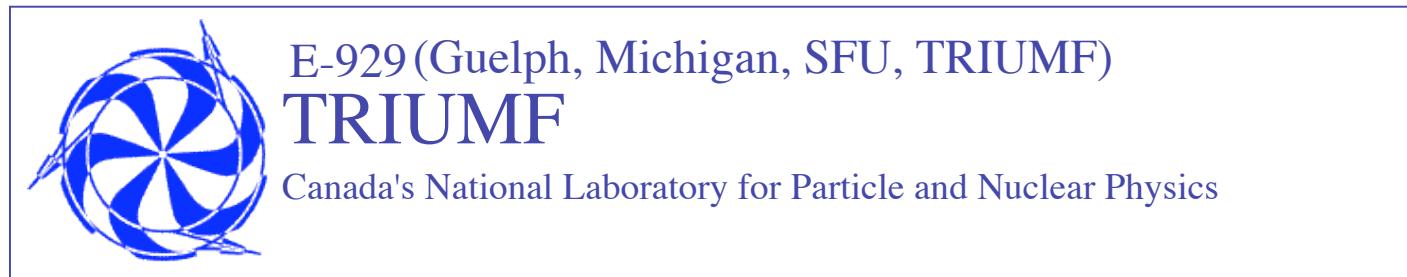


Radon-EDM Experiment

*Eric Tardiff, Tim Chupp, Wolfgang Lorenzon, Celia Cunningham, Jan Zirnstein (Michigan)
John Behr, Matt Pearson, Gordon Ball, Greg Hackman, Scott Williams, Adam Garnsworthy,
Jamie Kilkenny, Martin Djongolov (TRIUMF)
Carl Svensson, Paul Garrett, Smarajit Tirambak, Chandana Sumithrarachchi (Guelph)
Mike Hayden (SFU)*



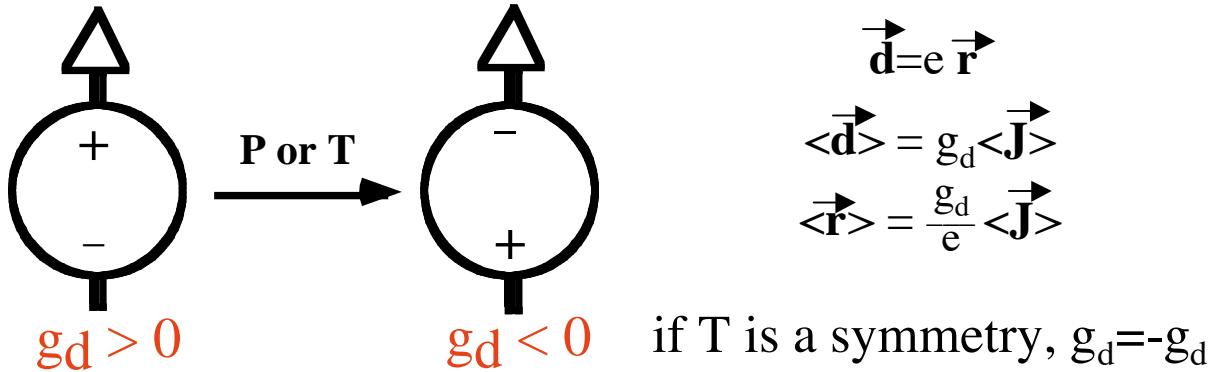
Spokesmen: Tim Chupp & Carl Svensson

Funding: NSF-Focus Center, DOE, NRC (TRIUMF), NSERC

S-929 has been given Stage-2 approval in December 2007 for 32 shifts of
EDM experiment development with $^{121/123}\text{Cs}$.

Atomic Electric Dipole Moment

Separation of Charge along J: $\langle \mathbf{d} \rangle = g_d \langle \mathbf{J} \rangle$



$$\langle \vec{d} \rangle = e \langle \vec{r} \rangle = e \int \vec{r} \rho \, d^3r$$

