The Radon EDM Experiment

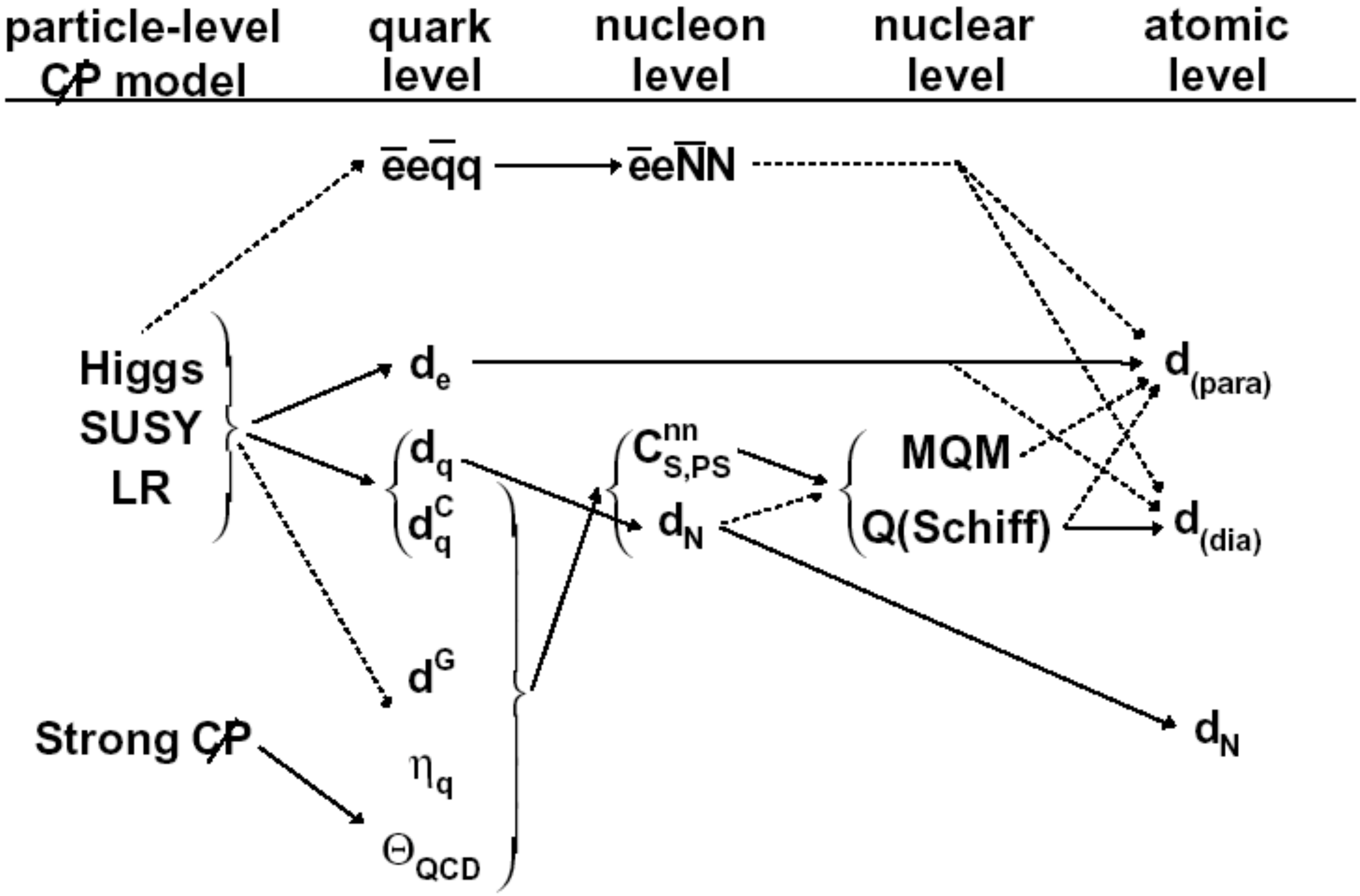
Eric Tardiff
WAPRA: June 3, 2009

Timothy Chupp & Carl Svensson, co-spokesmen
Gordon Ball, John Behr, Celia Cunningham, Greg Demand, Martin Djongolov, Paul Finley, Adam Garnsworthy, Paul Garrett, Katie Green, Greg Hackman, Mike Hayden, Carolyn Kierans, Jamie Kilkenny, Wolfgang Lorenzon, Matthew Pearson, Timothy Raben, Evan Rand, Chandana Sumithrarachchi, Eric Tardiff, Smarajit Triambak, Scott Williams, Jan Zirnstein

Outline

- Sensitivity to CP-violation in the Radon system
  - Octupole Enhancement in ^{223}Rn
  - Sensitivity relative to ^{199}Hg
- The Radon EDM experimental design
  - Polarizing radon through spin-exchange optical pumping
  - NMR using anisotropies in the distribution of emitted radiation
- Future schedule and ongoing development work

CP-Violation in Diamagnetic Atoms



particle-level $\not{C}P$ model

quark level

nucleon level

nuclear level

atomic level

$\bar{e}e\bar{q}q$

$\bar{e}e\bar{N}N$

Higgs
SUSY
LR

d_e

d_q

d_q^C

d^G

η_q

Θ_{QCD}

Strong $\not{C}P$

$C^{nn}_{S,PS}$

d_N

MQM

Q(Schiff)

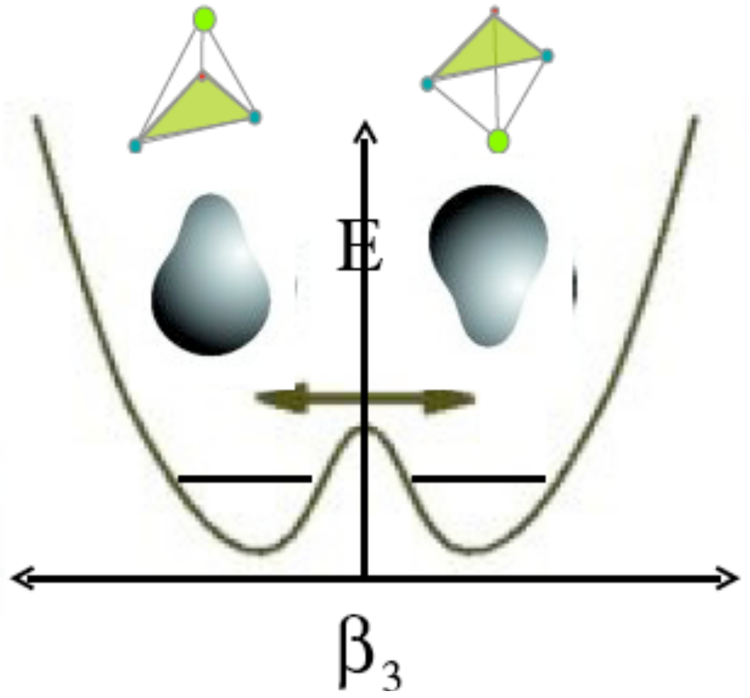
$d_{(para)}$

$d_{(dia)}$

d_N

Octupole Enhancement

$$S \sim \frac{\langle \mathbf{+} \mid \eta\, r^3 \cos\theta \mid \mathbf{-} \rangle}{E_+ - E_-} \sim \frac{\eta \beta_2 \beta_3^2 Z A^{2/3} r_0^3}{E_+ - E_-}$$



a

Nucleus	$S, 10^{-8} \eta_n\, e\ \text{fm}^3$	$d, 10^{-25} e\ \text{cm}\, \eta_n$
^{225}Ra	300	2500
^{223}Ra	400	3400
^{223}Rn	1000	3300

b

	^{223}Ra	^{225}Ra	^{223}Rn	^{221}Fr	^{223}Fr	^{225}Ac	^{229}Pa	^{199}Hg	^{129}Xe	^{133}Cs
$\alpha(WS)(10^7\eta)$	1	2	4	0.7	2	3	34			
$\Delta E(WS)$ (keV)	170	47	37	216	75	49	5			
π_p(WS)	0.81	-0.02	0.17	-0.55	-0.34	-0.35	0.01			
$\alpha(Nl)(10^7\eta)$	2	5	2							
$\Delta E(Nl)$ (keV)	171	55	137							
ΔE_{expt} (keV)	50.2	55.2		234	160.5	40.1	0.22			
$S_{\text{intr}}(e\ \text{fm}^3)$	24	24	15	21	20	28	25			
$S(10^8\eta e\ \text{fm}^3)$	400	300	1000	43	500	900	1.2×10^4	-1.4	1.75	3
d(at) $(10^{25}\eta e$ cm)	2700	2100	2000	240	2800			5.6	0.47	2.2

a: Flambaum & Zelevinsky, Phys. Rev. C **68**, 035502 (2003)

b: Spevak, Auerbach, and Flambaum, Phys. Rev. C **56**, 1357 (1997)

The ^{199}Hg Results

$$|\, d(^{199}\mathrm{Hg}) \,| = (0.49 \pm 1.29 \pm 0.76) \times 10^{-29}\ e \cdot \mathrm{cm}$$

$$|\, d(^{199}\mathrm{Hg}) \,| < 3.1 \times 10^{-29}\ e \cdot \mathrm{cm}$$

- The new ^{199}Hg results quote improved limits on d_p, d_d^C, C^T, and C^S.
- The ^{223}Rn octupole enhancement of 400-600 is an advantage for EDM detection.
- We will need to be more precise than 1-2×10^{-26} to be more sensitive to CP violation.
- Due to the uncertainties in nuclear calculations for octupole deformed nuclei*, in the case of a null result we would have to be much more precise to improve on the ^{199}Hg limits.

