\rho^2 \right. \\
 & \left. - 11.3 (h_\omega^0 + h_\omega^1) - 1.7 h_\rho^{1'} \right], \\
 g_n = 2.0 \times 10^5 W_\rho & \left[-118 \frac{W_\pi}{W_\rho} f_\pi - 18.9 h_\rho^0 + 8.4 h_\rho^1 - 1.3 h_\rho^2 \right. \\
 & \left. - 12.8 (h_\omega^0 - h_\omega^1) + 1.1 h_\rho^{1'} \right]. \tag{18}
 \end{aligned}$$

Coupling	“Best Value”	“Reasonable Range”
f_π	0.46	0.00→1.14
h_ρ^0	-1.14	1.14→-3.08
h_ρ^1	-0.019	-0.038→0.00
h_ρ^2	-0.95	-0.76→-1.10
h_ω^0	-0.19	0.57→-1.03
h_ω^1	-0.11	-0.19→-0.08

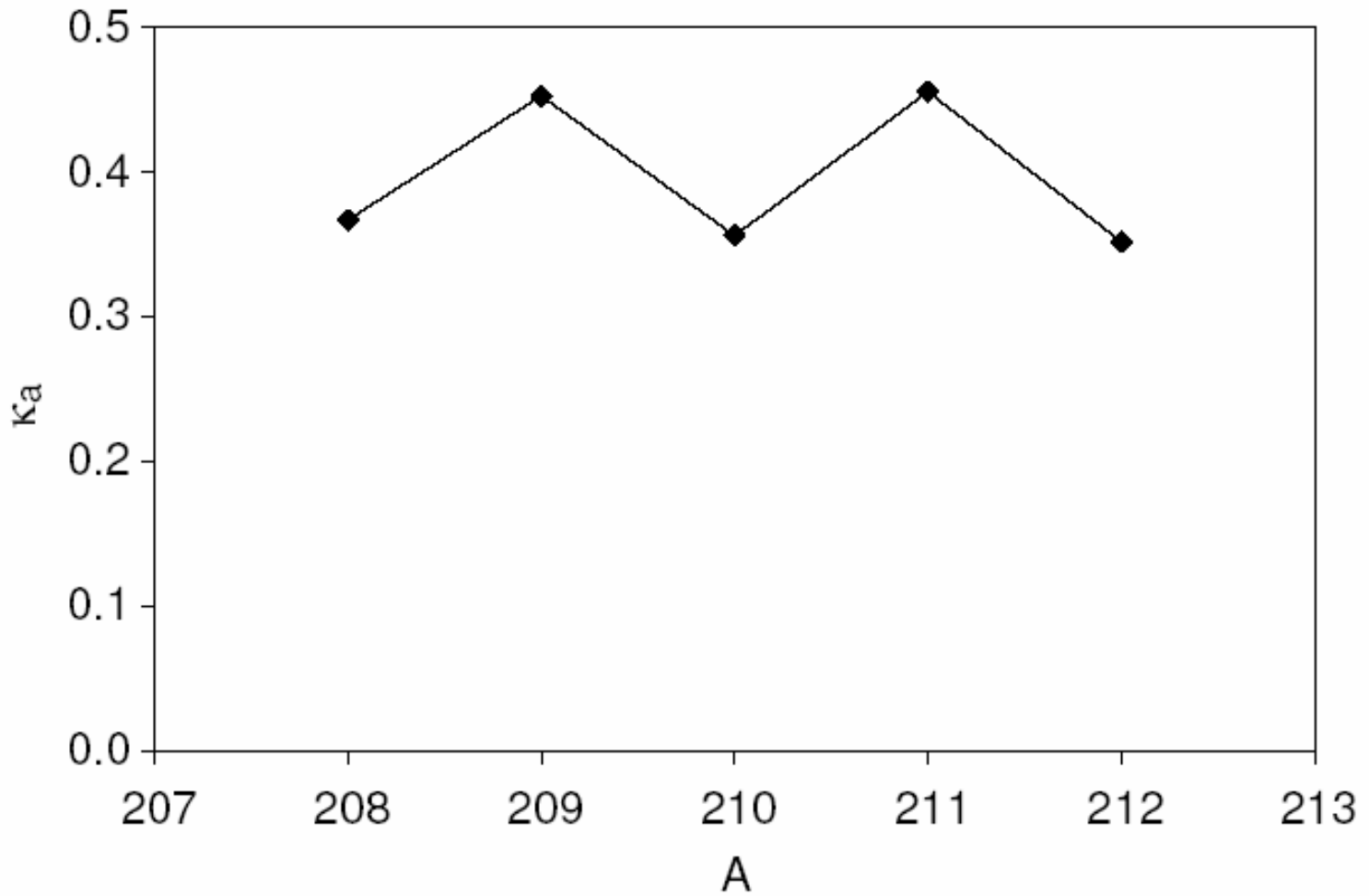
Weak meson-nucleon coupling “best values” and “reasonable ranges” (in units of 10^{-6}) from the standard-model calculations of Desplanques, Donoghue, and Holstein (DDH).

Anapole moment for an unpaired proton nucleus (^{211}Fr)

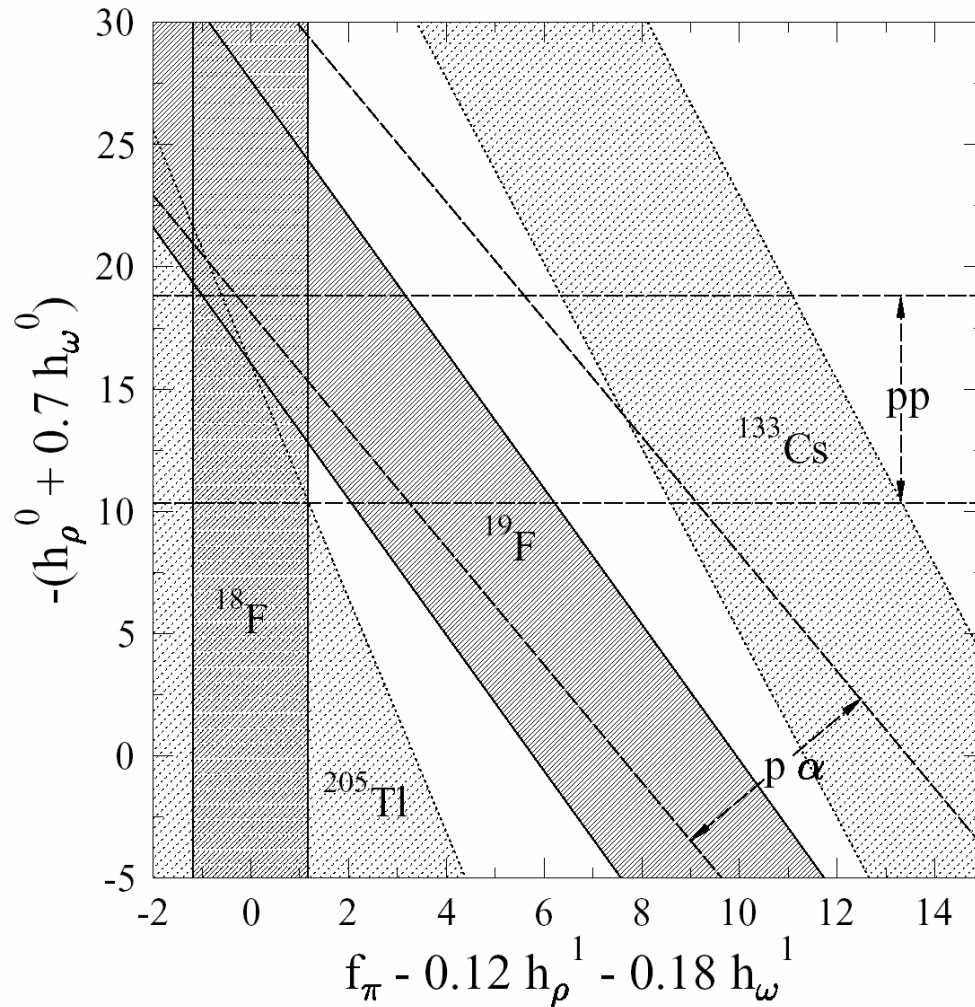
$$\mathbf{a} = \frac{1}{e} \frac{G}{\sqrt{2}} \frac{K \mathbf{j}}{j(j+1)} \kappa_a = C^{an} \mathbf{j};$$

