Nuclear structure and the anapole moment in francium; experiments and proposals .

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Work done in collaboration with Prof. Gene Sprouse from SUNYSB
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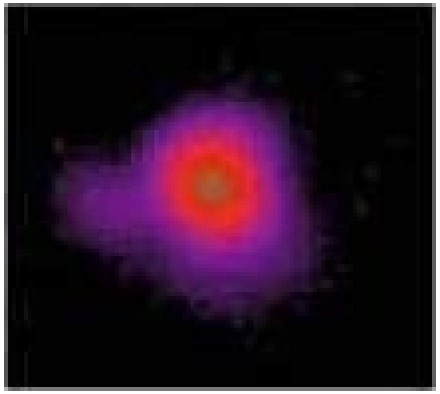
Supported by NSF

	IA	IIA	IIIB	IVB	VB	VIB	VIIB	VII			IB	IB	IIIA	IVA	VA	VIA	VIIA	0
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											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	57 *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	89 +Ac	104 Rf	105 Ha	106 106	107 107	108 108	109 109	110 110	111 111	112 112						

Naming conventions of new elements

* Lanthanide 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
+ Actinide Series	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



2,000 atom Fr MOT

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

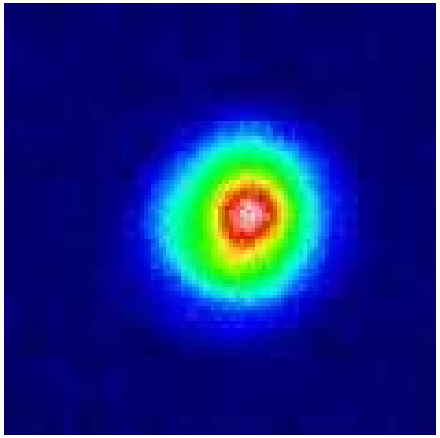
1995: Produced and Trapped Francium in a MOT.

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

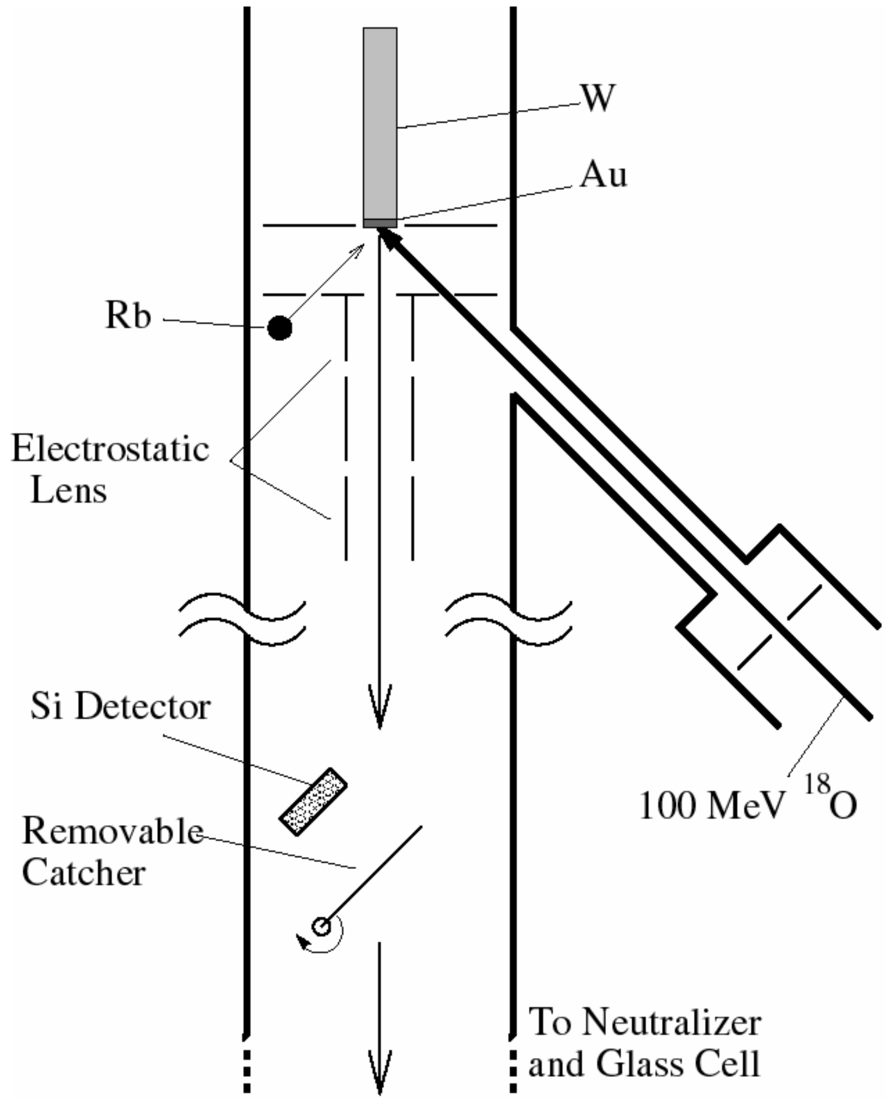
2000-2002: High efficiency trap.

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

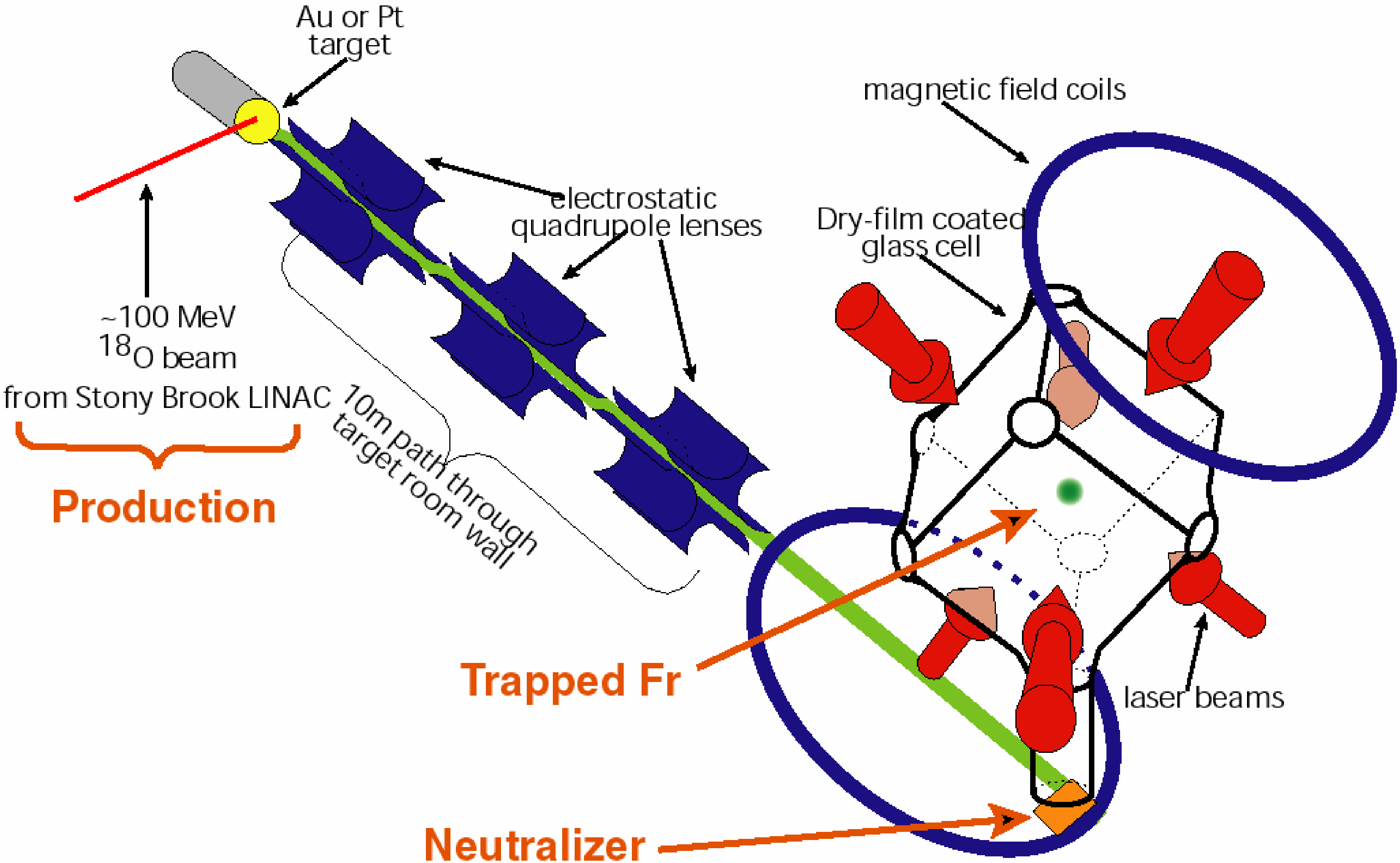
2004: Study of 8s levels (polarizablitiy).



