Neutron Radii and Atomic Parity Violation in Francium

- **Atomic parity violation and non-Standard Model physics**
- **Neutron radii and atomic parity violation**

What do we need to extract non Standard-Model physics?

Could we assume S.M. and measure neutron radii?

- **Can other experiments help n-rich Fr info [‘Hyperfine anomaly’]?**

atomic parity violation experiments

Boulder Cs $\not{P}$ (Bennett PRL 82 (1999) 2484) 0.4% exp. $\approx 1\sigma$ off S.M. [Dzuba Berengut Flambaum Roberts PRL 109 203003 (2012) + Roberts Dzuba Flambaum 1302.0593].

Cs $\not{P}$ 2%, stimulated Guena Bouchiat ModPL A20 375 2005

- **current atomic $\not{P}$ experiments:**

Ytterbium atom UC Berkeley, $\not{P}$ measured, 9% stat, 7% syst, Tsigutkin PRL 103 071601 (2009), PRA 81 032114 (2010), many stable isotopes, E1 $\not{P}$-Stark mixing, 100x Cs

Ra^+ KVI, Versolato et al. Can J Phys 89 65 (2011), several precision hyperfine structure and charge radii papers, are proceeding to single-ion trapping. Parity-violating frequency shifts for an S-D E2+$\not{P}$E1 transition.

Francium E1 $\not{P}$-Stark, 18x Cs: Manitoba/Maryland/TRIUMF; Legnaro

atomic PNC experiments II

Xe*, Hg* optical rotation Crete (Bougas PRL 108 210801 (2012))

Yb^+ Los Alamos (Torgeson, Cairns ICAP2010) frequency shift, similar also to Fortson Ba^+ frequency shift

H atomic spin echo Heidelberg (DeKieviet Hyp Int 200 35 (2011))

Deuterium atom, Dunford and Holt, Hyp Int 200:45 (2011)

molecules Yale (anapoles, C_2) D. DeMille PRL 100, 023003 (2008)

FrPNC collaboration

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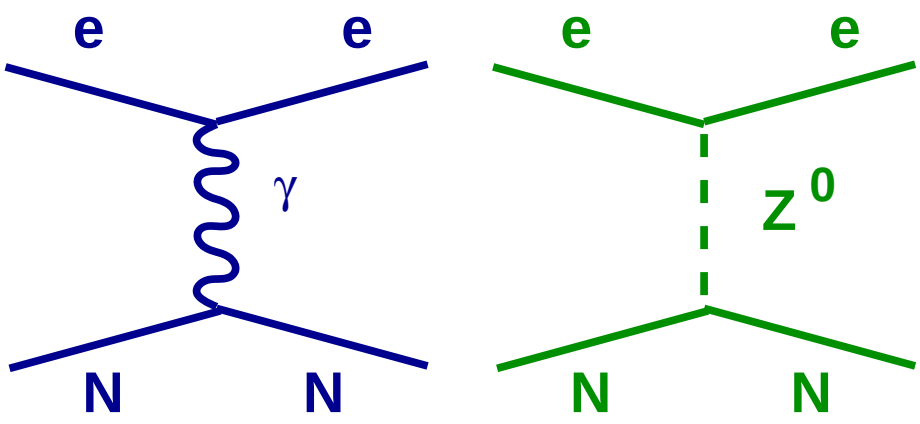
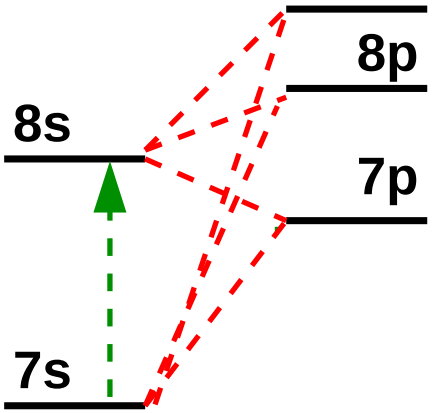
Approved TRIUMF experiments:

- **anapole moments (weak N-N interaction),**
- **towards optical PNC (lepton-quark weak couplings)**
- **'hyperfine anomalies' precision spectroscopy.**

Supported by NSF and DOE USA, NSERC and NRC Canada, CONACYT Mexico.

$\not{P}$ Francium: atom



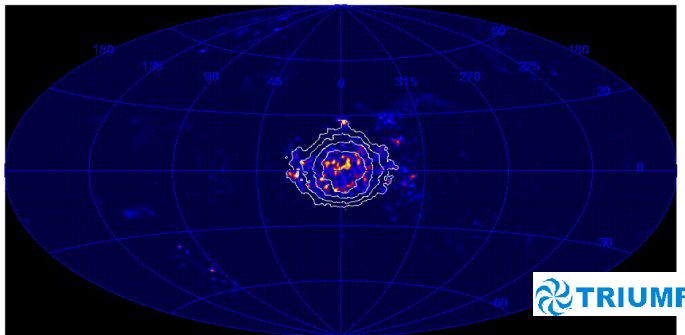


Z^0 mixes states of opposite parity, allowing $\not{P}$ E1 amplitude $\sim 10^{-9}$

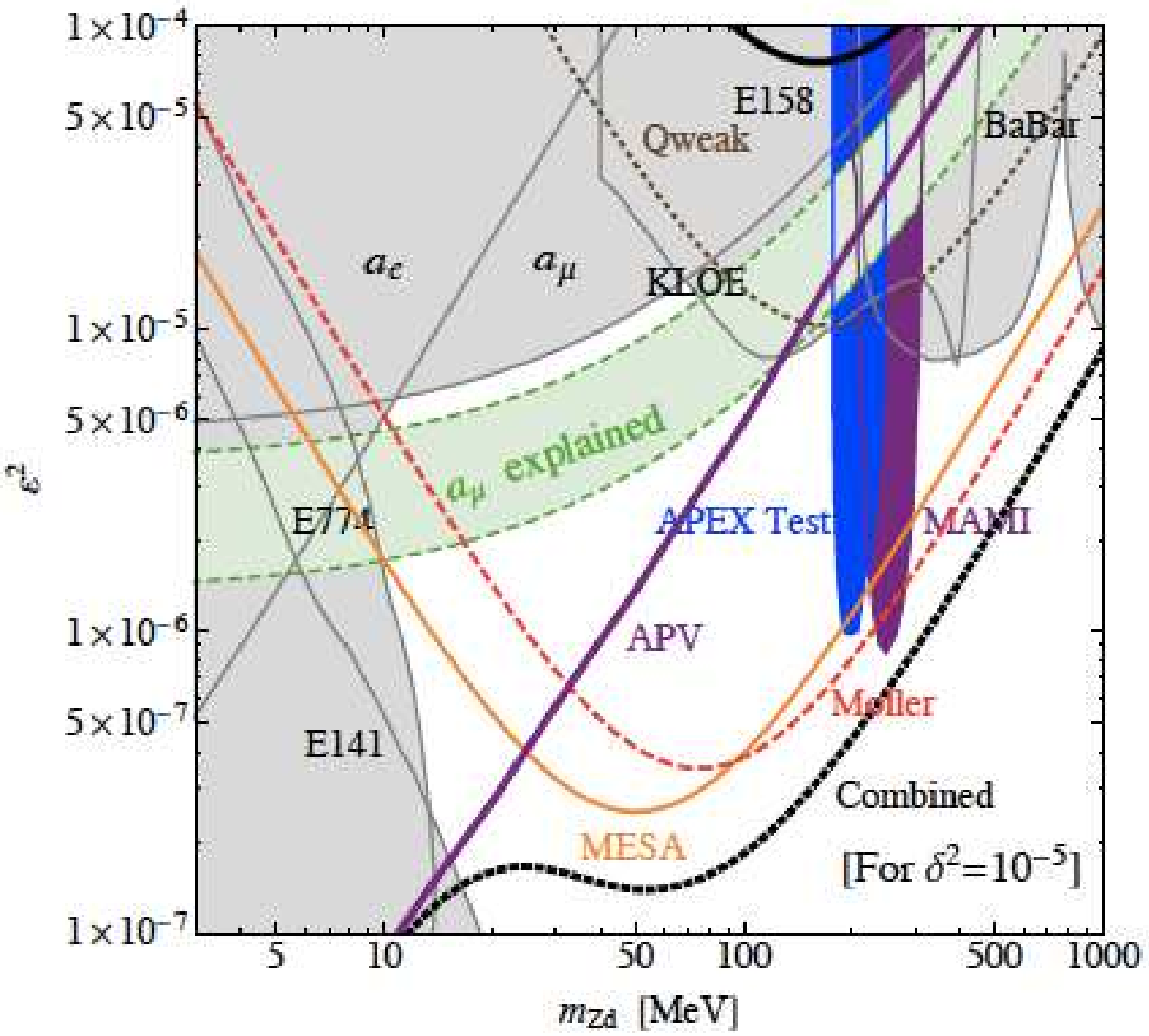
Cs $\not{P}$ accuracy 0.5%. Effect 18x bigger in Fr.