Anapole moment for an unpaired proton and unpaired neutron nucleus (^{210}Fr).

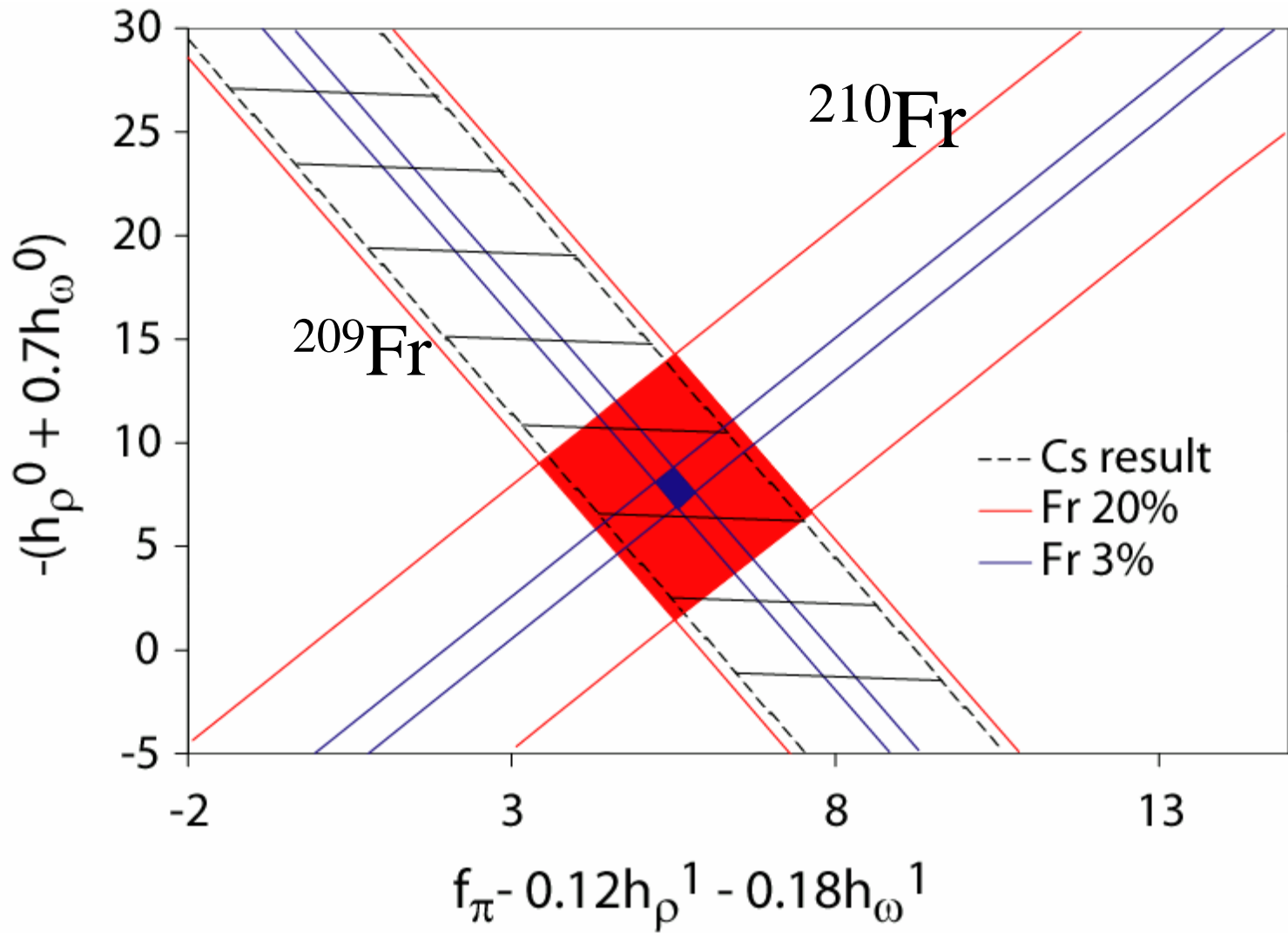
$$\mathbf{a} = \frac{C_p^{an} \mathbf{j}_p \cdot \mathbf{I} + C_n^{an} \mathbf{j}_n \cdot \mathbf{I}}{I^2} \mathbf{I};$$



Estimated anapole moment effective constant for the light Fr isotopes



Constraints on the PNC meson couplings (10^7) that follow from the results in Table 4 of Haxton and Wieman. The error bands are one standard deviation. The illustrated region contains all of the DDH “reasonable ranges” for the indicated parameters (From Haxton and Wieman).



Constraints of couplings from measuring two francium isotopes.

Measurement Strategy;

Mixing of states:

$$\begin{aligned} |\overline{sFm}\rangle &= |sFm\rangle - i5.9 \times 10^{-13} \kappa_a \\ &\quad \times (F(F+1) - 25.5) |pFm\rangle \end{aligned}$$