Parameter	Best Upper Limit	System
d_n	$6.3 \times 10^{-26} e \cdot \mathrm{cm}$	neutron
d_e	$1.6 \times 10^{-27} e \cdot \mathrm{cm}$	Tl
d_p	$\mathbf{7.9 \times 10^{-25} e \cdot cm}$	**Hg**
d_d^C	$\mathbf{6 \times 10^{-27} e \cdot cm}$	Hg
Θ_{QCD}	1.5×10^{-10}	neutron and Hg
ε_q^{SUSY}	2×10^{-3}	Hg
ε^{Higgs}	$0.3/\tan\beta$	Tl
x^{LR}	1×10^{-3}	Hg
η	1.6×10^{-3}	Hg
C^T	$\mathbf{1.5 \times 10^{-9}}$	Hg
C^S	$\mathbf{5.2 \times 10^{-8}}$	Hg
η_q	3.4×10^{-6}	Hg

*Pospelov & Ritz, Ann. Phys. **318**, 119-169 (2005)

Using NMR Techniques to Measure an EDM

- Polarize the nuclei of the atoms of interest. We use spin exchange with optically pumped rubidium vapor.
- Apply a high voltage. After an RF pulse, the atoms precess at the frequency

$$\hbar\omega_{\pm} = 2\mu B \pm 2dE$$

- The difference in precession frequency with electric field orientation gives a measure of the EDM:

$$d = \hbar\Delta\omega / 4E$$

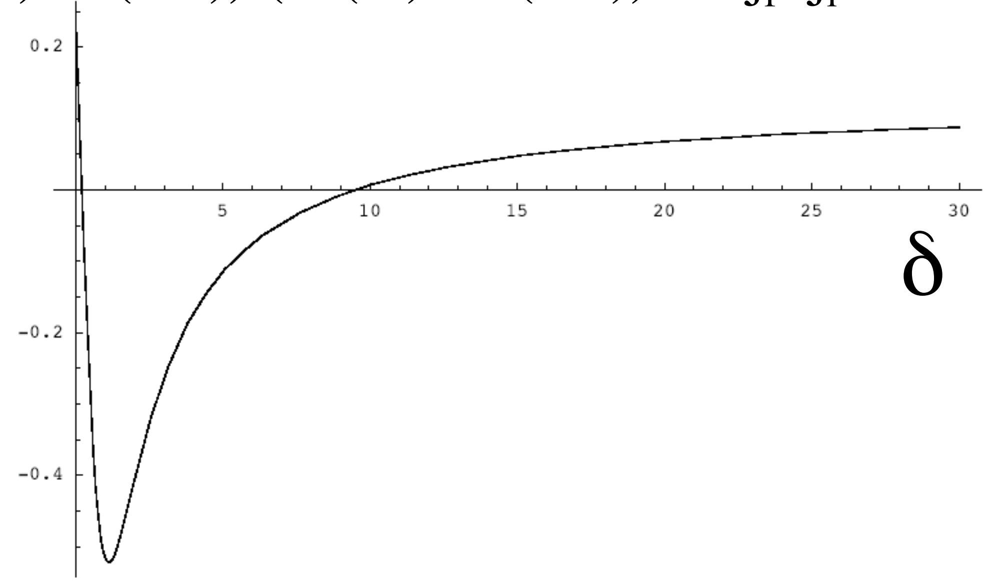
Gamma-ray Anisotropies

- Polarized, radioactive nuclei emit gamma rays with calculable directional distributions.

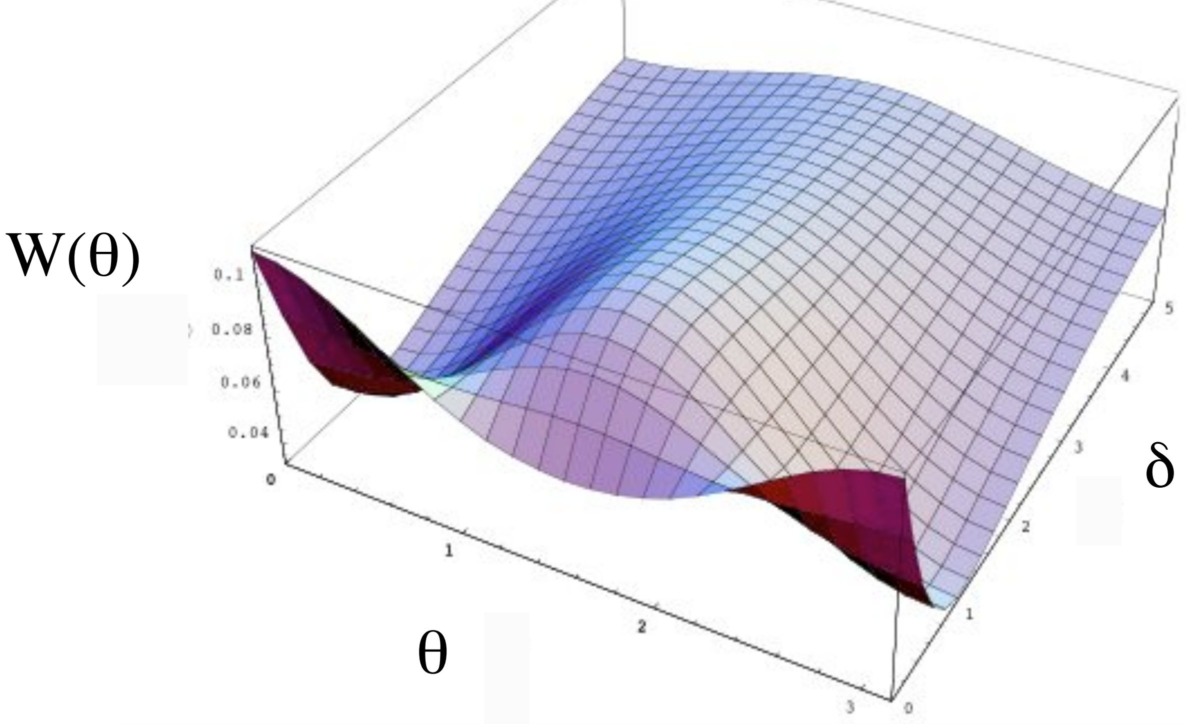
$j_f=j_i-1$ pure dipole transition

$$W(\theta) = \frac{1}{4\pi}\left\{1+\frac{3}{2j_i(2j_i-1)}\left[\sum_{m_i} m_i^2 a_{m_i} - \frac{1}{3}j_i(j_i+1)\right]P_2(\cos\theta)\right\}$$

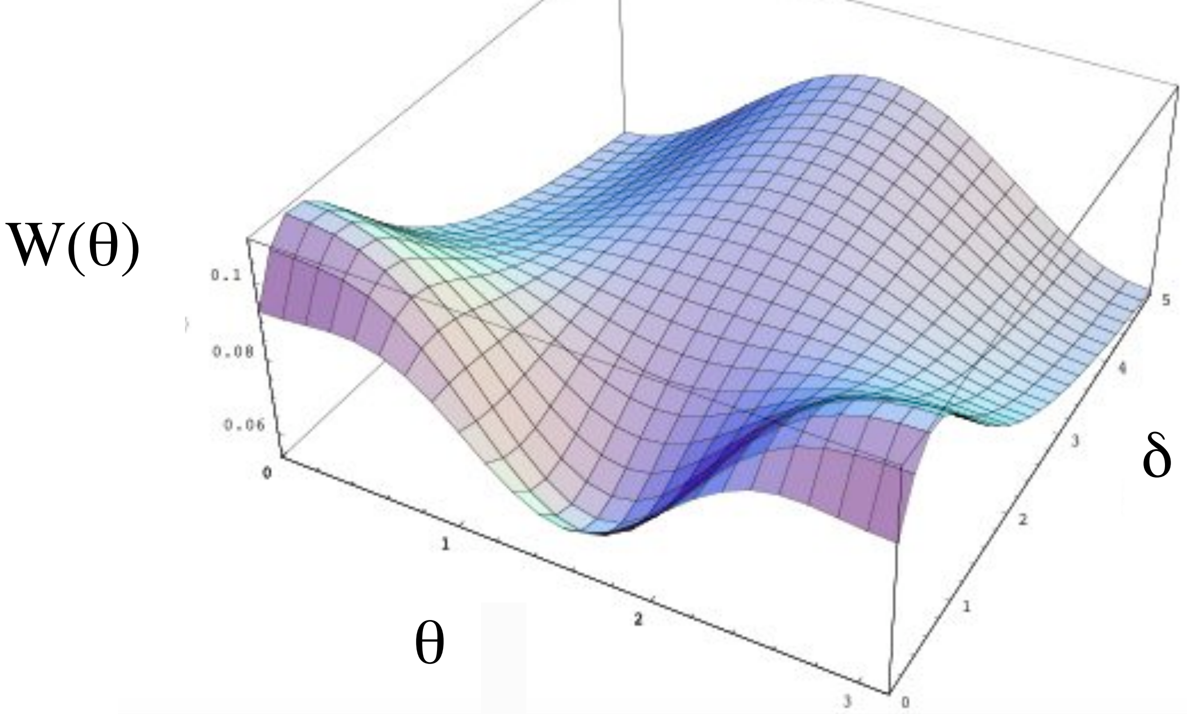
(W(0°)-W(90°))/(W(0°)+W(90°)) for $j_f=j_i+1$