- In some 'little Higgs' models (Diener Godfrey Turan 1111.4566) larger Z' 1st-generation couplings: 0.1% measurement of $\not{P}$ E1 in Fr sensitive to $m_{Z'} \sim 3.3$ TeV
- Constraints on processes to generate observed Fermilab $t\bar{t}$ asymmetry: Gresham 1203.1320, Grinstein 1203.2183

- Weakly coupled bosons 1 - 500 MeV (astrophysics, μ g-2) tightly constrained by Cs $\not{P}$.



μ g-2 3.6σ and Atomic PNC



Davoudiasi, Lee, and Marciano PRL, 1205.2709

10-500 MeV Z_d

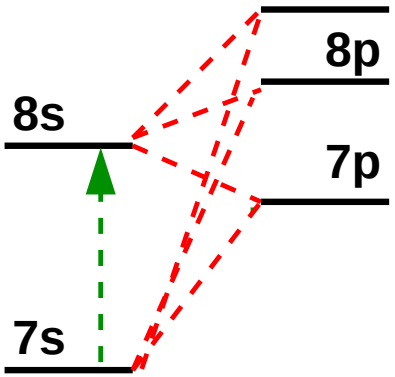
$$L_{\rm int} = -e\epsilon Z_d^\mu J_\mu^{em}$$

$$Z \to Z - \frac{m_{Zd}}{m_Z}\delta Z_d$$

Atomic and e^- scattering $\not{P}$ constrain different m_{Zd}

Stark - Weak interference: flip E field

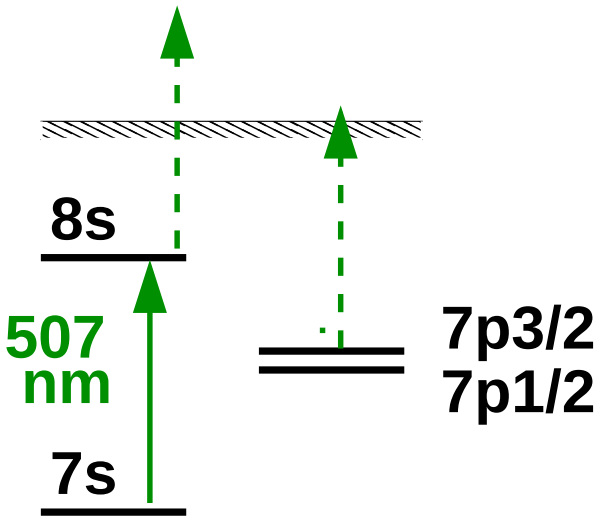
Emulating Boulder Cs scheme in Fr:
$|A_{7s\to 8s}|^2 = |E1_{\mathrm{Stark}} + E1_{\mathrm{PNC}} + M1|^2$



- **Minimize the M1 by light polarization, standing wave**
  $|A_{7s\to 8s}|^2 \approx |E1_{\mathrm{stark}}|^2 + 2E1_{\mathrm{Stark}}E1_{\mathrm{PNC}}$
  The interference term is $\sim 10^{-9}$ of an allowed E1 transition amplitude (rather than 10^{-18}).
- **Then calculate (or, preferably, measure) $E1_{\mathrm{Stark}}$ to extract $E1_{\mathrm{PNC}}$**

foibles of the trap I

Photoionization of atoms with the 507 nm light
Boulder lost several % from his atomic beam from Cs excited 7s to continuum



We will lose more:

- **trap**
- **Fr will ionize P3/2 state, and cross-section is 100x bigger for P states (measured at TRIUMF 2012)**

The good news: it's OK to turn down the 507nm power to avoid this. You still have good $E1_{PNC}/E1_{\mathrm{Stark}}$

S/N

- Time to obtain certain S/N:

$t = (S/N)^2/(Asym^2\ R\ N)$

Asym = 2×10^{-4}

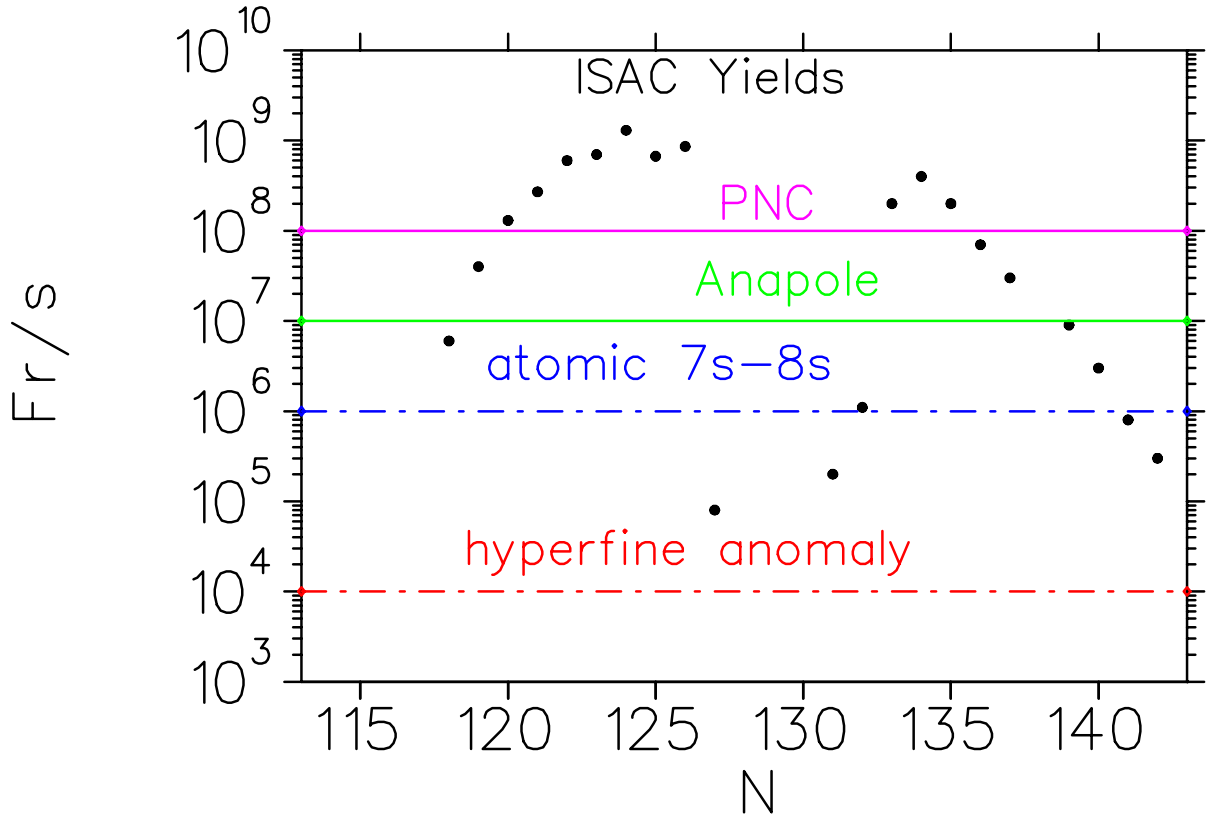
R = 30 Hz 7S $\rightarrow$ 8s excitation rate (need to avoid photoionization)

