What we know about Francium

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NIST

The slides are available at:

http://www.physics.umd.edu/rgroups/amo/orozco/results/2018/Results18.htm

FrPNC Collaboration (Summer 2017)

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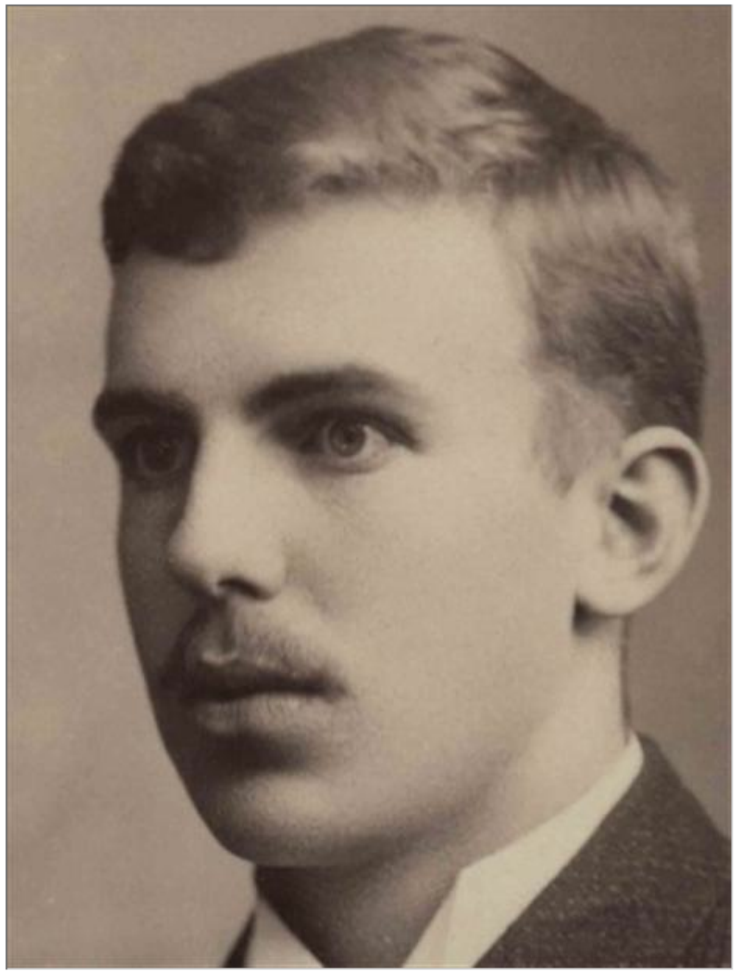
The weak interaction

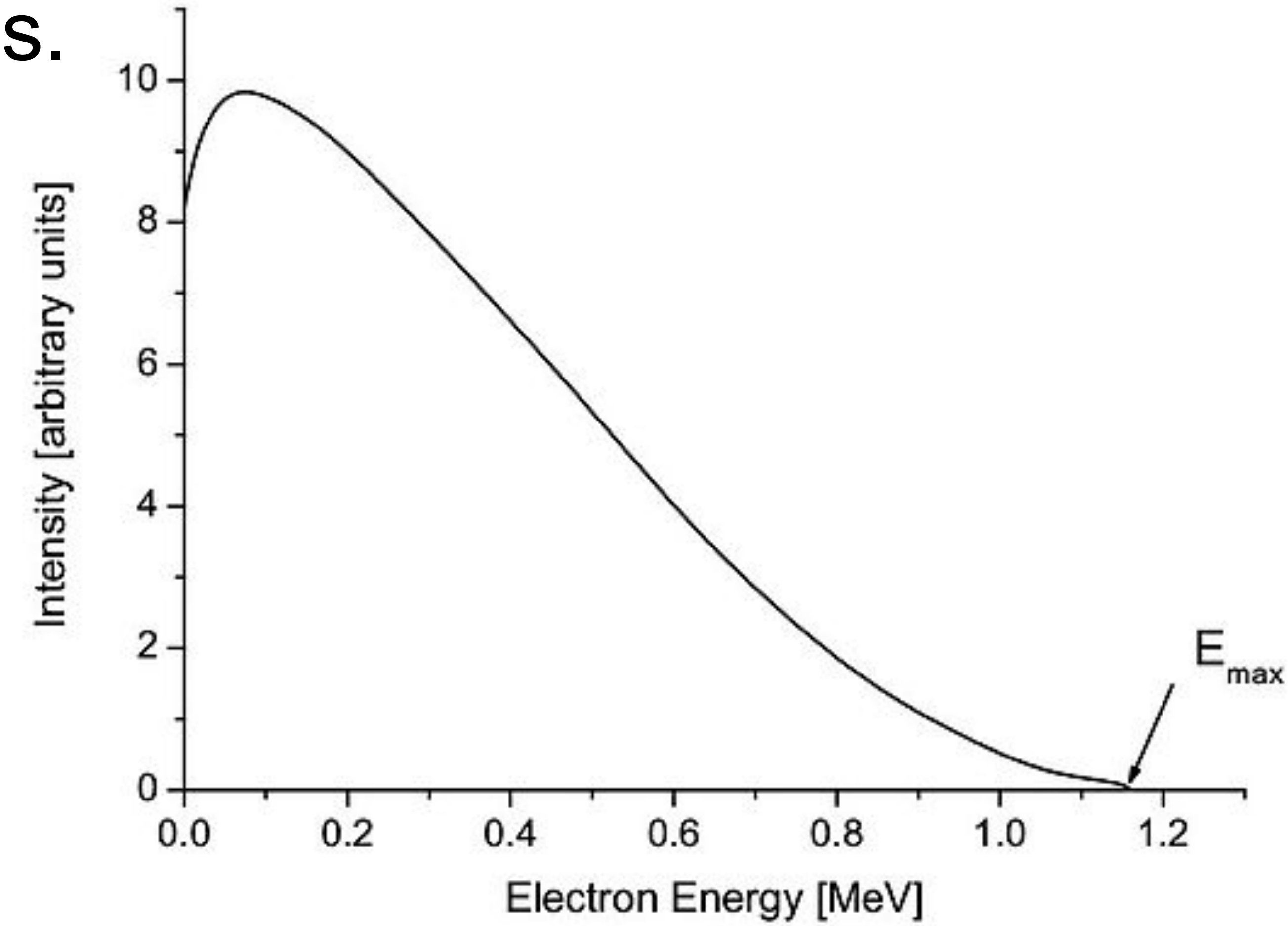
Rutherford discovered two kinds of radioactive rays (α, β), the second are electrons



Ernest Rutherford

Beta Decay:

Lise Meitner and Otto Hann (1911), Jean Danysz (1913), and James Chadwick (1914) measured the beta decay spectrum and see a continuum of energies.

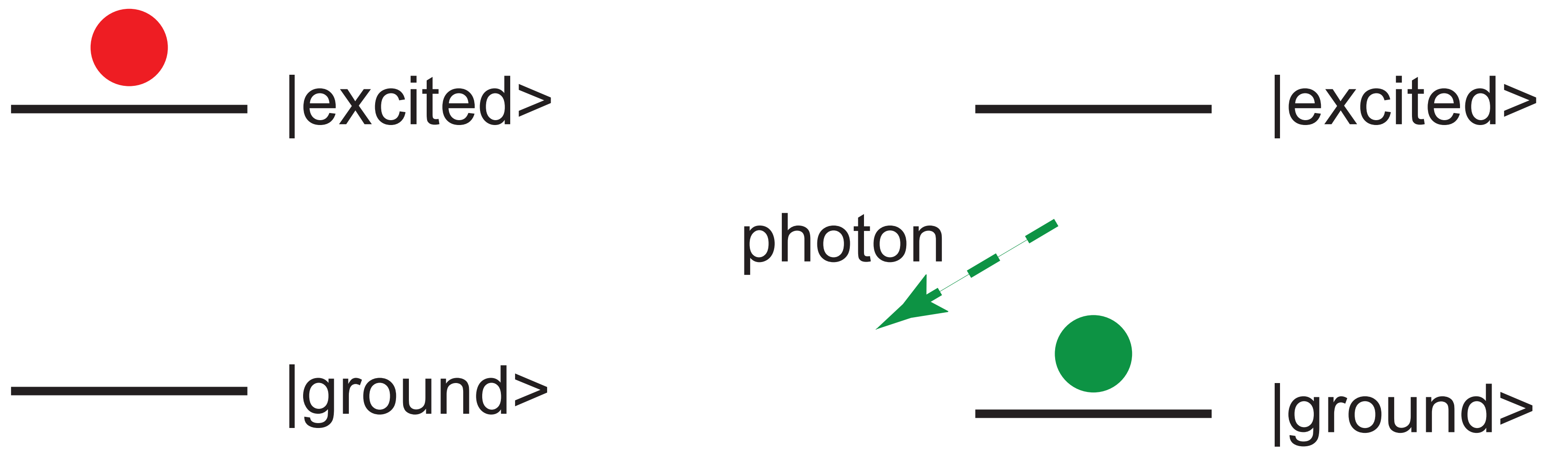


^{210}Bi

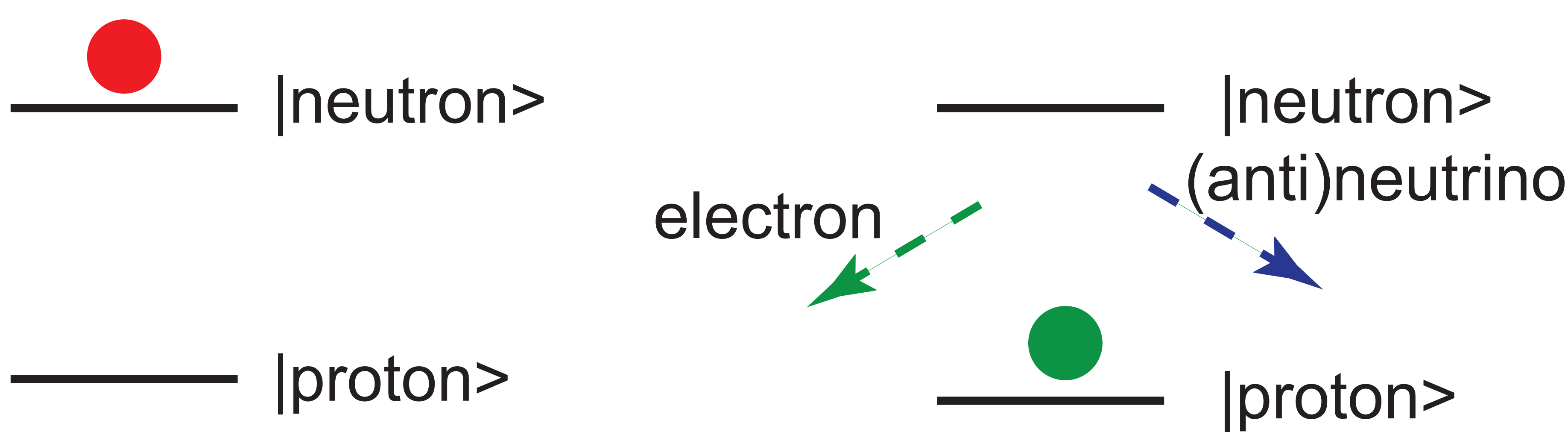
Theory of beta decay by Fermi (1934) treats the process as if it were spontaneous emission

Enrico Fermi

Spontaneous emission

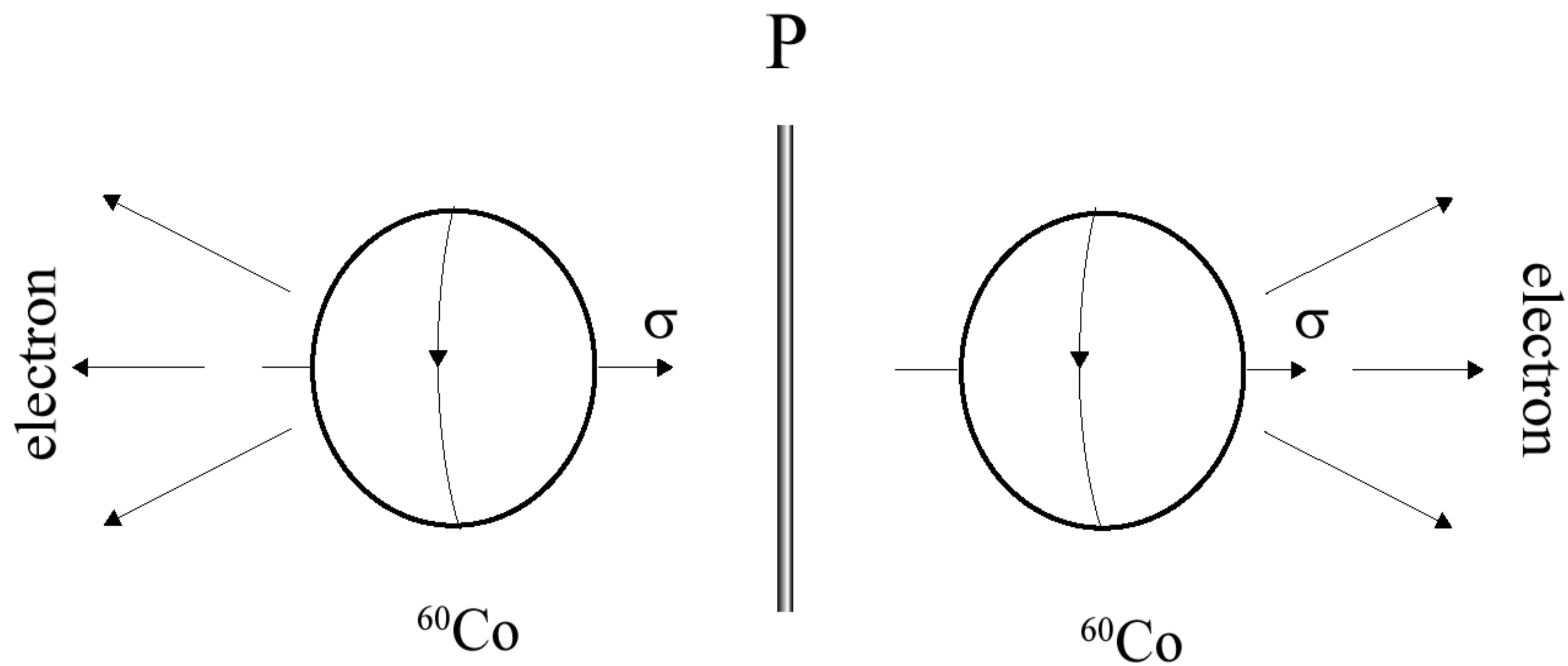


Beta decay



Parity non conservation

Nature (the weak interaction) lacks P symmetry.
1950 Purcell and Ramsey say it should be tested.
1956 T. D. Lee and C. N Yang point to the weak interaction.
1957 Three experiments show that the weak interaction violates P: Wu, Lederman, and Telegdi lead the three efforts.
The Columbia-NBS experiment by Wu, Ambler, Hayward, Hoppes and Hudson studied β decay of cobalt ($\sigma \bullet p$).