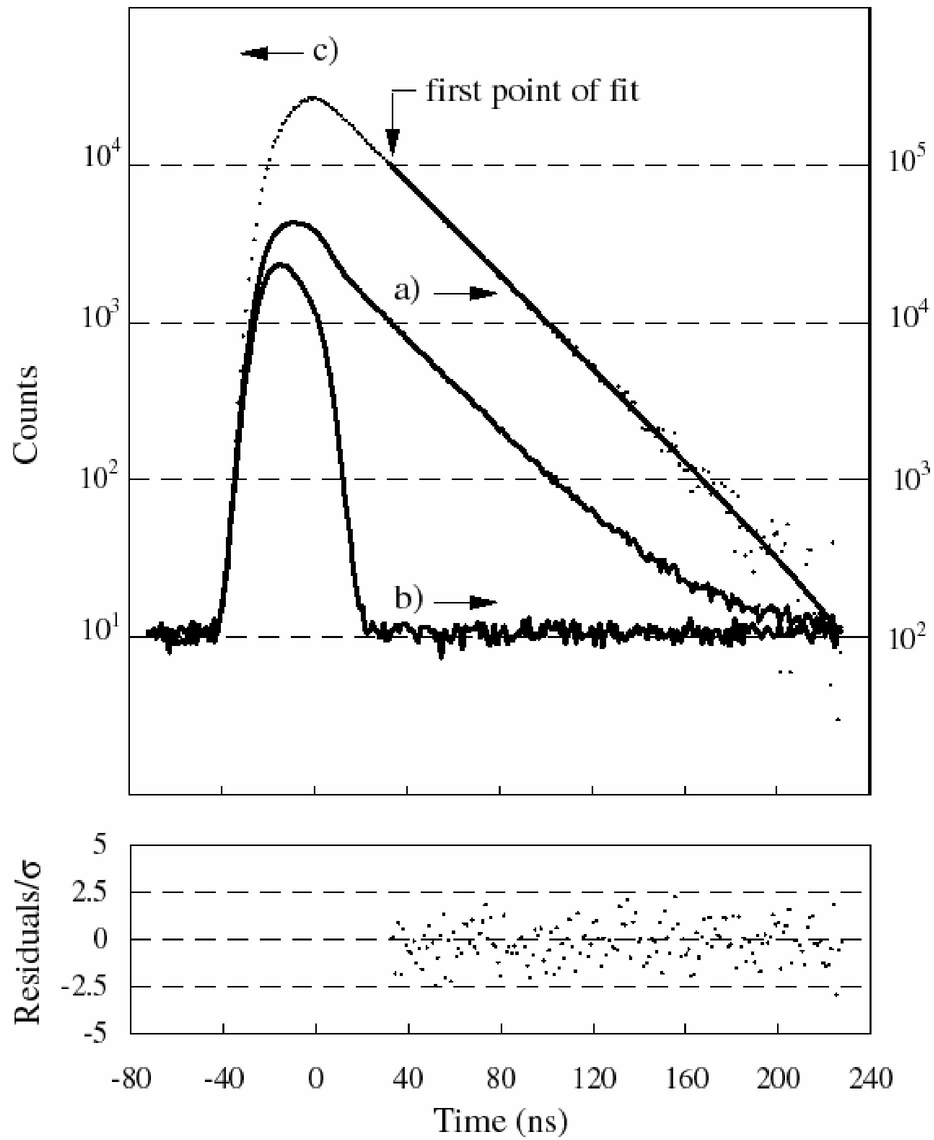
250,000 atom Fr MOT


W
Au
Rb
Electrostatic
Lens
Si Detector
Removable
Catcher
100 MeV ^{18}O
To Neutralizer
and Glass Cell

Apparatus for Production and Trapping of Francium



$7P_{1/2}$ lifetime of Fr



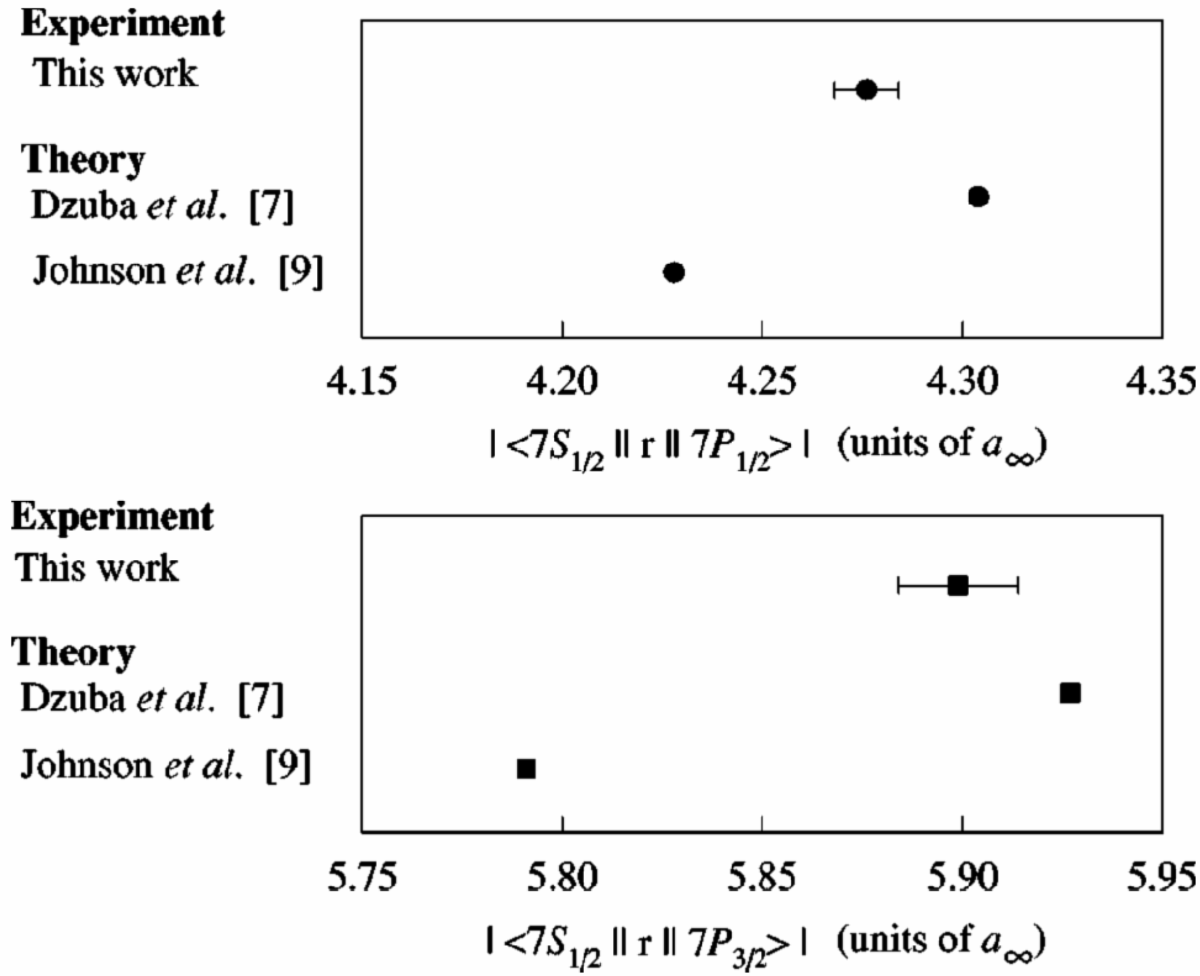
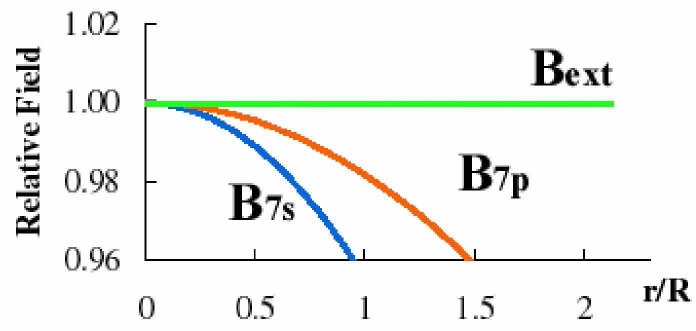
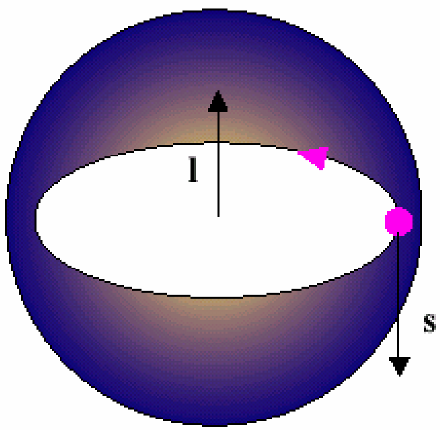
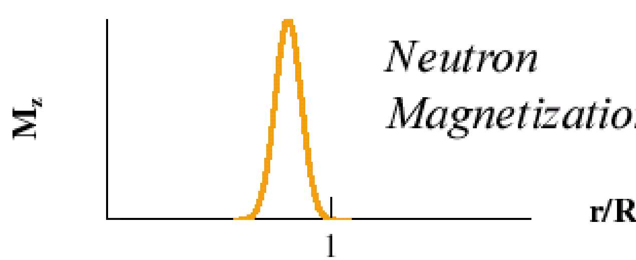