N = 10^6 trapped atoms

- Requires 2.5 hours to get to 1% statistics

- Boulder's main systematic was the residual M1-$E1_{stark}$ interference; smaller in Fr by about 2$\times$

ISAC TRIUMF Fr Yields



$^{207-213}$Fr and $^{220-223}$Fr have optical PNC experiments possible

Atomic $\not{P}$ calculations and n radii, incomplete history

Fortson Yang Wilets PRL 1990 'identified problem'

atomic $\not{P} \propto (1 - \frac{3}{70}(Z\alpha)^2[1 + 5\frac{R_n^2}{R_p^2}]) \rightarrow$

$\frac{\delta Qw_{\mathrm{n.s.}}}{Qw} \sim -\frac{3}{7}(Z\alpha)^2 \frac{\delta R_{n.s.}}{R}$

Pollock Wilets Fortson PRC 1992 explored many models

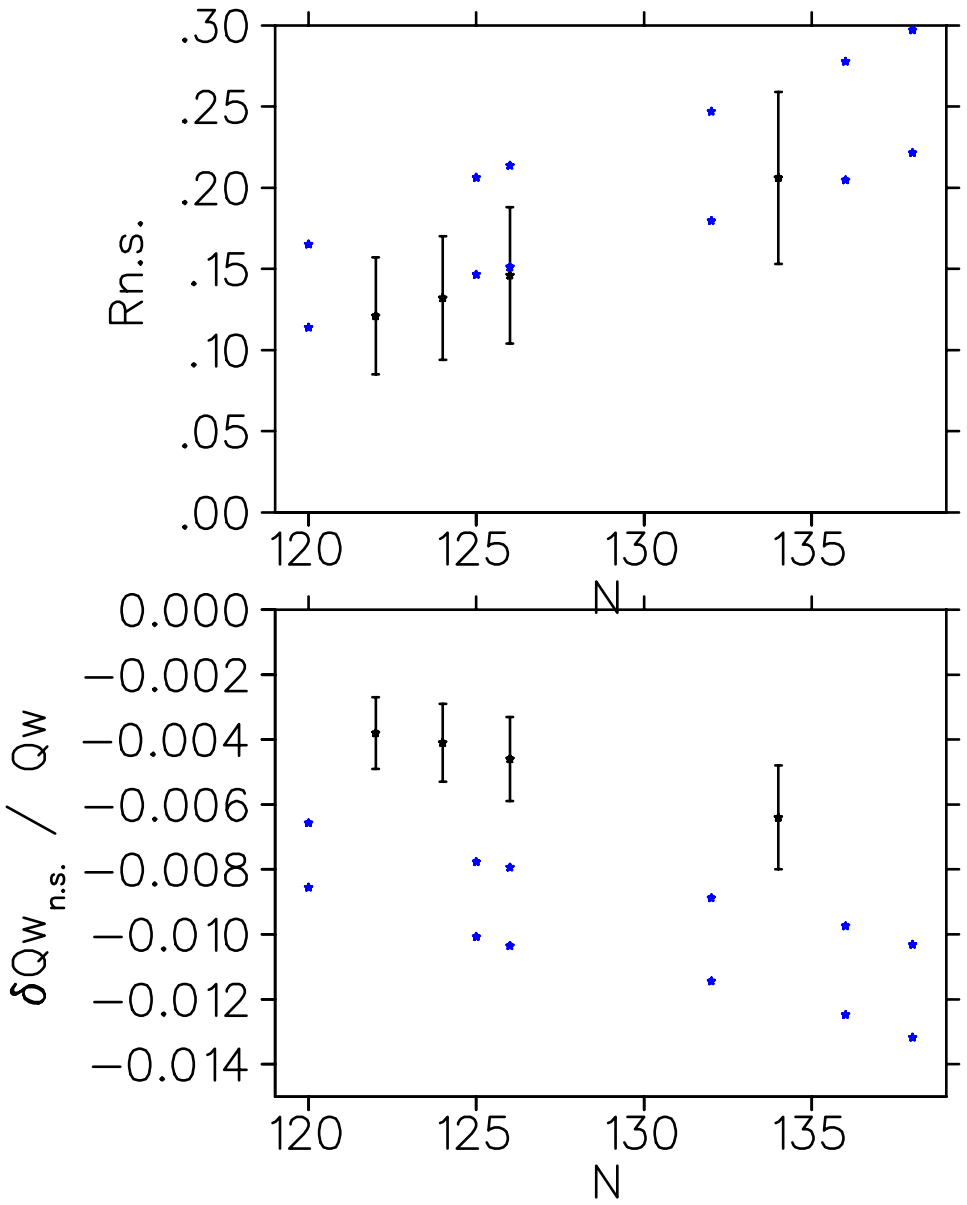
Chen Vogel PRC 1993 Dedicated calculation to Cs isotopes 'under control'

Derevianko Porsev PRA 65 052115 2002 reevaluated using Trzcinska PRL 87 082501 2001 antiprotonic atom work : 'ok in Cs but problems at higher Z'

Sil Centelles Viñas Piekarewicz PRC 71 045502 2005 QHD with IS-IV Λ_V Rn.s.[^{208}Pb]=0.28-0.21

Brown Derevianko Flambaum PRC 79 035501 2009 spherical Skyrme HF, parameters tuned from $\bar{p}$ data Rn.s.[^{208}Pb]=0.20$\pm$0.05

Atomic PNC calculations and n radii



Brown et al. PRC 2009, spherical Skyrme H-F, tuning $R_{ns}[^{208}Pb]=0.20\pm0.05$,