$j_f=j_i+1$



$j_f=j_i$



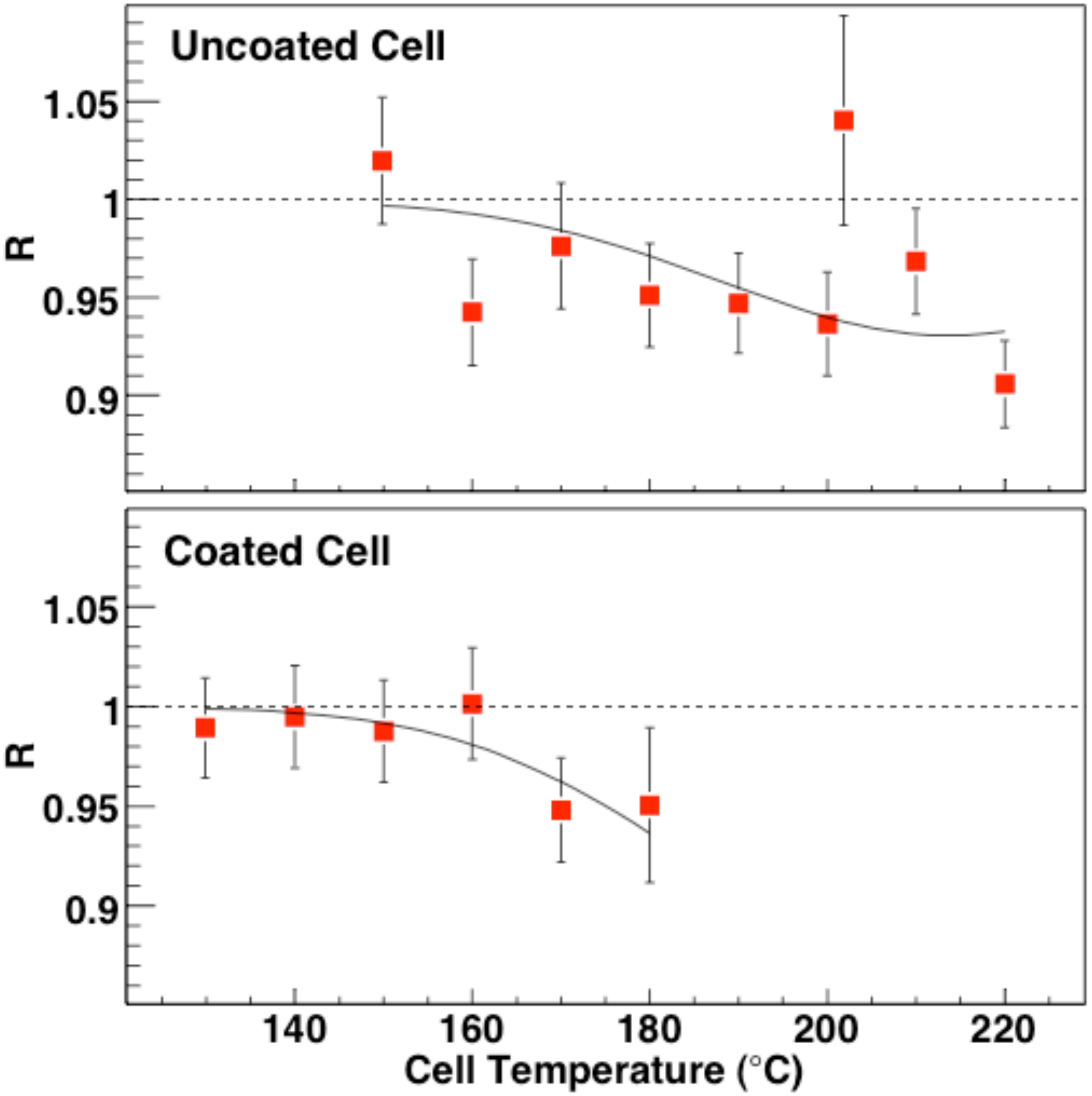
Stony Brook ^{209}Rn Studies

- The ^{223}Rn source at TRIUMF is not yet available, so we used the Stony Brook francium beam to produce ^{209}Rn.
- ^{209}Rn (I=5/2, $T_{1/2}$=28.5 min) and ^{223}Rn (I=7/2, $T_{1/2}$=23.2 min) will exhibit similar relaxation mechanisms.
- Quadrupole relaxation is expected to be the dominant mechanism: $\Gamma_2(\mathrm{T}) = \Gamma_2^{\infty} e^{\mathrm{T}_0/\mathrm{T}}$
- Study ^{209}Rn polarization to determine the implications for a ^{223}Rn EDM measurement.

Radon Polarization Measurements

- Data were taken at cell temperatures from 130 to 220ºC
- Each radon measurement cycle was split into about 4 segments, alternating laser on and off.
- Find $R = \frac{(0^\circ/90^\circ),\mathrm{LON}}{(0^\circ/90^\circ),\mathrm{LOFF}}$
- Octadecyltrichlorosilane (OTS) coating was used, and the data indicated it was beneficial for the ^{209}Rn polarization.

337 keV Data



EDM Measurement Precision

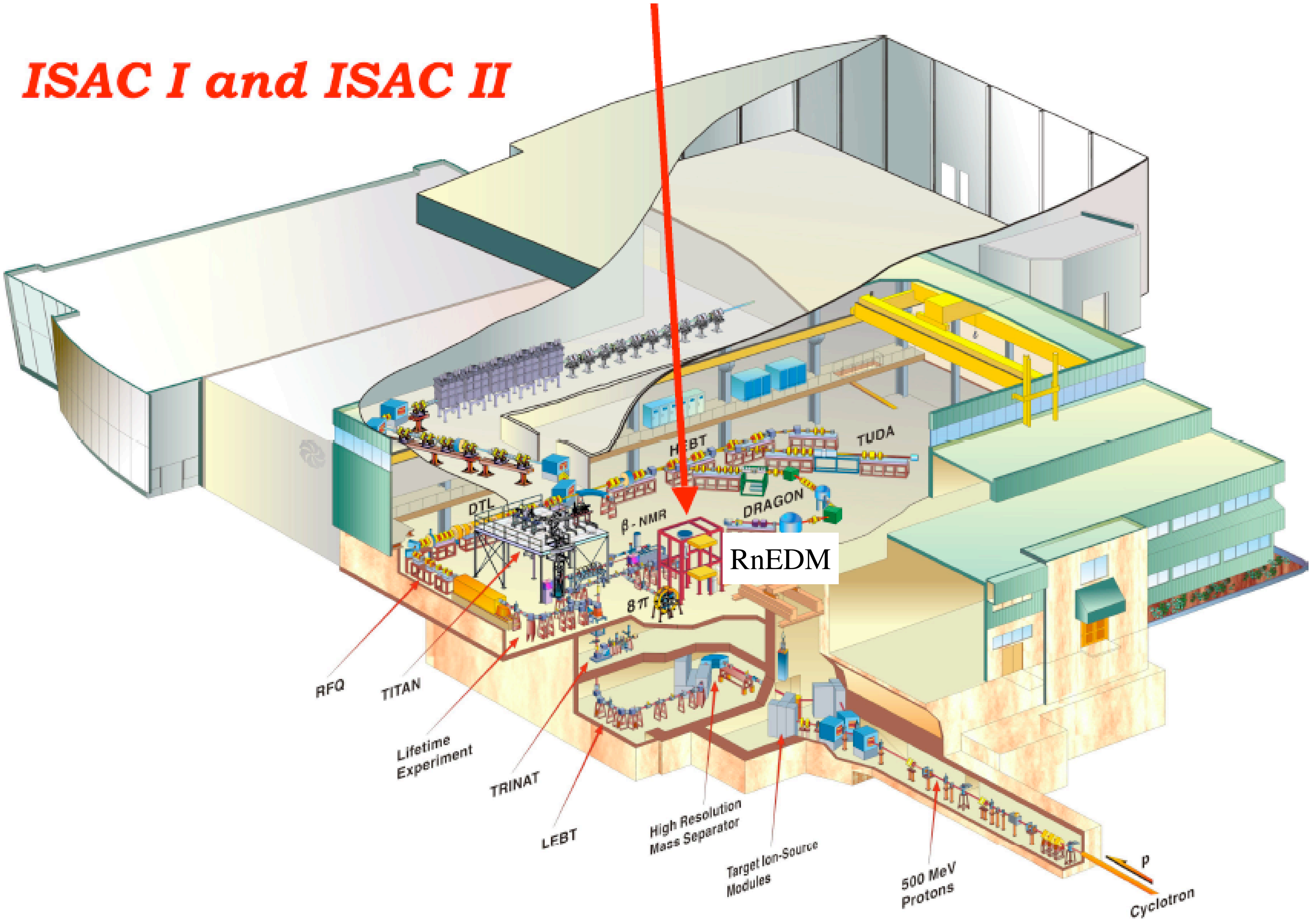
- The expected statistical uncertainty in the EDM experiment is given by:

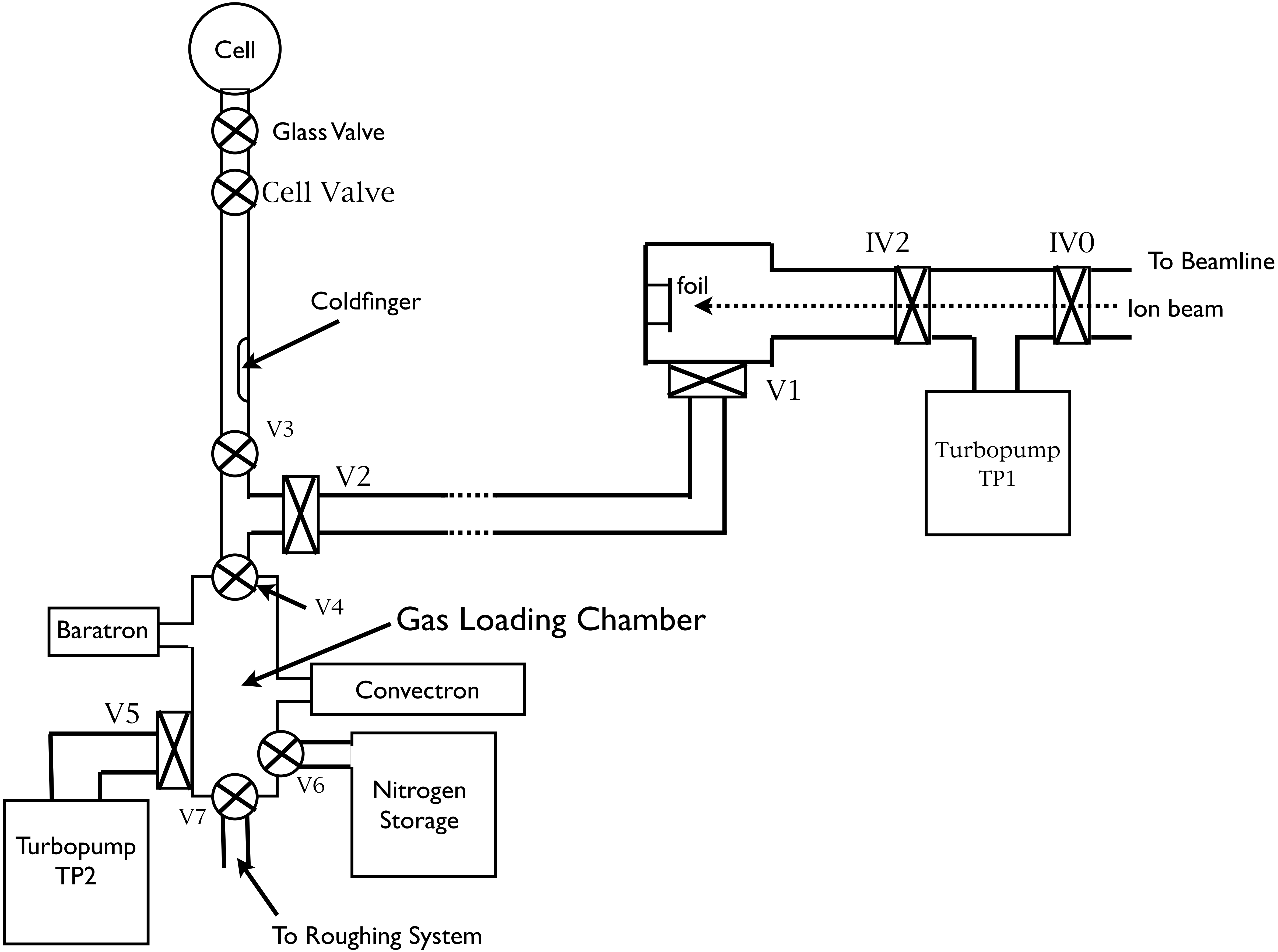
$$\delta_d = \frac{\hbar}{2ET_2}\sqrt{\frac{1}{A^2(1-B)^2N}}$$

- Using E = 10 kV/cm, N = 10^{12}, A = 0.1, B = 0.01, T_2 = 12 s (based on the ^{209}Rn measurements),
  - δ_d of 3×10^{-26} $e \cdot$cm is expected.
- With enhancement of 400-600, this should result in close to the same sensitivity to CP violation as ^{199}Hg.

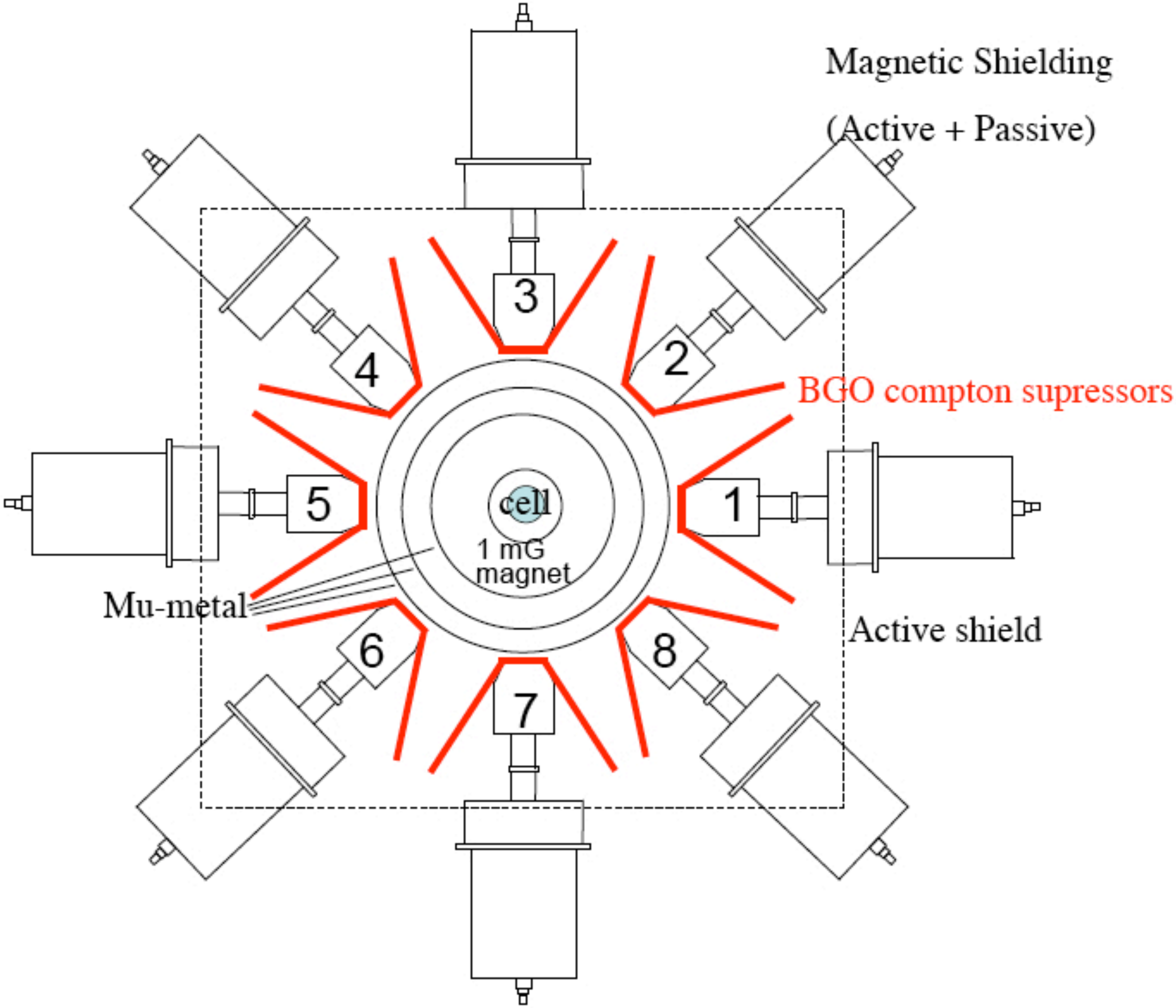
$$|\,d(^{199}\text{Hg})\,| < 3.1 \times 10^{-29}\ e\cdot\text{cm}$$

RadonEDM at TRIUMF



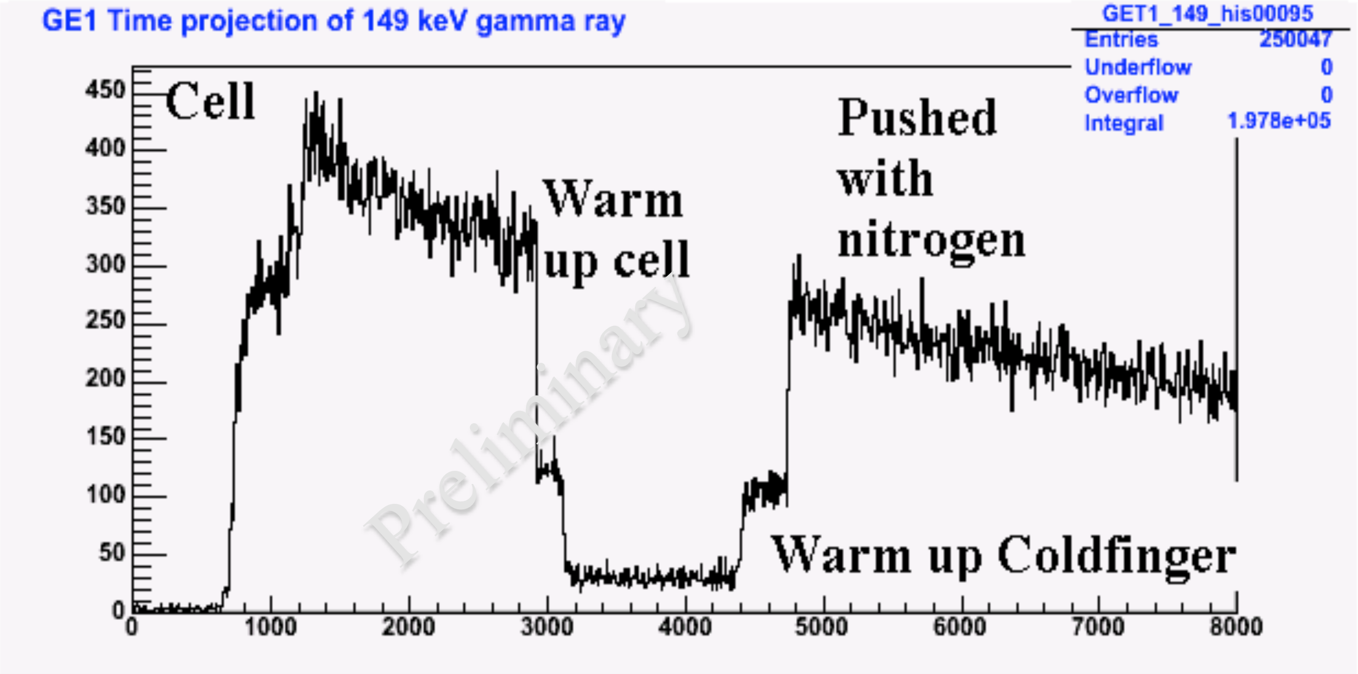

Cell
Glass Valve
Cell Valve
Coldfinger
V3
V2
V1
foil
IV2
IV0
To Beamline
Ion beam
Turbopump TP1
V4
Gas Loading Chamber
Baratron
Convectron
V5
V6
V7
Nitrogen Storage
Turbopump TP2
To Roughing System