FIG. 8. Comparison of the absolute values of the $7S_{1/2} \rightarrow 7P_{1/2,3/2}$ transition radial matrix element with *ab initio* calculations from Refs. [7,9].

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







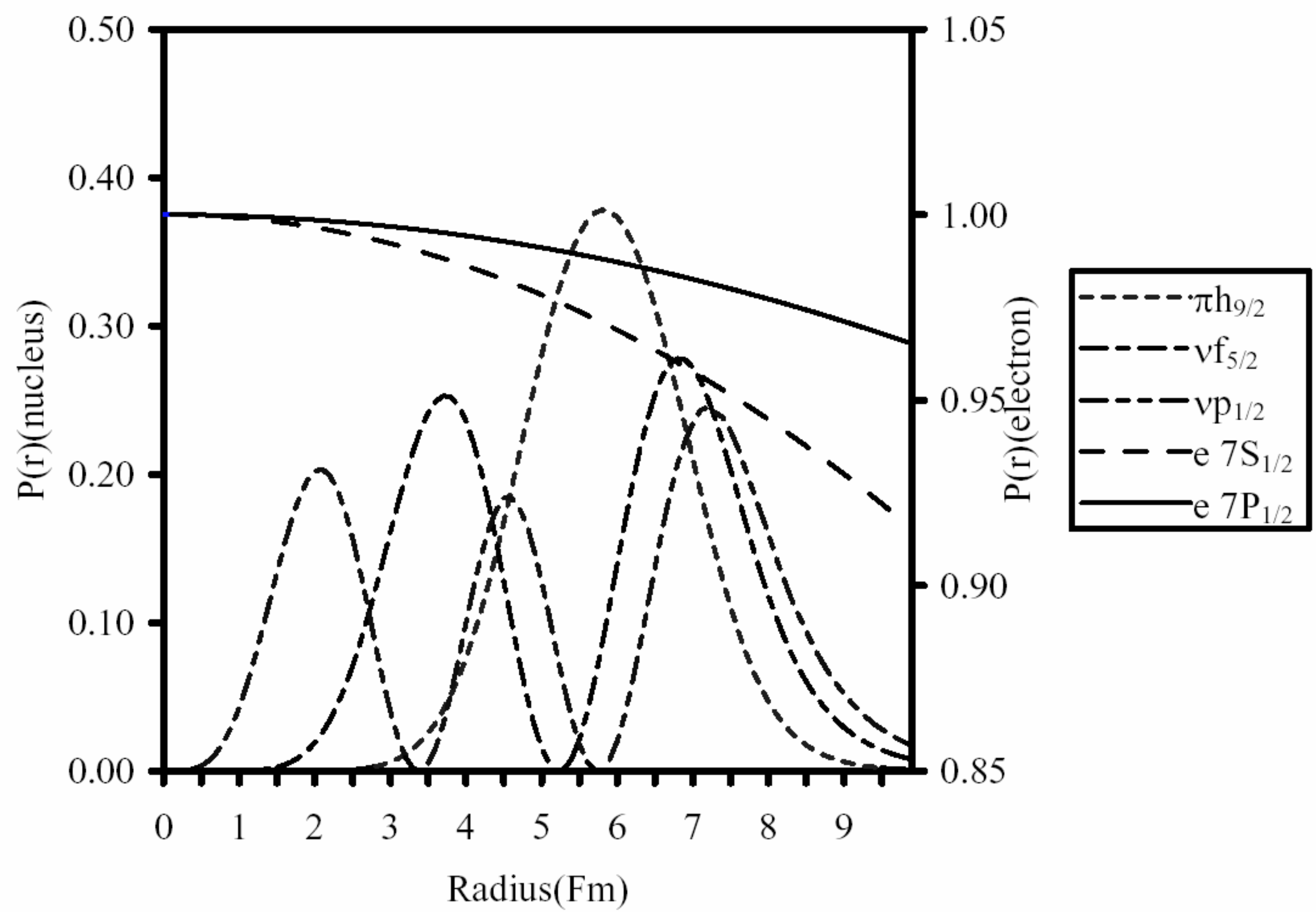
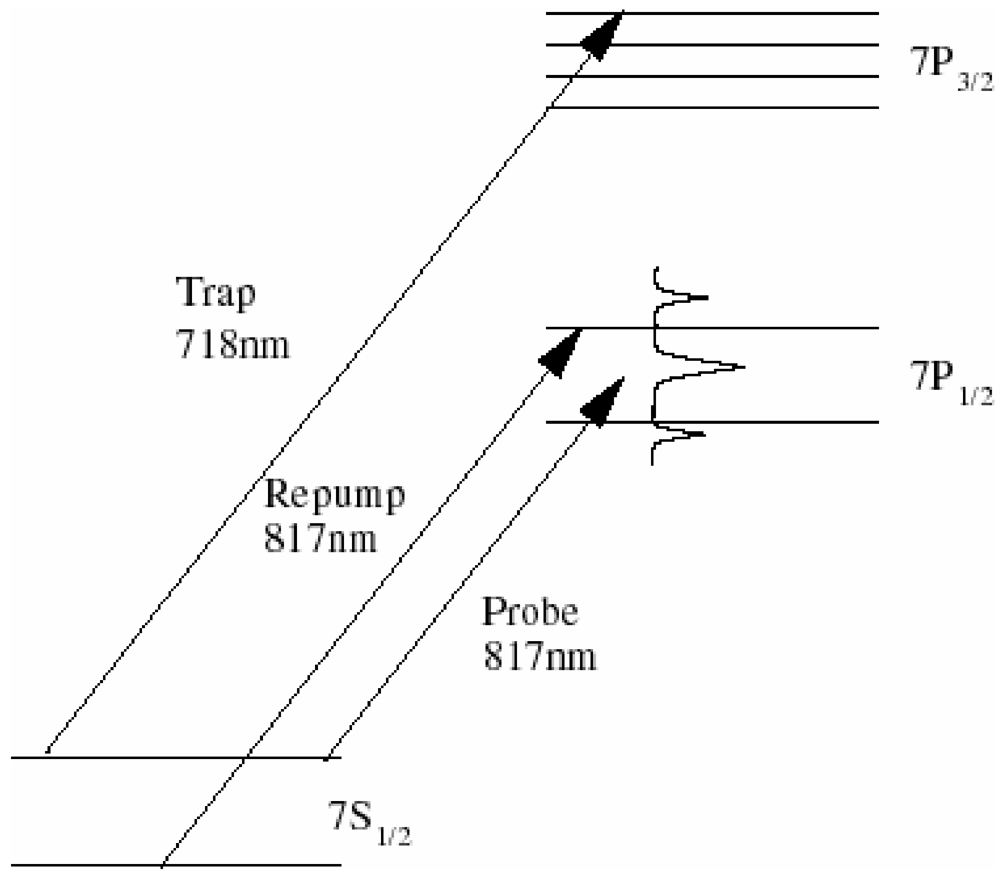
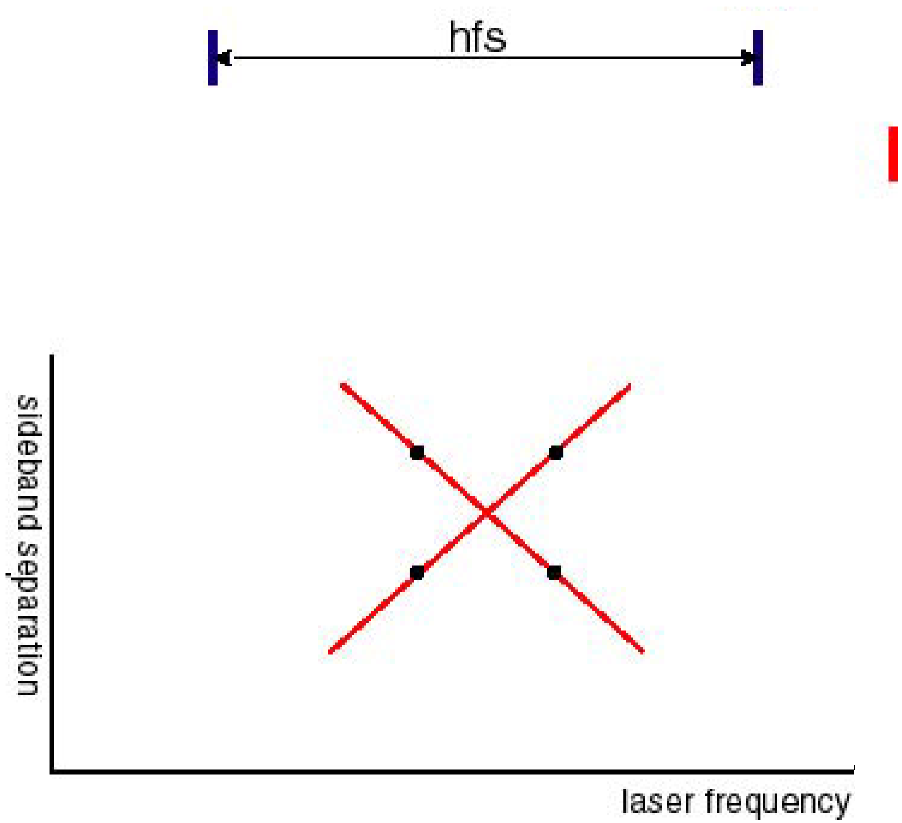
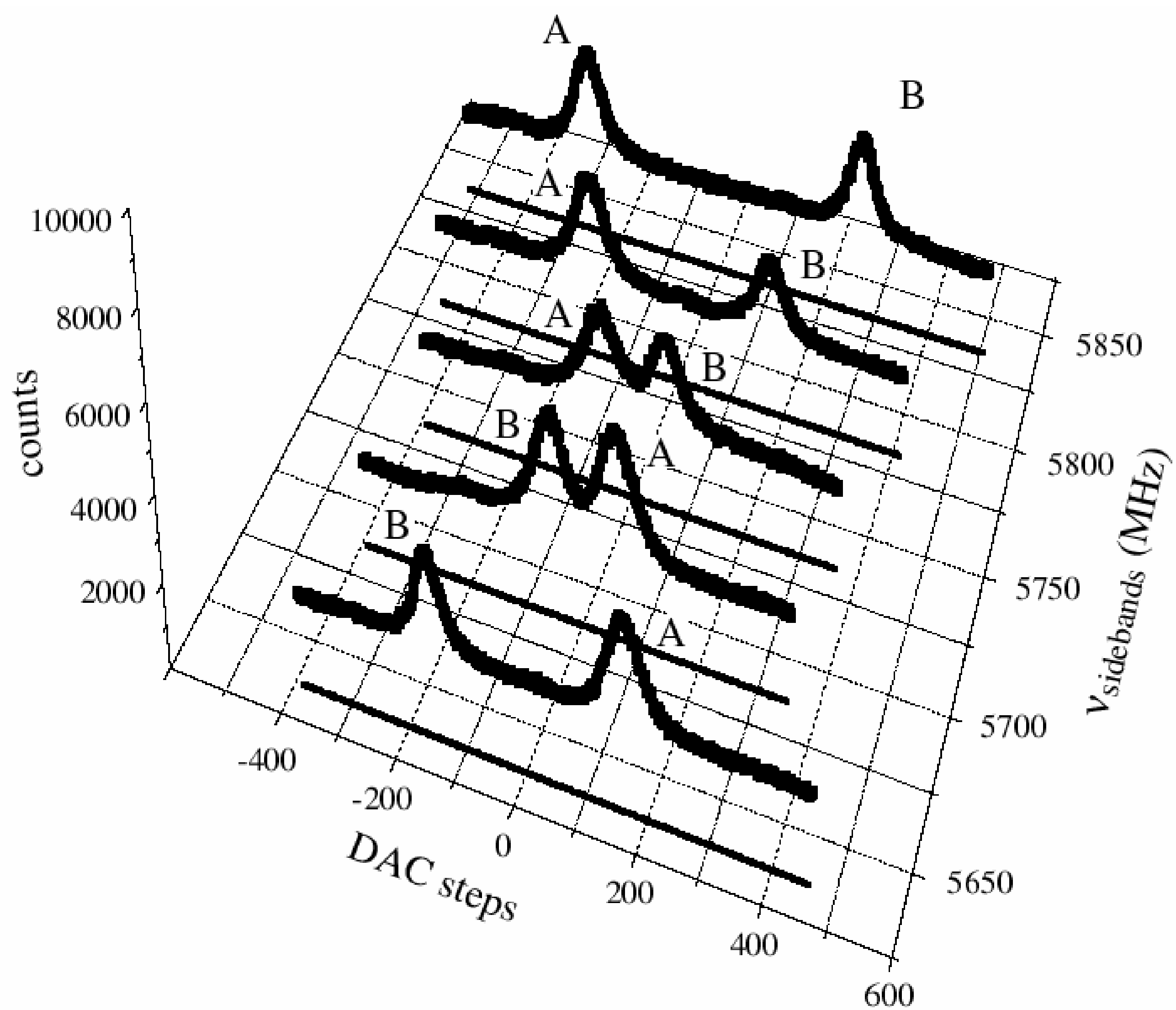