Sil PRC 2005

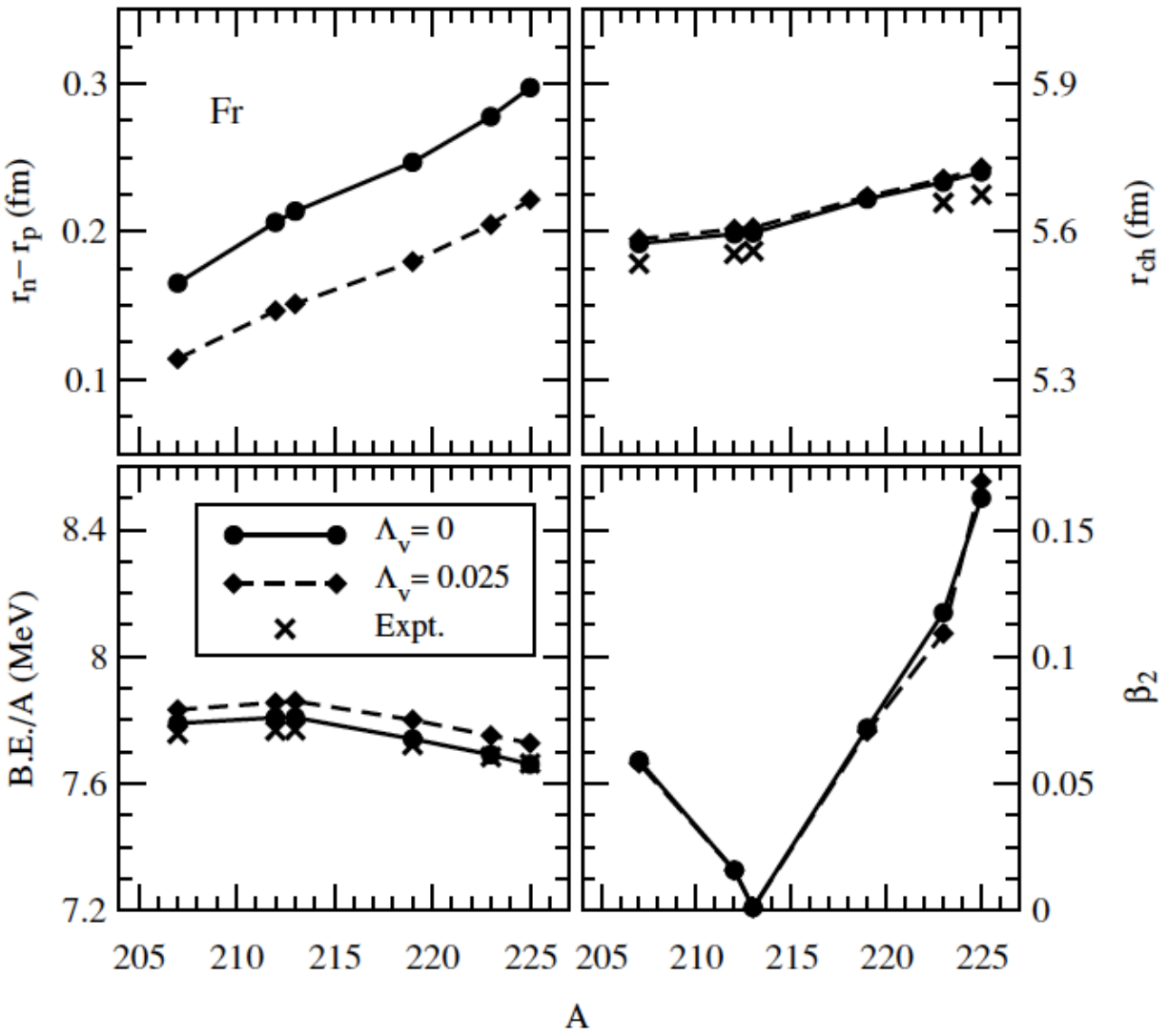
QHD $R_{ns}[^{208}Pb]=0.28-0.21$

^{213}Fr 0.0013 atomic PNC determination $\rightarrow$ 0.05 fm accuracy for ΔR_{np} (needs better atomic theory)

^{207}Fr, ^{225}Fr 0.0013 experiment $\rightarrow$ ΔRns to 0.05?

similar for Yb, Ra^{+}

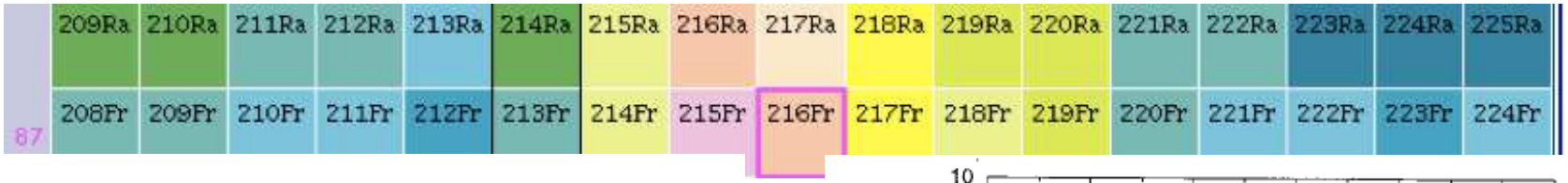
Chain of isotopes and n radii: Sil

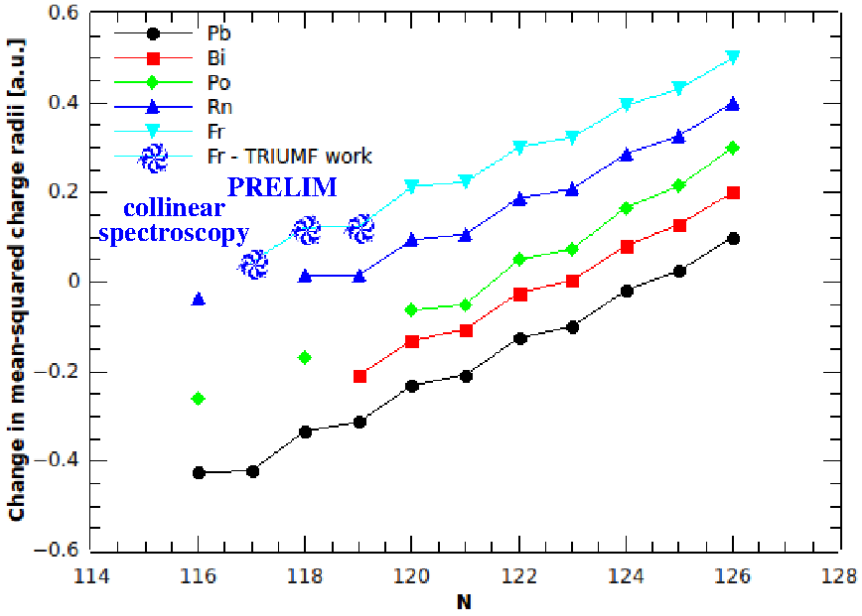


PRC 71 045502 (2005) global QHD model results for Fr

observables insensitive to Λ_V

Charge Radii very regular N<126





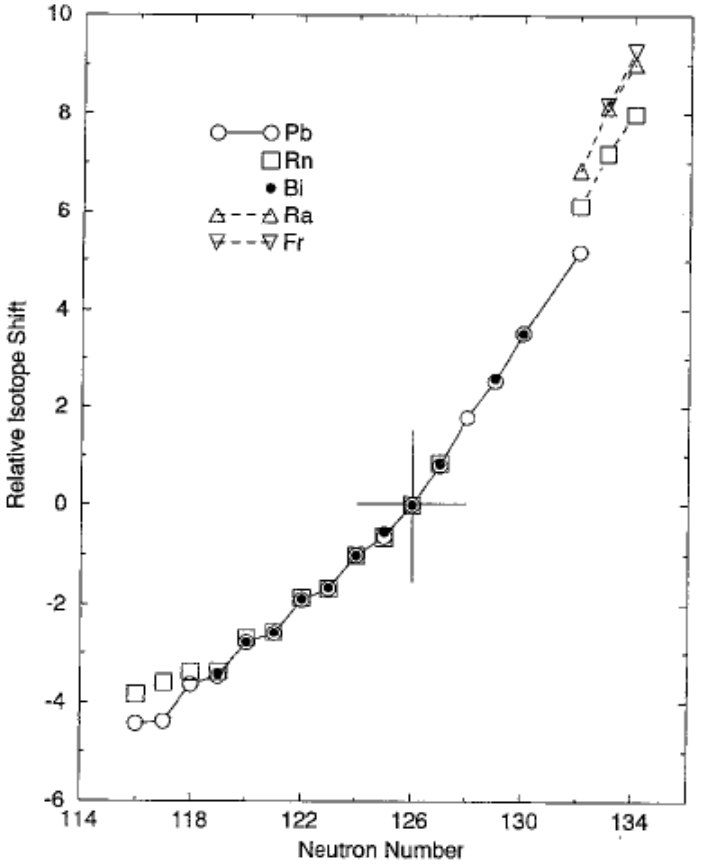


Fig. 3. Comparison of the Pb, Bi, Rn, Fr and Ra relative isotope shifts with each chain normalized to IS($N = 124, N' = 126$) = 1.

N>126 not as regular; deformation

Kilgallon PLB 405 31 →

We gain a lot of new physics leverage from N>126; can we get direct info for these extra n's?

Hyperfine anomaly

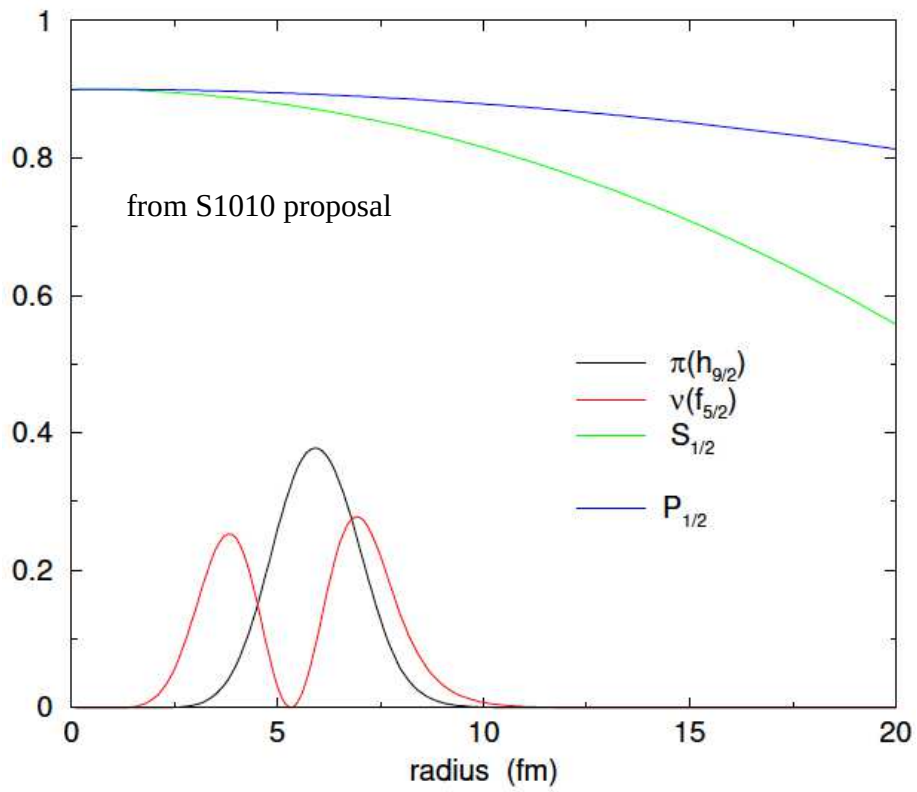
Measure μ=gI, compare to atomic hyperfine A_s