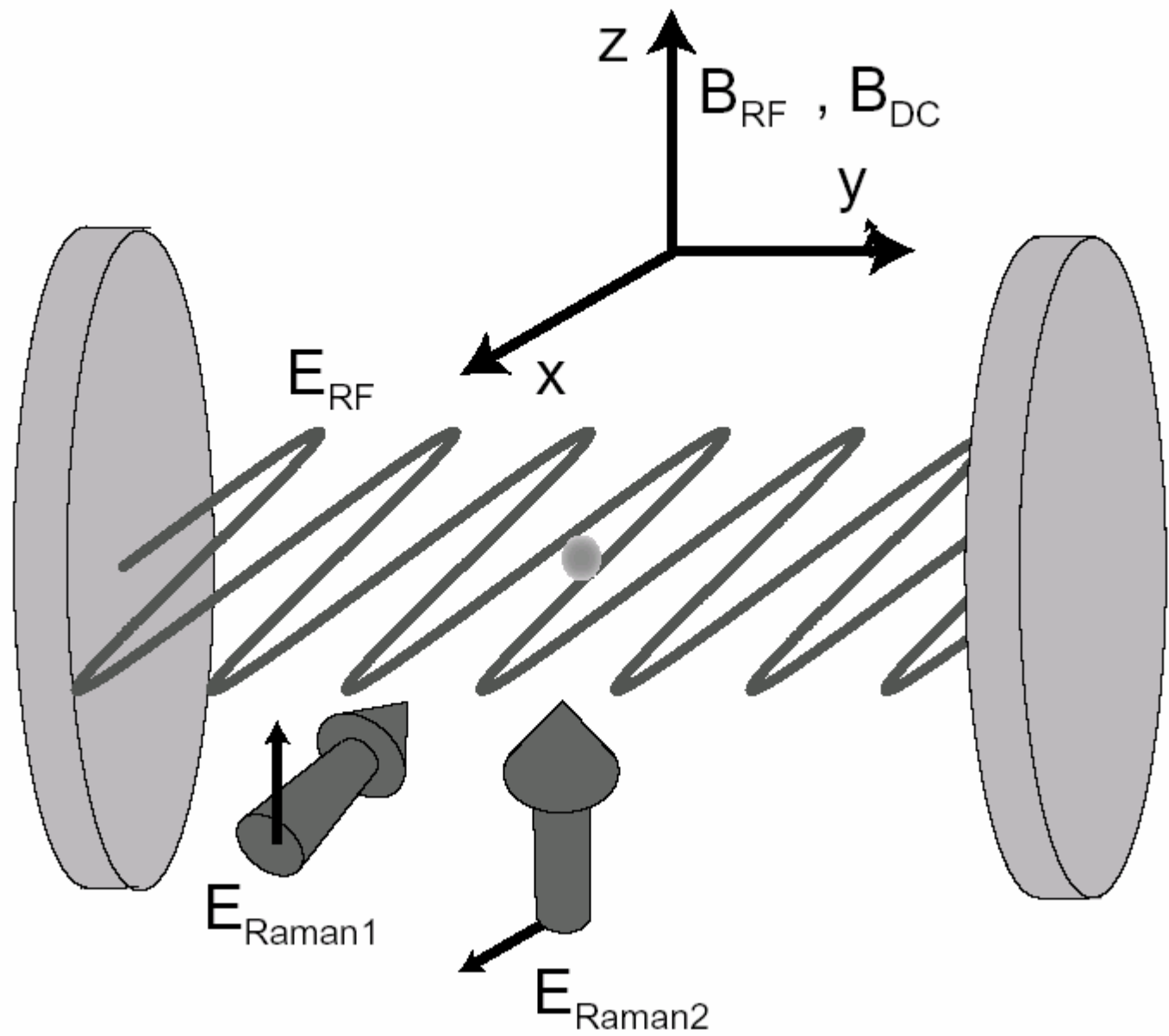
Interfere Raman with E1 transitions

Look at transitions (larger by a factor of 10 larger than Cs).

$$\begin{aligned} A_{E1}/\hbar &= \langle \bar{f} | -e\mathbf{E} \cdot \mathbf{r} | \bar{i} \rangle / \hbar \\ &= 0.01i \left[\frac{E}{476\text{V/cm}} \right] \left[\frac{\kappa_a}{0.45} \right] \text{ rad.} \end{aligned}$$

Reverse the Axis

$$\mathbf{i}(\mathbf{E}_{\text{RF}} \times (\mathbf{E}_{\text{R1}} \times \mathbf{E}_{\text{R2}})) \cdot \mathbf{B}_{\text{DC}}$$



Measure the number of atoms that make the transition

$$\bar{\Xi}_{\pm} = N |c_e|^2 = N \sin^2 \left(\frac{(A_R \pm A_{E1})t_R}{2\hbar} \right)$$

Reverse the axis of coordinates and take the difference between the two:

$$\begin{aligned} \mathcal{S} = \bar{\Xi}_+ - \bar{\Xi}_- &= N \sin \left(\frac{A_R t_R}{\hbar} \right) \sin \left(\frac{A_{E1} t_R}{\hbar} \right) \\ &\simeq N \sin \left(\frac{A_R t_R}{\hbar} \right) \left(\frac{A_{E1} t_R}{\hbar} \right), \end{aligned}$$

Signal to Noise ratio

Operate with the Raman pulses of $\pi/2$, $|c_e|^2=1/2$

If the measurement is limited by projection noise:

$$\mathcal{N}_P = \sqrt{N|c_e|^2(1 - |c_e|^2)}.$$

$$\frac{\mathcal{S}}{\mathcal{N}_P} = 2 \frac{A_{E1} t_R}{\hbar} \sqrt{N}.$$

$$\frac{\textit{Signal}}{\textit{Noise}} = 2\Omega_{E1}\Delta t\sqrt{N} = 20$$

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

$\Omega_{E1} \sim 10$ mrad

Interaction time = $\Delta t \sim 1$ s

1.- DC Magnetic field:

Find the place where the energy separation between Zeeman sublevels goes through a minimum, so the sensitivity to fluctuations is minimized.

Control to 3 parts in 10^5 is sufficient.

For ^{209}Fr we could use $|F=4, m_1\rangle$, $|F=5, m_2\rangle$

Swapping m_1 and m_2 is good as a consistency check.