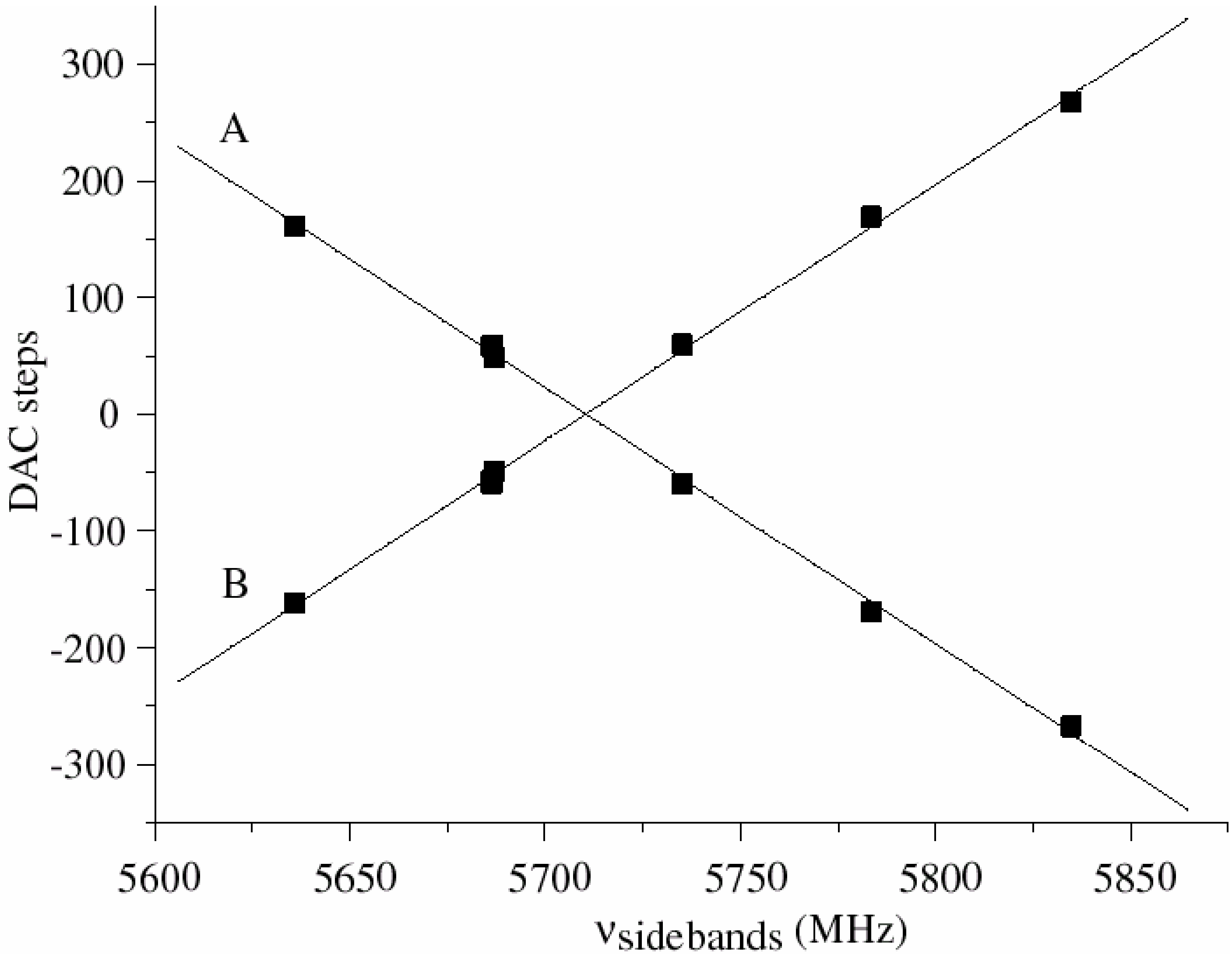
Figure 3.12: Model wavefunctions in the nucleus of neutrons, the last unpaired proton, and $S_{1/2}$ and $P_{1/2}$ electrons. The nucleon probability densities should be read from the left axis and the electron probability densities should be read from the right axis. The electron probability densities have been normalized to be 1 at $r = 0$.


7P3/2
Trap
718nm
7P1/2
Repump
817nm
Probe
817nm
7S1/2


hfs
sideband separation
laser frequency

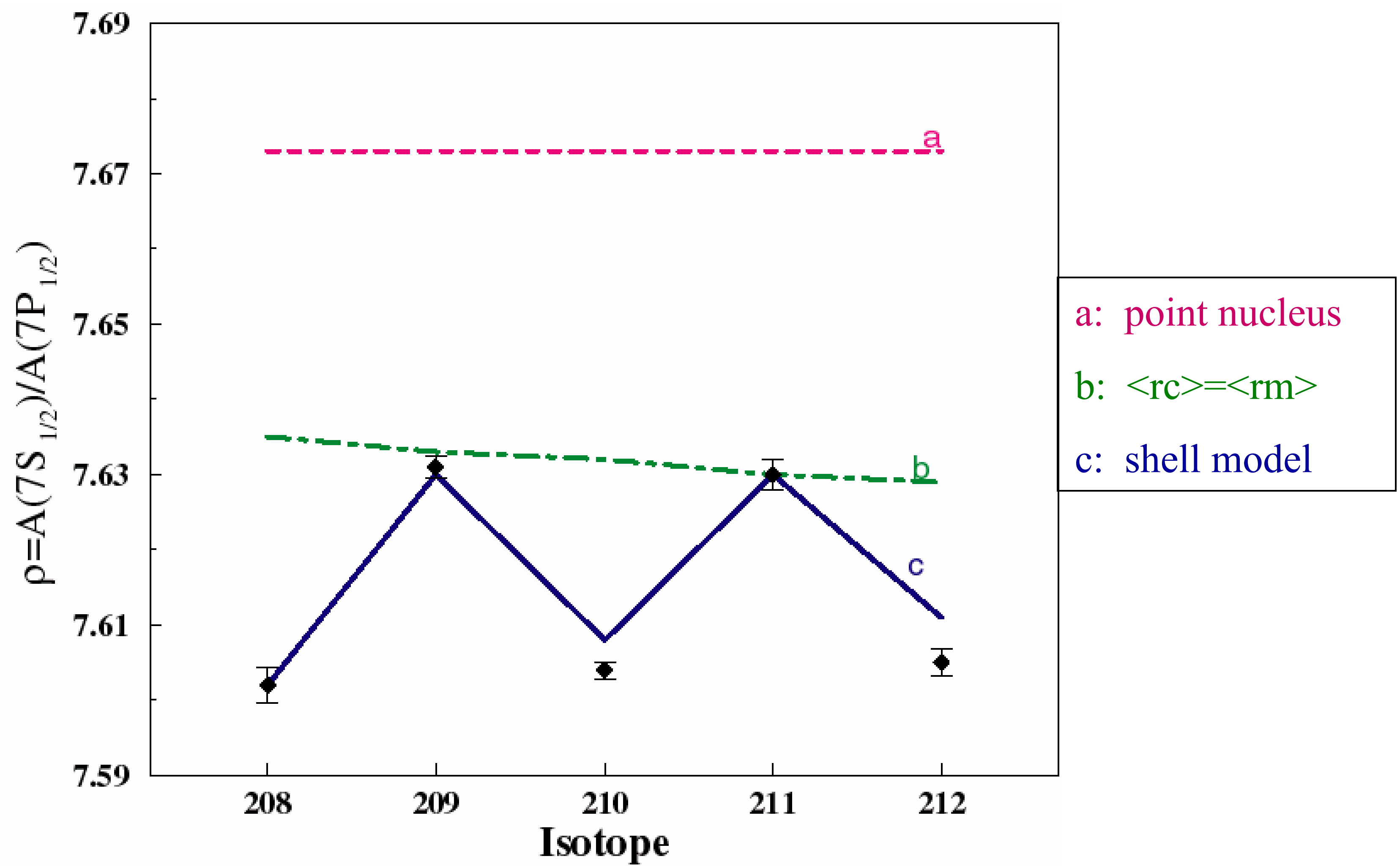
Fluorescence from the two $7P_{1/2}$ hyperfine states excited with FM sidebands





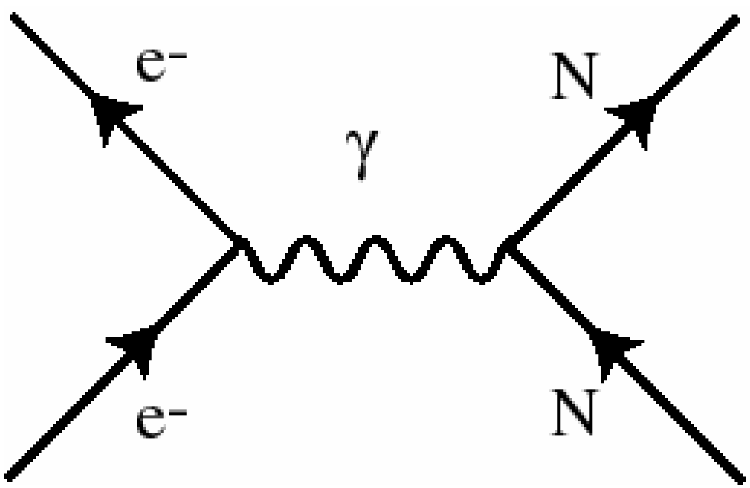
300
200
100
0
-100
-200
-300
DAC steps
A
B
5600
5650
5700
5750
5800
5850
νsidebands (MHz)

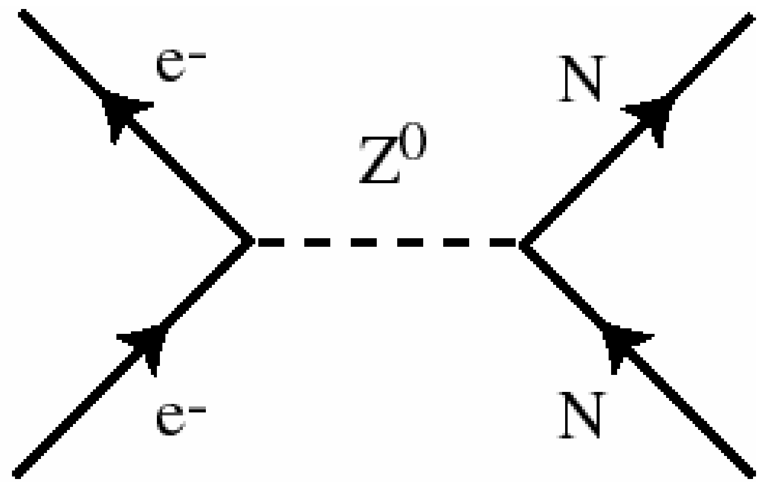
Hyperfine Anomaly



"In the Glashow Weinberg Salam theory of the electroweak interaction, for each channel there is always a Z channel accompanying it. At low energy, the Z channel is suppressed by a factor of $Q^2/M^2(Z)$ where Q is the momentum transferred and M(Z) is the mass of the Z particle. Nevertheless, this tiny effect can be detected if it is enhanced by some mechanism."