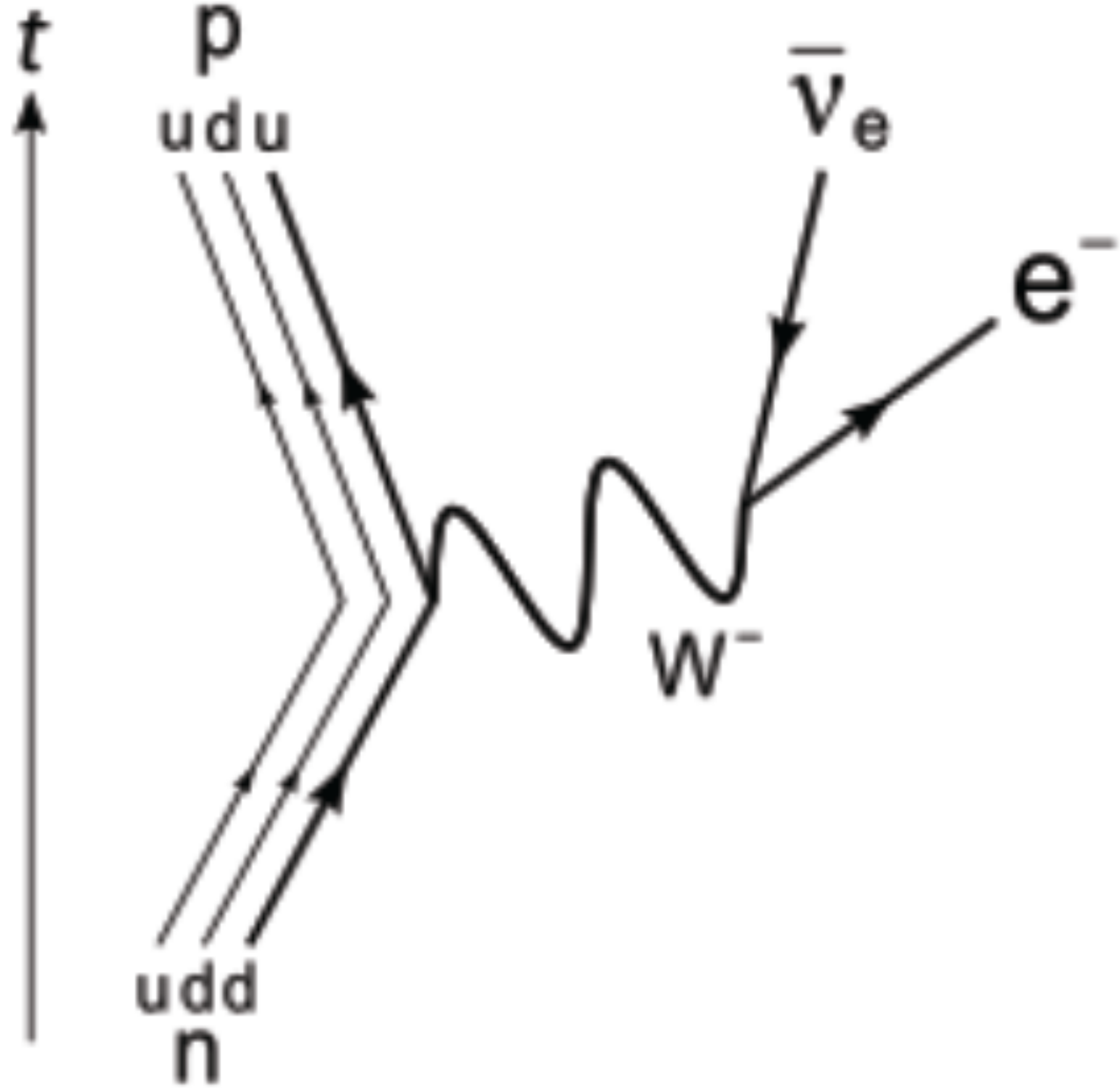


β decay ^{60}Co Wu, Ambler, Hayward, Hoppes, and Hudson; Columbia, National Bureau of Standards (ahora NIST).

They look at the correlation between the nuclear spin nuclear σ and the electron momentum **p**

$$\langle \vec{\sigma} \cdot \vec{p} \rangle$$

Parity is maximally violated in the weak interaction.



Feynman diagram of beta decay of a neutron. The W^- is very heavy (about a Rb atom), so the interaction is short range, There are three carriers of the interaction: W^+ W^- and Z^0.

The weak interaction in atomic physics

Coulomb, spin-orbit, etc.

Parity violating. (1958 Zel'dovich)

$$H_{atomic} = H_0 + H_{PV}$$

The new Hamiltonian induces a perturbation on the eigenstates:

$$|\varphi_0\rangle \rightarrow |\Psi\rangle = |\varphi_0\rangle + \sum_n \frac{\langle \varphi_n | H_{PV} | \varphi_0 \rangle}{E_0 - E_n} |\varphi_n\rangle$$

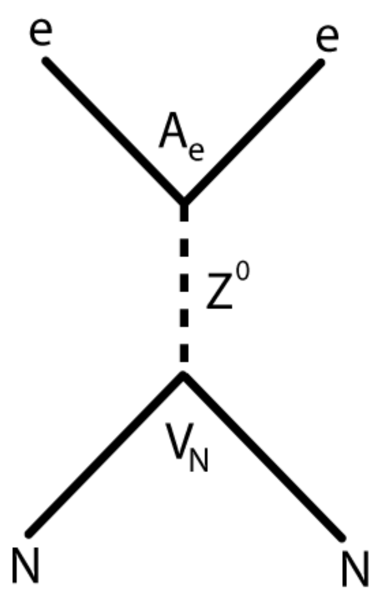
The ground state of alkali: $|\Psi\rangle = |nS_{1/2}\rangle + \delta |nP_{1/2}\rangle + \ldots$

Forbidden transitions (*e.g.* E1 between S states) become allowed $A \propto \langle \Psi_i | r | \Psi_f \rangle \neq 0$

$$H_{PV} = \frac{G_F}{\sqrt{2}}\left(\boxed{\kappa_{1i}\gamma_5} - \boxed{\kappa_{nsd,i}\sigma_n \cdot \alpha}\right)\delta(\mathbf{r})$$

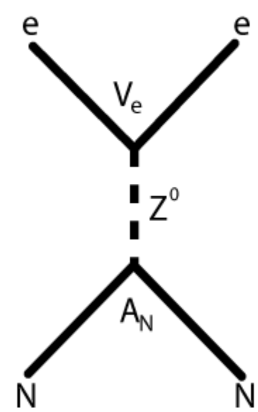
H_{PV}^{NSI}

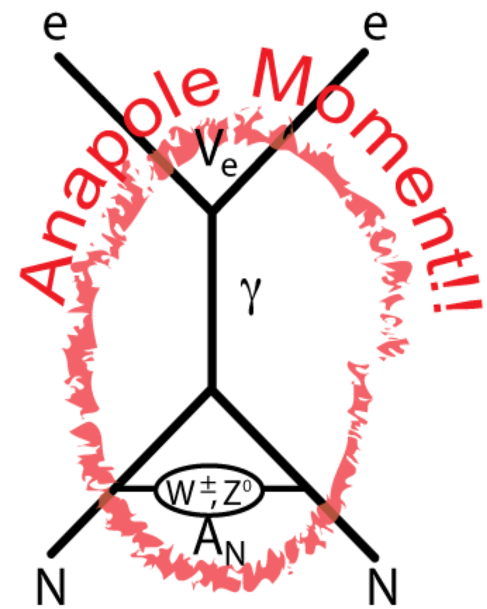
Nuclear spin independent Interaction:
- Coherent over all nucleons.
- Measurement increases as Z^3, from Q_{weak}, |S> and |P>

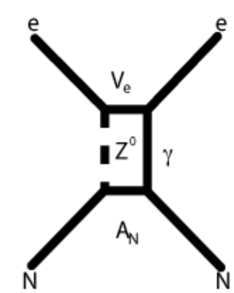


H_{PV}^{NSD}

Nuclear spin dependent interaction:
- Only from valence nucleons.
- Measurement increases as $Z^{8/3}$
- Main contribution from anapole moment for heavy nuclei.







parity conserving atom

$$|\Psi\rangle = |P_{1/2}\rangle$$

parity violating atom

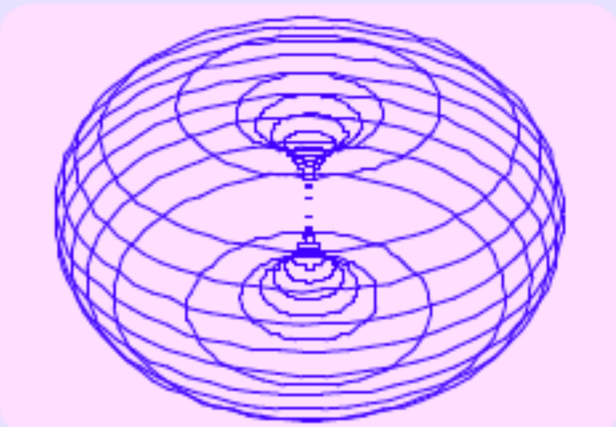
$$|\Psi\rangle = |P_{1/2}\rangle + i\,\varepsilon_{pv}\,|S_{1/2}\rangle$$

in H-atom: $\varepsilon = 10^{-11}$

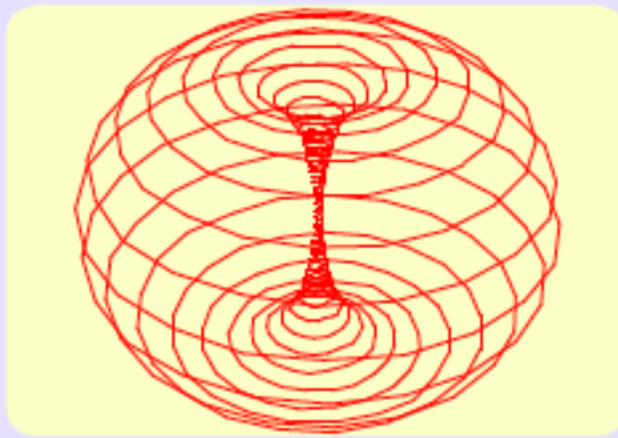
here: $\varepsilon = 5\,\%$

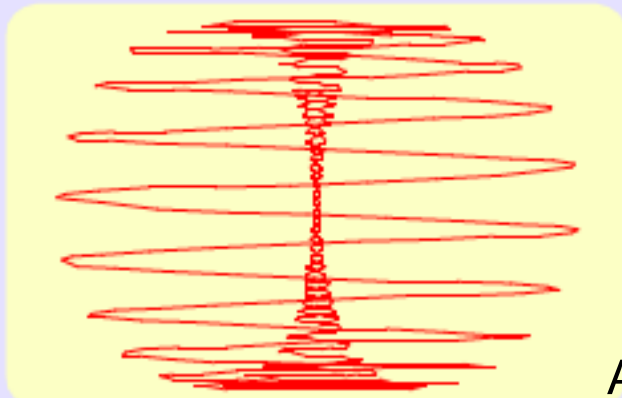
lines = electrical current $\vec{j} = e\,\langle\Psi|\,\vec{v}\,|\Psi\rangle$ of electronic wave function $|\Psi\rangle$

current = circles on torus



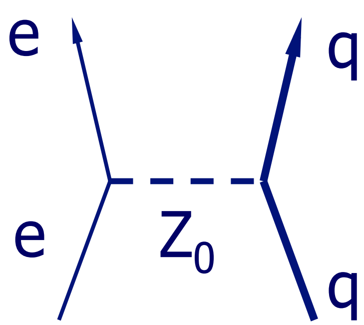
current = helix on torus





A. Weiss

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:

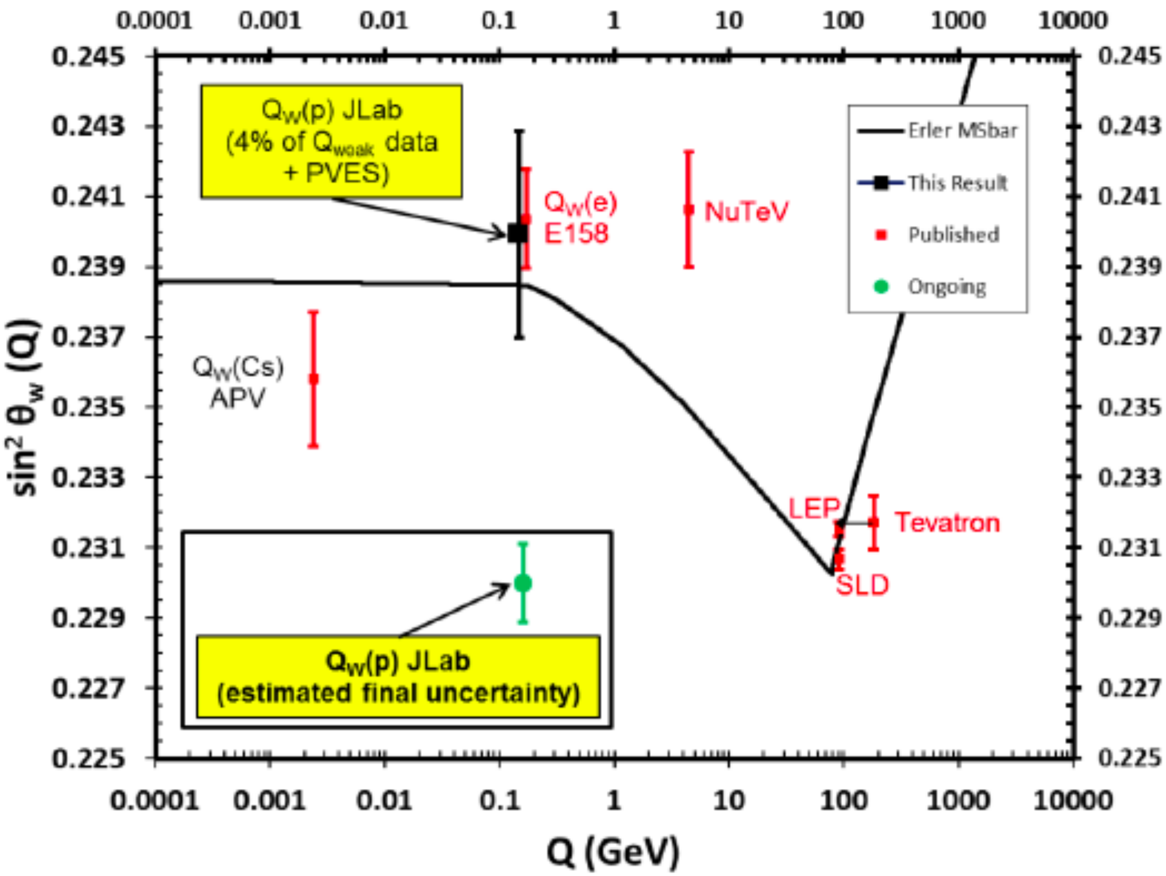
Theoretical calculation of PNC amplitude

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

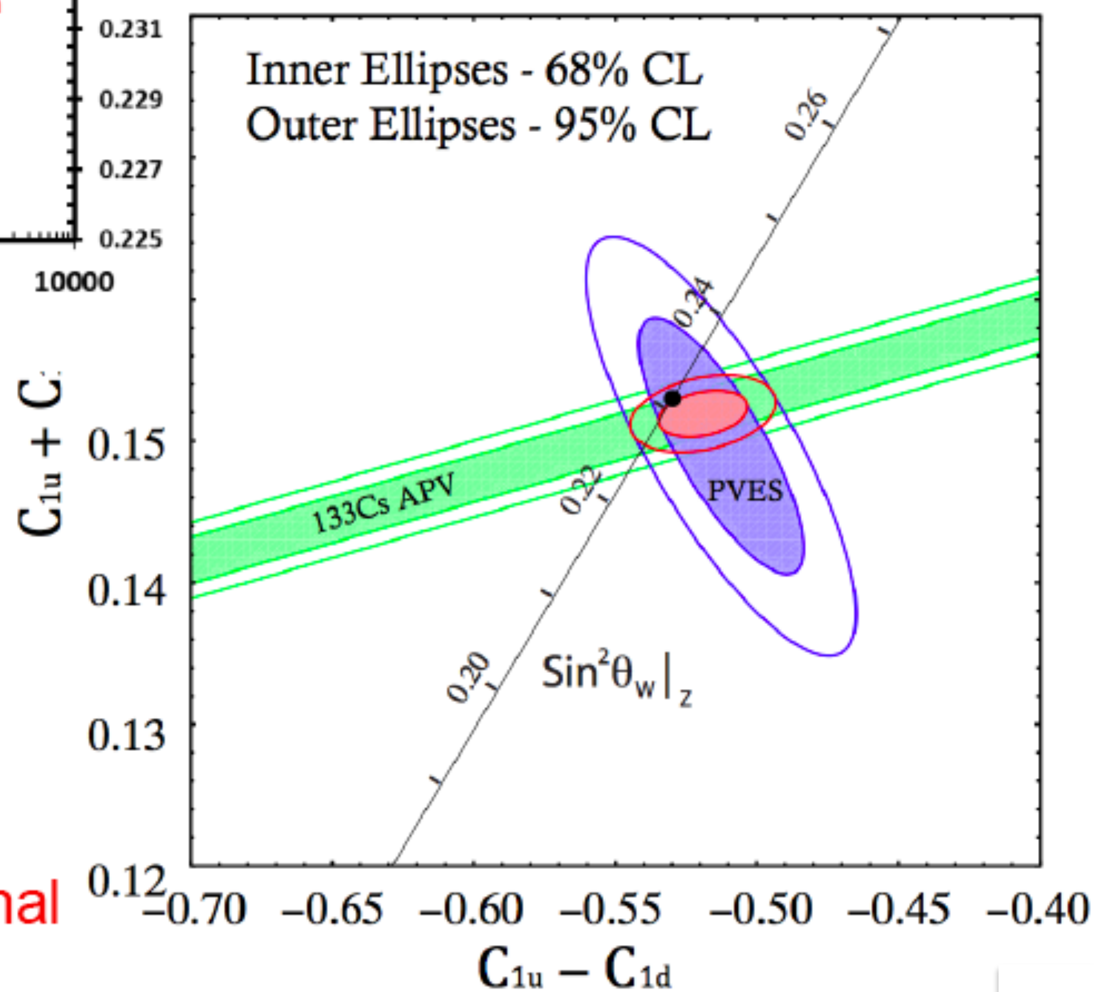
Safranova

Measure APNC and compare to predictions of the SM and study if the weak interaction gets affected by the presnece of lots of nucleons.