$$H = A\vec{I}\cdot\vec{J} = \int \mu(\vec{r})\cdot B(\vec{r})d^3r$$

Atomic s wavefunction varies over nucleus, so A_s/g can change if nuclear radius changes

Bohr and Weisskopf interpreted this as $\langle r^2_{magnetism}\rangle$

Reviews: Büttgenbach, Persson

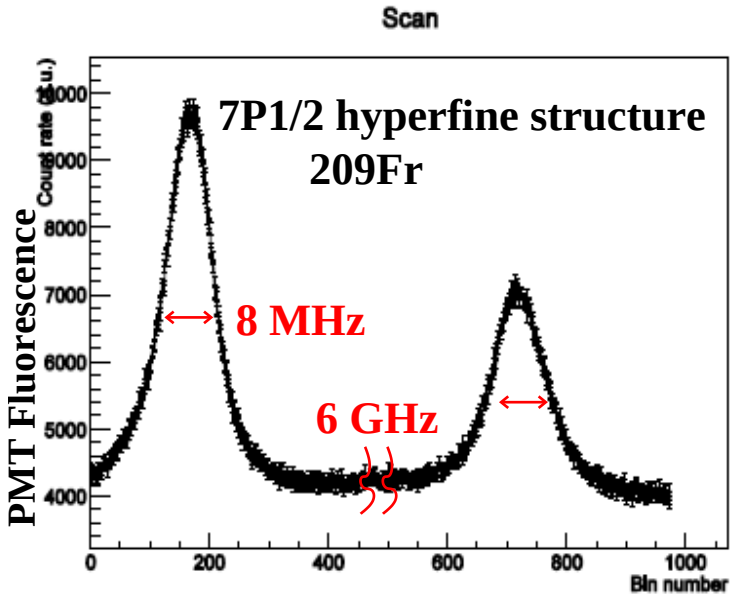


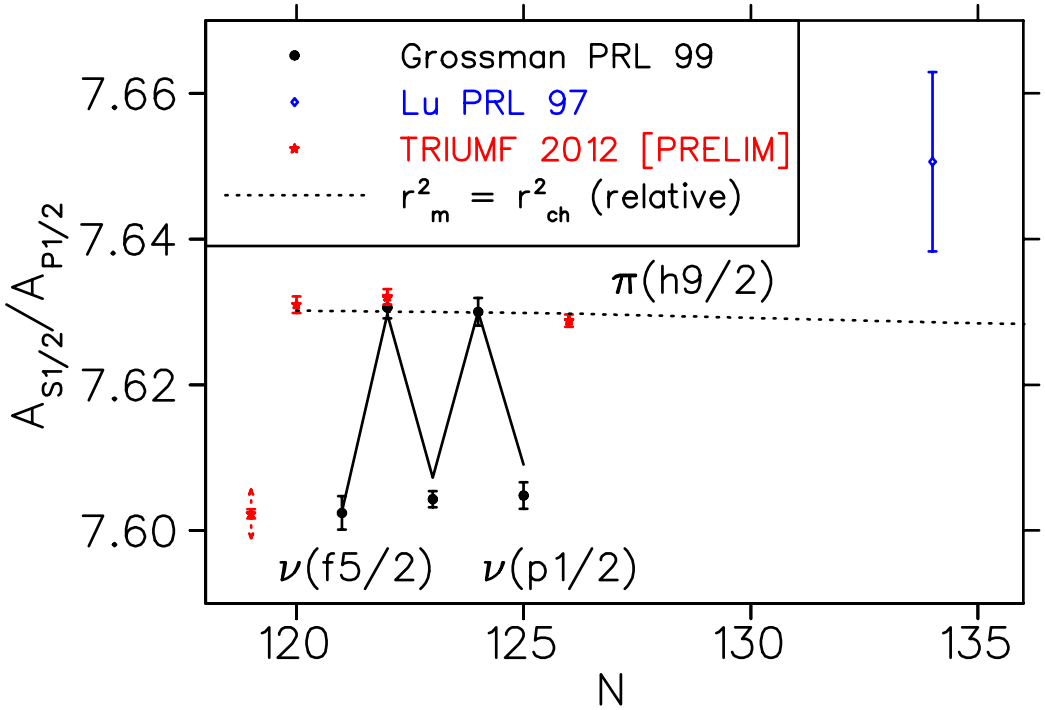
- Stony Brook version: ratio A_s/A_p, as the latter changes less over the nucleus. (Could combine with point μ)

Similar integral of nucleus over s1/2, p1/2 wavefunctions needed by atomic $\not{P}$, but for valence nucleon only

Hyperfine anomaly in Francium

Assuming we are given R_n for N=126





For N>126, experimental μ, Q modelled in Ekstrom Robertsson Rosen Phys Scripta 1984

$^{223-225}$Fr by simple Nilsson orbital configurations

$^{220-222}$Fr situation is more complex.

Would HFA provide more direct info on $\langle r_n^2 \rangle$ that we need?

Neutron Radii and Atomic Parity Violation in Francium

What do we need to extract non Standard-Model physics?
$R_{ns}[^{208}Pb]$ to 0.05 fm and some other observable for $N \neq 126$

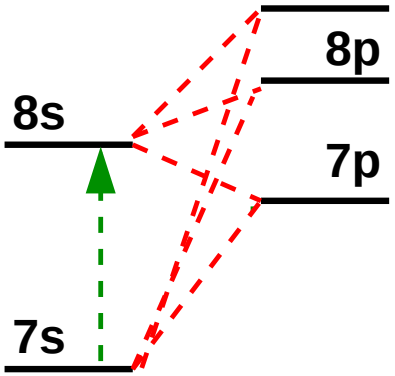
Could we assume S.M. and measure neutron radii?
σ=0.001 Fr $\not{P} \sim$ 0.05 fm Rns
but that needs theory to 0.001
σ=0.0013 Δ Fr $\not{P} \sim$ 0.05 fm Δ Rns
Fr,Ra^+ would be similar; Yb also likely to be sensitive

- **Other experiments like hyperfine anomally should eventually be needed to help with deformed n-rich Fr**
We are curious about Fr inverse kinematics reactions

Stark - Weak interference: flip E field

Emulating Boulder Cs scheme:

$|A_{7s\to 8s}|^2 = |E1_{\mathrm{Stark}} + E1_{\mathrm{PNC}} + M1|^2$



- **Minimize the M1 by light polarization, standing wave (note $M1 \approx 10^{+4} E1_{\mathrm{PNC}}$) $\rightarrow$**

$|A_{7s\to 8s}|^2 \approx |E1_{\mathrm{stark}}|^2 + 2E1_{\mathrm{Stark}} E1_{\mathrm{PNC}}$

The interference term is $\sim 10^{-9}$ of an allowed E1 transition amplitude (rather than 10^{-18}).