Langacker





For a vector-axial vector type weak force, the Lagrangian for the parity violating quark-electron interaction in the low energy limit is:

$$\mathsf{L} = \frac{G_F}{\sqrt{2}} \sum_{i=u,d} \left[C_{1i} \bar{e} \gamma^{\mu} \gamma^{5} e \bar{q}_i \gamma_{\mu} q_i + C_{2i} \bar{e} \gamma^{\mu} e \bar{q}_i \gamma_{\mu} \gamma^{5} q_i \right]$$

$A_e - V_N$ $\qquad$ $V_e - A_N$

$C_{1u,d}$ strength of the interaction of the electronic axial vector with the hadronic vector current. $C_{2u,d}$ has the hadronic axial vector with the electronic vector current. At tree-level the standard model predicts with [$x=\sin^2\theta_w(M_z)\approx 0.2323$]

$$C_{1u} = \frac{1}{2}\left(1 - \frac{8}{3}x\right)$$

$$C_{1d} = -\frac{1}{2}\left(1 - \frac{4}{3}x\right)$$

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

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 ($V_n A_e$).

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

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

$\kappa_2 \sim -0.05$

in ^{209}Fr, $\kappa_a / \kappa_{Q_W} \simeq 15$.

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

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

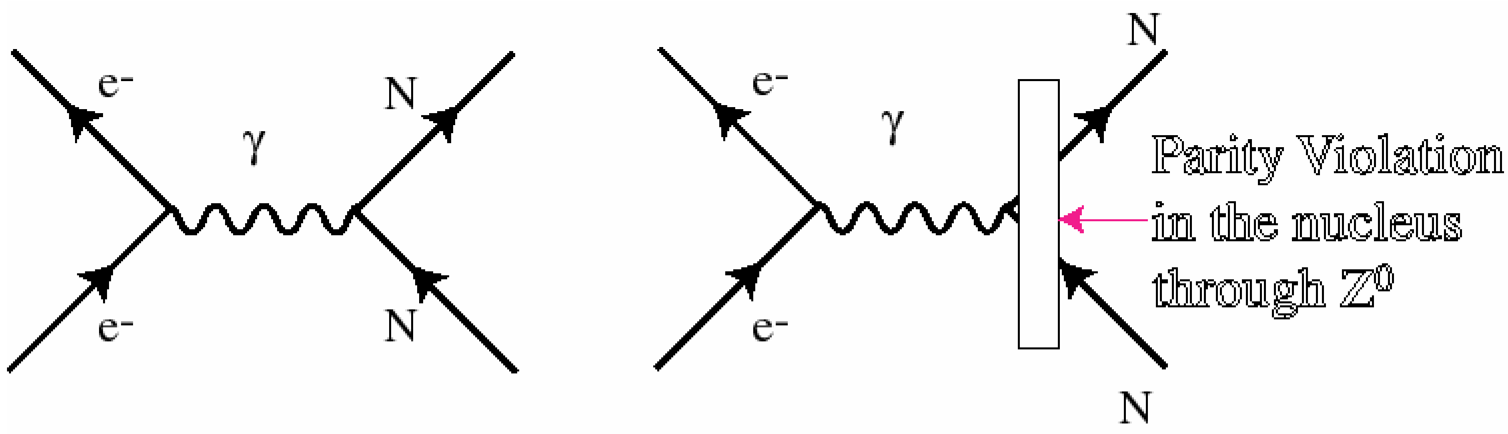
$$\kappa_{Q_W} = -\frac{1}{3} Q_W \frac{\alpha\mu_N}{m_p \tilde{r}_0 \mathcal{A}} \mathcal{A}^{2/3},$$