We measure $g_d \langle \vec{J} \cdot \vec{E} \rangle$

E

EDM Motivations

Undiscovered

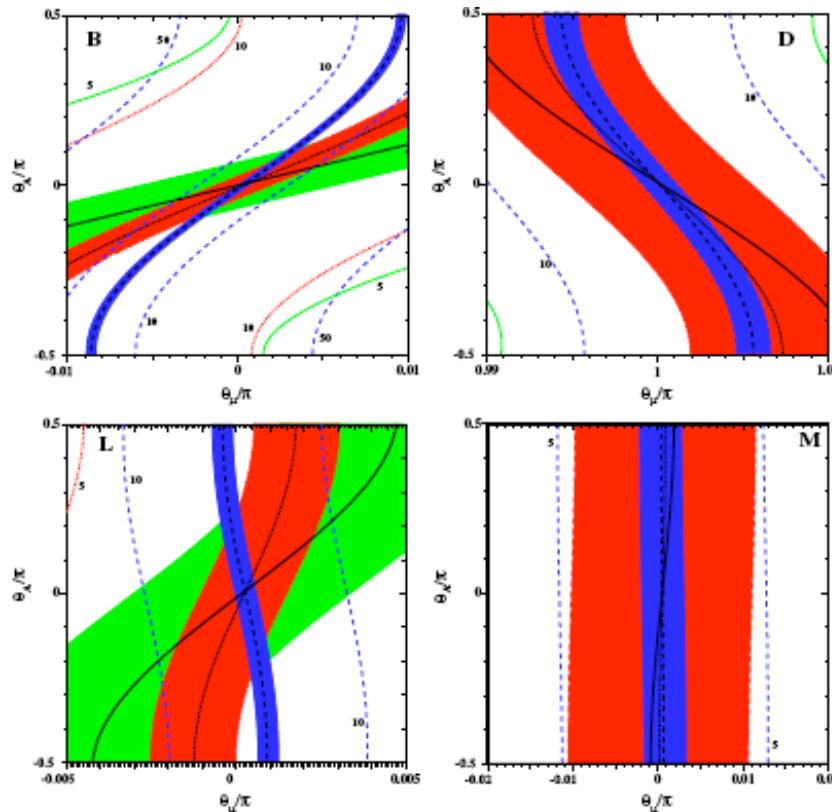
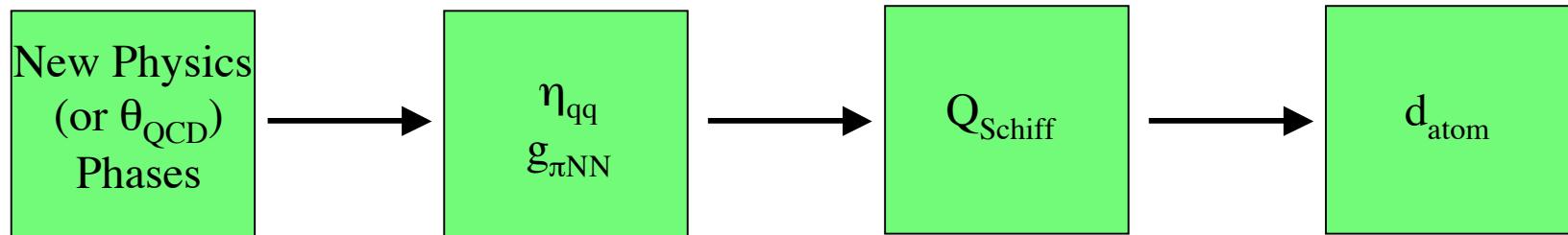
Study CP violation: mass scale

Signal of NEW PHYSICS (beyond SM - CKM)

Cosmological Baryon Asymmetry

EDMs and New Physics

CKM CP violation nearly vanishes



Keith A. Olive,¹ Maxim Pospelov,^{2,3,4} Adam Ritz,⁵ and Yudi Santoso^{2,3}
PHYSICAL REVIEW D 72, 075001 (2005)

Benchmark point ($m_{1/2}$, m_0 , $\tan\beta$)

B (250, 75, 10)

D (525, 130, 10)

L (450, 355, 50)

M (1500, 1100, 57)

- Neutron, electron and Schiff are complementary
- Even upper limits are important

EDMs and New Physics

CKM CP violation nearly vanishes

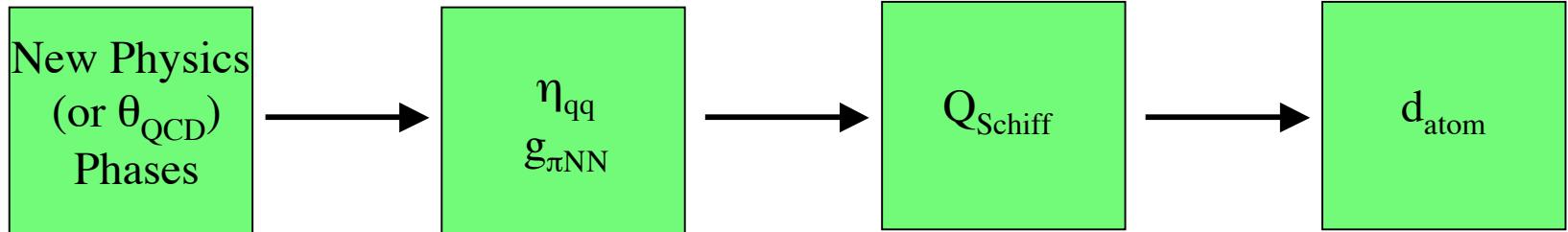


Table 1: Limits (90% C.L.) on phenomenological parameters of CP violation, including the most recent neutron EDM result[21] and evaluation of atomic sensitivities from reference [24].

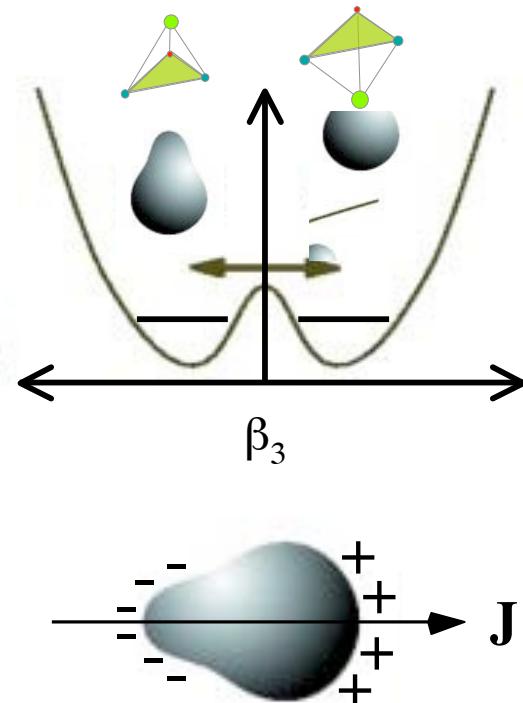
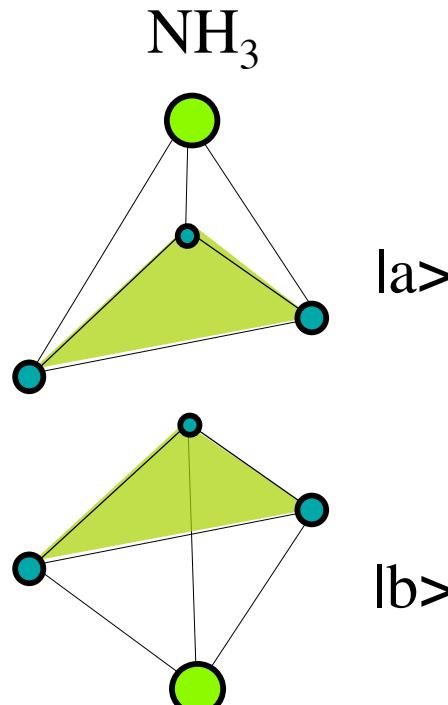
Parameter	^{199}Hg limit[20]	Neutron limit[21]	Other limits	Theory Ref.
θ_{QCD}	1.5×10^{-10}	4.1×10^{-10}	-	[26]
down quark EDM	-	5×10^{-26} e-cm	-	[23]
color EDM	3×10^{-26} e-cm	-	-	[26]
ϵ_q^{SUSY}	2×10^{-3}	5×10^{-3}	-	[27]
$\epsilon_q^{\text{Higgs}}$	$0.4 / \tan \beta^*$	-	$0.3 / \tan \beta$ (Tl)[18]	[27]
x^{LR}	1×10^{-3}	5×10^{-3}	-	[27]
C_T	1×10^{-8}	-	5×10^{-7} (Tl)[28]	[29]
C_S	3×10^{-7}	-	2×10^{-7} (Tl) [18]	[29]