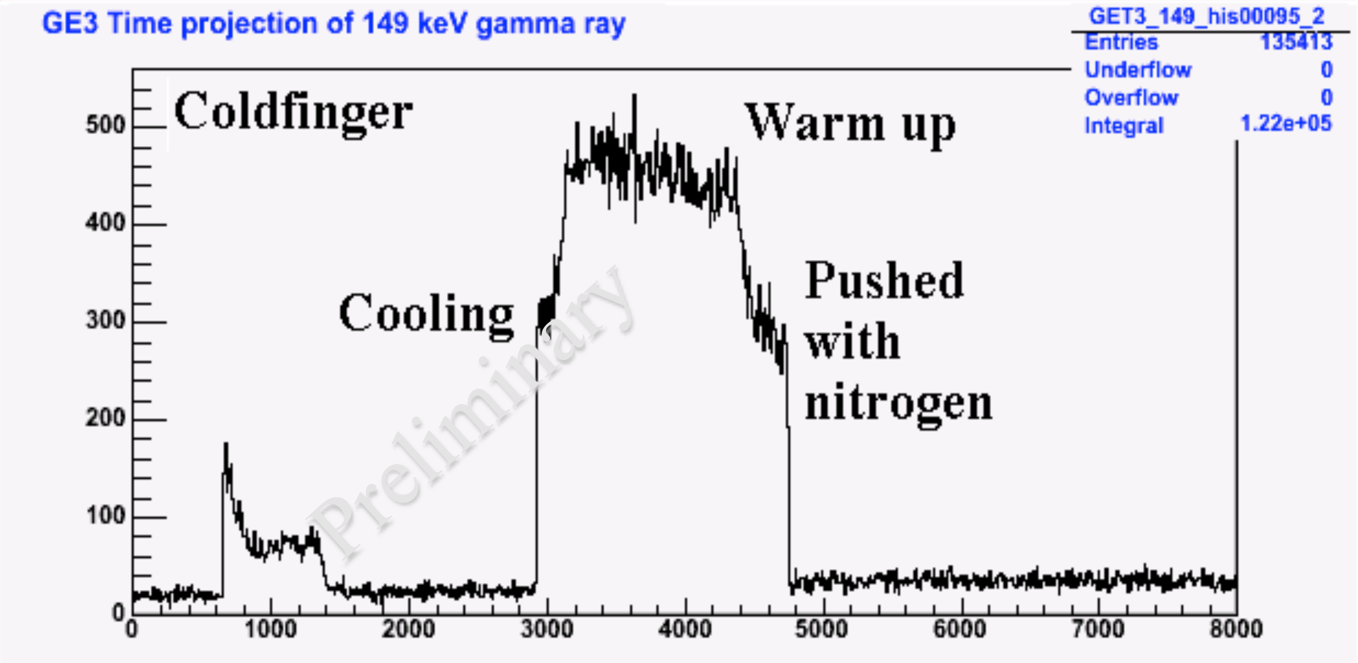
Radiation Detection of NMR Signal



Gas Transfer Tests

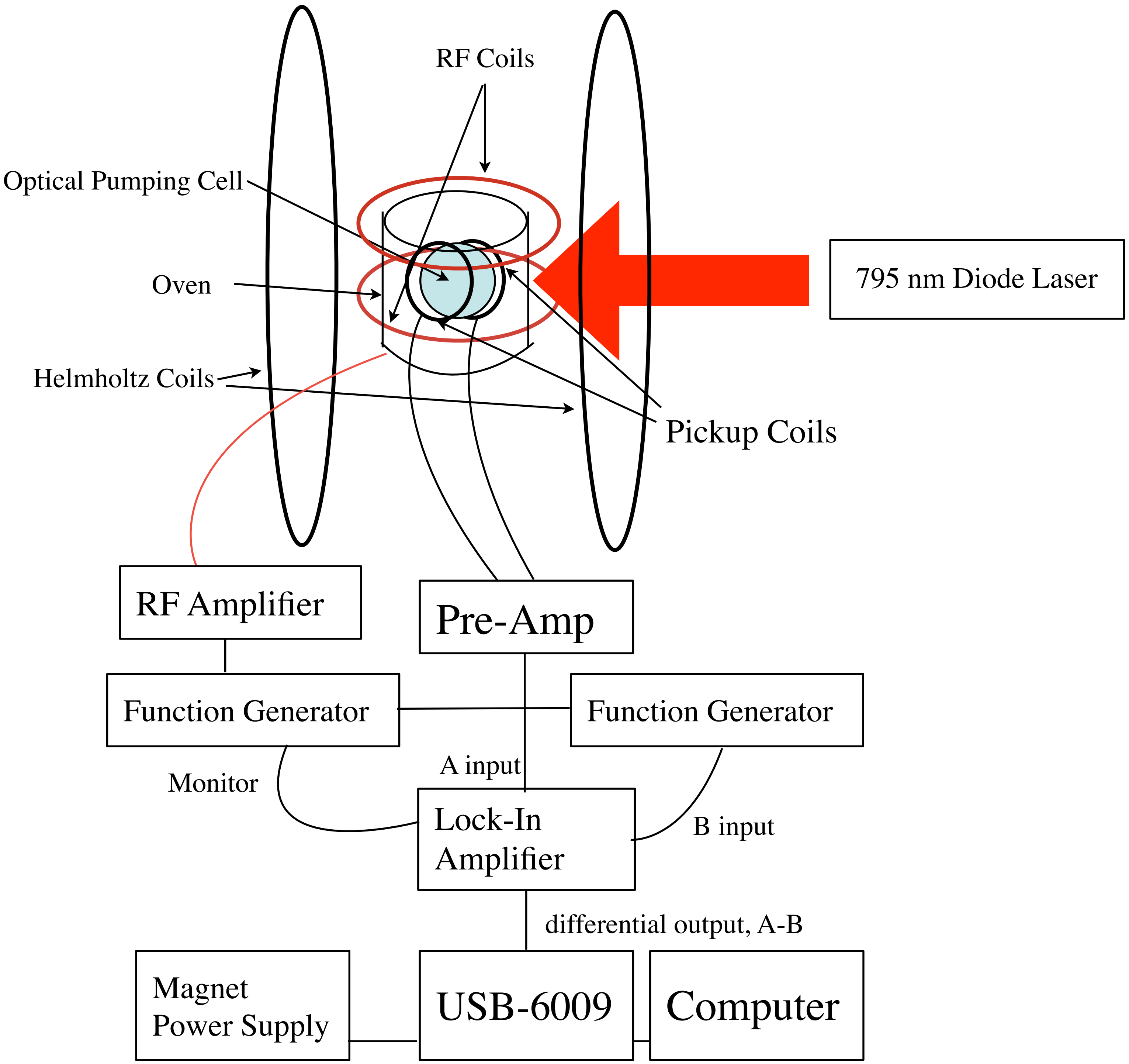
- Used ^{123}Xe ($T_{1/2}$~2hrs) from a ^{123}Cs beam to test the efficiency of the gas transfer system.
- Cryopump from the foil directly into the cell.
- Warm the cell and cryopump to the coldfinger.
- Push the xenon into the cell with a jet of nitrogen.
- We also studied the dependence of the relative gamma-ray rates at the cell and coldfinger over a range of coldfinger temperatures to determine a wall binding energy for ^{123}Xe: $E_B = 2.09(11)\times10^3$ K (preliminary result)





Xenon AFP Diagnostics

- Natural xenon contains ^{129}Xe (I=1/2) and ^{131}Xe (I=3/2).
- We can study the temperature dependence of dipole and quadrupole relaxation rates with two separate species in the same cell.
- Help determine the optimum temperature for isotopes affected by quadrupole relaxation.
- Study the reproducibility of the polarization signal over multiple fills.