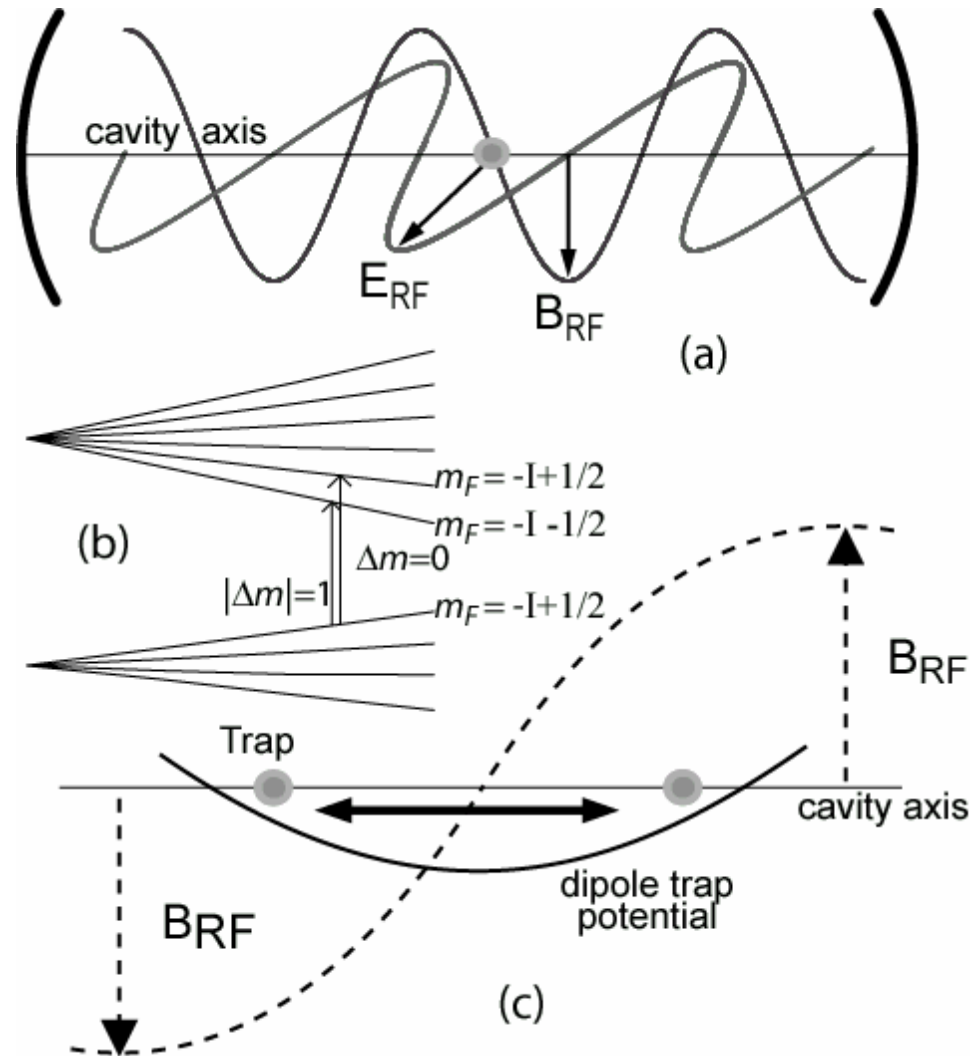
2.- M1 Transition $|A_{E1}/A_{M1}| \sim 10^{-9}$:

Placing atoms at the node of the magnetic field, reduction of 5×10^{-3}

M1 polarized in the z axis, M1 will be such that $\Delta m=0$, microwave resonant for $|\Delta m|=1$ E1 transitions (the microwave electric field is polarized along the x axis) suppression by 10^{-3} .

Dynamical suppression by the oscillations of the trap.

M1 suppression mechanisms



3.- Microwave cavity:

Field of 476 V/cm (we can do with our equipment).

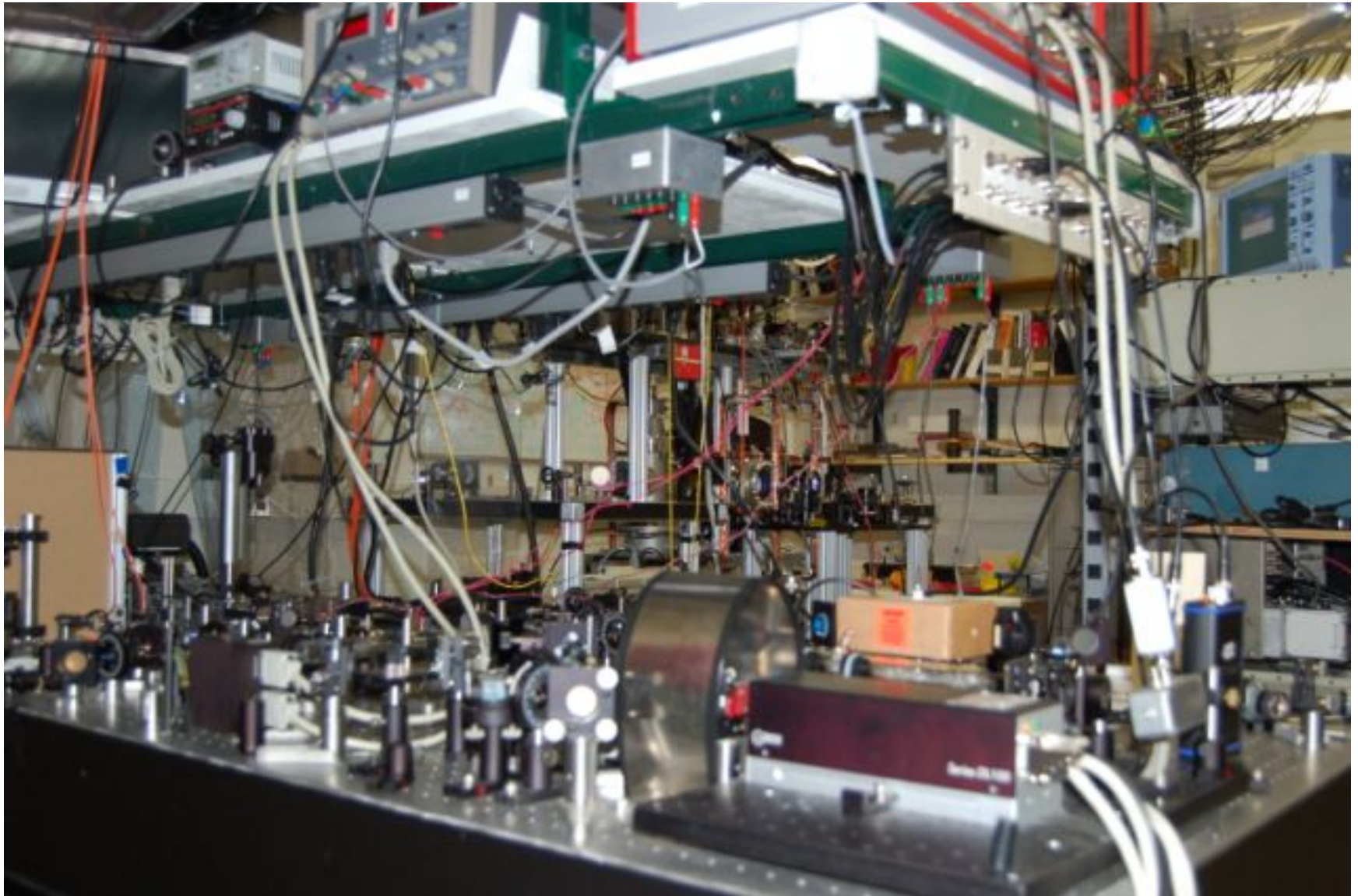
Drive bi-directionally to avoid traveling wave, suppression 10^{-7}