*The ratio of masses of the two Higgs bosons in this theory is $\tan \beta$.

Atom	Year	95% upper bound [e-cm]	Ref.
^{129}Xe	1984	2.3E-26	Vold, Raab, Heckel, Fortson, PRL 52, 2229
	2001	6.6E-27	Rosenberry, Chupp, PRL 86, 22
^{199}Hg	1987	3.4E-26	Lamoreaux et al., PRL 59, 2275
	1993	1.3E-27	Jacobs et al., PRL 71, 3782
	1995	8.7E-28	Jacobs et al. PRA 52, 3521
	2001	2.1E-28	Romalis, Griffith, Jacobs, Fortson, PRL 86, 2505

Octupole Deformation-Parity Doublets

(see Feynman vol 3.)



$$|\psi_{\pm}\rangle = \frac{1}{\sqrt{2}} (|a\rangle \pm |b\rangle)$$

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

Nuclei with Octupole Deformation/Vibration

(Haxton & Henley; Auerbach, Flambaum, Spevak; Engel et al., Hayes & Friar, etc.)

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

$\eta_{qq} = 3.75 \times 10^{-4}$

	^{223}Rn	^{223}Ra	^{225}Ra	^{223}Fr	^{129}Xe	^{199}Hg
$t_{1/2}$	23.2 m	11.4 d	14.9 d	22 m		
I	7/2	3/2	1/2	3/2	1/2	1/2
ΔE th (keV)	37*	170	47	75		
ΔE exp (keV)	-	50.2	55.2	160.5		
$10^{11} S$ (e-fm ³)	375	150	115	185	0.6	-0.75
$10^{28} d_A$ (e-cm)	1250	1250	940	1050	0.3	2.1

Ref: Dzuba PRA66, 012111 (2002) - Uncertainties of 50%

*Based on Woods-Saxon Potential

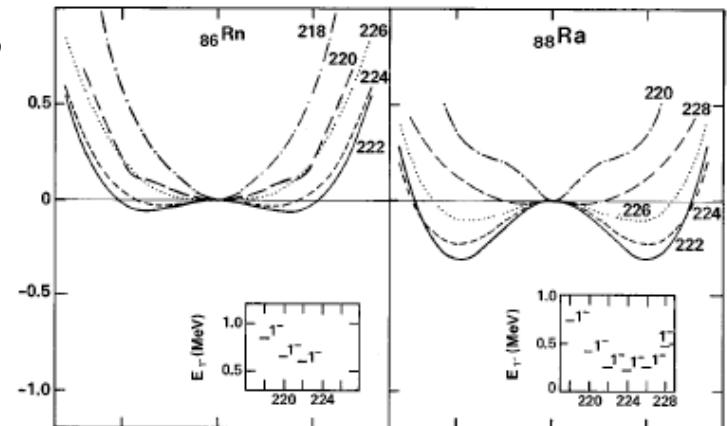
† Nilsson Potential Prediction is 137 keV

NOTES:

Octupole Enhancements

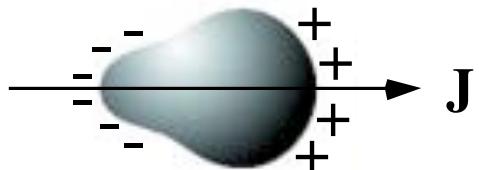
Engel et al. agree with Flambaum et al.

Even octupole vibrations enhance S (Engel, Flambaum& Zelevinsky)



Nuclei with Octupole Deformation/Vibration

(Haxton & Henley; Auerbach, Flambaum, Spevak; Engel et al., Hayes & Friar, etc.)