$$g_p \sim 4$$

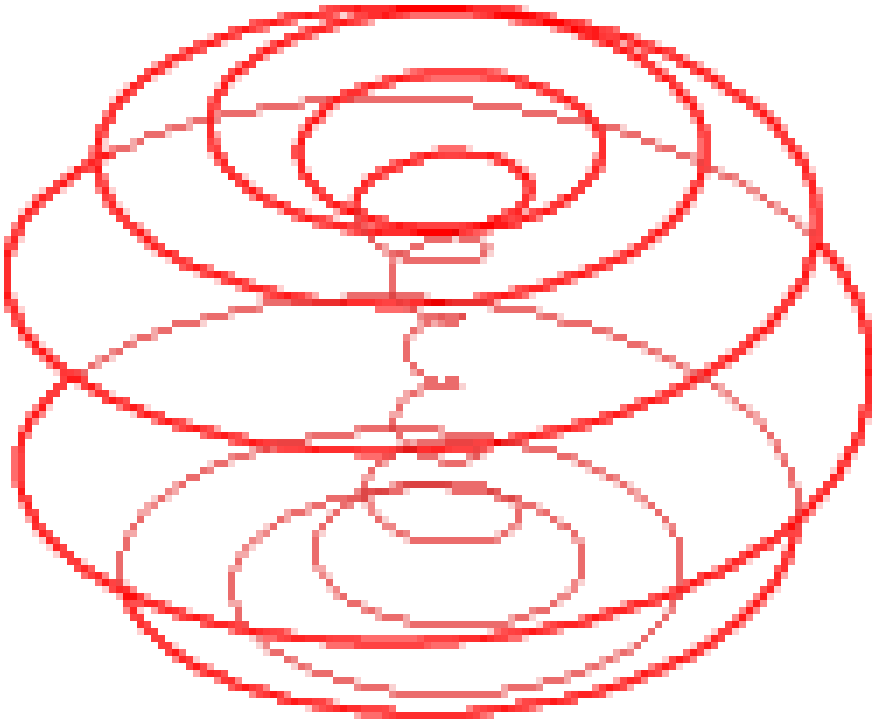
$0.2 < g_n < 1$ for neutrons

The Anapole Moment

1958 Zel'dovich, Vaks
1980 Khriplovich, Flambaum
1997 Boulder experiment



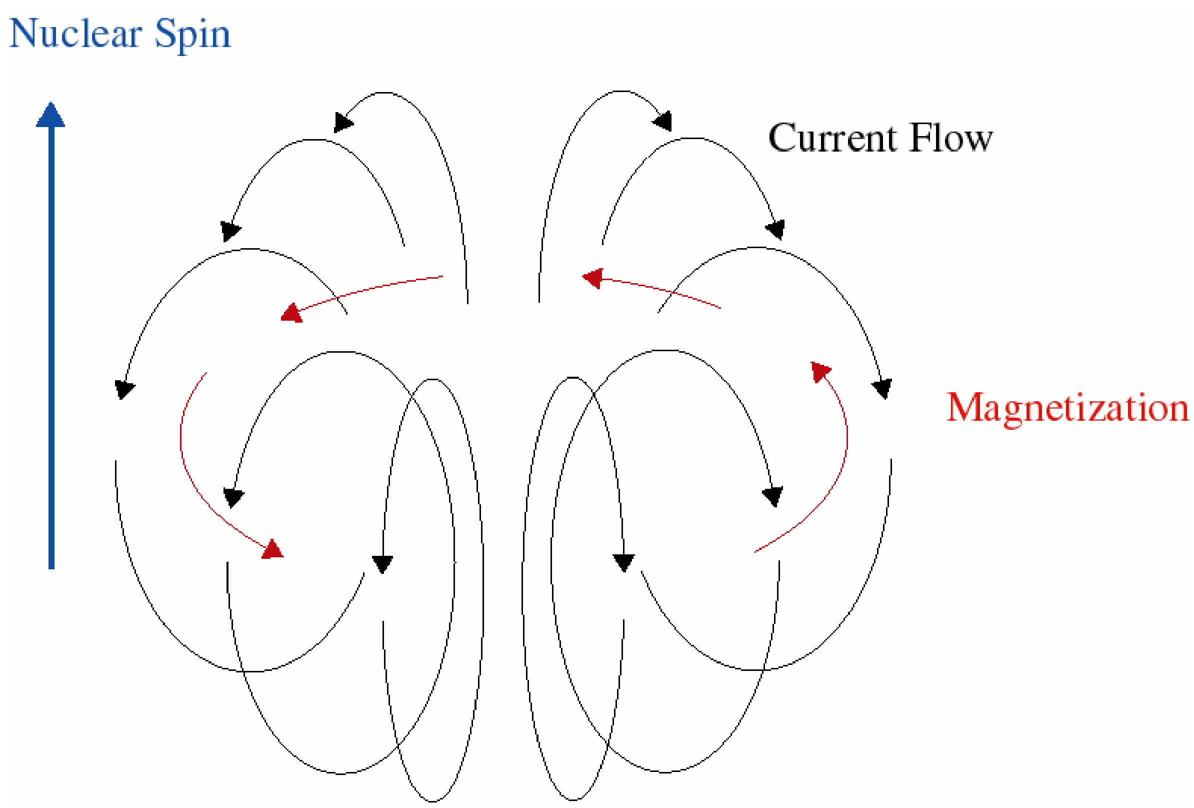
It can be thought as a "weak radiative correction". The nuclear wave function has parity violating components (V_e A_N). It has to be probed inside the nucleus by an electromagnetic interaction.

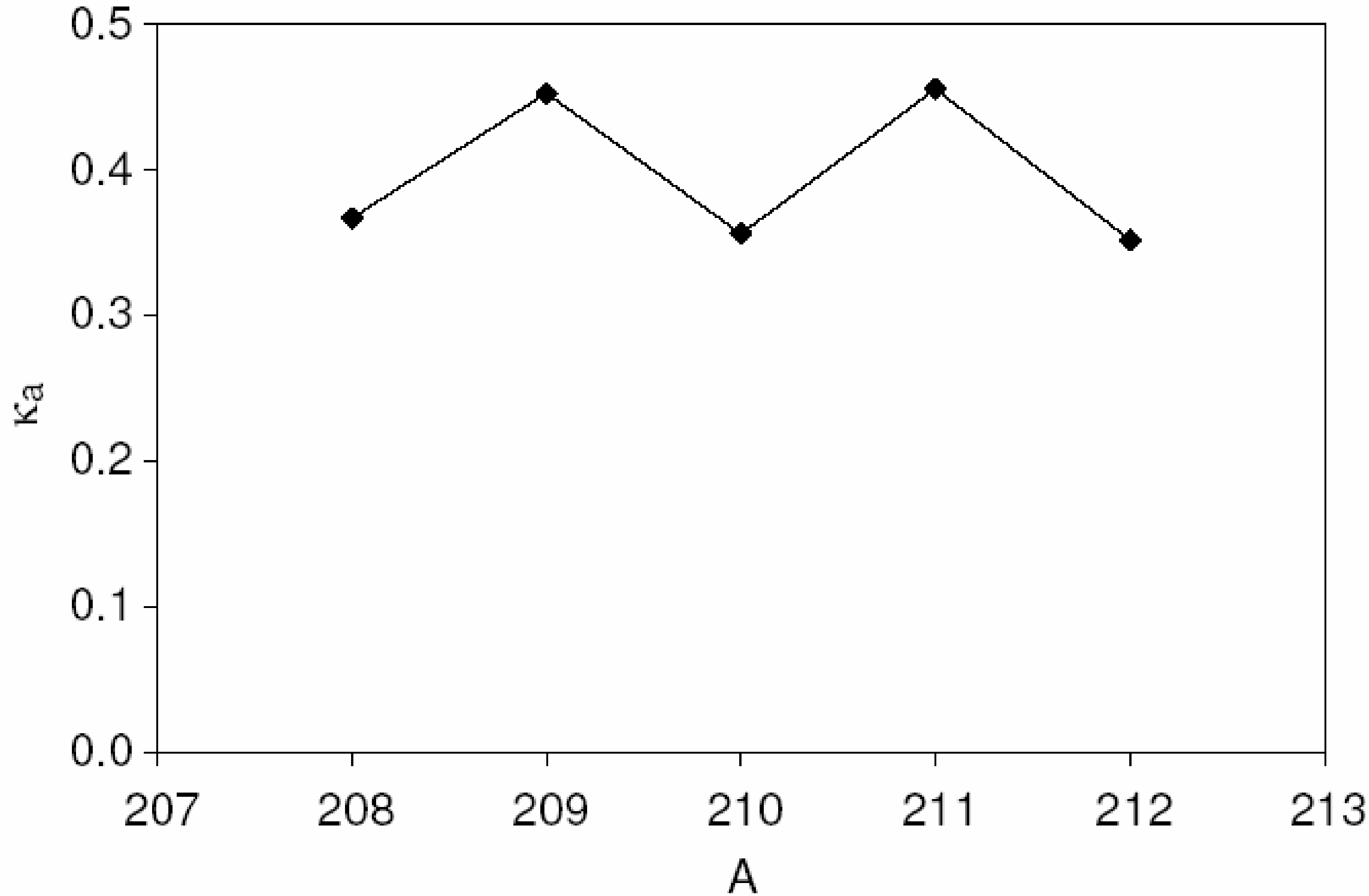