Use a heavy atom (Buchiats) as the measurements scale faster than Z^3 and $Z^{8/3}$



Graphs courtesy Qweak collaboration Shelley Page



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})

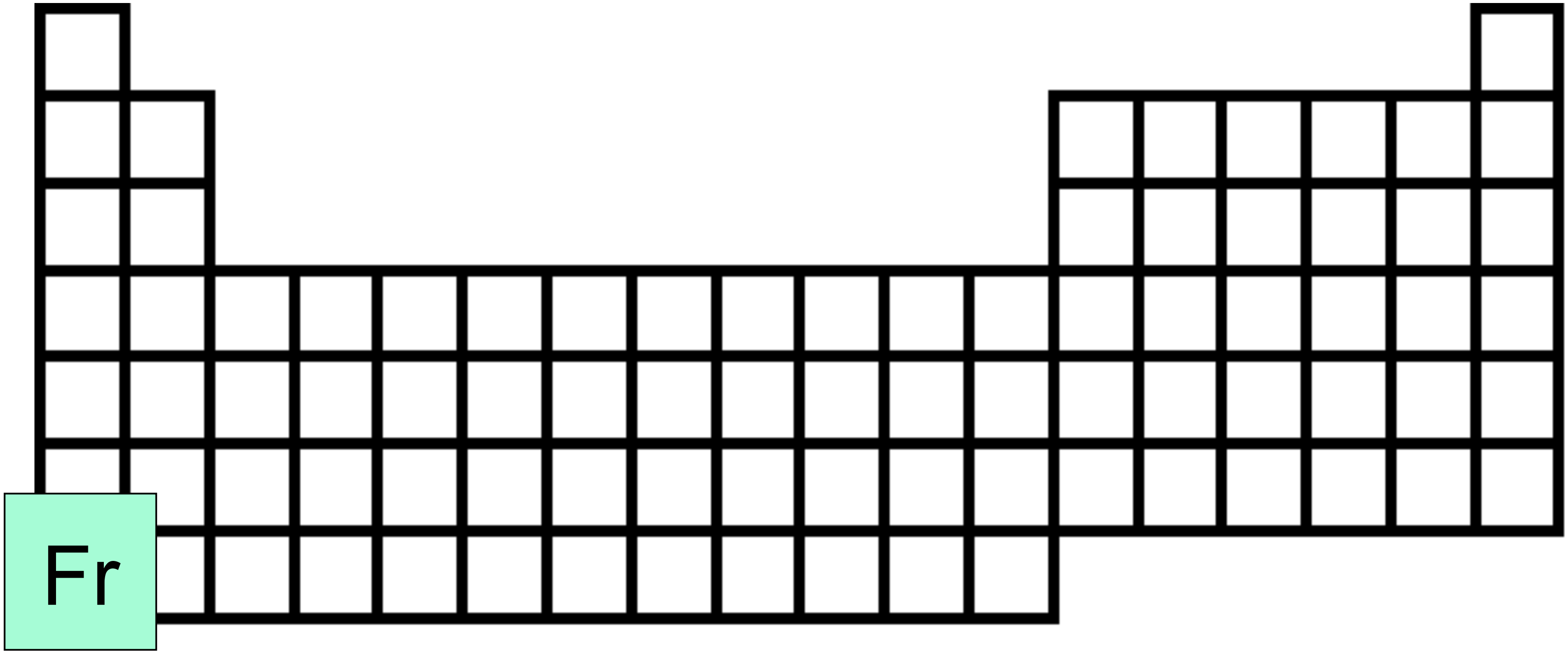
Francium

Discovery as a product of actinium decay 1939

$$^{227}_{89}\mathrm{Ac} \longrightarrow {}^{223}_{87}\mathrm{Fr} + {}^{4}_{2}\alpha$$

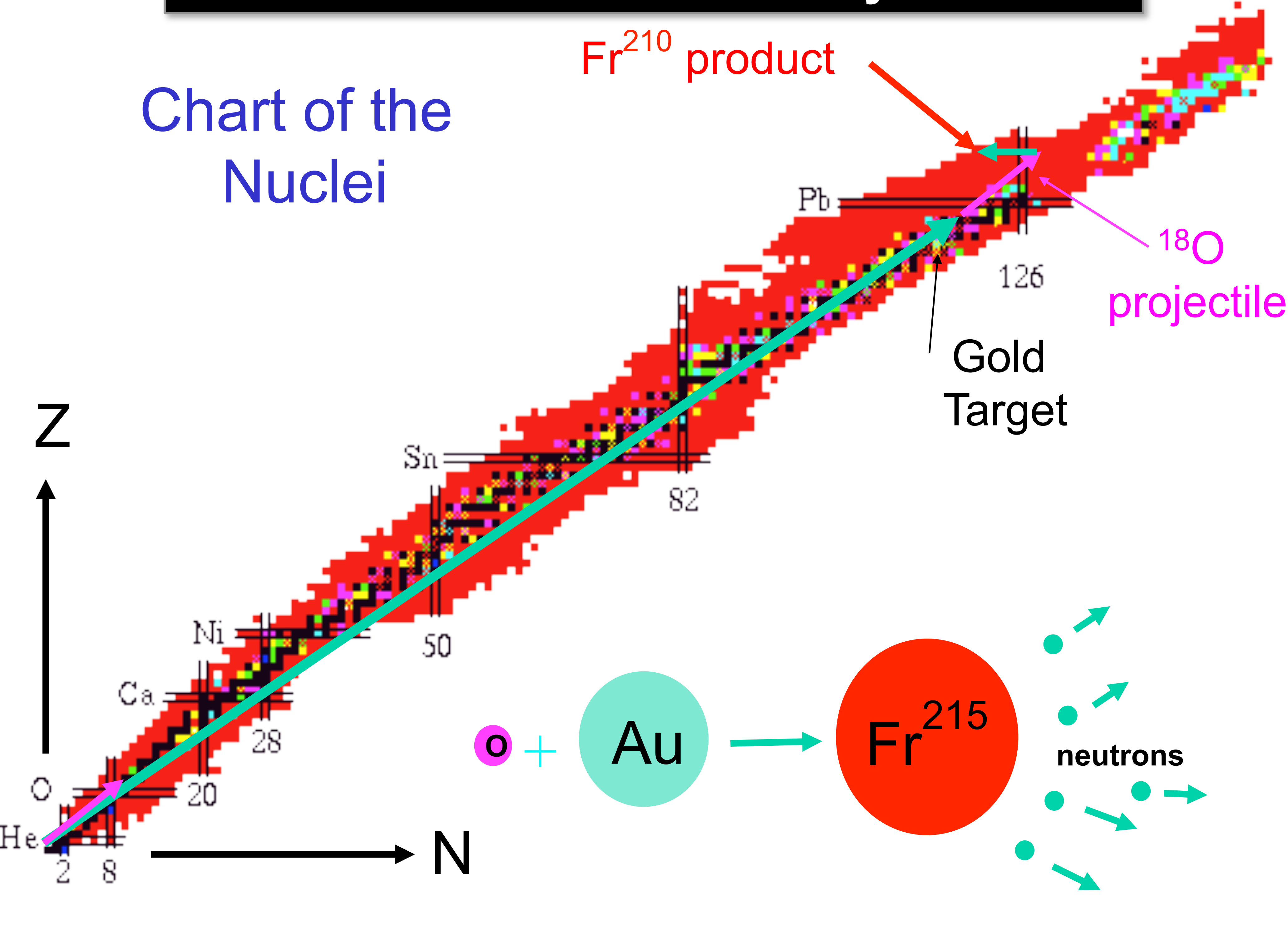
Actinium Francium Alpha Particle

Margarite Perey, first row left, Radium Institute, Paris~1939



- $Z=87$; $A=206$-213 and neutron rich 221 (TRIUMF)
- Radioactive (^{212}Fr: $\tau_{1/2}=20$min; ^{209}Fr: $\tau_{1/2}=1$ min)
- Make it and trap it.
- Simple atomic structure, quantitatively understandable
- We want to use it as a laboratory to study the weak interaction through the signature of parity non-conservation.

How did we make Fr at Stony Brook ?

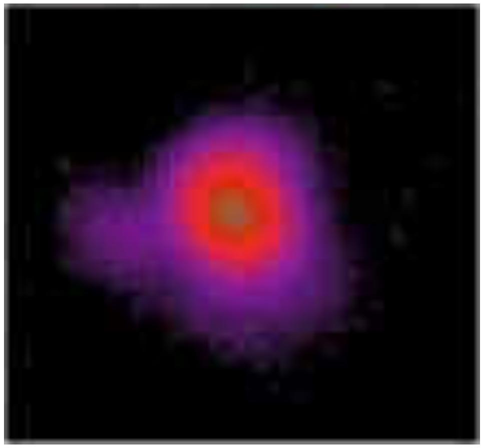


A Brief History of Francium at Stony Brook

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

1995: Produced and Trapped Francium in a MOT.

1996-2000: Laser spectroscopy of Francium.



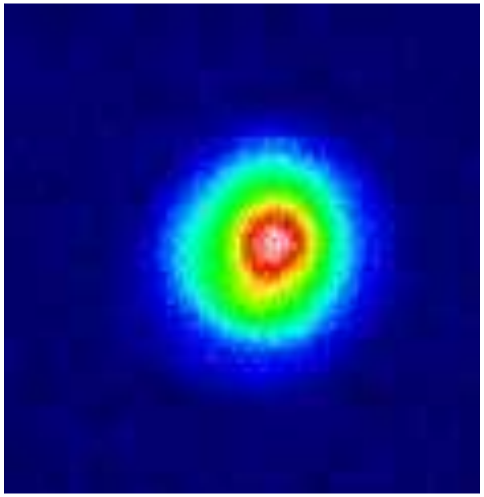
2,000 atoms
Fr MOT

2000-2002: High efficiency trap.

2003: Spectroscopy.

2004: Lifetime of 8S level.

2007: Magnetic moment ^{210}Fr .



250,000 atoms
Fr MOT

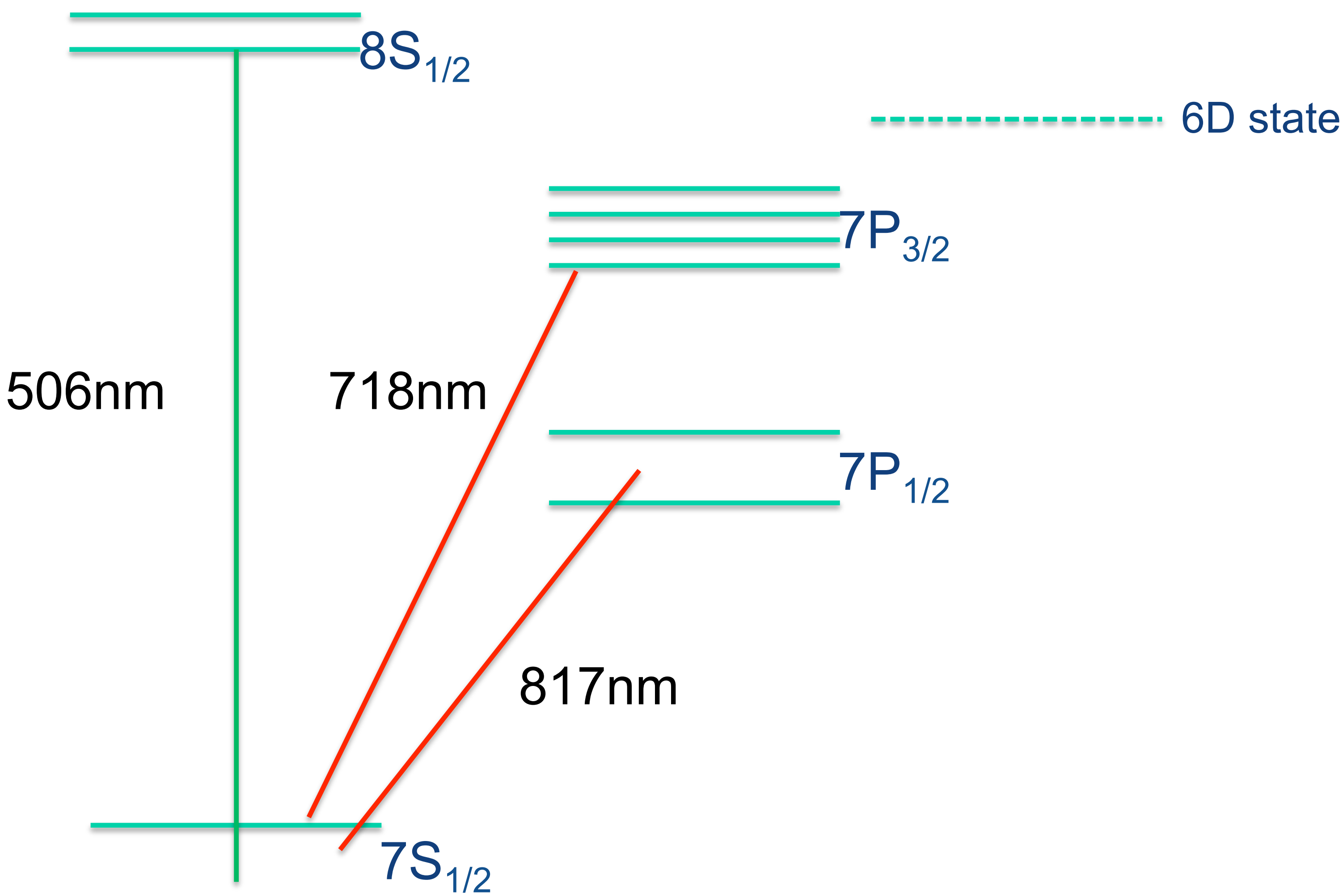
Spectroscopy studies of francium

Ideal cold sample of trapped atoms (no Doppler broadening)