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


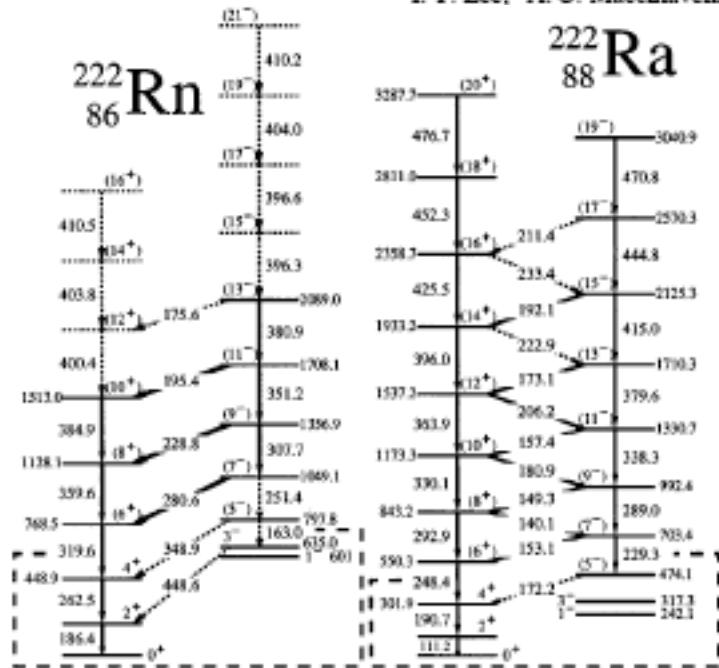
VOLUME 78, NUMBER 15

PHYSICAL REVIEW LETTERS

14 APRIL 1997

Observation of Octupole Structures in Radon and Radium Isotopes and Their Contrasting Behavior at High Spin

J. F. C. Cocks,¹ P. A. Butler,¹ K. J. Cawn,¹ P. T. Greenlees,¹ G. D. Jones,¹ S. Asztalos,² P. Bhattacharyya,³ R. Broda,⁴ R. M. Clark,² M. A. Deleplanque,² R. M. Diamond,² P. Fallon,² B. Formal,⁴ P. M. Jones,⁵ R. Julin,⁵ T. Lauritsen,⁶ I. Y. Lee,² A. O. Macchiavelli,² R. W. MacLeod,² J. F. Smith,⁷ F. S. Stephens,² and C. T. Zhang³



β decay Studies of Rn Structure

8π @ TRIUMF

- Very high-level density in the odd-A Rn isotopes within the β decay Q-value window
- Many/most of the transitions will be highly converted.
- Long chain of radioactive daughters requires flexible collect, count, move, cycles.
- In this environment a γ -ray or electron singles spectrum is of little use in establishing structure/(i.e. a decay scheme).
- High statistics β : γ - γ , γ -e, e-e are required
- The 8π Spectrometer at ISAC is certainly the world's best facility for such studies.
- Timeline Issues: At beams at ISAC – 2010 (2008?) + 1 year for analysis
(meets start of RadonEDM)

Why $^{223}/^{221}\text{Rn}$?

- Octupole vibration or deformation enhancement.
- Long(er) half-life
- EDM measurement in cells (see ^{129}Xe)
- Co-magnometer measurement

VOLUME 86, NUMBER 1

PHYSICAL REVIEW LETTERS

1 JANUARY 2001

Atomic Electric Dipole Moment Measurement Using Spin Exchange Pumped Masers of ^{129}Xe and ^3He

M. A. Rosenberry* and T. E. Chupp

University of Michigan, Ann Arbor, Michigan 48109

(Received 1 August 2000)

We have measured the T -odd permanent electric dipole moment of ^{129}Xe with spin exchange pumped masers and a ^3He comagnetometer. The comagnetometer provides a direct measure of several systematic effects that may limit electric dipole moment sensitivity, and we have directly measured the effects of changes in leakage current that result when the applied electric field is changed. Our result, $d(^{129}\text{Xe}) = 0.7 \pm 3.3(\text{stat}) \pm 0.1(\text{syst}) \times 10^{-27}e\text{ cm}$, is a fourfold improvement in sensitivity.

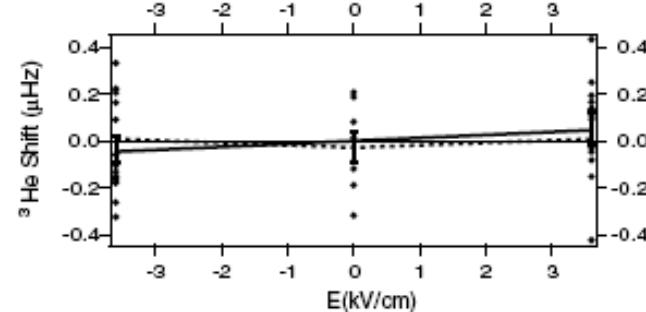
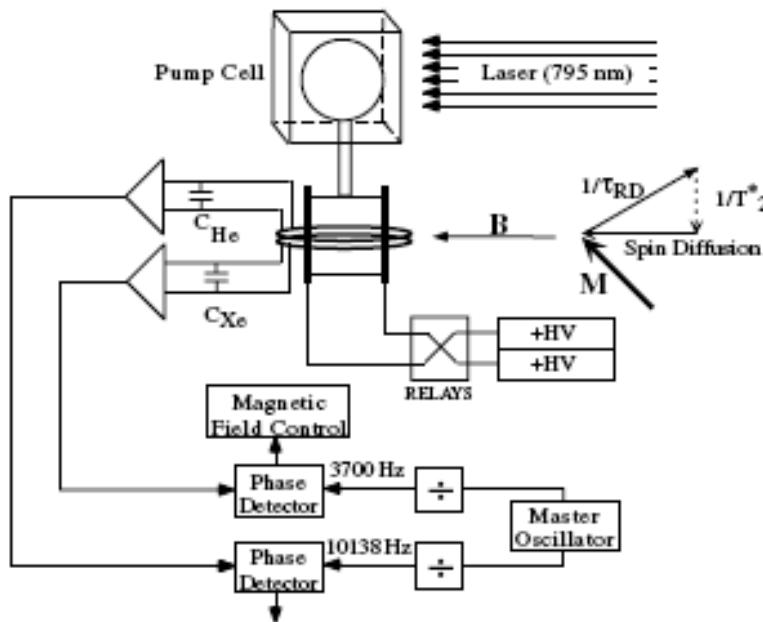
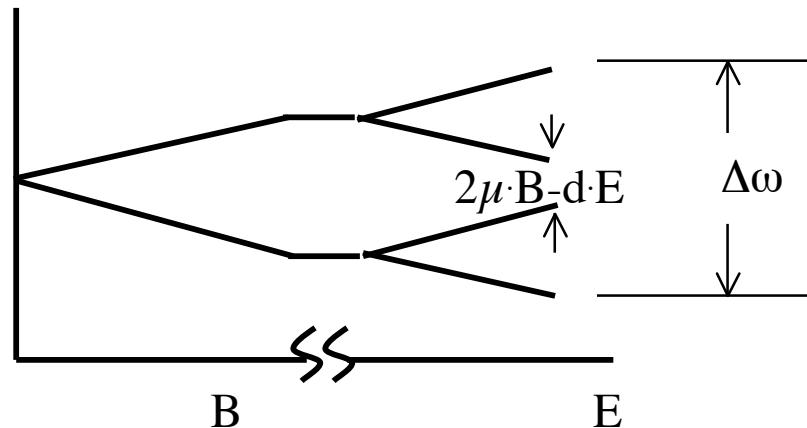
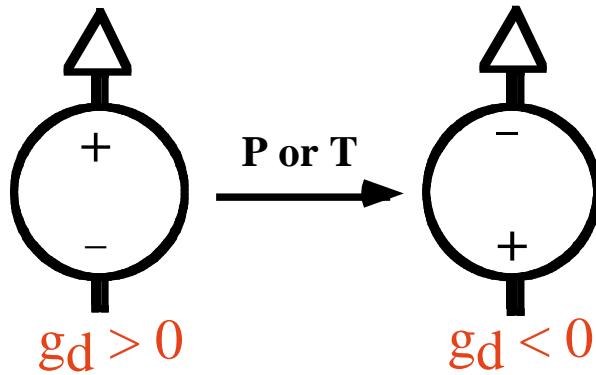