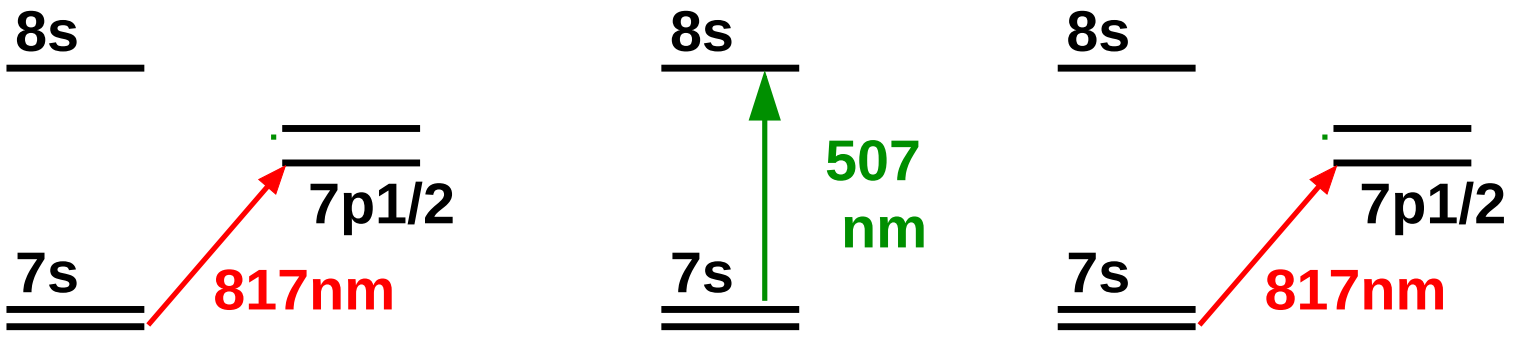
- $E1_{\mathrm{stark}}(F, m \rightarrow F', m') =$

$\alpha \vec{E} \cdot \vec{\epsilon}\, \delta_{F,F'} \delta_{m,m'} + i\beta(\vec{E} \times \vec{\epsilon}) \cdot \langle F'm' | \vec{\sigma} | Fm \rangle$

flipping $\vec{E}$ changes the rate, with an asymmetry linear in $E1_{\mathrm{PNC}}$. You are free to choose $|\vec{E}|$.

- **Then calculate (or, preferably, measure) $E1_{\mathrm{Stark}}$ to extract $E1_{\mathrm{PNC}}$**

scheme for A_{weak} in Fr

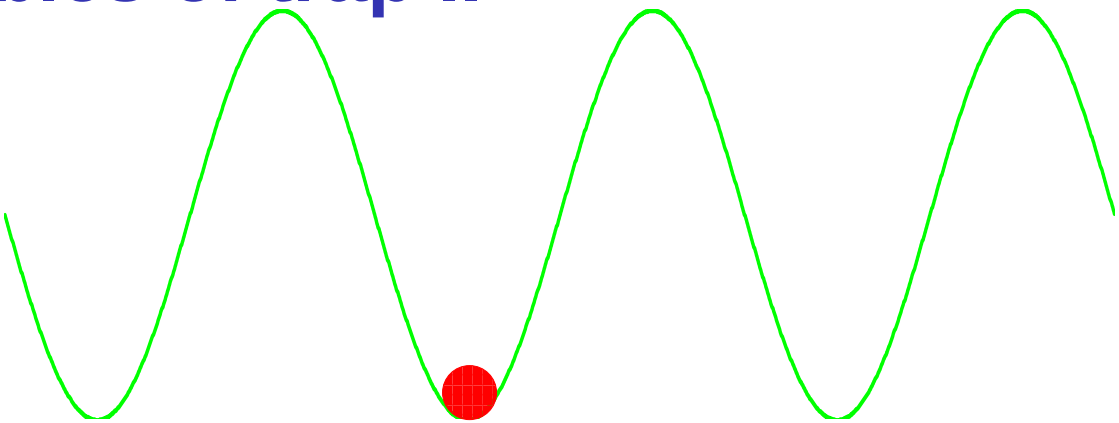


- depopulate one hyperfine ground state by optical hyperfine pumping
- Drive 7S to 8S transition, with $\vec{E}$=250 V/cm
- Measure remaining population by resonant fluorescence– so you get good statistics on each atom

Boulder did this in an atomic beam, with spatially separated regions

Using laser-cooled atoms in a MOT, we will separate these steps in time

foibles of trap II



The 507 nm light power buildup cavity makes an 'optical lattice': cold atoms will try to go to minimum of blue-detuned standing wave. Possible solutions:

- **add sideband to light 1 FSR away**
- **~~use a travelling wave~~ on-resonance standing wave is needed to kill M1**
- **the lower power to avoid photoionization will help with this as well.**

(Wieman and Vieira pointed out this feature in a Los Alamos 1992 proposal. Their suggested solution was to heat the atoms.)

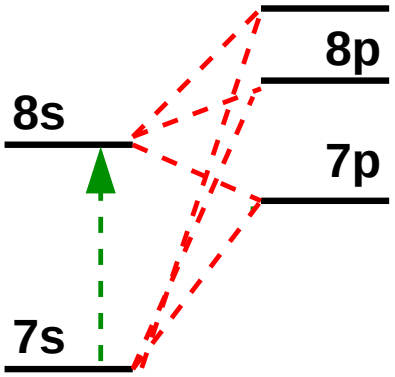
First measure the M1 strength

$|A_{7s\to 8s}|^2 = |E1_{\mathrm{Stark}} + M1|^2 \approx$
$|E1_{\mathrm{Stark}}|^2 + 2E1_{\mathrm{Stark}}M1$

$\vec{E} \approx$ 20 V/cm makes $E1_{\mathrm{Stark}} > M1$

B$\sim$10 G to split m levels

$\eta = 2\frac{|E1+M1|^2-|E1-M1|^2}{|E1+M1|^2+|E1-M1|^2} = 0.21$



ns $\rightarrow$ (n+1)s is forbidden non-relativistically.

Some relativistic corrections are more interesting than others.

Can separate $M1_{\mathrm{hyperfine}}$ from $M1_{\mathrm{relativistic}}$ by dependence on hyperfine levels

Savukov et al. PRL 83 2914 (1999)

TABLE I. Contributions to reduced matrix elements of the M_1 operator in atomic units multiplied by a factor of 10^5. Row 1, lowest-order DHF value; row 2, second-order no-pair contribution; row 3, negative-energy state contributions in second order; row 4, total value of M_1 matrix element.

Z	Li 3	Na 11	K 19	Rb 37	Cs 55	Fr 87
I	0.91	1.16	1.15	1.38	1.51	2.09
II, no-pair	0.12	0.03	−0.08	−1.86	−10.69	−116
II, NES	0.02	0.13	0.20	0.31	0.40	0.64
Total	1.05	1.06	1.27	−0.17	−8.78	−113

Rb has highest % contribution of 'negative energy states'; pursued at U. Manitoba (and USAFA)

Heavy-ion reactions

Fr reactions are possible in inverse kinematics (RexISOLDE, TRIUMF?, ...)
see this workshop
the example I was considering doesn't work
Our favorite was to plan 221Fr(d,p) isobaric analog resonance (Nolen Schiffer Williams PL 27B 1 1968) not noticing that the answer comes in low for ^{208}Pb
Anti-analog GDR Krasznahorkay Paar Vretenar Harakeh PLB 720 428 (2013)
Pygmy giant resonance: this workshop

Chain of isotopes and n radii

From a theory error on global parameter on $\bar{p}$ only
Can local info help?