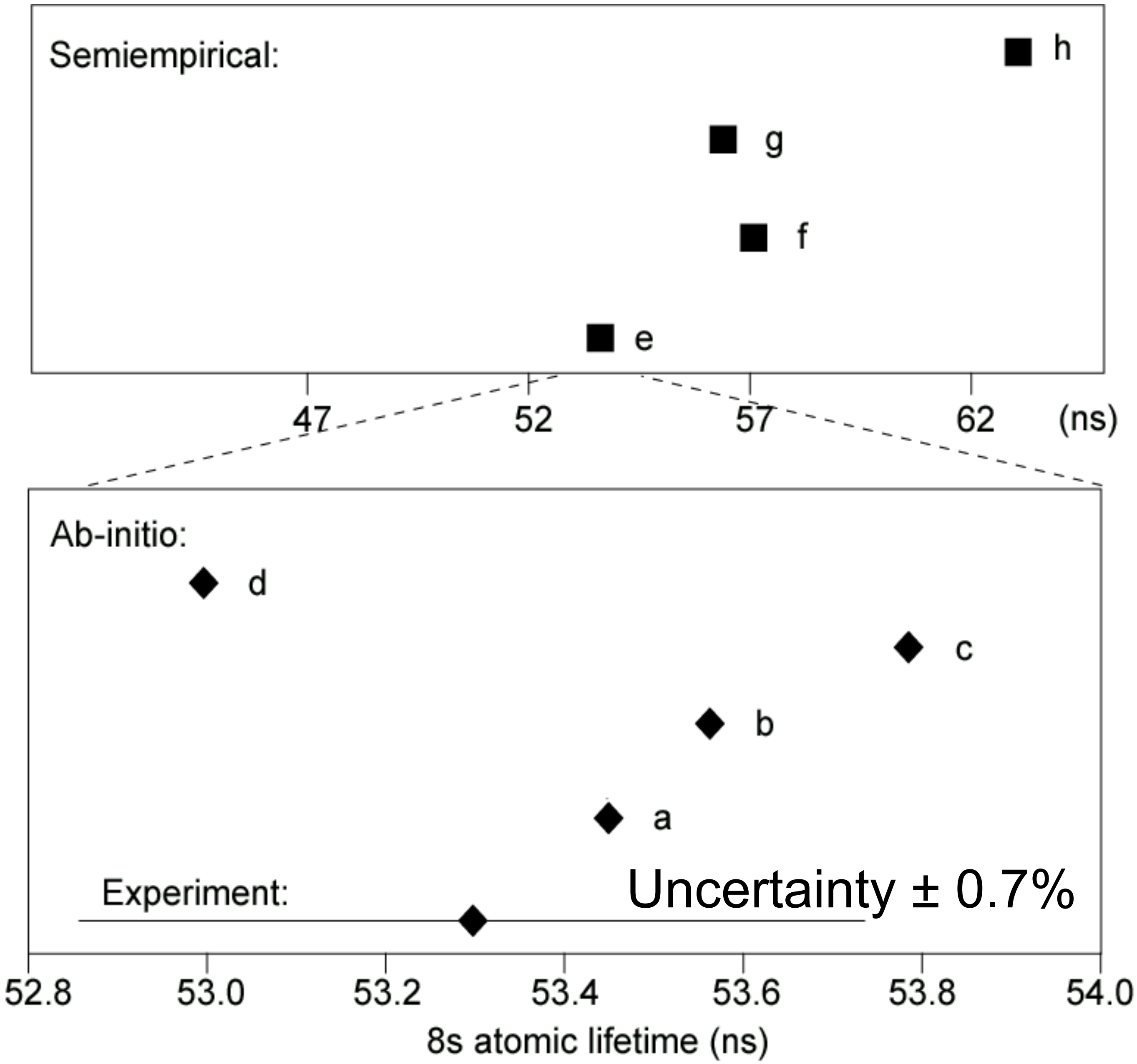
Energy levels
Excited state lifetimes (transition matrix elements)
Hyperfine splittings (wavefunctions at the nucleus)

Quantitative comparisons to *ab initio* calculations.
Nuclear structure studies (nuclear magnetization).

Francium Atomic Energy Levels



8s atomic lifetime measurement and 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.*

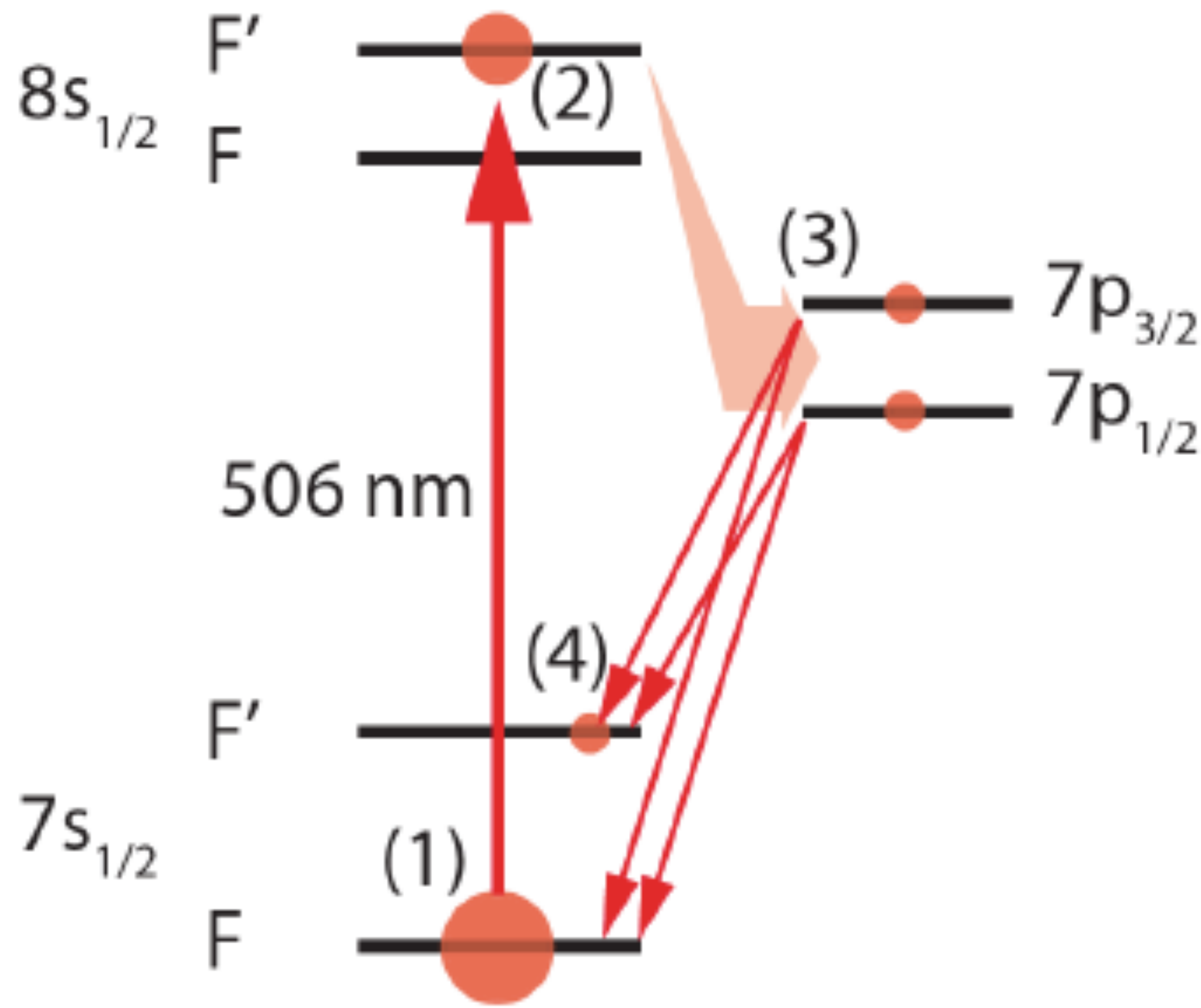
h) Van Wijngaarden *et.al.*

Spin independent APNC

APNC in Cesium at Boulder

1997 Wieman (Boulder) 0.35% measurement from an experiment in one isotope of Cesium. The most accurate test of the standard model with atomic physics.

- Follows the suggestion of the Bouchiats to use heavy atoms.
- Uses interference with a Stark Induced transition to enhance the signal.
- Uses atomic beams optically pumped
- Uses a cavity enhancing the 6S to 7S transition.

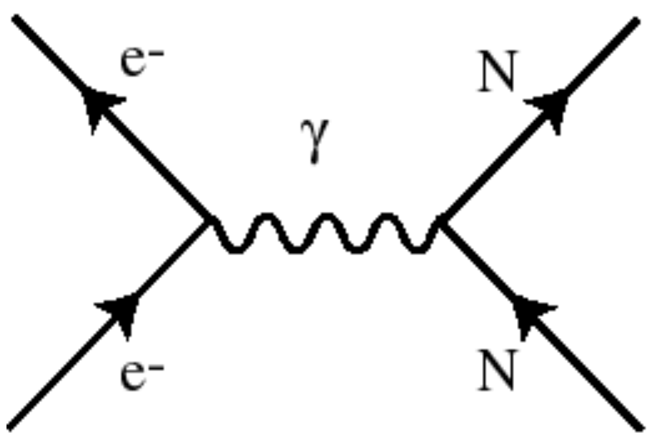


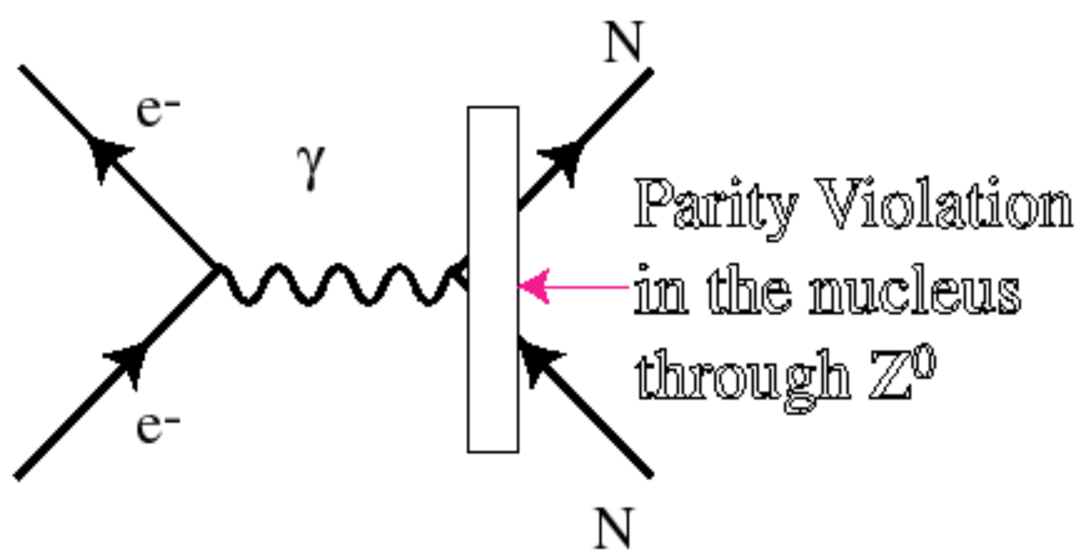
Schematic of the Fr energy levels for optical PNC with the sequence of decays that facilitates recycling detection.