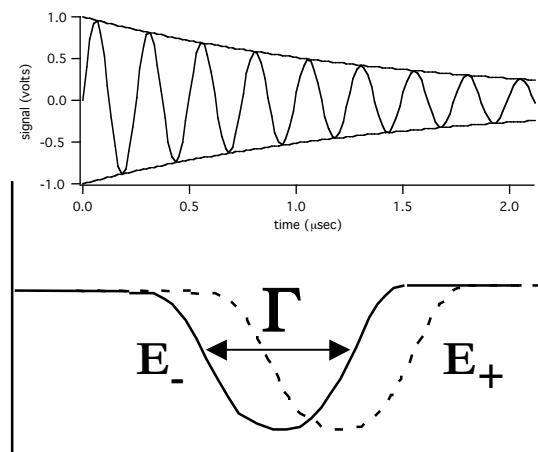
FIG. 2. Corrected ^3He beat frequencies for a single run plotted

Atomic Electric Dipole Moment - Techniques



Polarize RF pulse Measure
 E+

Collect



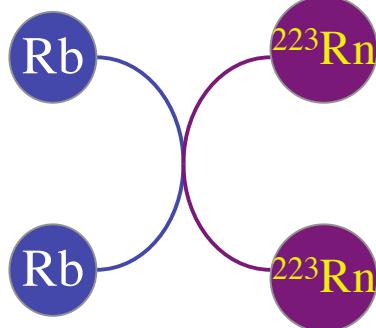
T₂
RF power
B homogeneity

Precision: $(\sigma_d)^{-1} = 4E\Gamma^{-1}$ (S/N)

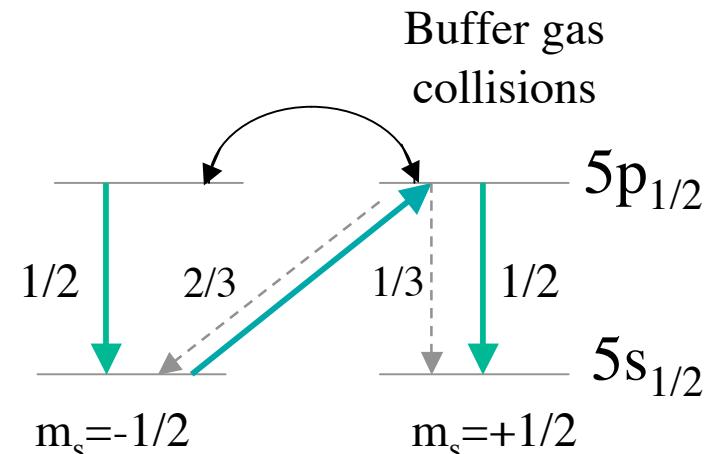
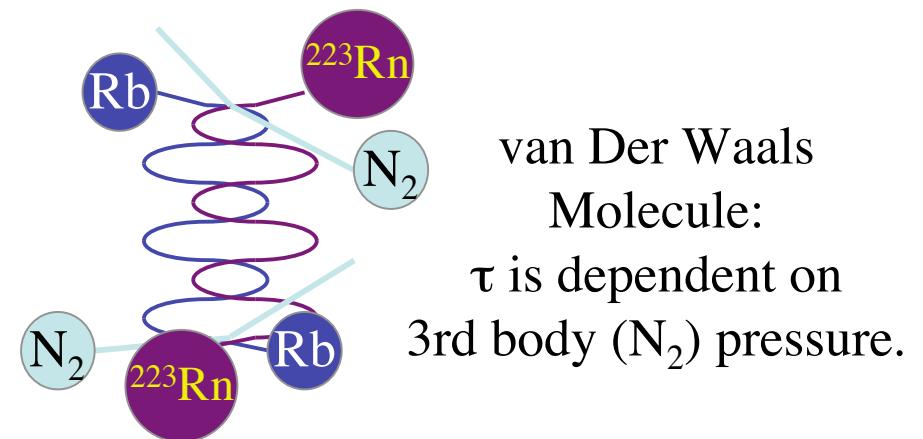
$$S/N = \sqrt{A^2 N_{Rn}}$$

Spin-Exchange Optical Pumping

- Optically pump the Rb with circularly polarized laser light.
- Spin-exchange collisions transfer the polarization to the radon nuclei.