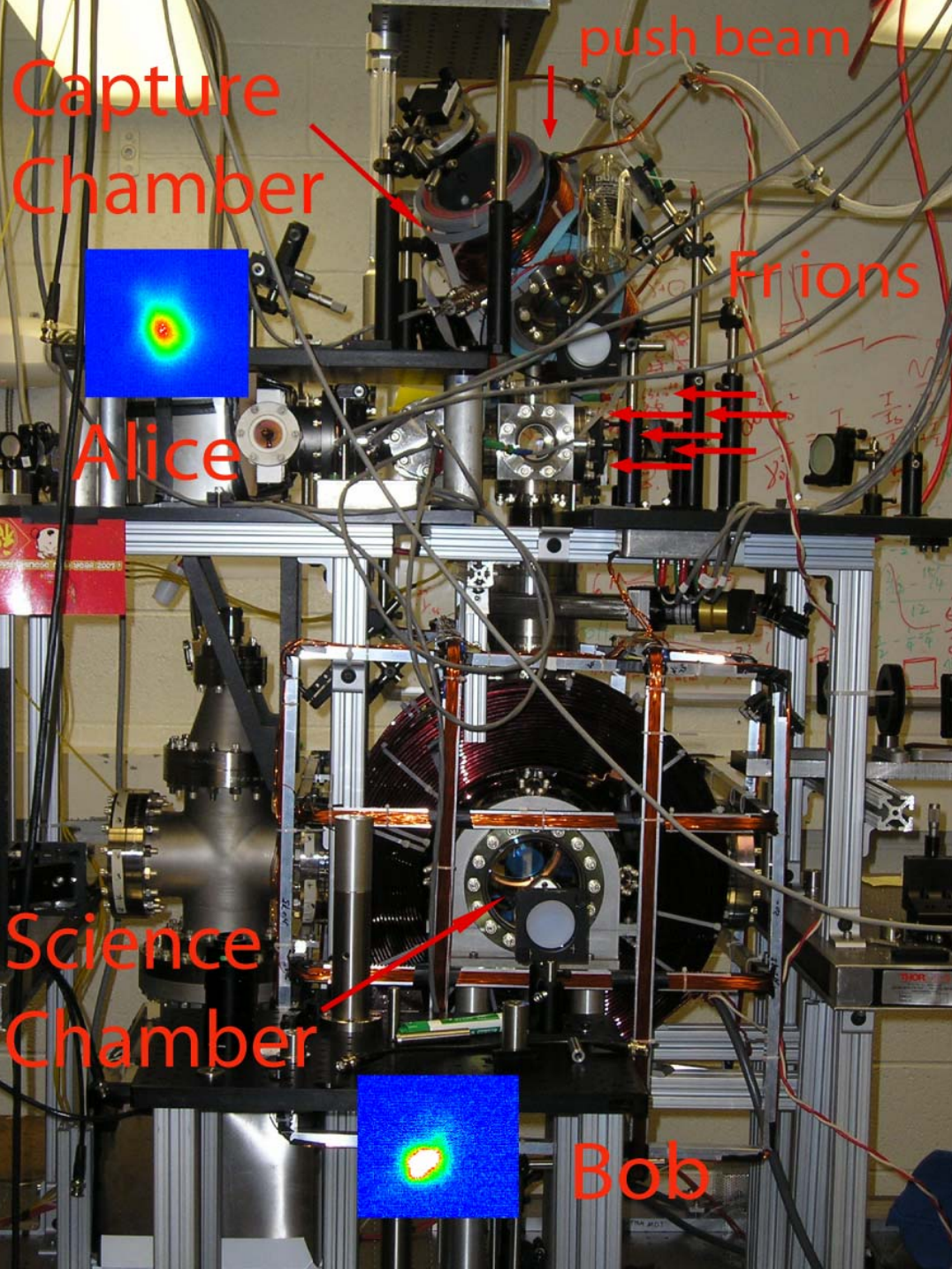
4.- Dipole Trap:

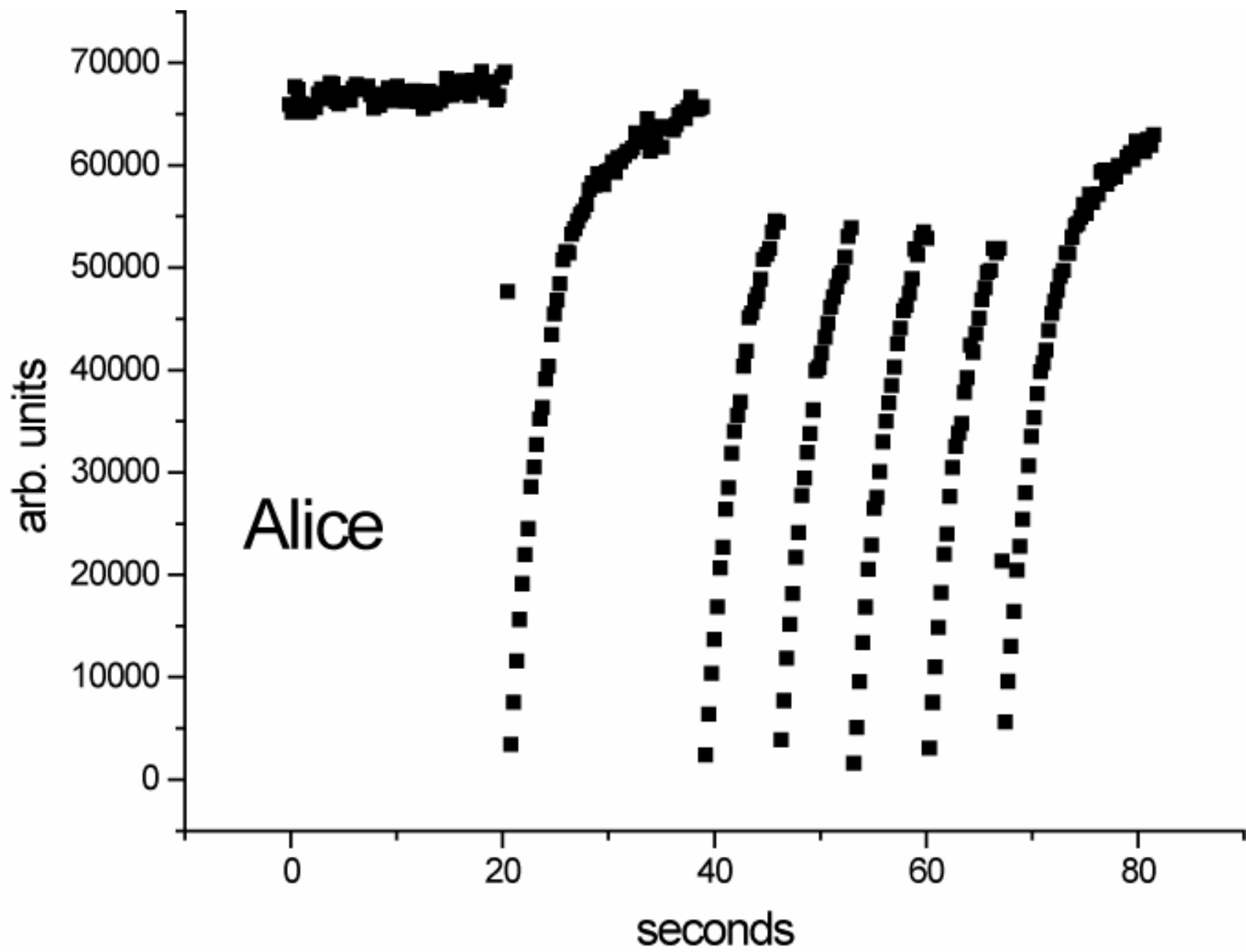
Blue detuned trap to avoid AC Stark shifts. Hollowed beams.