Spin dependent APNC

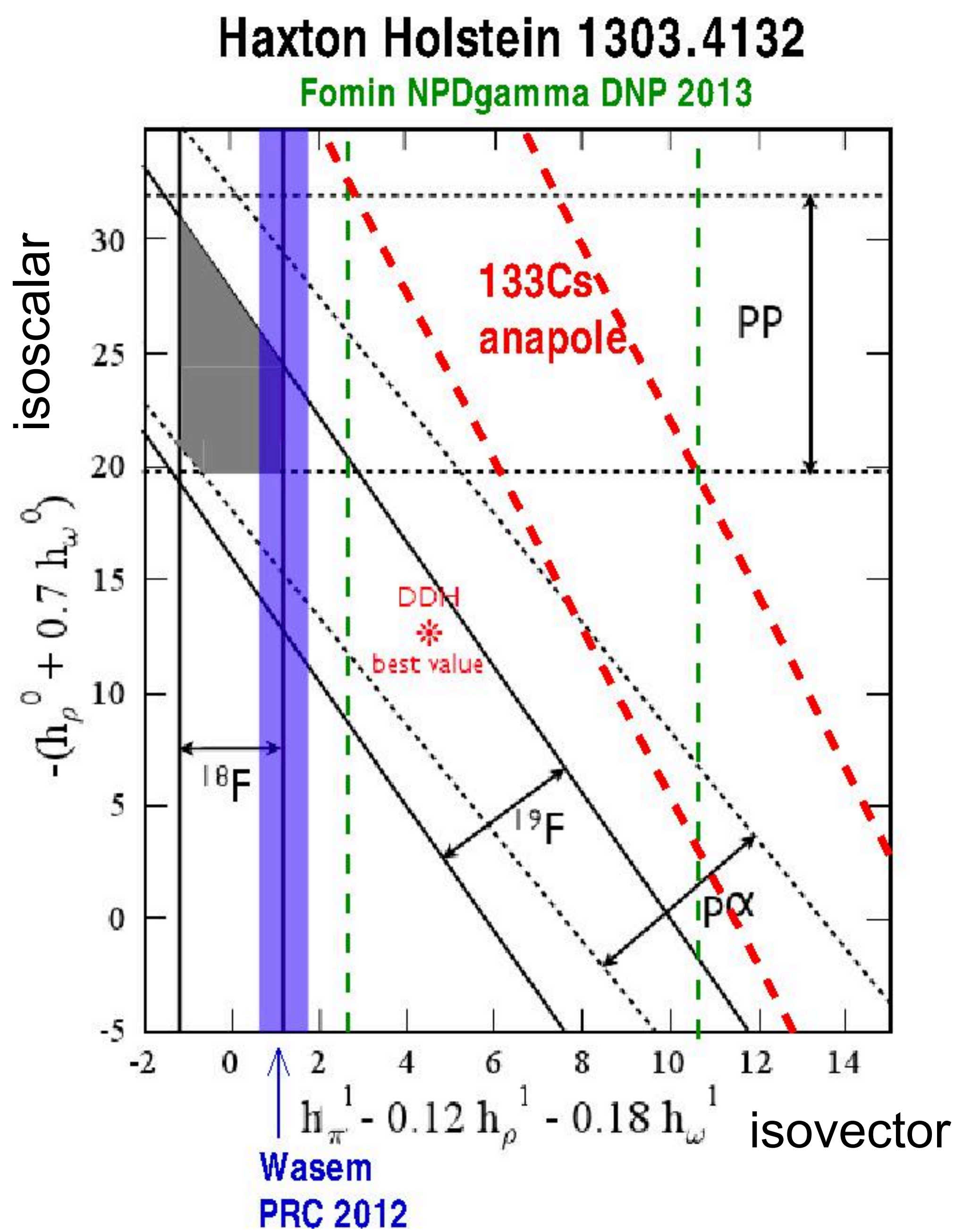
The Anapole Moment History

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 in one isotope of Cesium

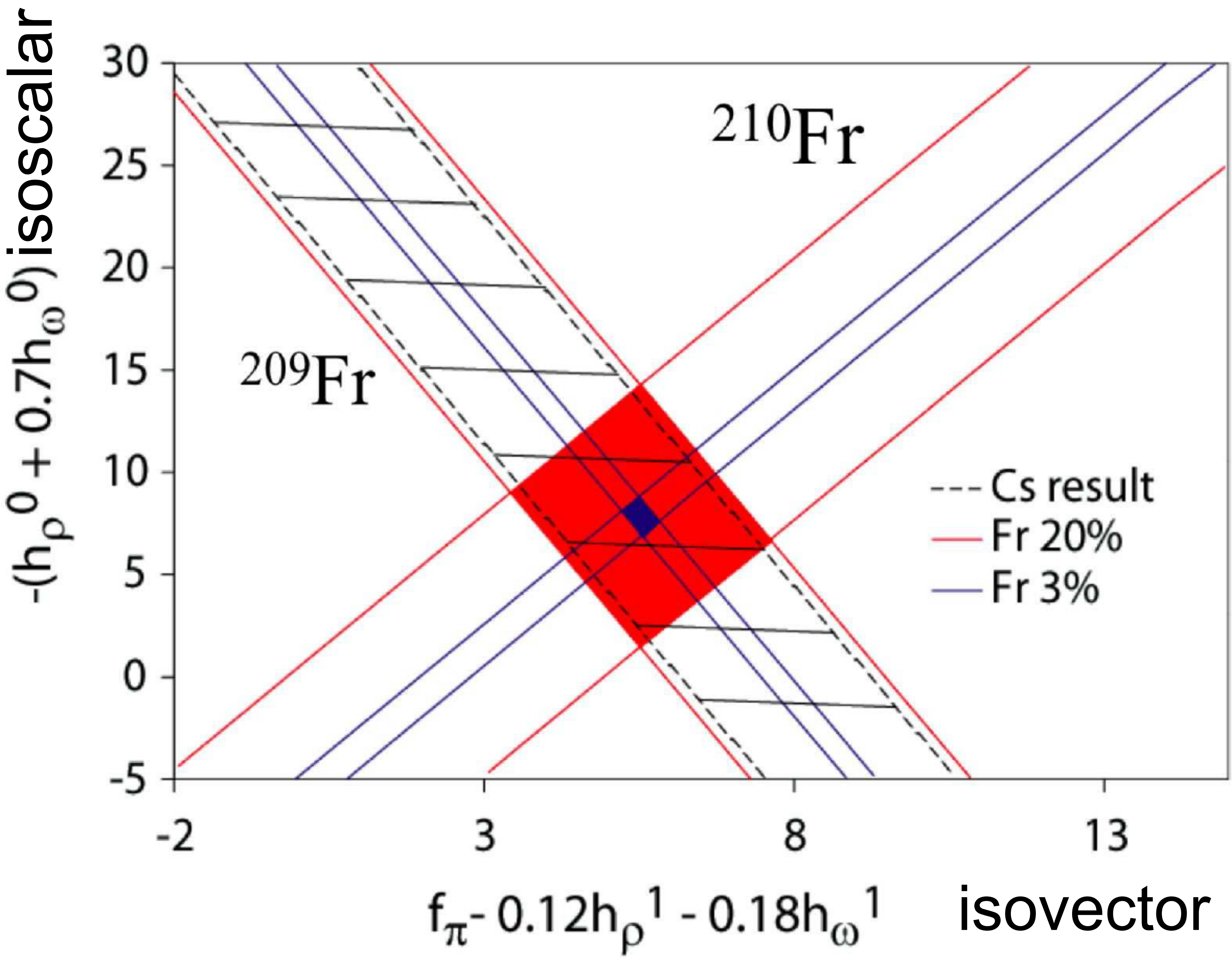




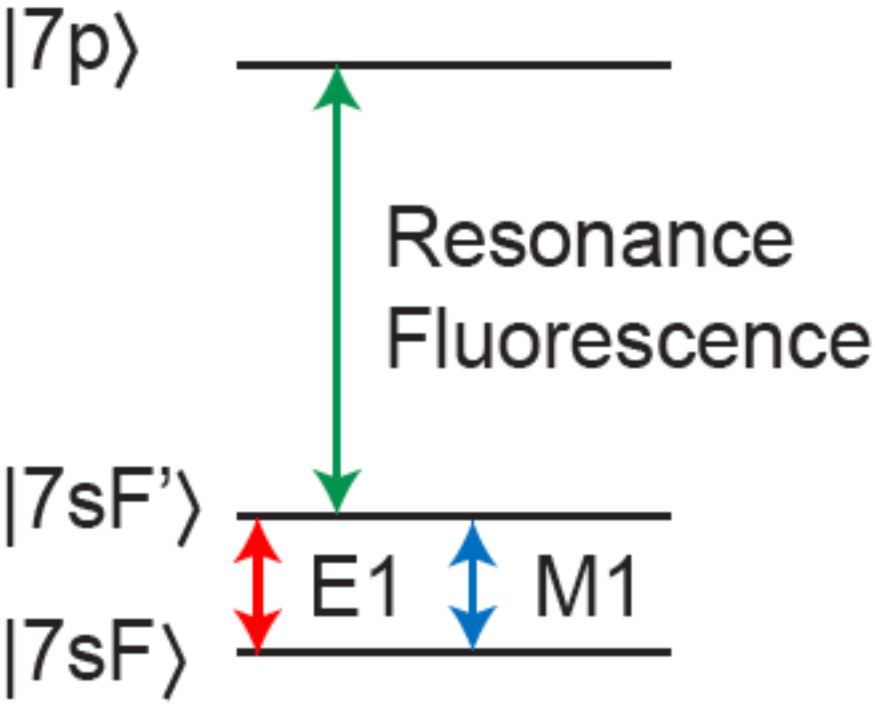
Does weak N-N interaction change in heavy nuclei?



The dream in francium



Method



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:

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

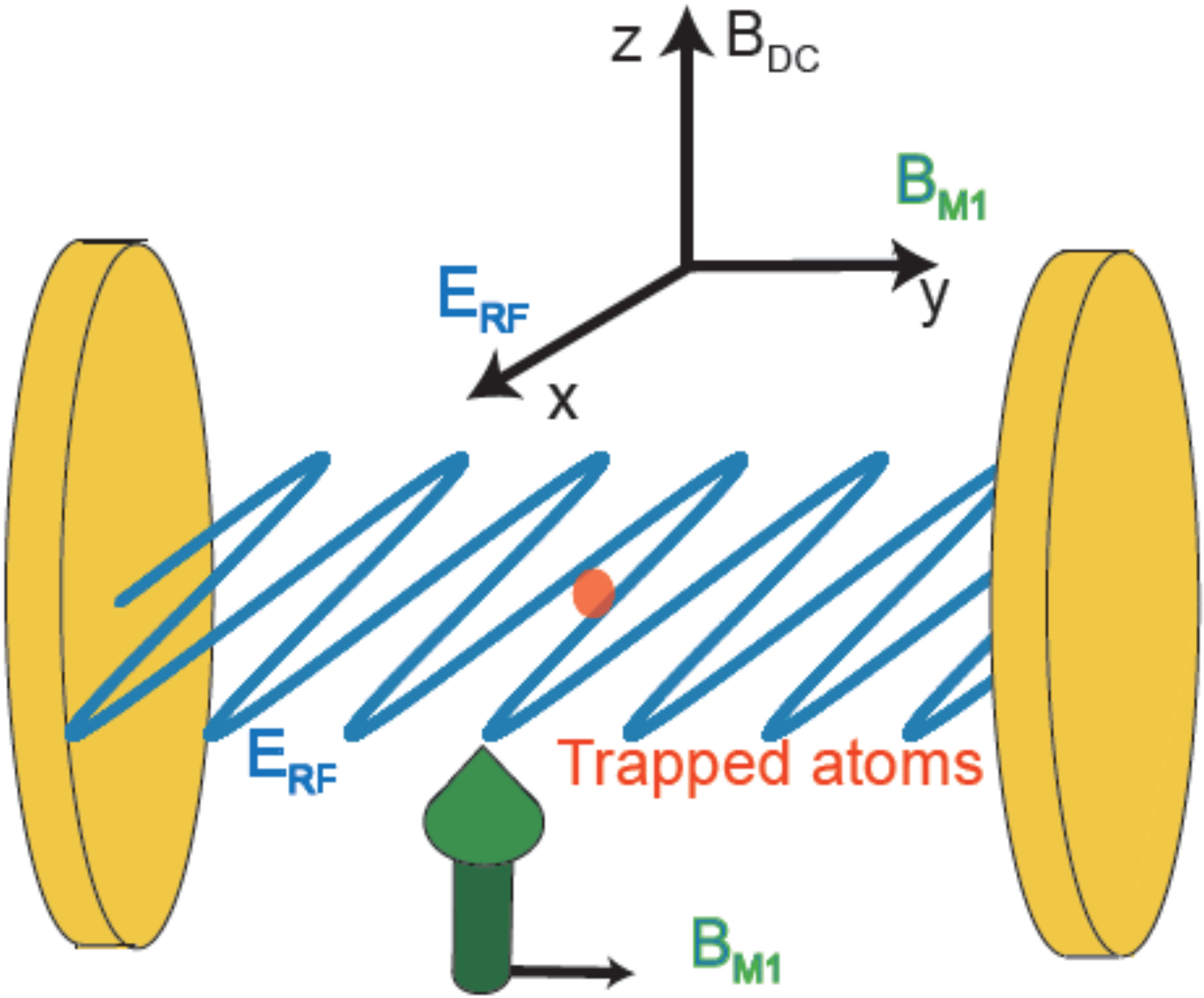
3.- Measure rate of transition through resonance fluorescence.

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

4.- Change handedness of apparatus

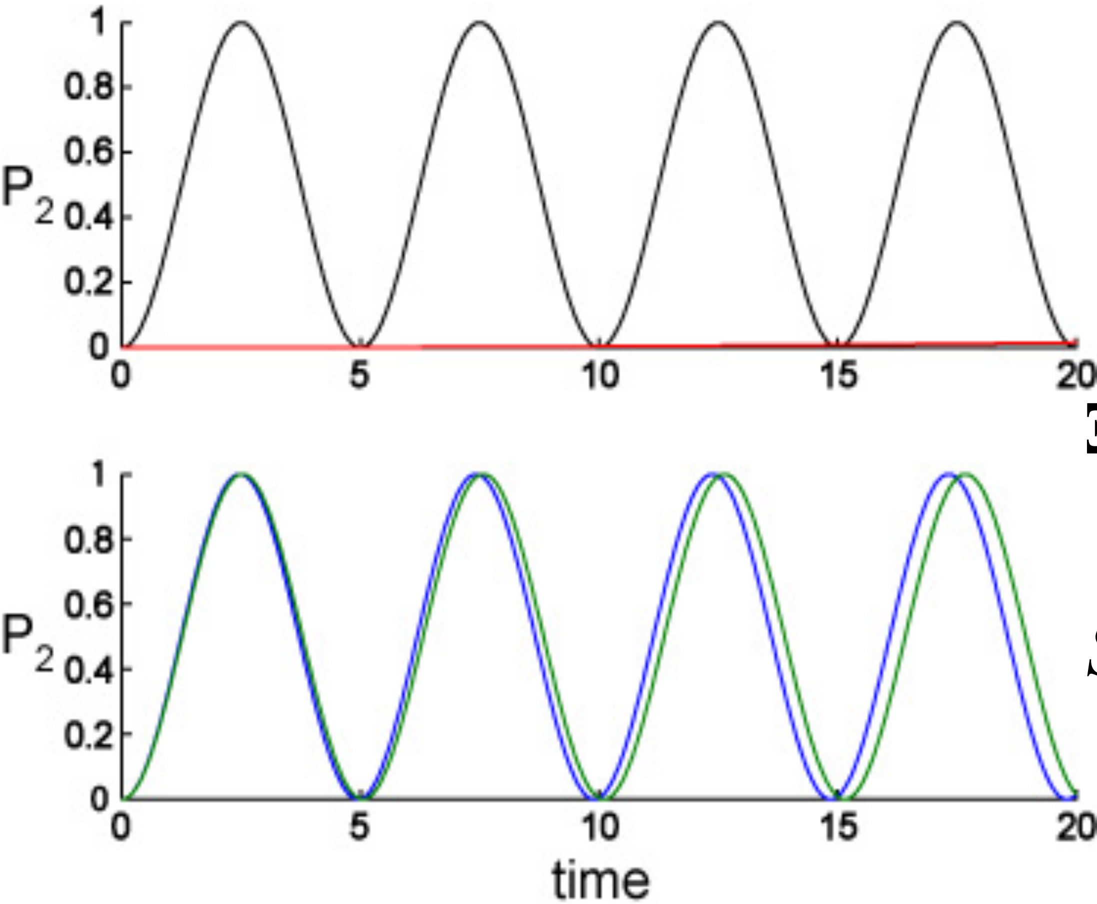
$$Signal \propto \left|A_{total}^{+}\right|^2 - \left|A_{total}^{-}\right|^2$$

5.- Repeat.



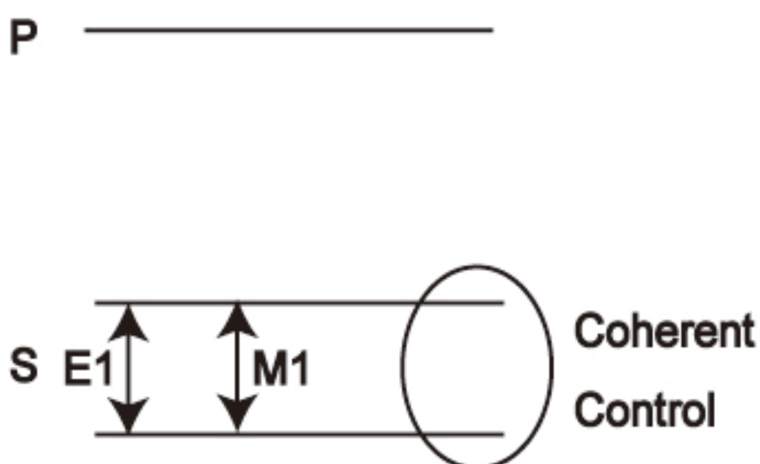
z
B_{DC}
B_{M1}
E_{RF}
y
x
E_{RF}
Trapped atoms
B_{M1}

Principle of the measurement



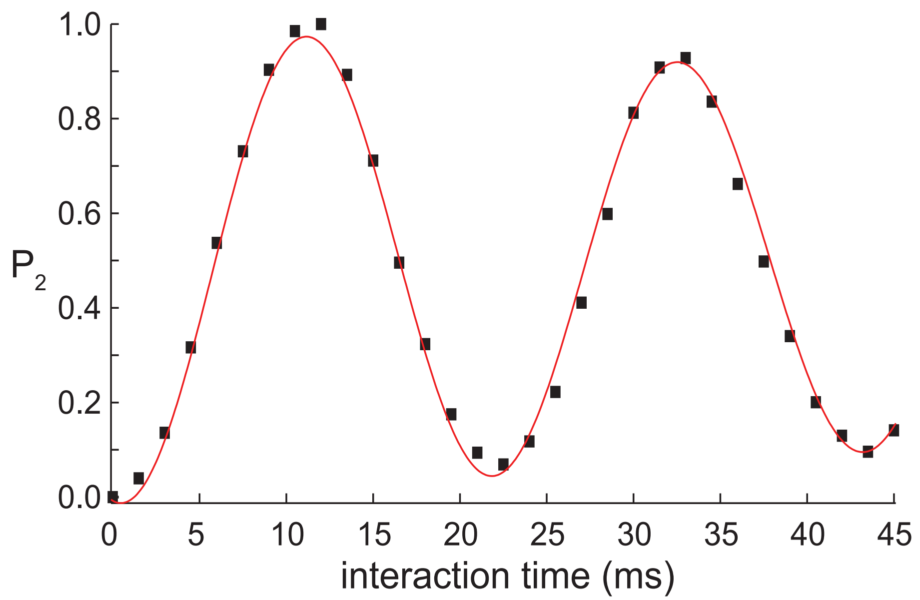
$$\Xi_{\pm} = N \sin^2\left(\frac{(A_{M1} \pm A_{E1})t_c}{2\hbar}\right)$$

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

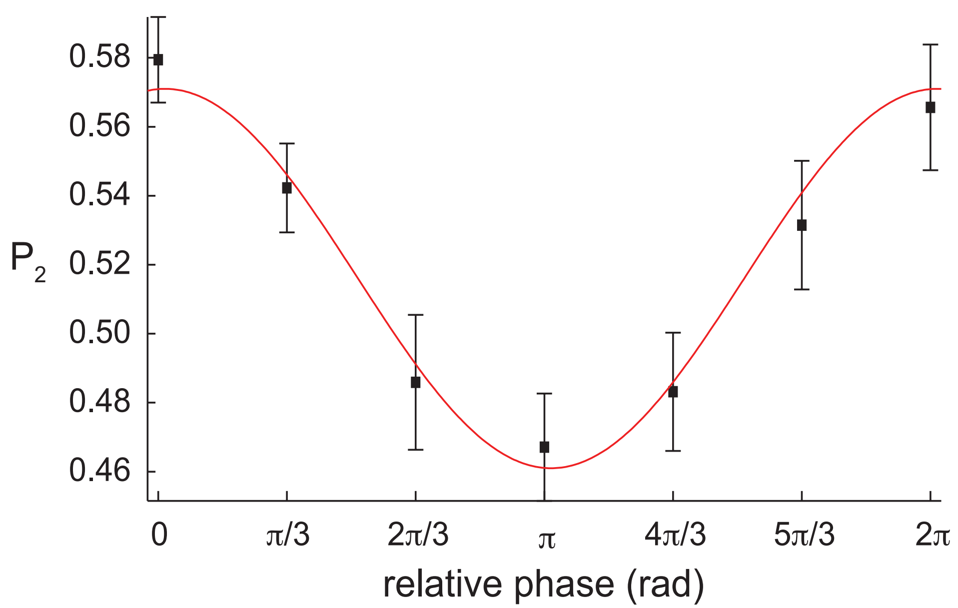


Control phase of different interactions
Ground state hyperfine splitting
Fr ~46 GHz, Z=87
Rb ~6.834 GHz, Z=37

Oscillations and sensitivity test



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



At 37.5 ms, add a second microwave source with 10^4 attenuation, change of the phase.