Binary Collision:
 $\tau \sim 10^{-12}$ sec.

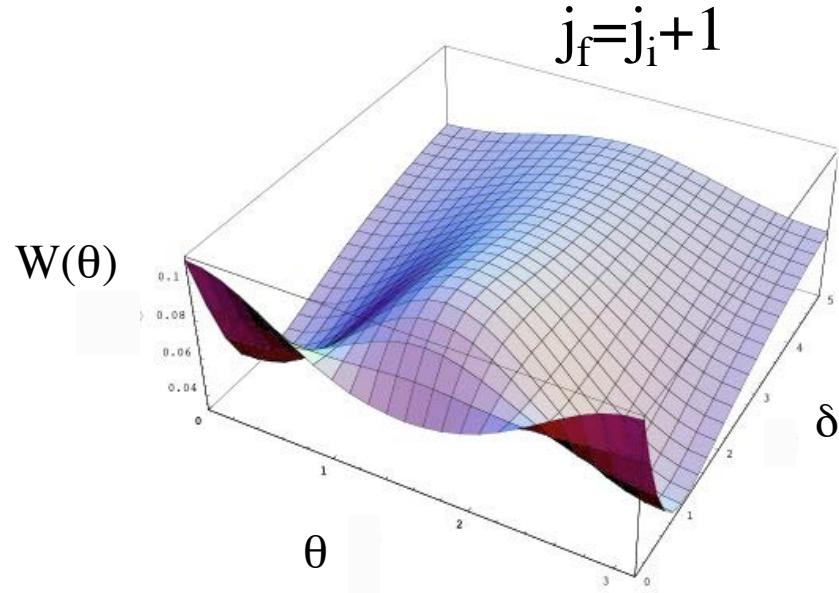


Gamma Ray Anisotropies

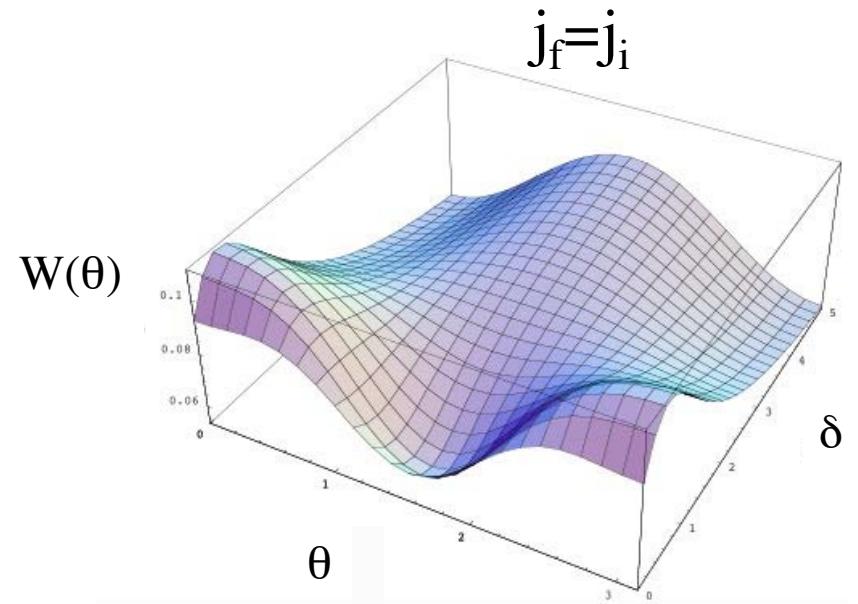
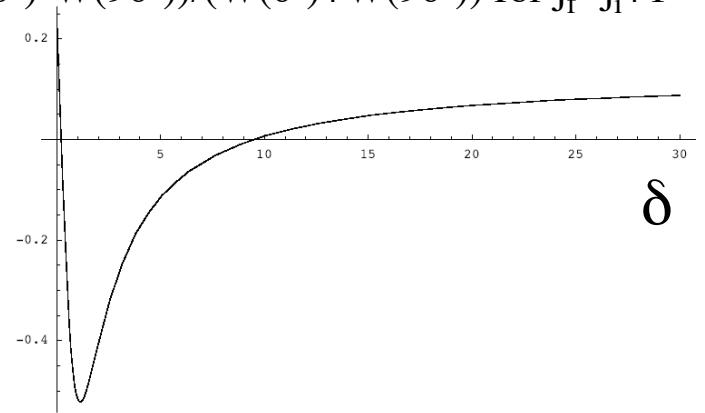
- Polarized nuclei emit gamma rays with calculable directional distributions.