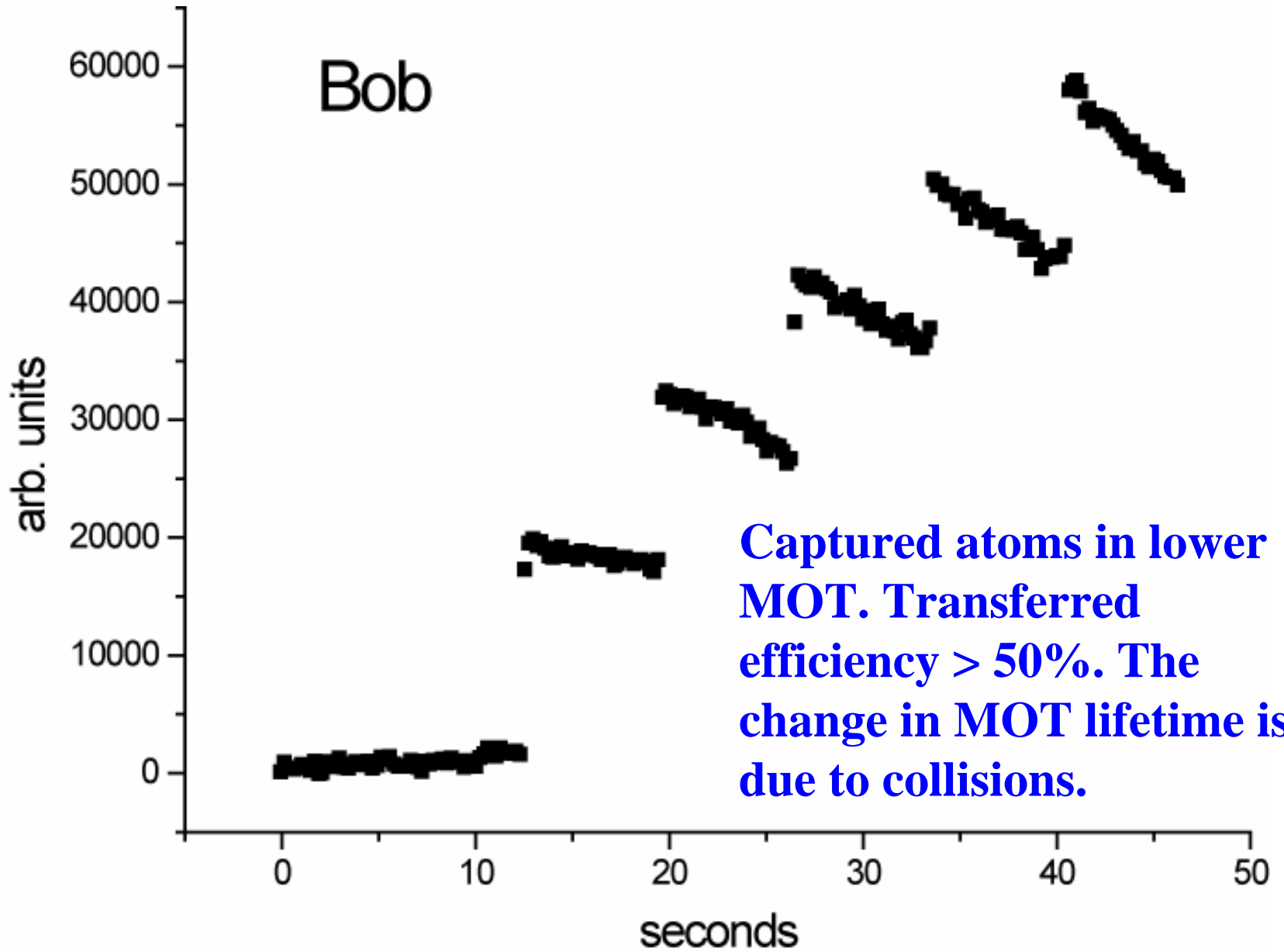
Coherence time of about 100 ms using echo techniques.