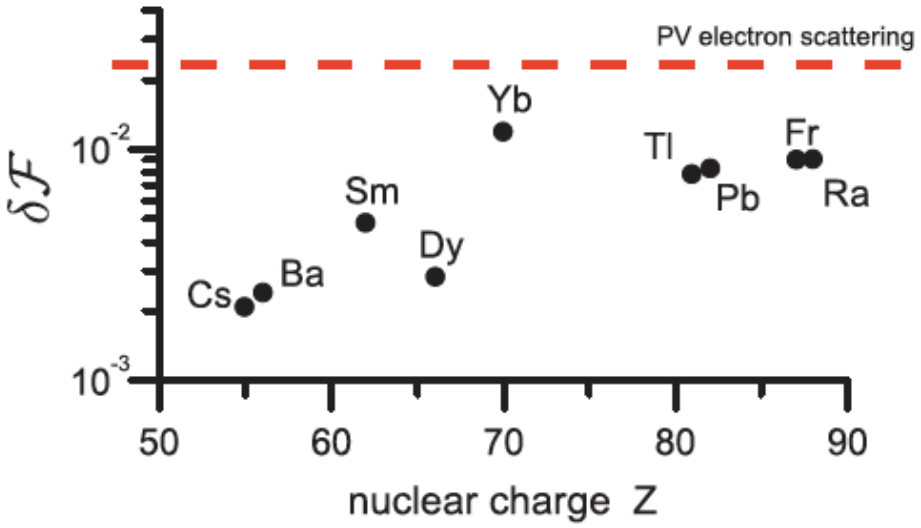


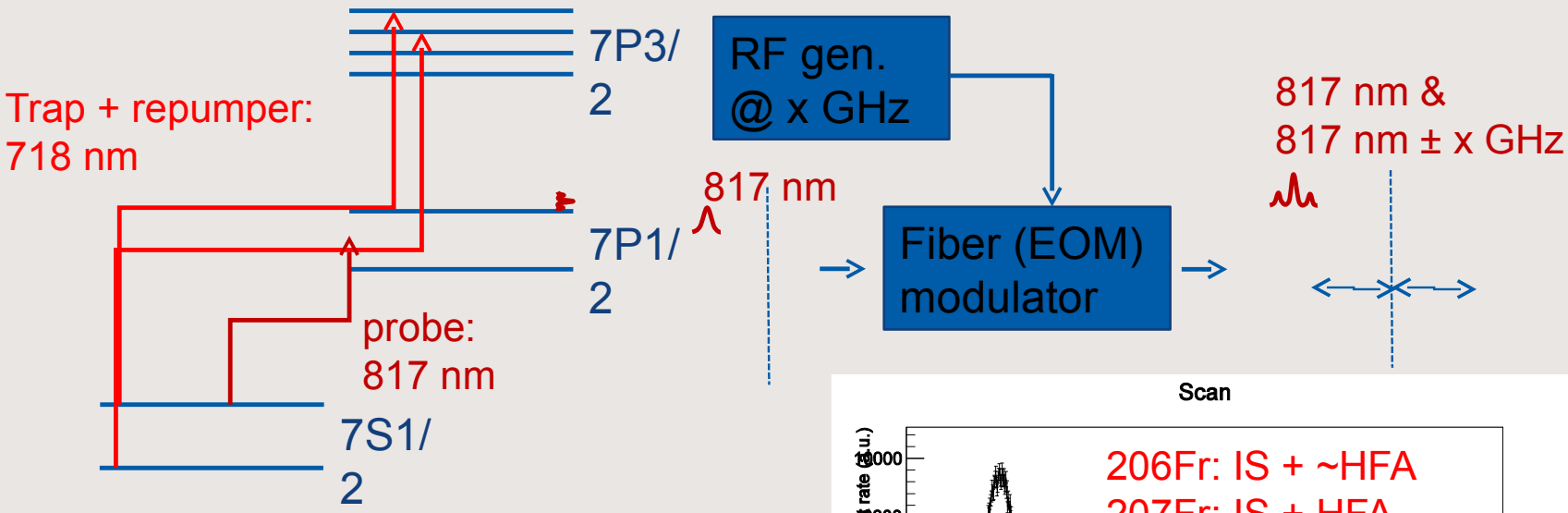
FIG. 2. (Color online) The neutron-skin-induced uncertainties, $\delta\mathcal{F}$, for isotopic chains compared with the constraints from parity-violating electron scattering, $\mathcal{F}$.

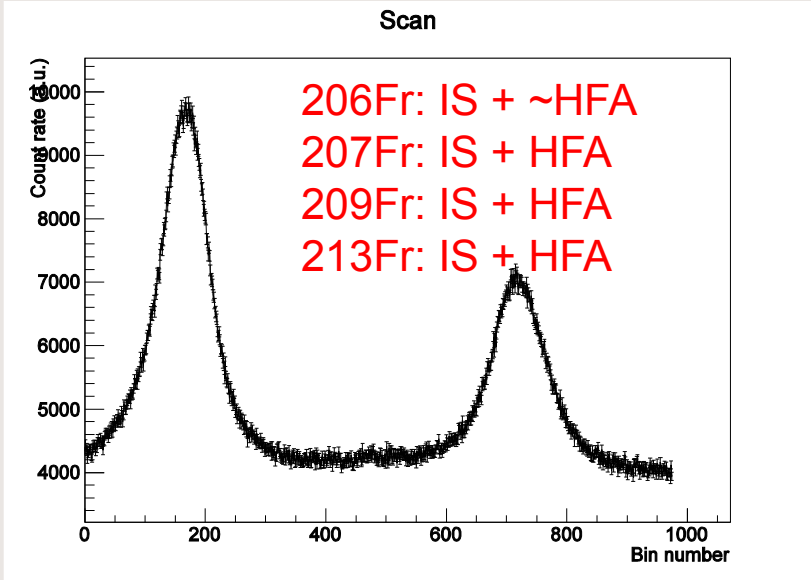
Brown Derevianko Flambaum PRC 79 035501 (2009)
Using Rn[^{208}Pb]=0.20±0.05 from $\bar{p}$ atoms
Errors from a chain, removing correlations

Spherical Skyrme H-F calculation: N>126 needs deformation
Yb has wide range of stable isotopes

TRIUMF

Bohr-Weisskopf effect and Isotope shift (Nov 2012)





Isotope shift:

206Fr

209Fr

Keep carrier locked to ref. cavity

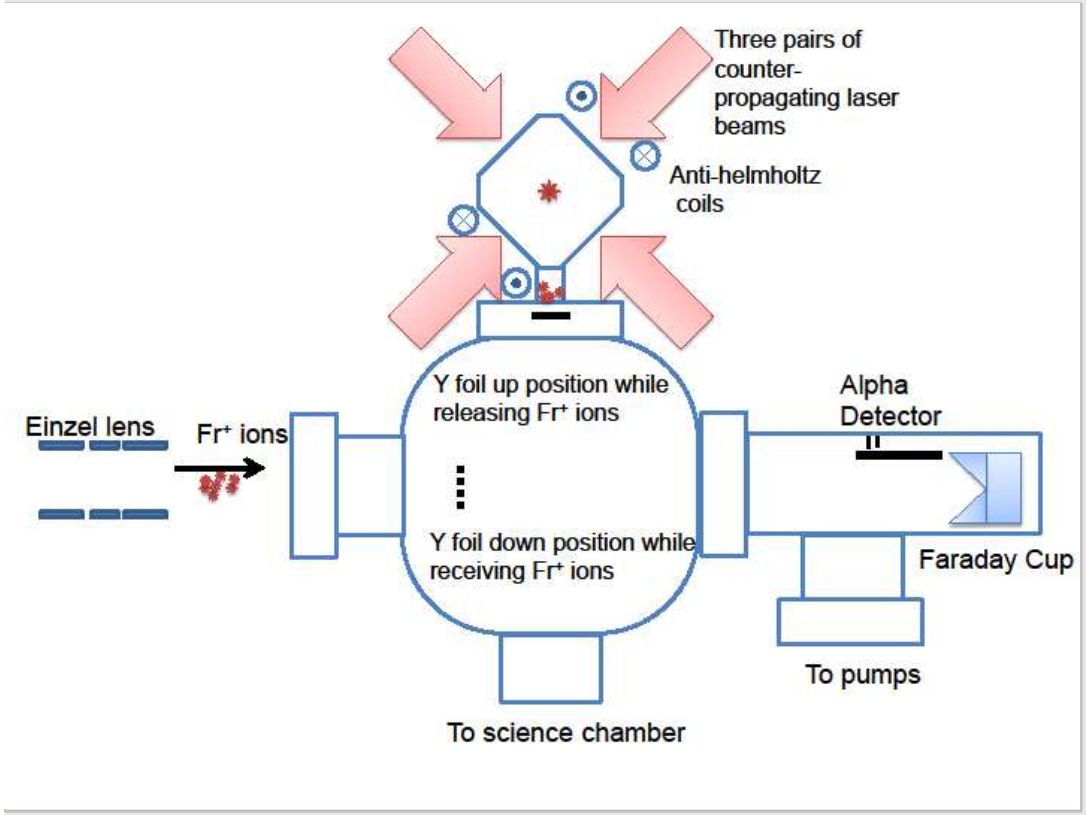
November 15, 2012 Francium PNC experiment