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

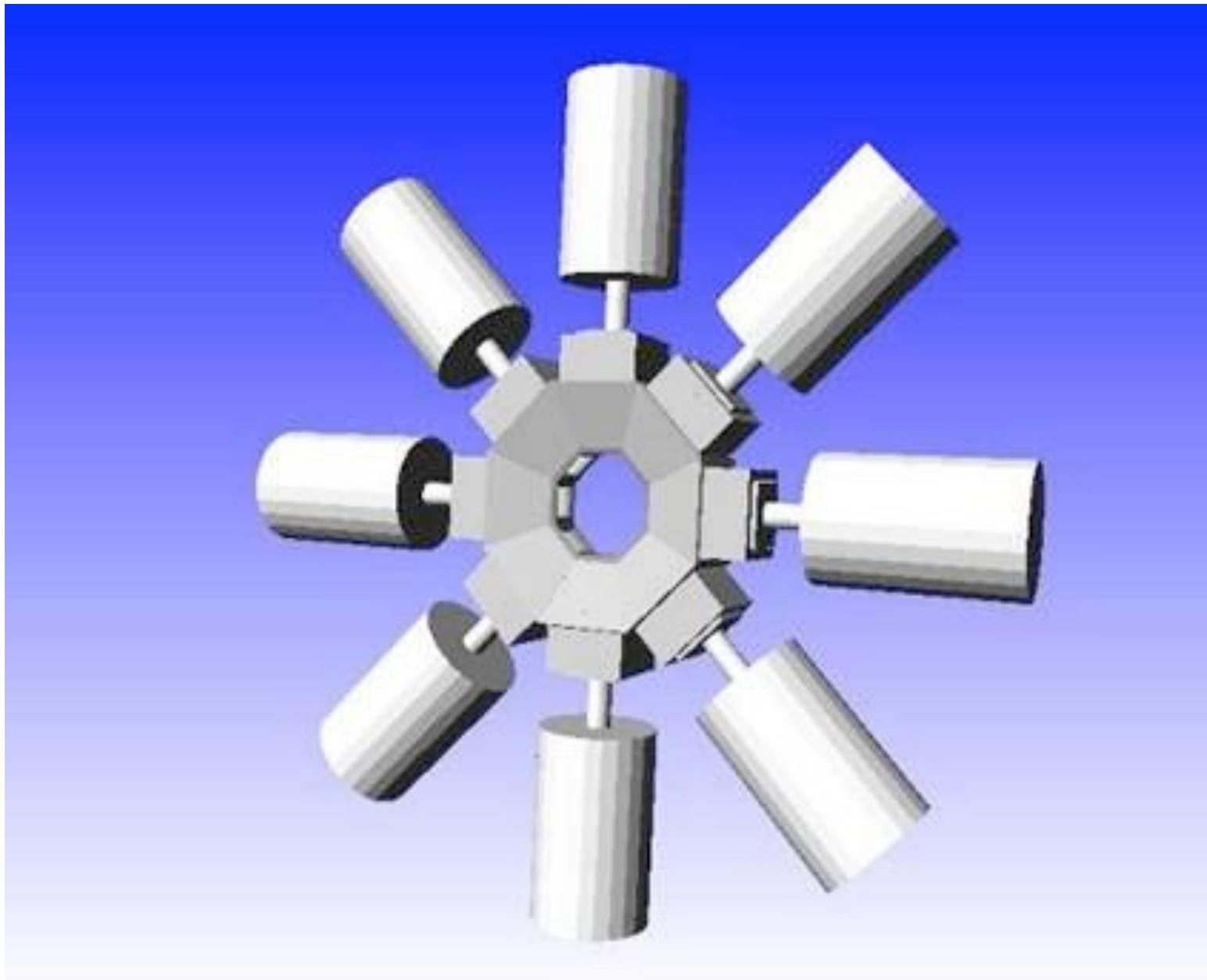
$j_f = j_i - 1$ pure dipole transition



$$(W(0^\circ) - W(90^\circ)) / (W(0^\circ) + W(90^\circ)) \text{ for } j_f = j_i + 1$$