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

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

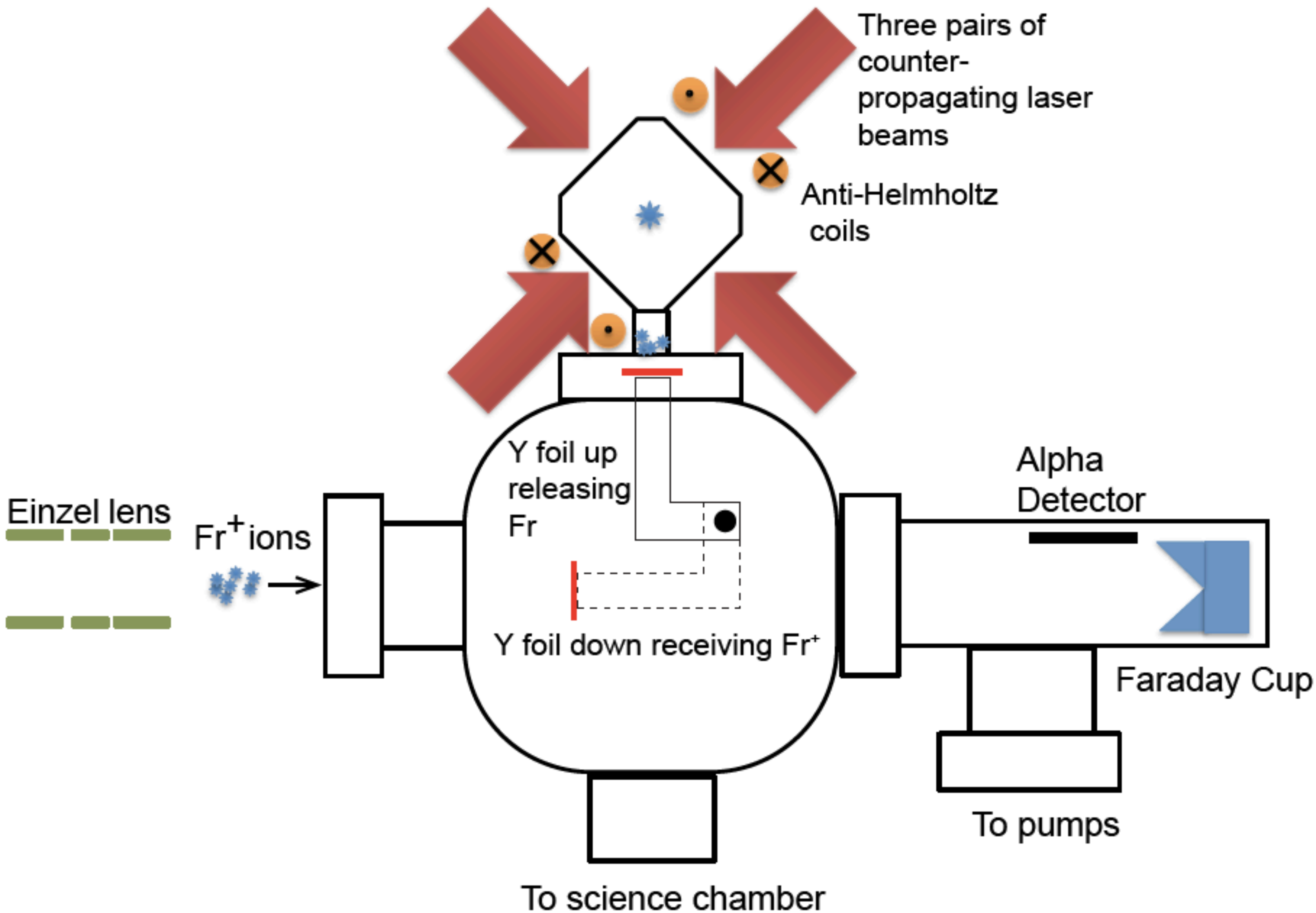
$\Omega_{E1} \sim 10$ mrad

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

The Francium Trapping Facility at TRIUMF

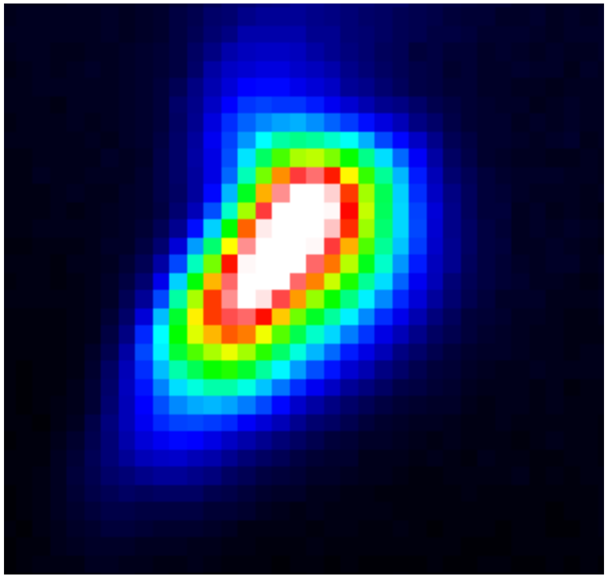
ISAC I hall at TRIUMF, Francium Trapping Facility

High efficiency capture MOT



Commissioning of Apparatus:

- Trapped atoms: ~ 10^5 to 10^6 now 10^7
- Efficiency ~ 1% now higher.
- Trap lifetimes ~ 30s



Measurements at TRIUMF

Need to understand the atom and the nuclear properties that enter for the calculation:

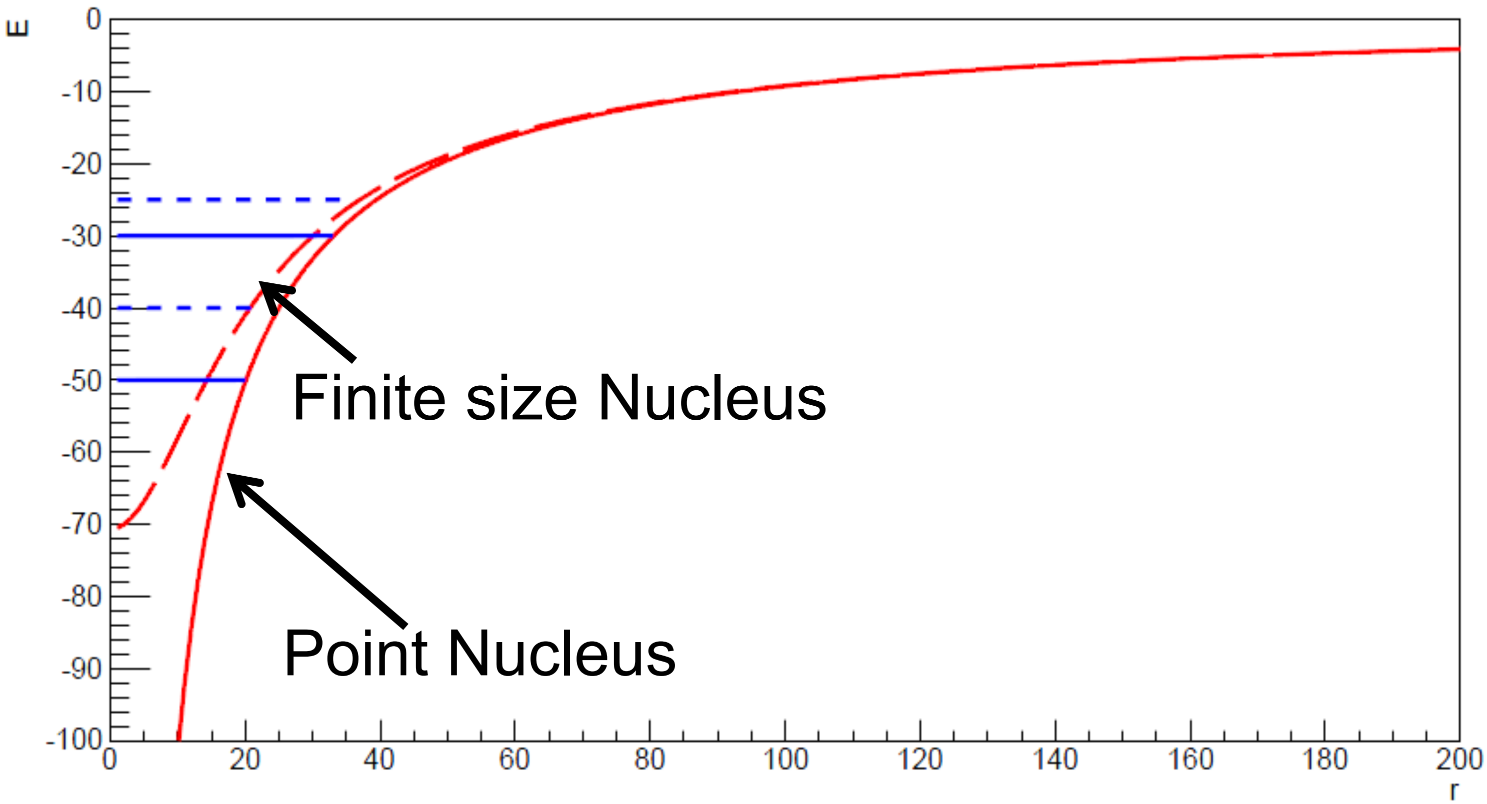
- Charge radius.

- Magnetization radius.

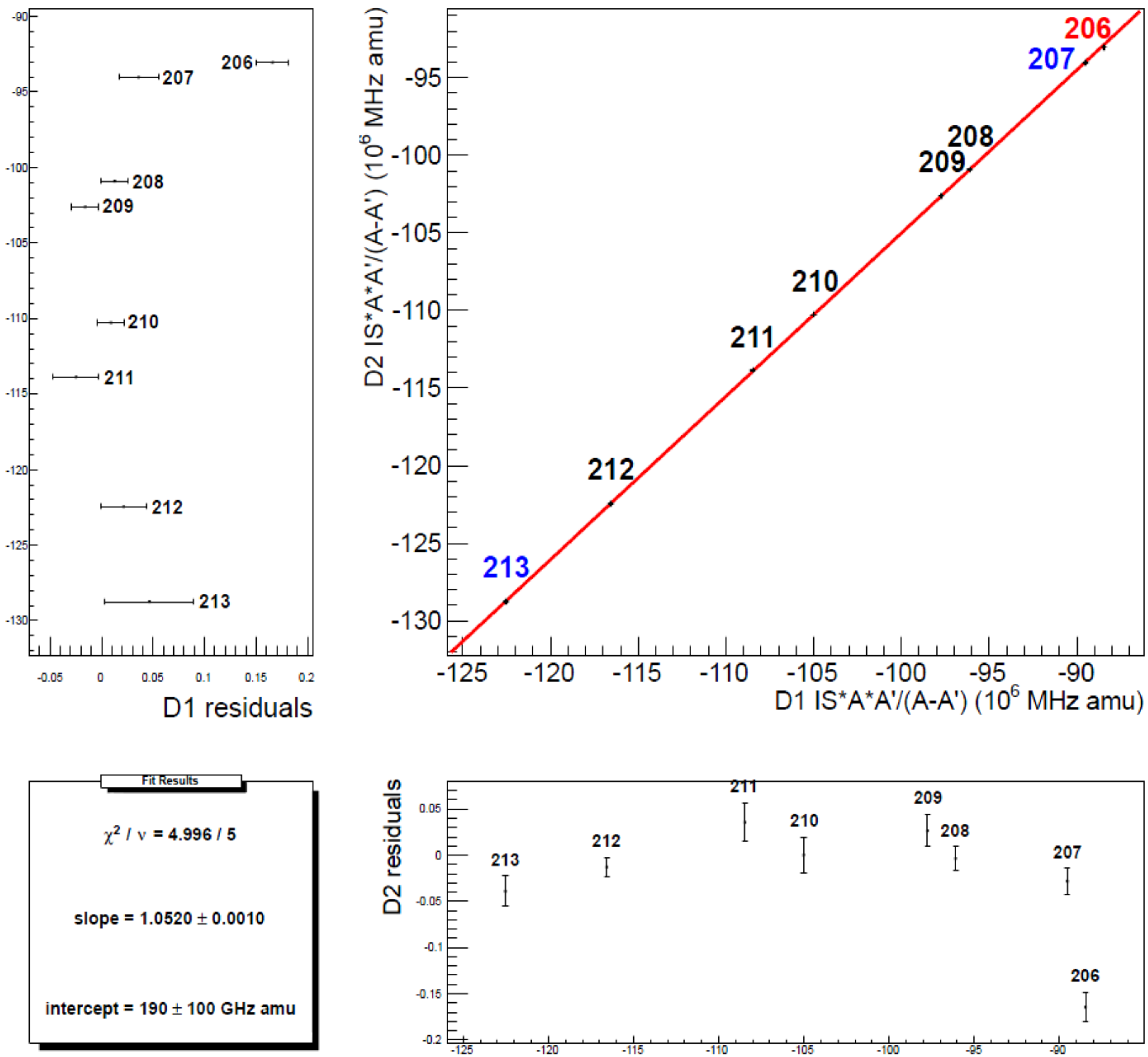
Measure the scalar (alpha) and vector (beta) polarizabilities for the Stark induced transition.

Isotope Shift

- Mass Shift
  - Reduced mass (easy)
  - Electronic correlations (difficult)
- Field Shift



King plot



D1 residuals
206
207
208
209
210
211
212
213
D2 IS*A*A'/(A-A') (10^6 MHz amu)
D1 IS*A*A'/(A-A') (10^6 MHz amu)
Fit Results
χ^2 / ν = 4.996 / 5
slope = 1.0520 ± 0.0010
intercept = 190 ± 100 GHz amu
D2 residuals

Results

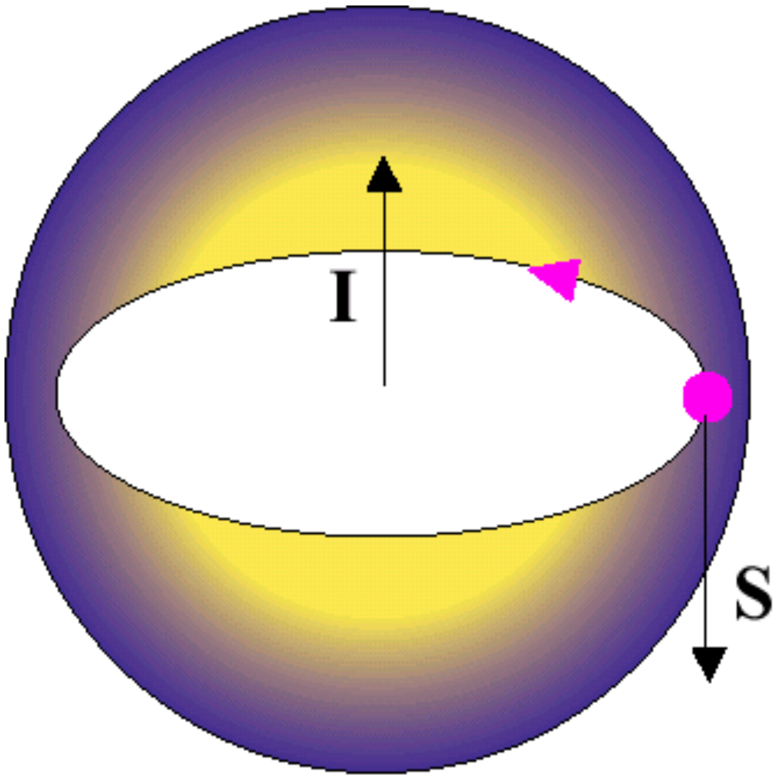
$$\frac{F_{D2}}{F_{D1}} = 1.052\ (1)$$

$$S_{D2} - S_{D1}\frac{F_{D2}}{F_{D1}} = 190\ (100)\ \text{GHz amu}$$

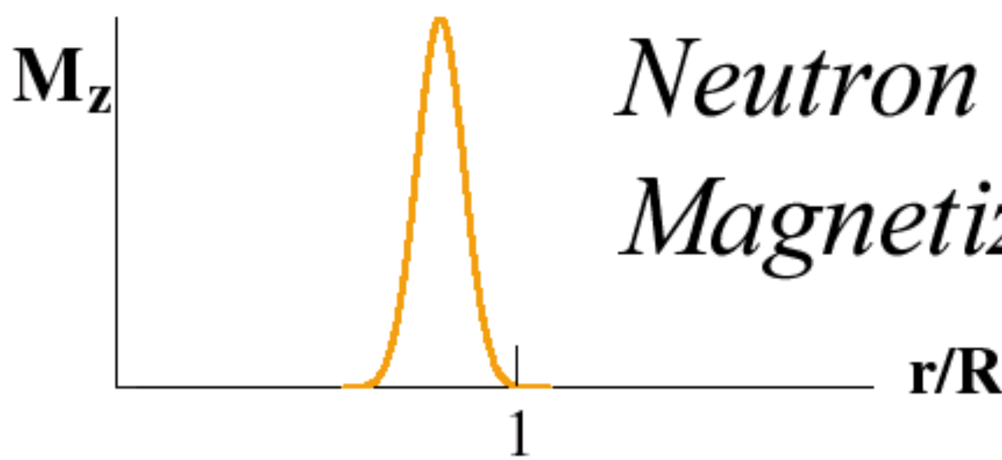
Method	$7S_{1/2}$	$7P_{1/2}$	$7P_{3/2}$	F_{D2}/F_{D1}
BO(Σ^{∞})	-20463	-693	303	1.0504
SD + E3	-20188	-640	361	1.0512
M-P	-20782	-696	245	1.0468