RF Coils

Optical Pumping Cell

Oven

Helmholtz Coils

Pickup Coils

795 nm Diode Laser

RF Amplifier

Pre-Amp

Function Generator

Function Generator

Monitor

A input

B input

Lock-In Amplifier

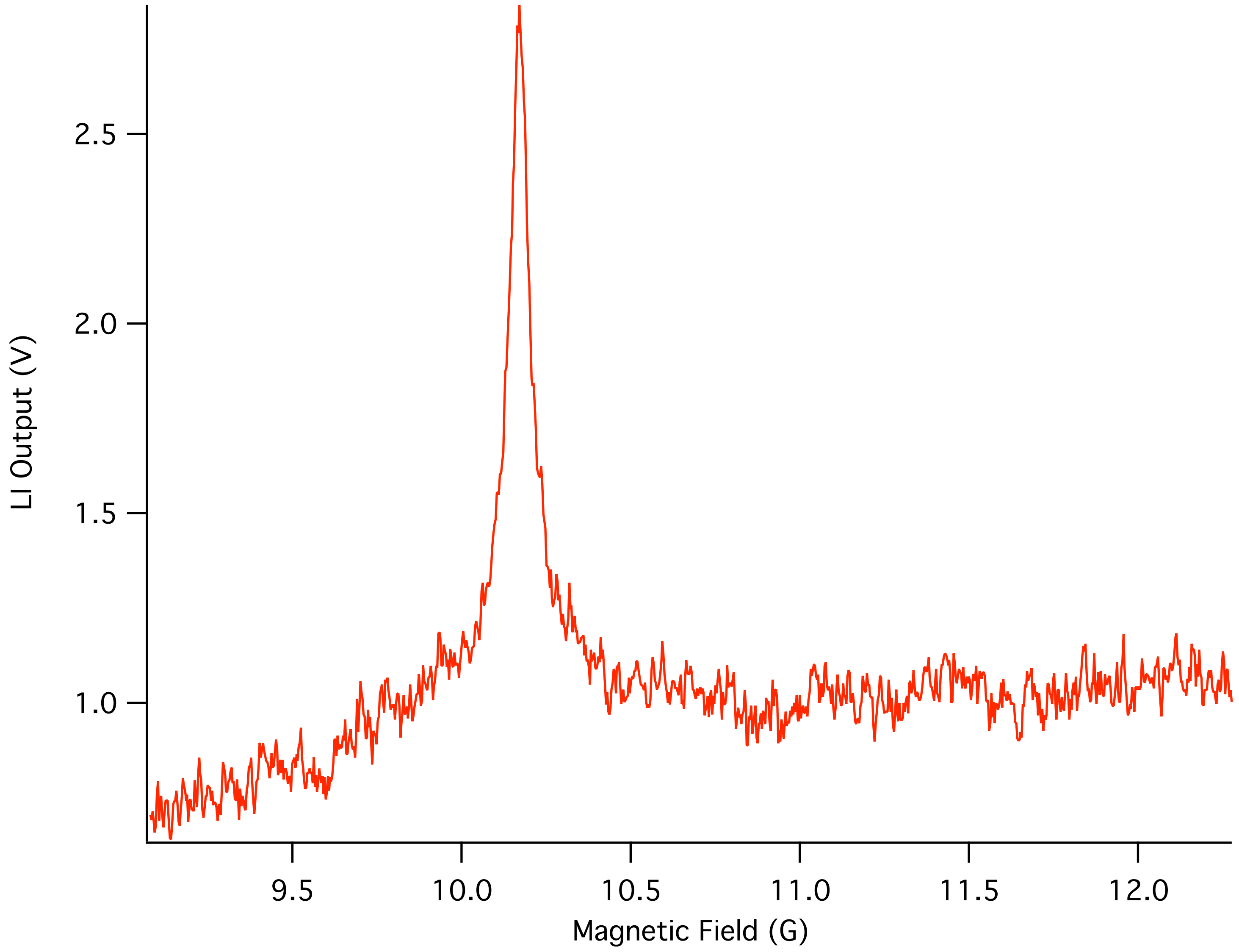
differential output, A-B

Magnet Power Supply

USB-6009

Computer

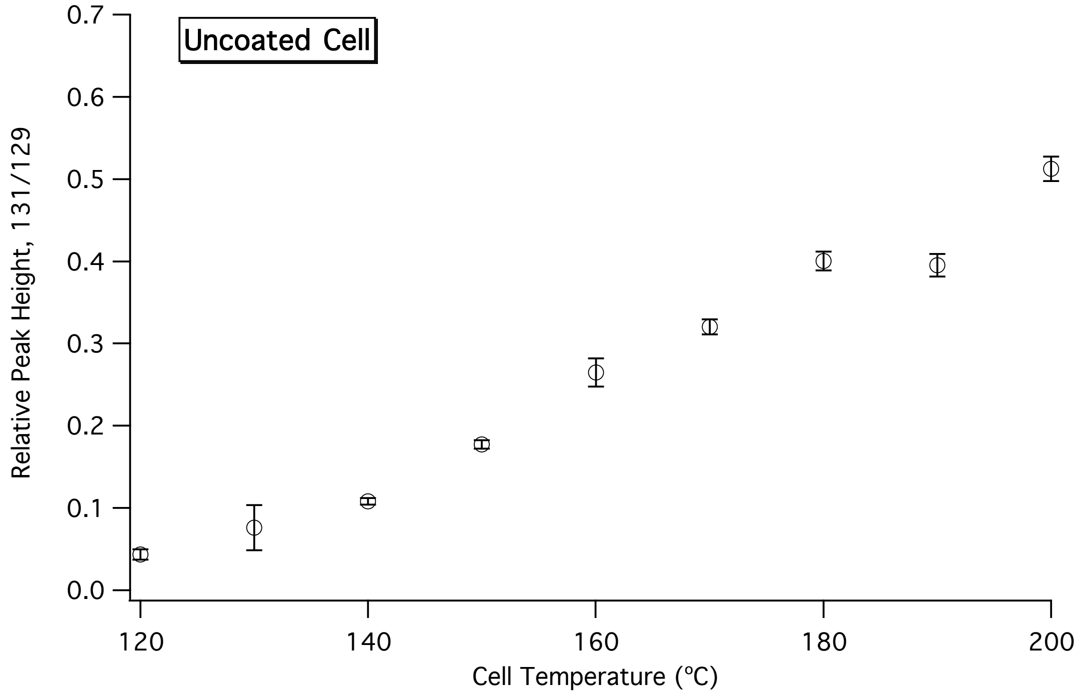
Xenon AFP Signal

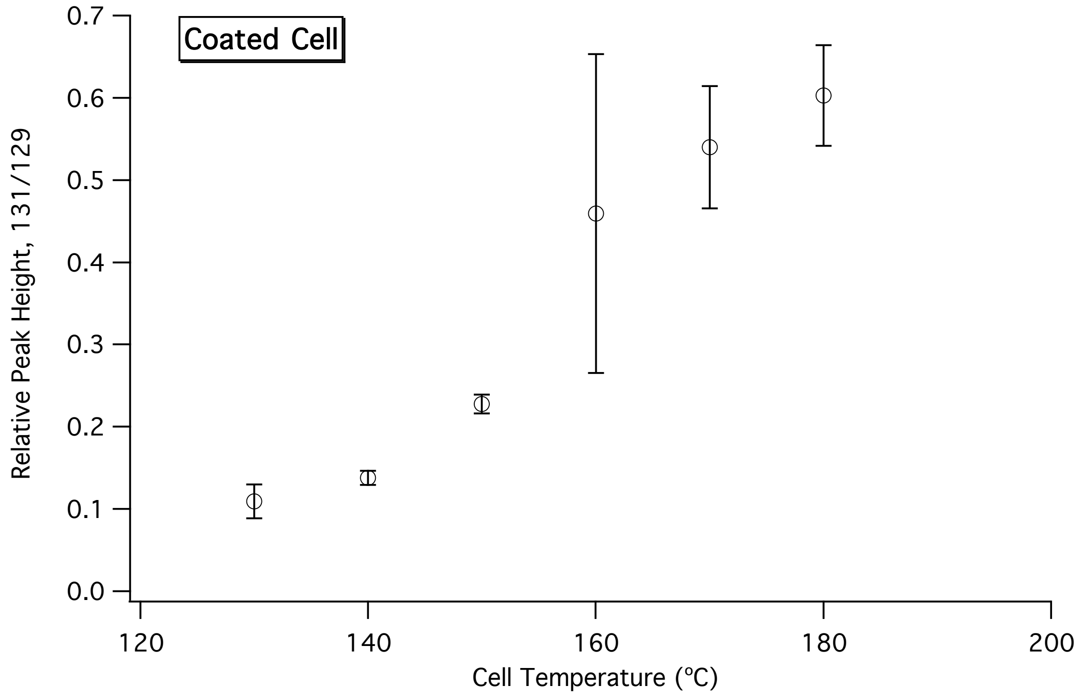


- We have begun the diagnostics at TRIUMF using a supply of natural xenon attached to the gas handling system.
- In anticipation of testing the polarization and detection apparatus using ^{121}Xe, we will attempt to optimize the ^{131}Xe polarization signal.

Relative Peak-Height Results

- Preliminary studies at Michigan indicated that an OTS-coated cell had a larger ^{131}Xe polarization signal relative to ^{129}Xe.
- This is consistent with our conclusions from the ^{209}Rn polarization data.
- OTS coatings are known to be beneficial for ^{129}Xe polarization.





Future Schedule

- Upcoming work at TRIUMF:
  - July 9-14, 2009: Collect and polarize ^{121}Xe (from a ^{121}Cs beam) to measure polarization transients. $J_{121}=5/2$
  - Fall 2009: Actinide Target will be ready, allowing ^{221,223}Rn (from At beams)
    - use 8π apparatus to measure the nuclear structure of multiple radon isotopes
    - measure ΔE to experimentally determine the EDM enhancement
- 2010: Xenon free precession measurement using a good magnet and 2+ Tigress modules
- 2011: Start Radon EDM measurements