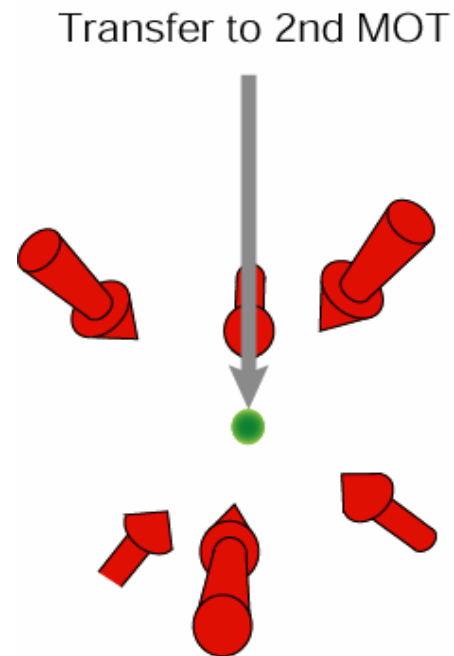
Third generation under construction



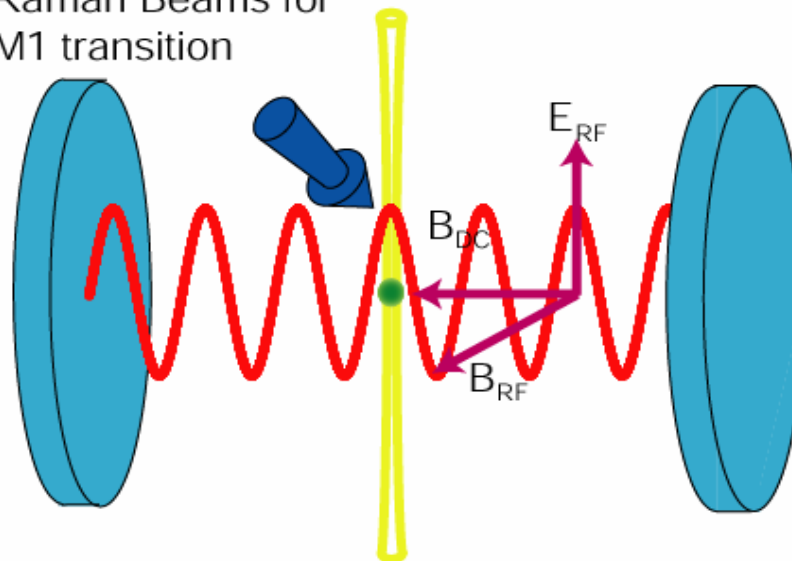






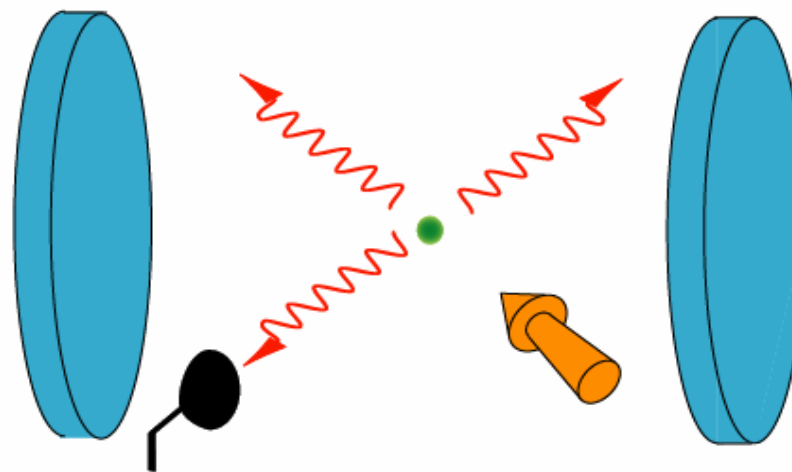


Raman Beams for
M1 transition



Microwave Fabry-Perot
for E1 transition

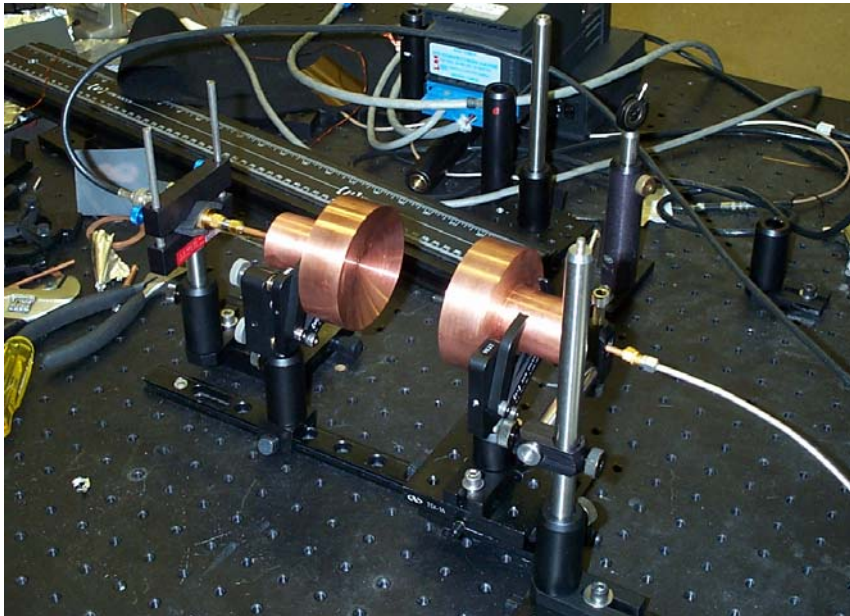
Single beam optical
dipole trap for Fr atoms



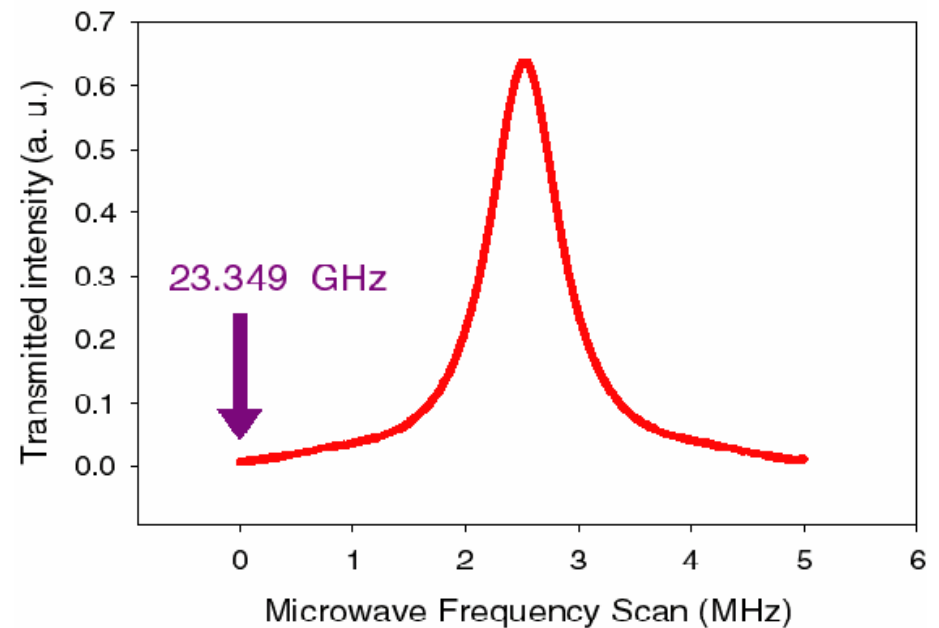
Resonant Beam on
D₂ line for detection

Hardware advances for the Anapole measurement

Prototype Microwave Fabry-Perot.



Microwave Cavity Transmission Profile



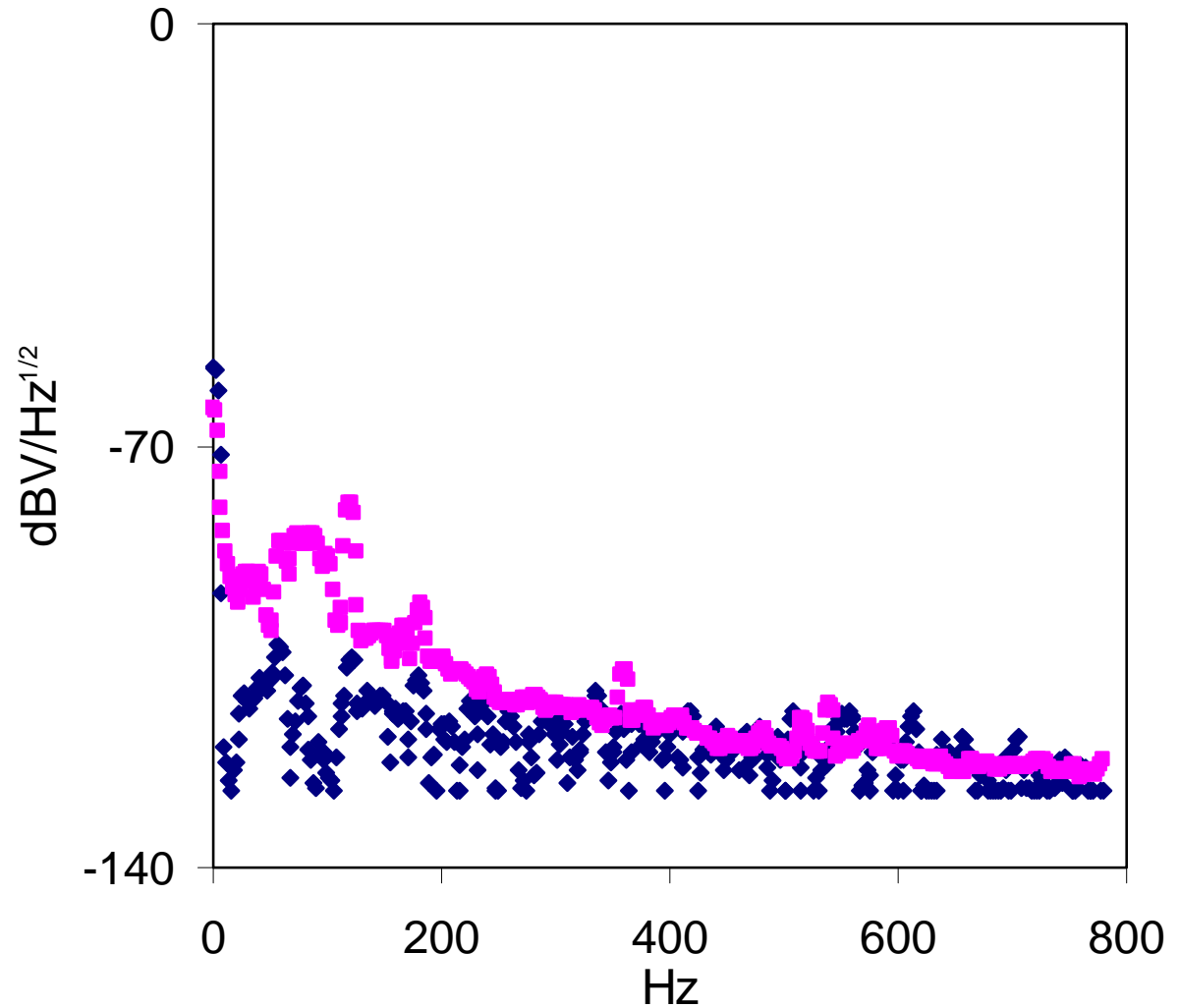
Pointing stability of laser, first round of results:

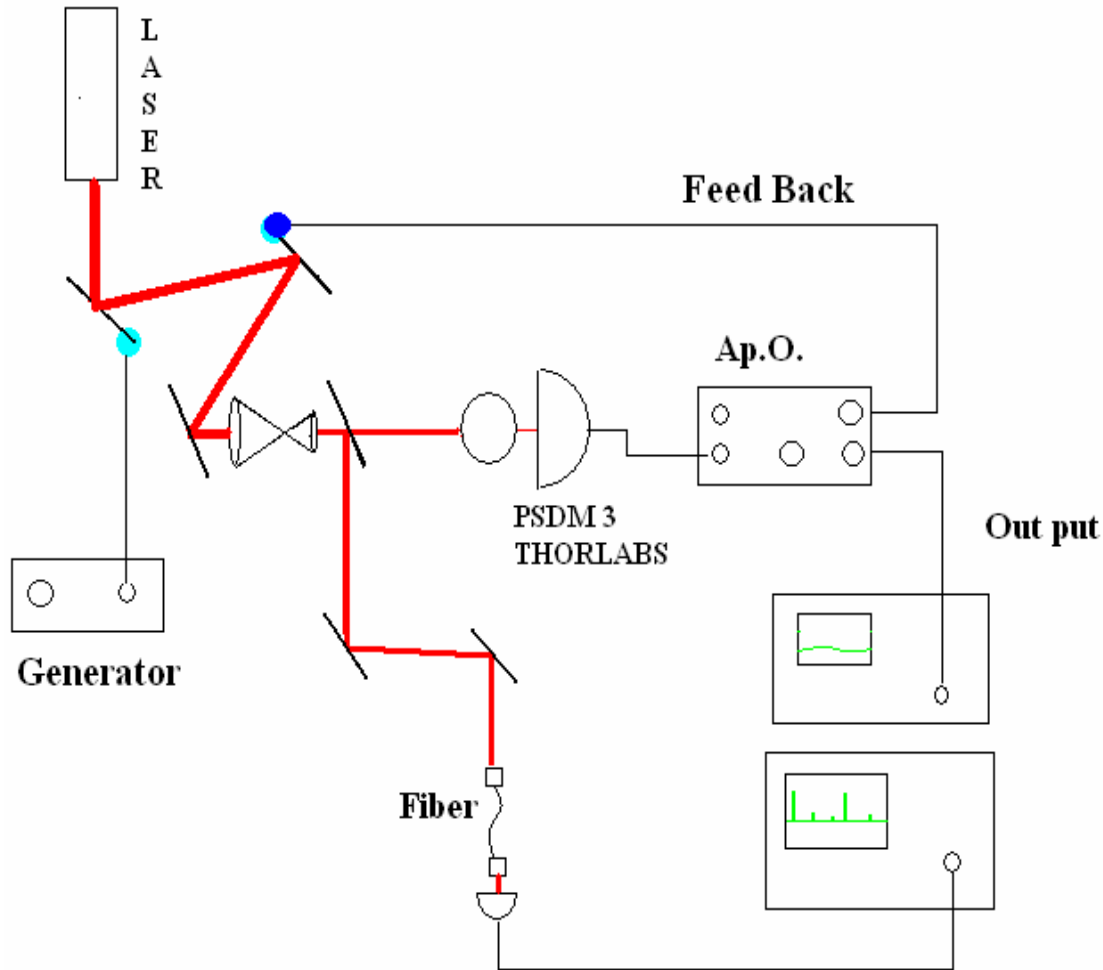
Passive stability

$$4.31 \times 10^{-10} \text{ m} / \sqrt{\text{Hz}}$$

Shot noise limit

$$1.88 \times 10^{-10} \text{ m} / \sqrt{\text{Hz}}$$





Reduced the noise
 over a bandwidth of
 30 Hz by a factor of
 8, limited by shot
 noise

Road Map for Fr project

- Test system with Rb at UMD.
- The apparatus also works for Optical PNC
- 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 $1 \text{ (Hz)}^{-1/2}$.
- Calculations of atomic and nuclear structure will allow the extraction of coupling constants.

References for anapole moment proposal:

C.E. Loving, and P. G. H. Sandars, J. Phys. B. **10**, 2755 (1977).

V. G. Gorshkov, V. F. Ezhov, M. G. Kozlov, and A. I. Mikhailov, Sov. J. Nucl. Phys. **48**, 867 (1988).

I. B. Khriplovich, Parity Nonconservation in Atomic Phenomena (Gordon and Breach Science Publishers, Philadelphia, 1991).

E. N. Fortson, Phys. Rev. Lett. 70, 2383 (1993).

P. A. Vetter, D. M. Meekhof, P. K. Majumder, S. K. Lamoreaux, and E. N. Fortson, Phys. Rev. Lett. 74, 2658 (1995).

D. Budker, in Physics Beyond the Standard Model, ed. P. Herczeg, C. M. Hoffman, and H. V. Plapdor-Klinfronthaus (World Scientific, Singapore, 1998).

C. S. Wood, S. C. Bennett, D. Cho, B. P. Masterson, J. L. Roberts, C. E. Tanner, and C. Wieman, Science **275**, 1759 (1997); W. C. Haxton and C. E. Wieman, Nucl-th/0104026.

S. G. Porsev, M. G. Kozlov, Phys. Rev. A 64, 064101 (2001).

E. Gomez, S. Aubin, G. D. Sprouse, L. A. Orozco, and D. P. DeMille, "Measurement method for the nuclear anapole moment of laser-trapped alkali-metal atoms, " Phys. Rev. A 75, 033418 (2007).