Dzuba, Johnson and Safronova, *Phys. Rev. A* **72**, 022503 (2005)
Mårtensson-Pendrill, *Mol. Phys.* **98**, 1201 (2000)

Nuclear Magnetization



Unpaired Neutron $2f_{5/2}$



Neutron Magnetization

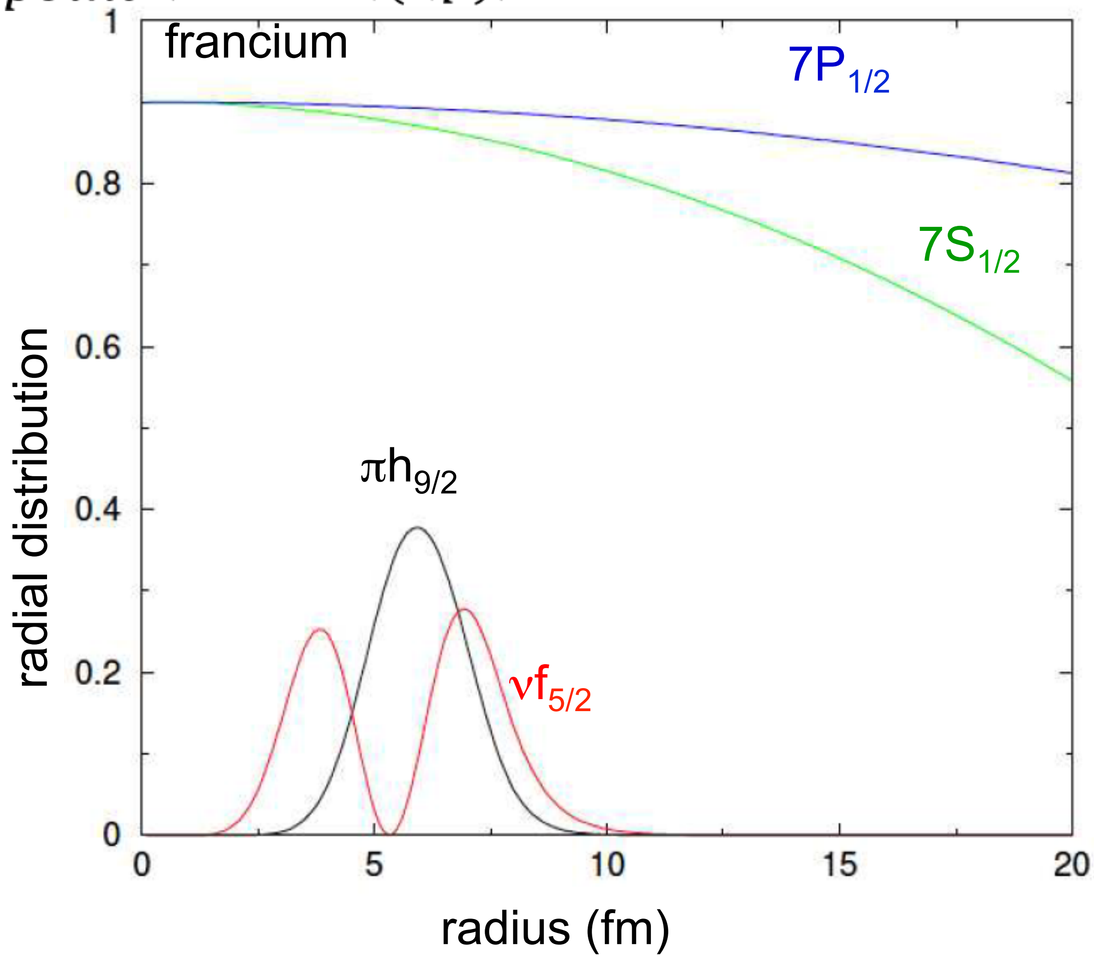
Hyperfine Interaction: Interaction of electron with the magnetic moment of nucleus.

Hyperfine Anomaly: ε quantifies the effect of the finite size of the nucleus.

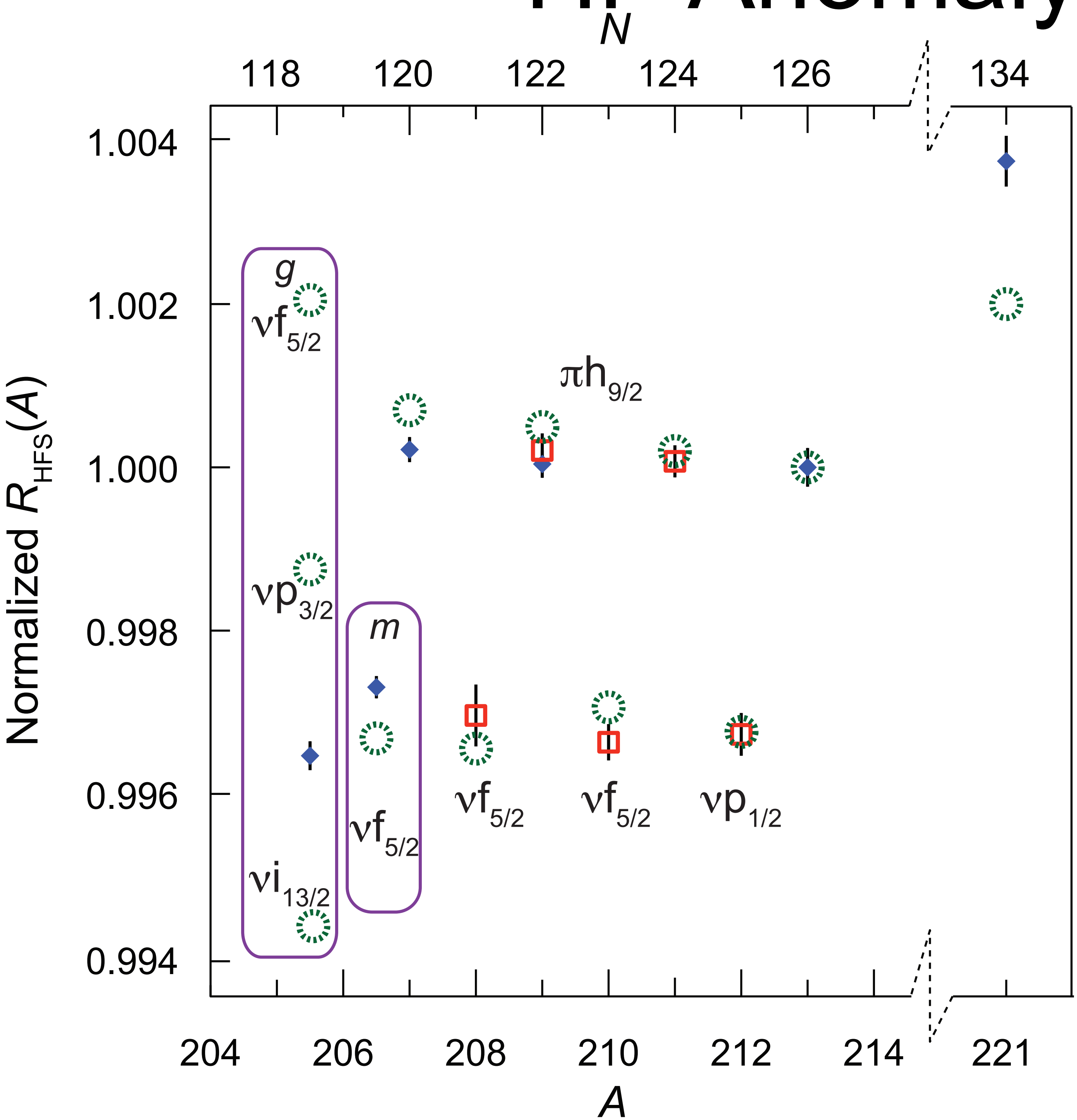
$A_{S,P}$ [ρ]= hyperfine coefficient ∝ hyperfine splitting

$$W_{hyper} = h\,A_{S,P}[\rho]\,\vec{I}\cdot\vec{J} = W^{S,P}_{point}\left(1+\epsilon_{N,(s,p)}\right)$$