The chirality of an atom arising from the neutral current weak interaction between the electron and a nucleon can be shown by plotting the electron probability current density for a given atomic state, shown here for the $2p_{1/2}$ state in hydrogen. Under a parity transformation, or equivalently under mirror reversal, the helicity of the streamlines is reversed: the atom is fundamentally handed. (After R. A. Hegstrom et al, Am. J. Phys. 56,1086, 1988).

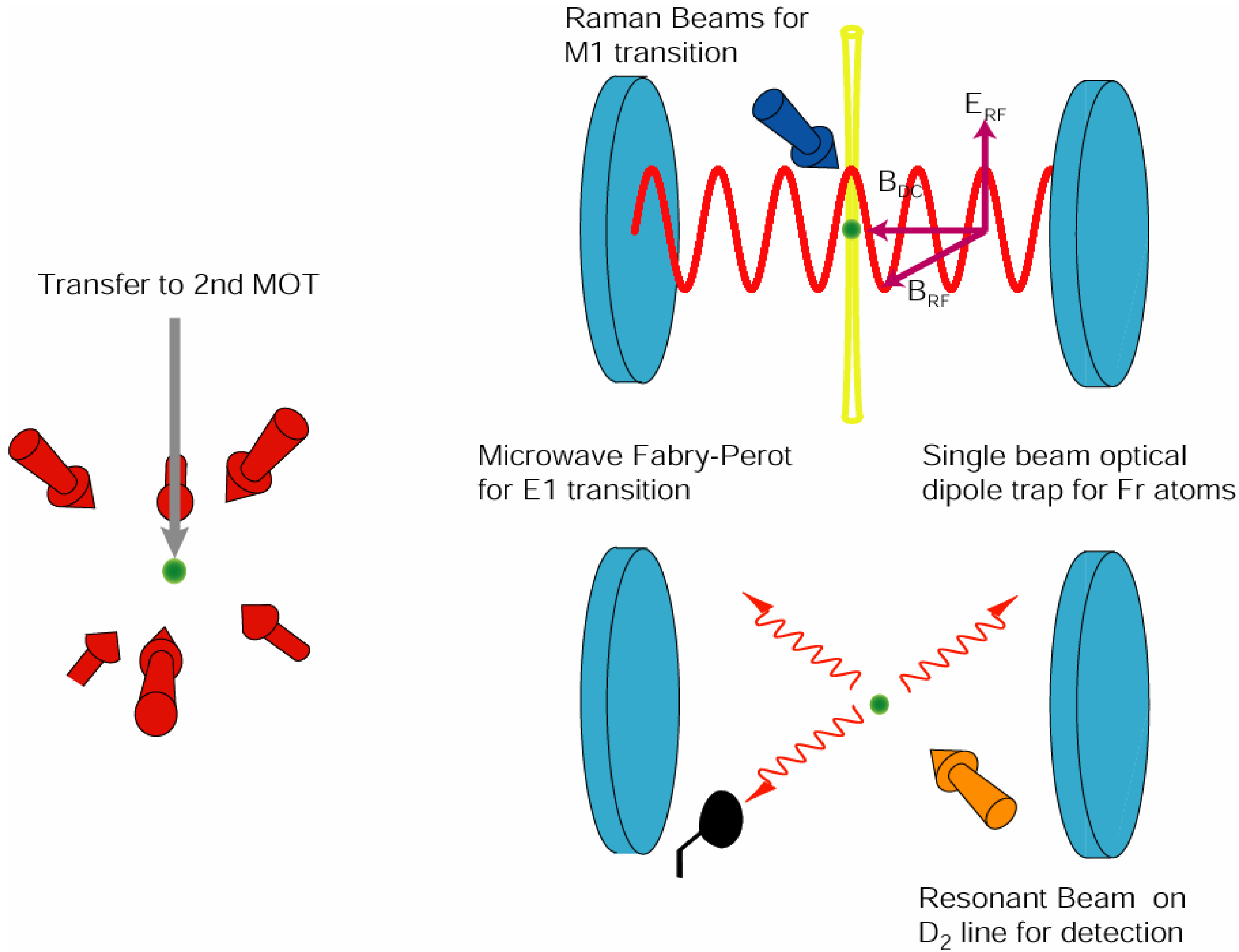
See: Fortson Group - Atomic Chirality
http://www.phys.washington.edu/~fortson/chiral.html