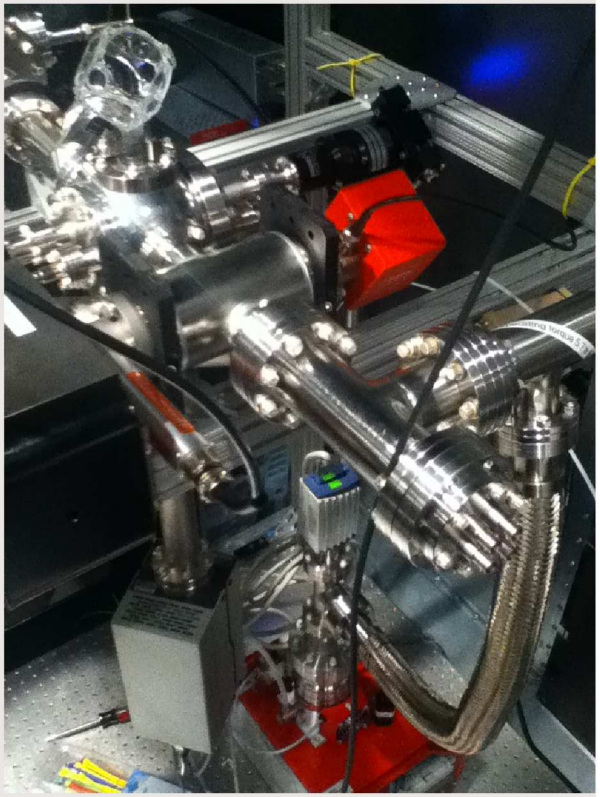
TRIUMF

TRIUMF

Set-up

Francium produced at ISAC (TRIUMF) by 500 MeV protons (10 μA) on a UCx target





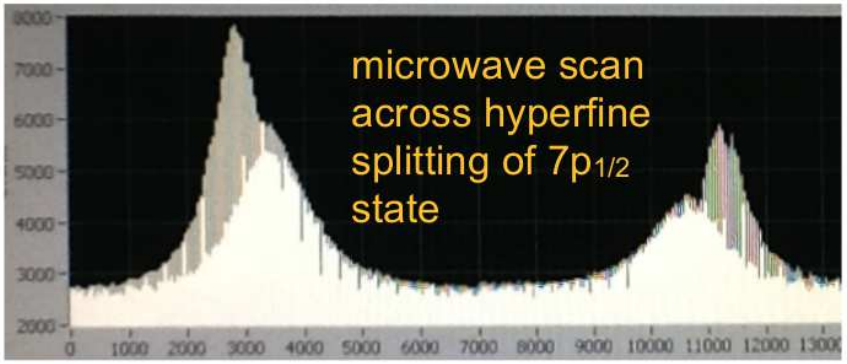
Fr Physics at ISAC

Francium
[Rn] $7s^1$

FrPNC collaboration:
TRIUMF - Maryland - Manitoba
San Luis Potosi - William & Mary
Shanxi - Stony Brook - New South Wales

Sep 2012: Commissioning run

- Fr laser trapping demonstrated
  - isotopes 209, 207*, 221



Nov 2012: First physics run

- Hyperfine anomalies and isotope shifts in isotopes 209, 207, 213*, 206*
- Demonstration of impressive sensitivity: hyperfine splitting in 213 and isotope shift to 209 measured in less than 1 hour!

* not prev. trapped

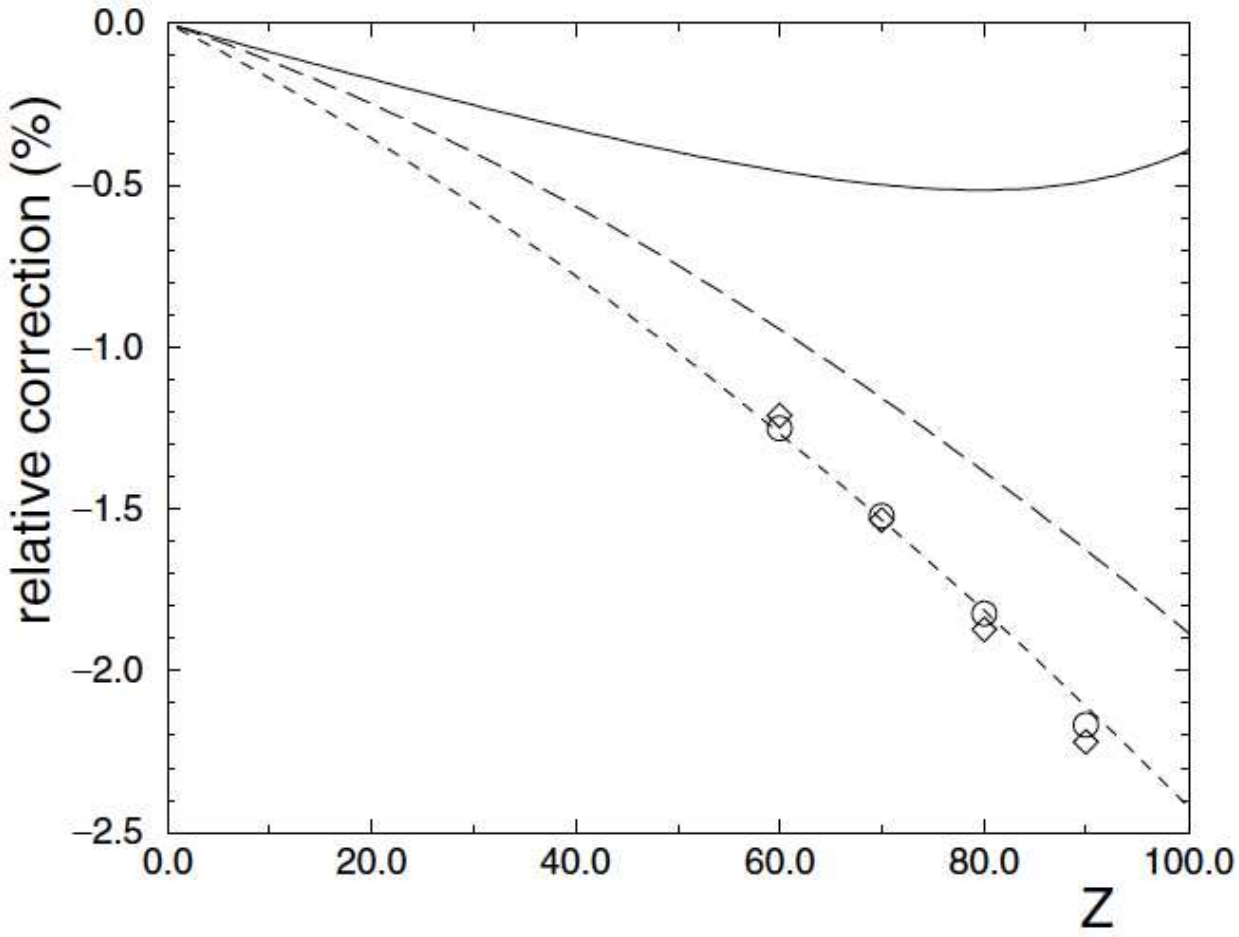
Long term goal: parity non-conservation measurements

- nuclear spin dependent → anapole moment
- nuclear spin independent → Standard model test

electromagnetically shielded Fr room

Radiative corrections

Since Cs $\not{P}$ is still moving from higher-order corrections, there is value in a result in a higher-Z system to test these



Milstein Sushkov Terekhov PRL 89 283003 2002 Radiative corrections as a function of Z