Ongoing and Future Development Work

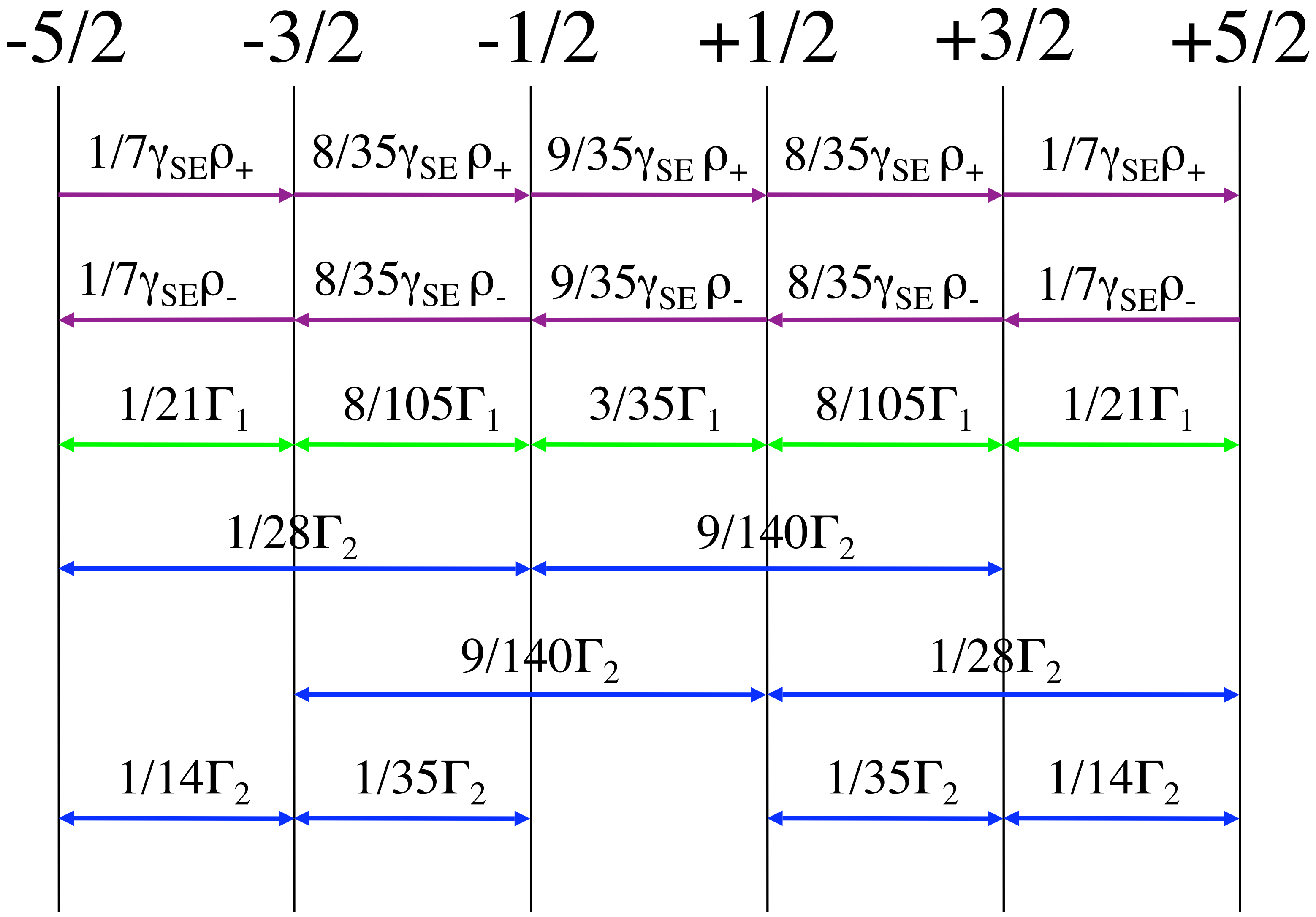
- EDM cell development: minimizing leakage currents.
- Design cells that will allow for beta asymmetry measurements: can run in current mode, so we won't be count rate limited.
- Decide on an isotope to use as a co-magnetometer.
- Build a deep UV laser that will allow direct polarization of the radon atoms.

Summary

- OTS-coated cells appear to be beneficial for polarizing isotopes sensitive to quadrupolar wall interactions.
- We should be able to measure the ^{223}Rn EDM with a sensitivity of 10^{-26} $e\cdot$cm or better.
- The octupole enhancements make this competitive with the ^{199}Hg system.

Modeling Polarization

- Can calculate the expected angular distribution of gamma rays as a function of spin-exchange and relaxation rates.
- The spin-exchange rate γ_{SE} depends on the Rb density, which depends on cell temperature, and the spin-exchange cross-section.
- The dipole and quadrupole relaxation rates, Γ_1 and Γ_2, must be determined from data.
- Γ_2 dominates the relaxation, so Γ_1 is set to zero.



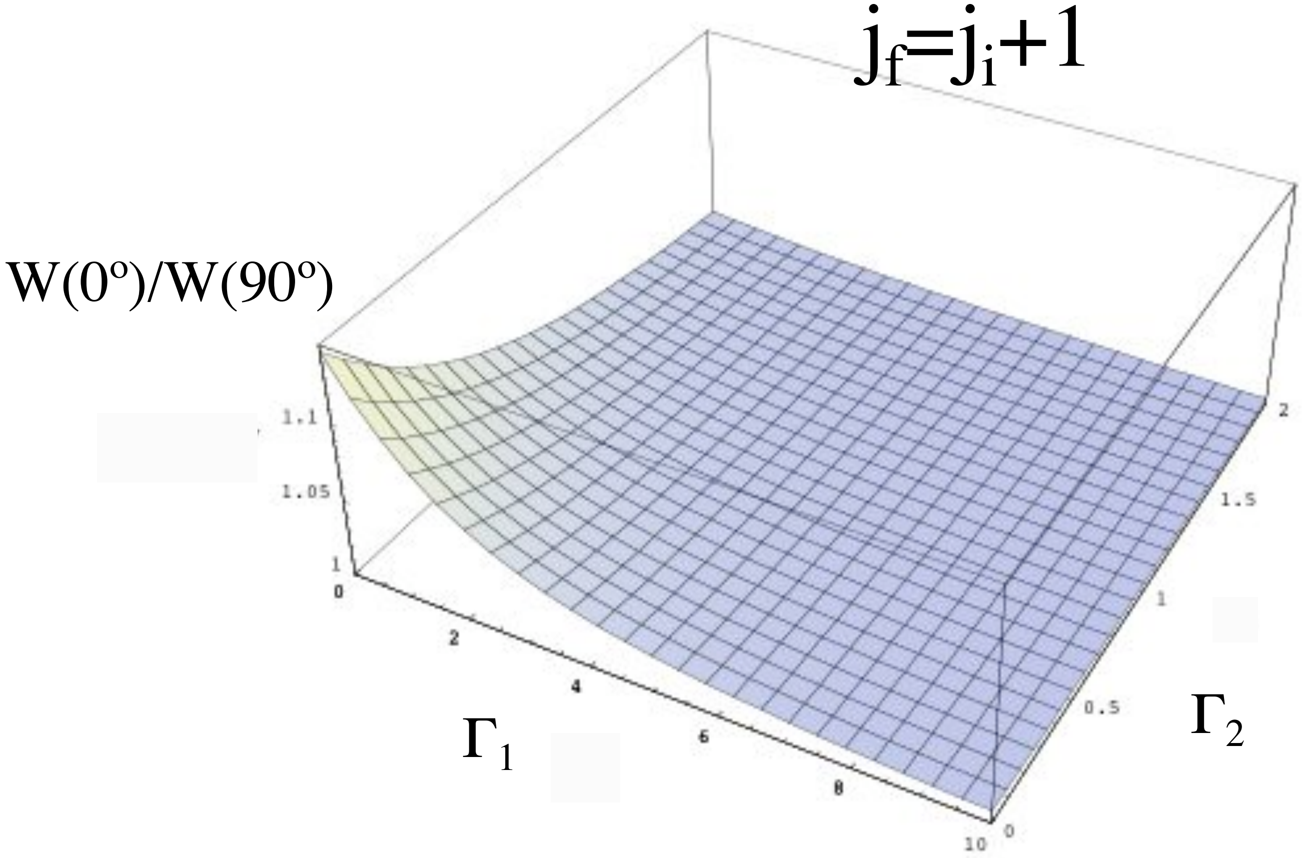
$$\rho_\pm = (1 \pm P_{\mathrm{Rb}})/2$$

$$\Gamma_2(\mathrm{T}) = \Gamma_2^\infty e^{\mathrm{T}_0/\mathrm{T}}$$

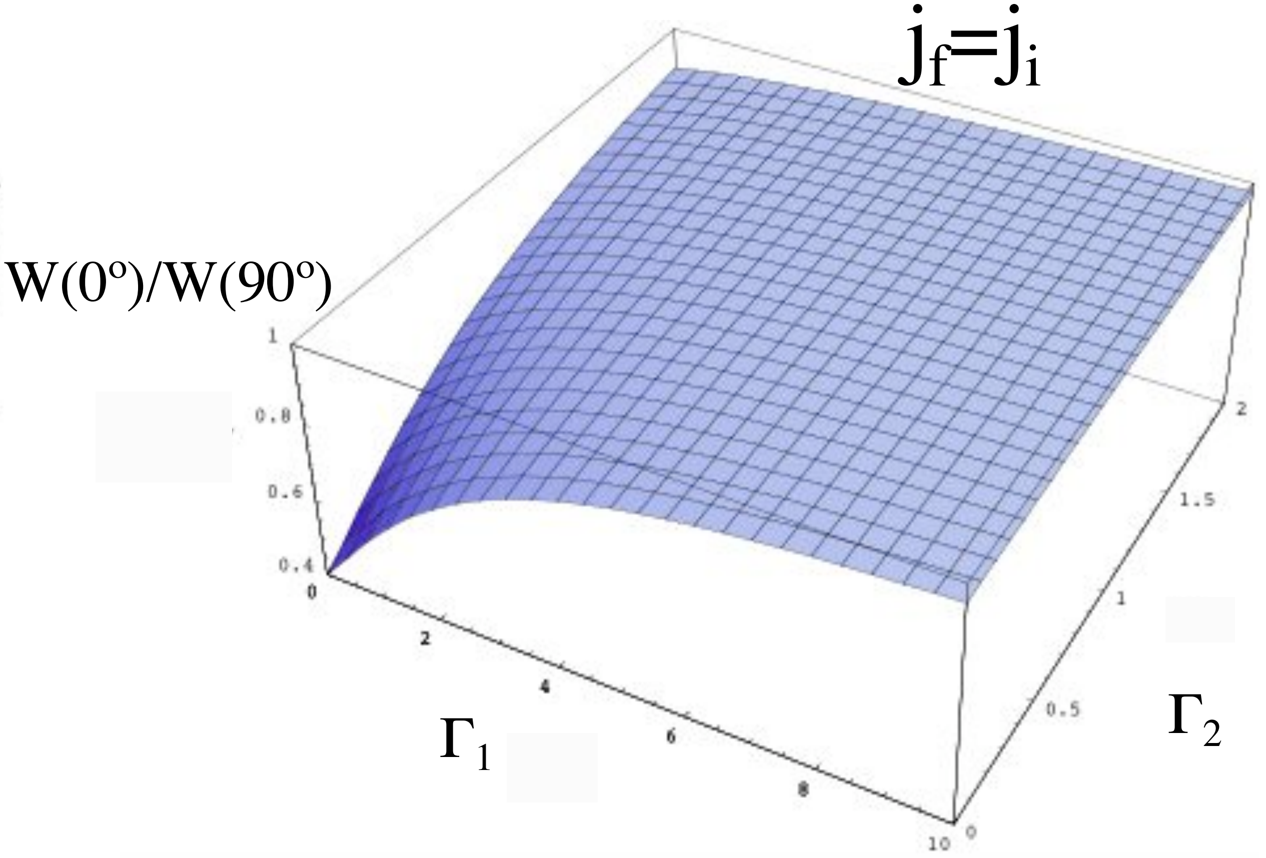
Modeling Polarization

- Quadrupole relaxation should be the dominant mechanism.
- As a first approximation, set Γ_1=0, calculate γ_{SE} for a given T, and calculate the expected anisotropies.