The wavefunction of a nucleon violates parity and so its current has a certain chirality. The current can be separated in two components. One an axial rotation and the second a current flowing in a torus. It is this last part that generates a magnetic field inside the nucleus. It changes the magnetization in a chiral form and manifests itself differently depending on the hyperfine state of the interacting nucleus-electron.





Estimated anapole moment effective constat for the light Fr isotopes


Raman Beams for
M1 transition
E_RF
B_DC
B_RF
Transfer to 2nd MOT
Microwave Fabry-Perot
for E1 transition
Single beam optical
dipole trap for Fr atoms
Resonant Beam on
D2 line for detection

METHOD

•Optically prepare the atoms in a particular m sublevel of the ground state, tip by an angle(θ) the population with a Raman pulses that we provide in just as a microwave M1 transition that is orthogonal to the E1 cavity.

•A second longer pulse will be applied from the **E1 cavity**. The probability of making the transition is proportional to **$| M1(\theta)B_R + d_{pnc}E_{rf} |^2$** which has an interference term that changes with the handedness of the coordinate axes.

$$S \sim |M1(\theta)B_R + d_{pnc}E_{rf}|^2 - |M1(\theta)B_R - d_{pnc}E_{rf}|^2$$

$$S \sim 2M1(\theta)B_R\, d_{pnc}E_{rf}$$

$$\text{Noise} \sim M1(\theta)B_R^{\ 2}$$

The **handedness** is determined by the ***static magnetic field*** (to lift the degeneracy of the Zeeman sublevels) and the ***polarizations*** of microwave electric and Raman fields (equivalent to a microwave magnetic field). This establishes a pseudo-scalar proportional to the measured quantity

$\mathbf{i(E\times (E_{R1} \times E_{R2}))\cdot B}$

Measure the transferred population turning the dipole trap off and using optical techniques in the appropriate cycling transition that will produce a very high detection efficiency.

Signal-to-noise

The experiment measures the transition probability:

$$P_{|g2\rangle} = \tfrac{1}{2}\left(1 \pm \Omega \Delta t\right)$$

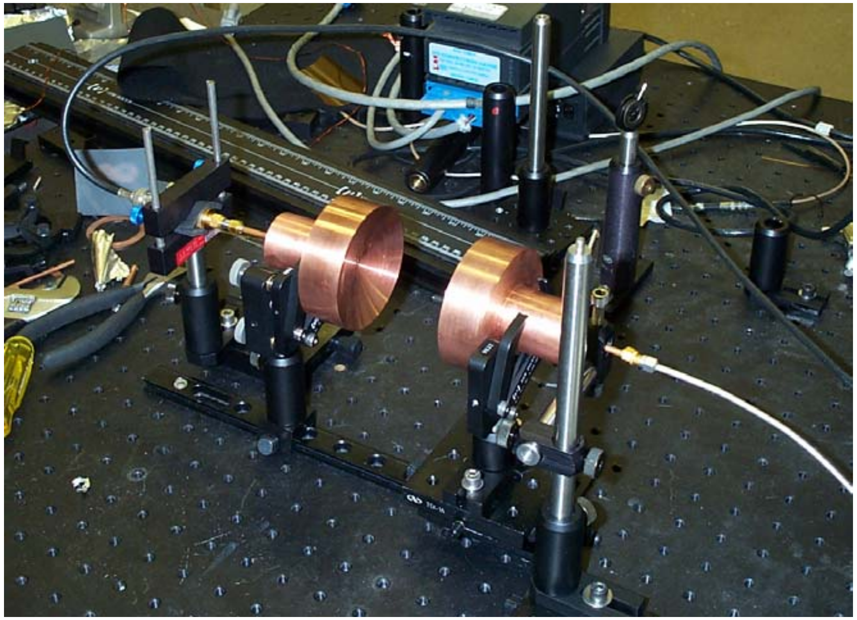
The expected shot noise limited **signal-to-noise** for detecting this rate is

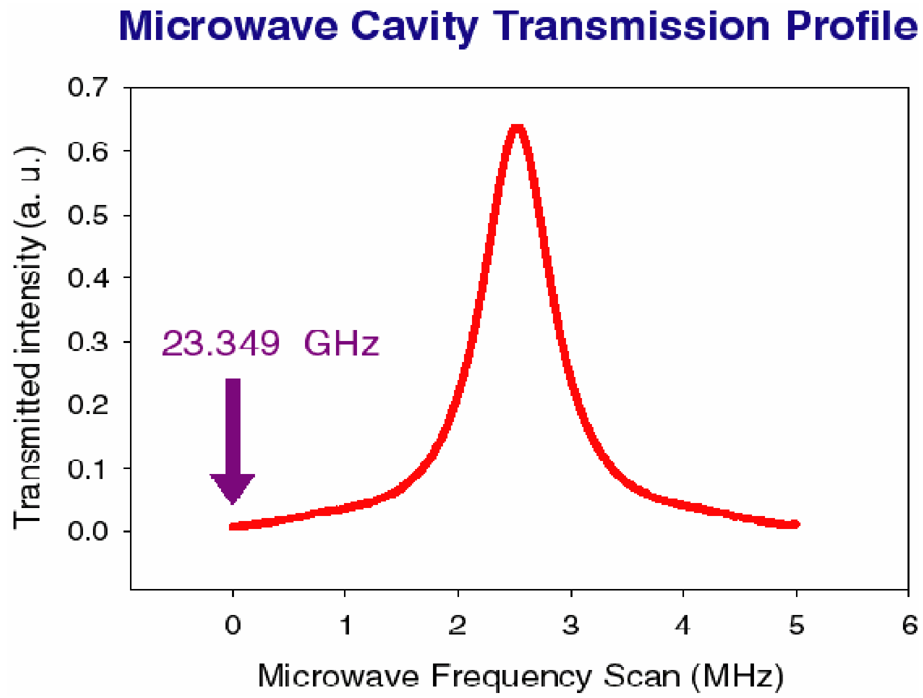
$$\boxed{\begin{aligned} \frac{Signal}{Noise} &= 2\Omega\sqrt{\Delta t}\sqrt{N} \\ &\cong 1 \quad \left(\sqrt{Hz}\right)^{-1} \end{aligned}}$$

The final number is for **10^6** atoms in an rf E1 field of **1kVolts/m**, and **$\Delta t \sim 1$ s** per cycle. For 10^4 cycles one can reach a 1% measurement.

Hardware advances for the Anapole measurement

Prototype Microwave Fabry-Perot.





Road Map for Fr project

•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 $(\mathrm{Hz})^{-1/2}$.

•Calculations of atomic and nuclear structure will allow the extraction of coupling constants.

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