ρ=nuclear magnetization distribution



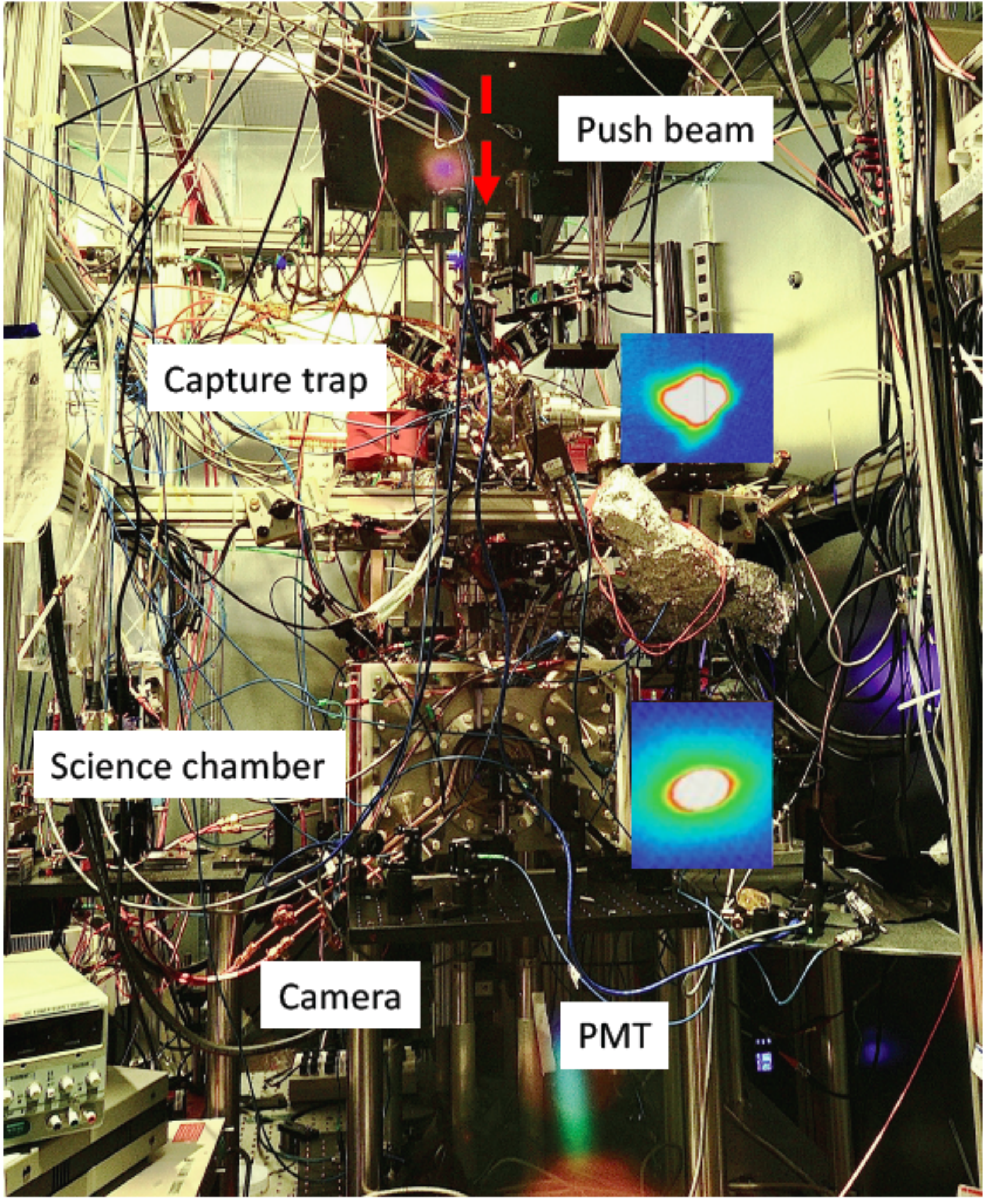
HF Anomaly

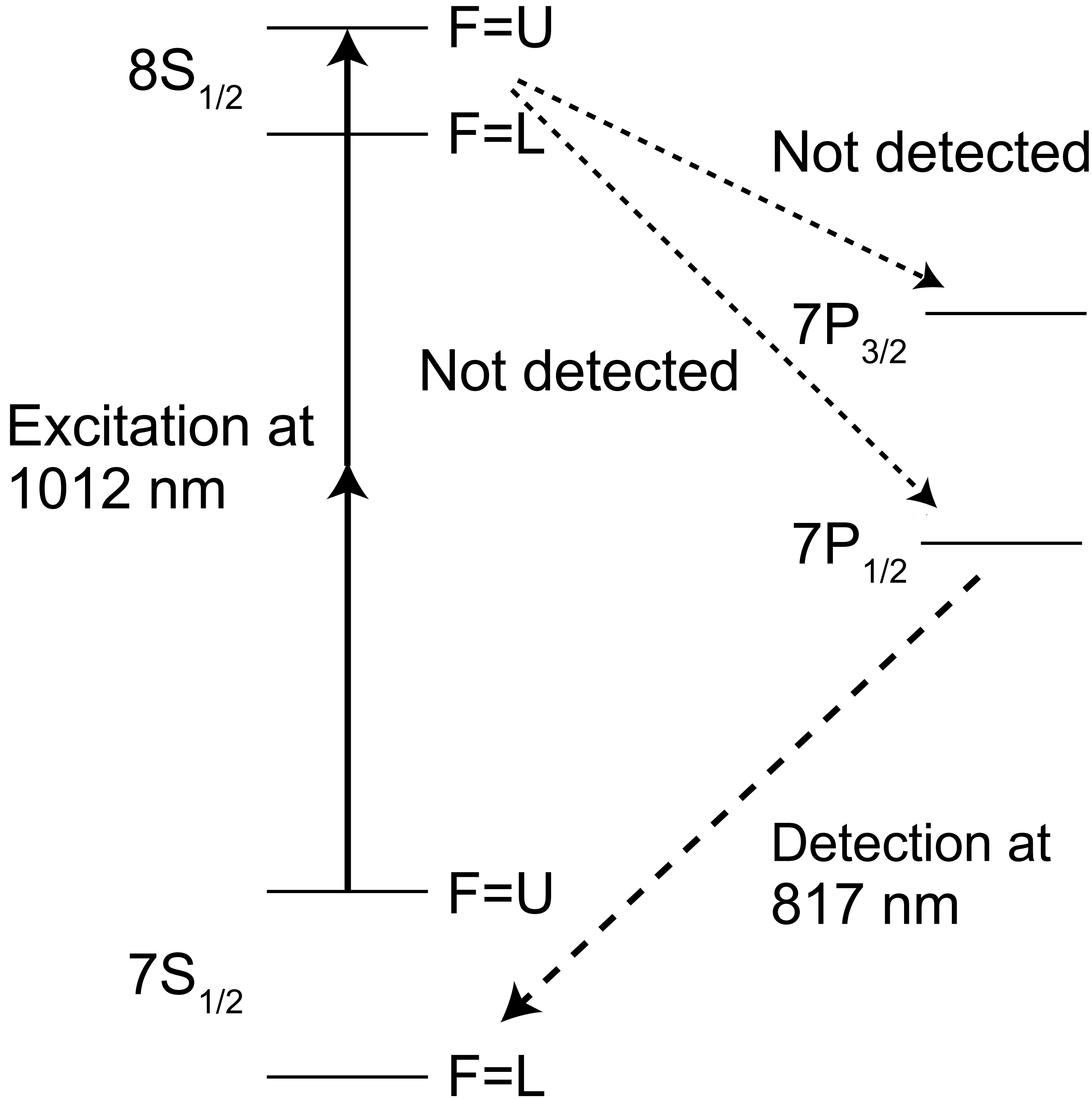


Green: Nuclear Structure Theory

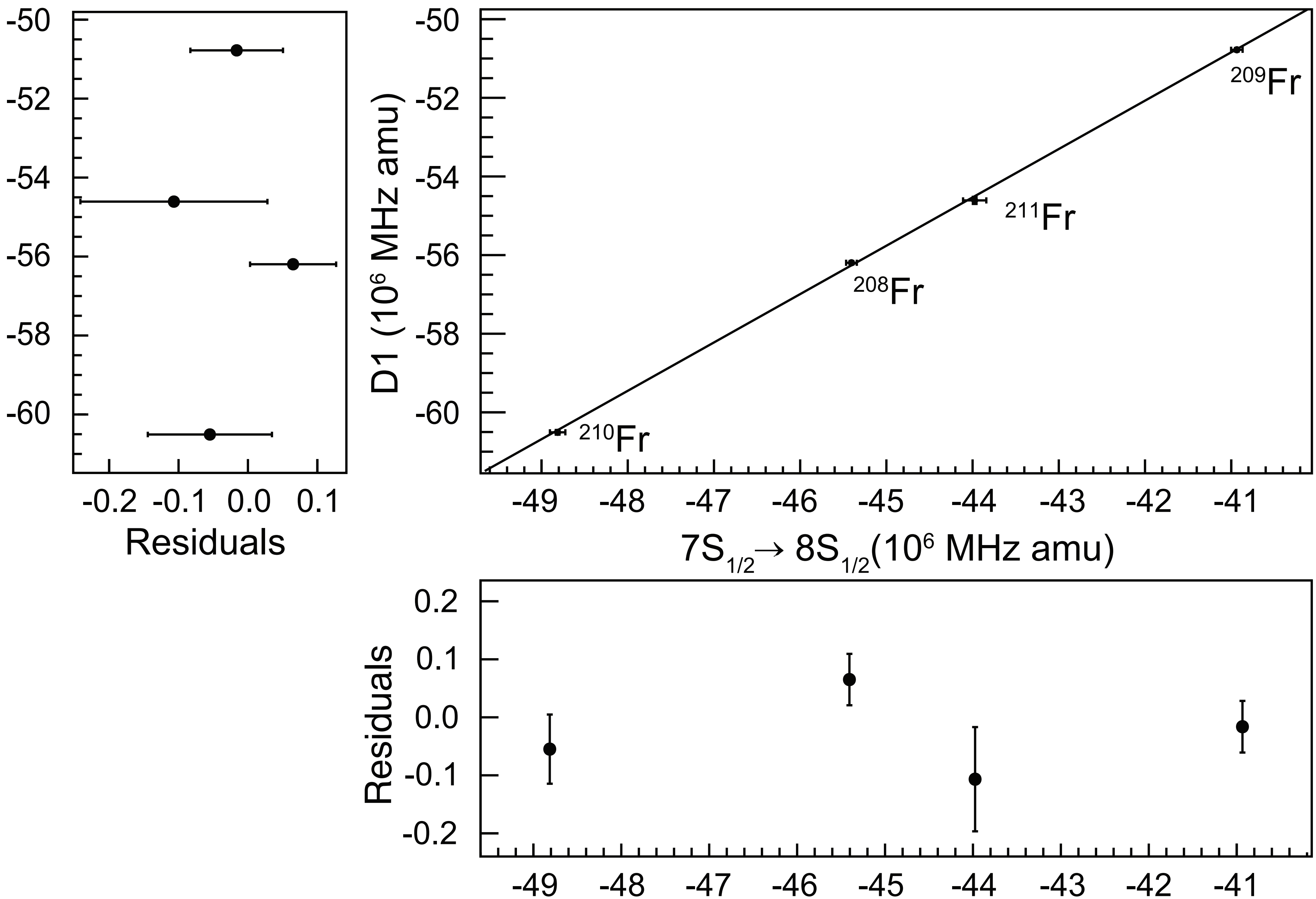
Blue and Red: Measurements

Two isomers for 206 *g* and *m*


Push beam
Capture trap
Science chamber
Camera
PMT


F=U
8S1/2
F=L
Not detected
7P3/2
Not detected
Excitation at
1012 nm
7P1/2
Detection at
817 nm
F=U
7S1/2
F=L

King plot two-photon vs D1 shifts relative to ^{213}Fr



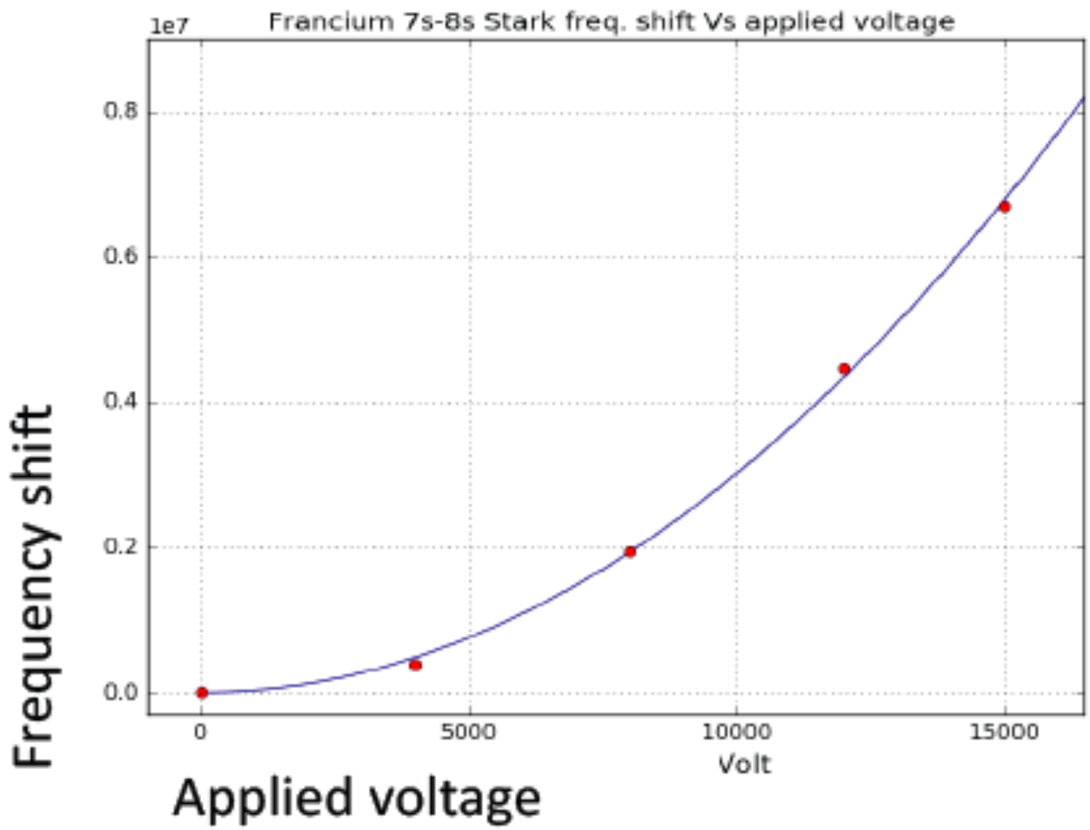
Comparison of the slope from the King plot

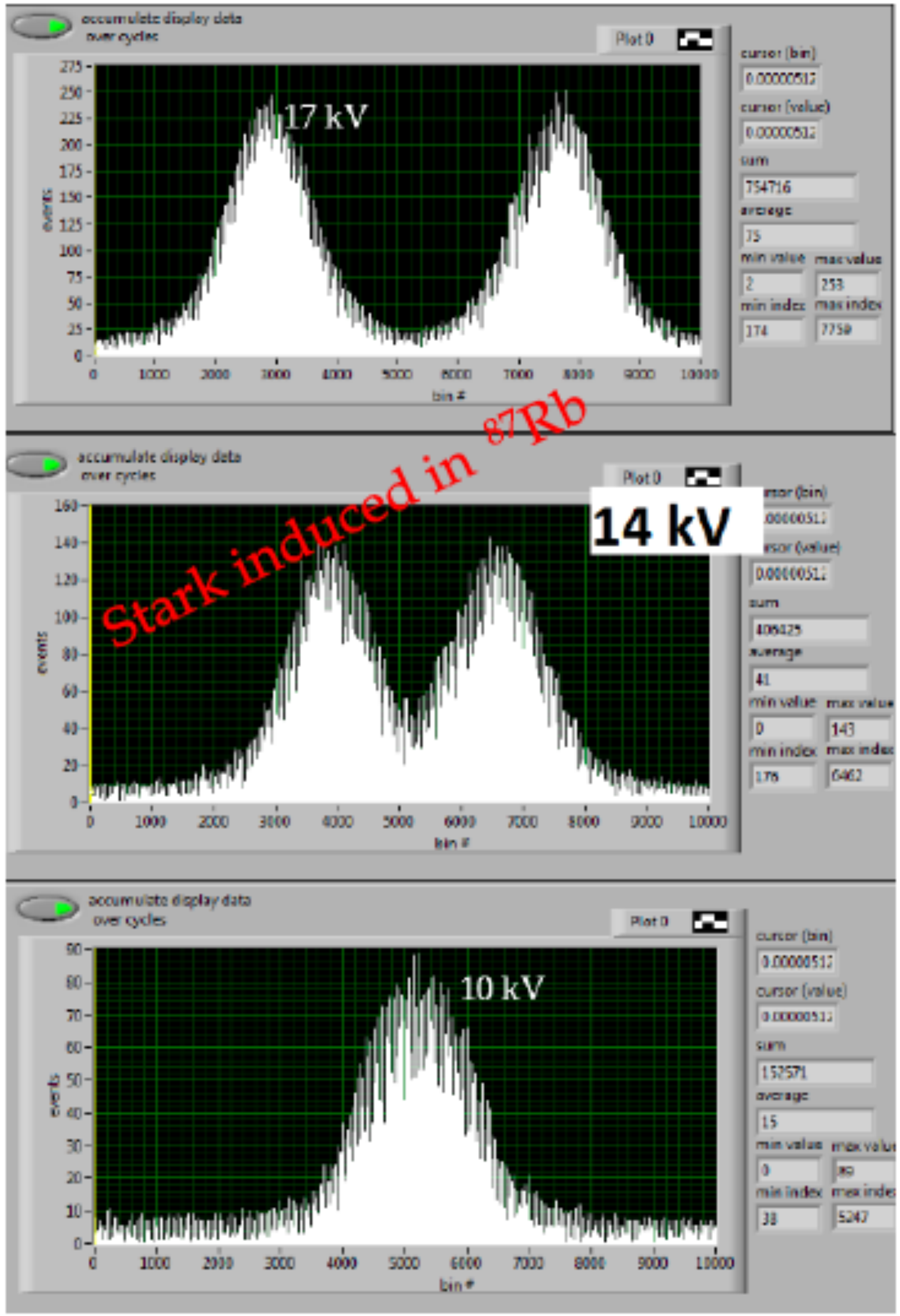
Experiment: 1.230 ± 0.019
Theory: 1.234 ± 0.010

Next step
DC Stark Shift for the 7S to 8S transition in Fr.
We have the results in Rb

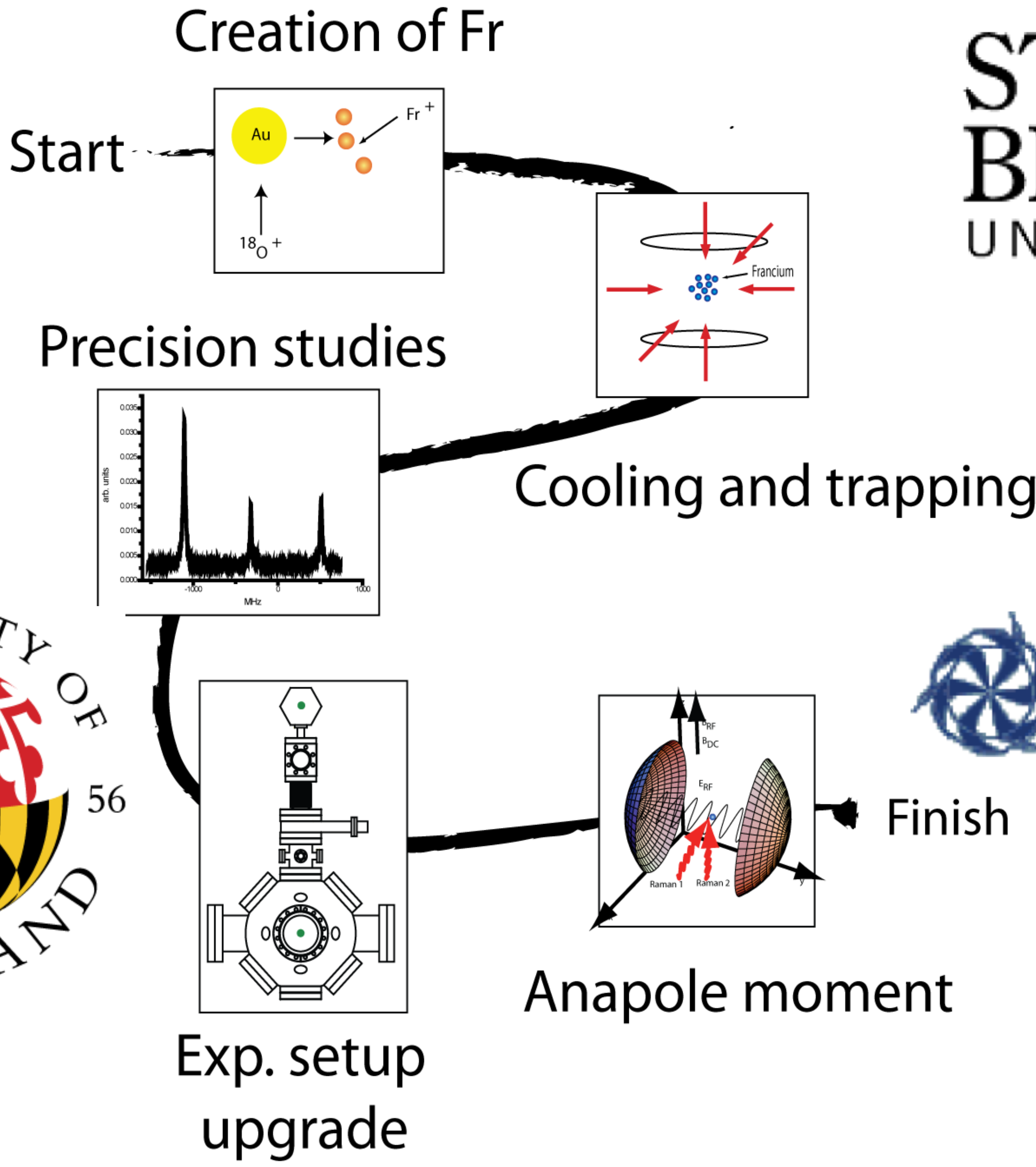
Progress so far

- DC Stark shift of the 7s-8s transition.
- Electrodes with holes




17 kV
Stark induced in ^{87}Rb
14 kV
10 kV
accumulate display data over cycles
Plot 0
events
bin #
cursor (bin)
cursor (value)
sum
754716
average
75
min value
max value
2
253
min index
max index
174
7759
406425
41
0
143
176
6462
152571
15
0
90
38
5247

- Isotope shifts of $^{206,207,213}Fr$ with respect to ^{209}Fr measured to within a few MHz in two transitions. Changes in the charge radius.
- $7P_{1/2}$ splitting measured for $^{206,207,209,213,221}Fr$ to a few kHz for the Hyperfine anomaly. Changes in the magnetization radius.
- DC Startk shift observed, but now need to measure it in controlled environment



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谢谢