$$\gamma_{SE} = [\mathrm{Rb}]\langle \sigma_{SE} v \rangle \qquad [\mathrm{Rb}] = 10^{9.318 - \frac{4040}{T}} / k_B T$$

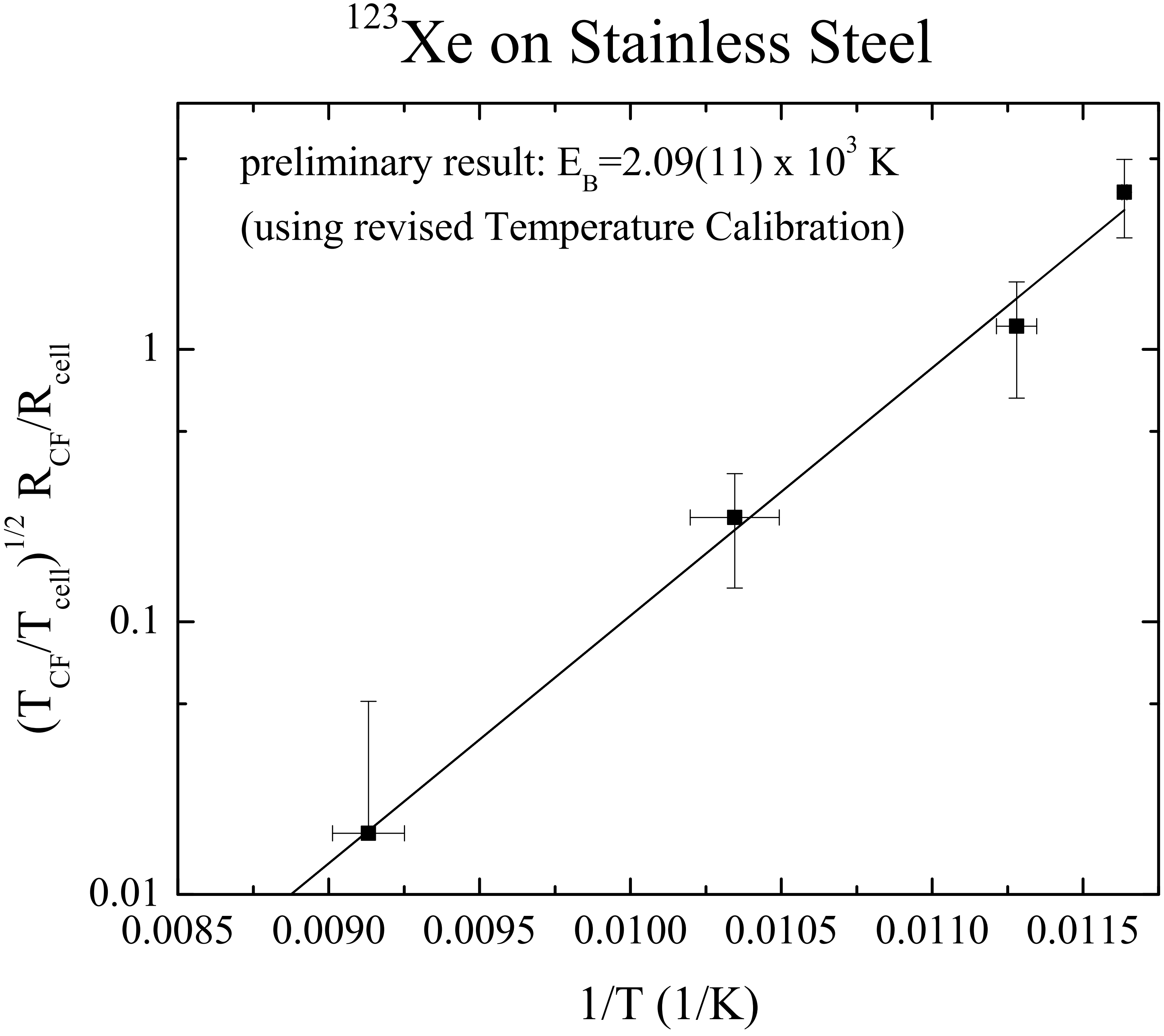


$j_f=j_i+1$



$j_f=j_i$

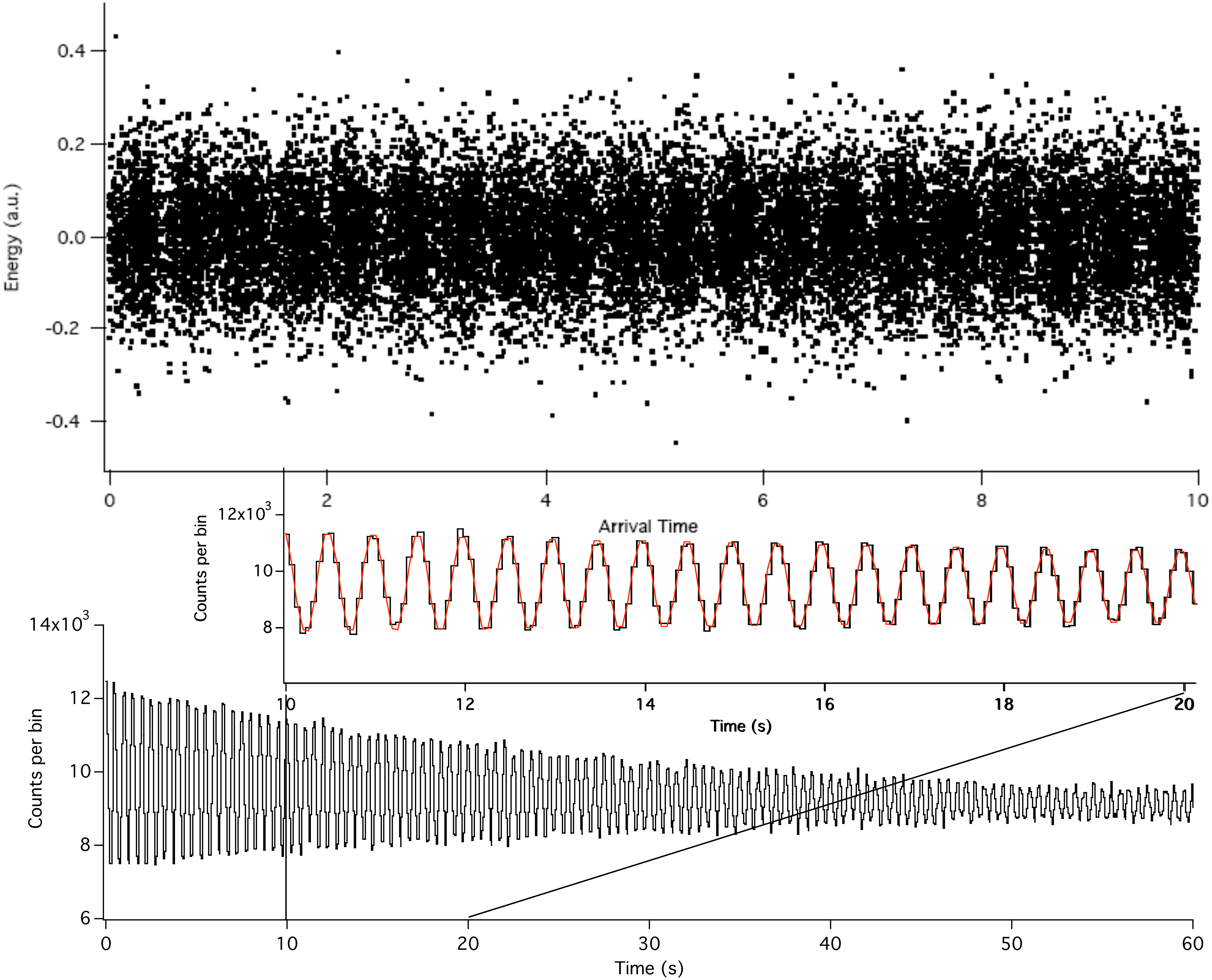
^{123}Xe Wall Binding Energy



^{123}Xe on Stainless Steel

preliminary result: E_B=2.09(11) x 10^3 K

(using revised Temperature Calibration)


Energy (a.u.)
0.4
0.2
0.0
-0.2
-0.4
0
2
4
6
8
10
Arrival Time
Counts per bin
$12x10^3$
10
8
10
12
14
16
18
20
Time (s)
Counts per bin
$14x10^3$
12
10
8
6
0
10
20
30
40
50
60
Time (s)