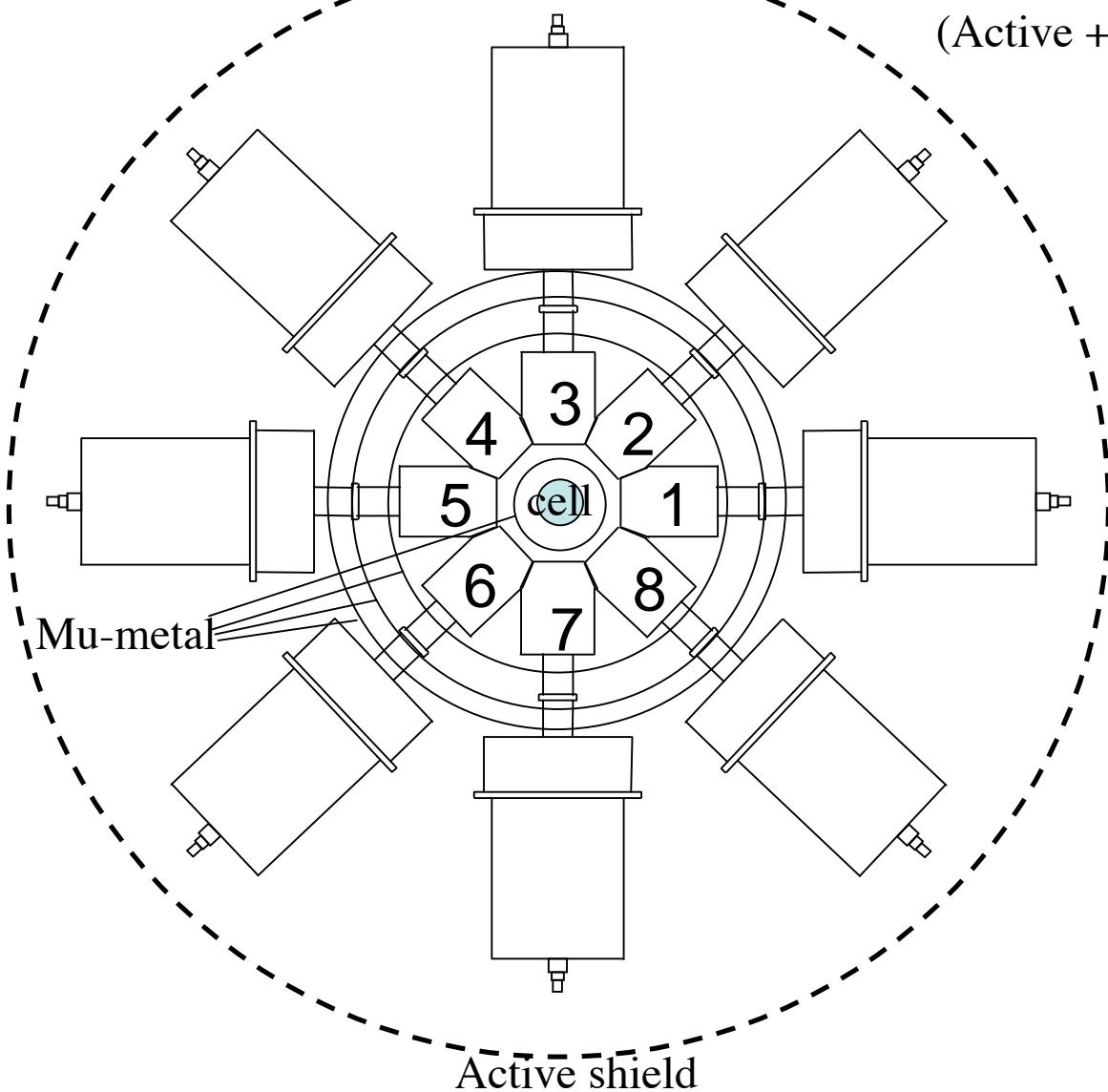
Tigress/Griffin



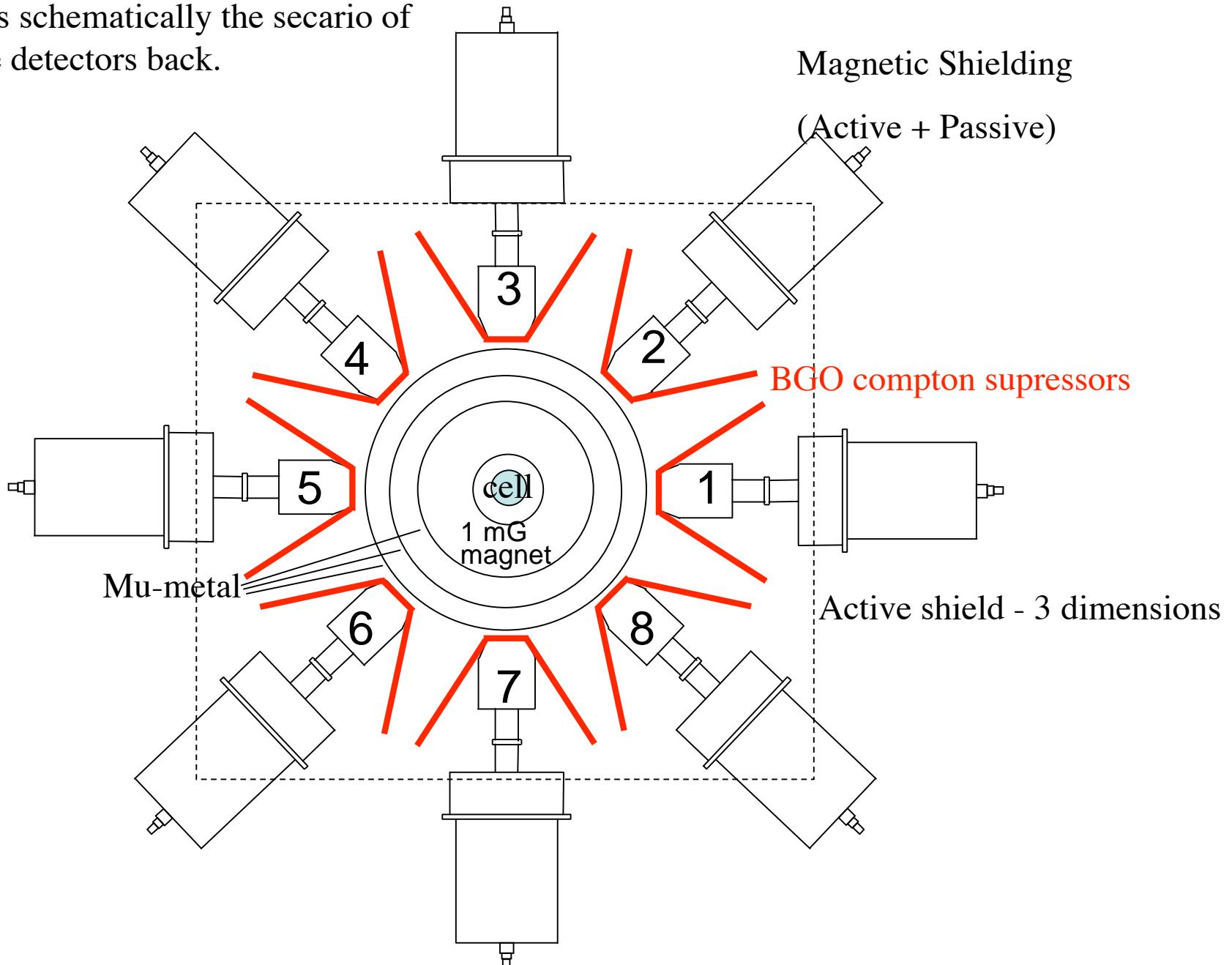
8-Trigress/Griffin detectors

Magnetic Shielding

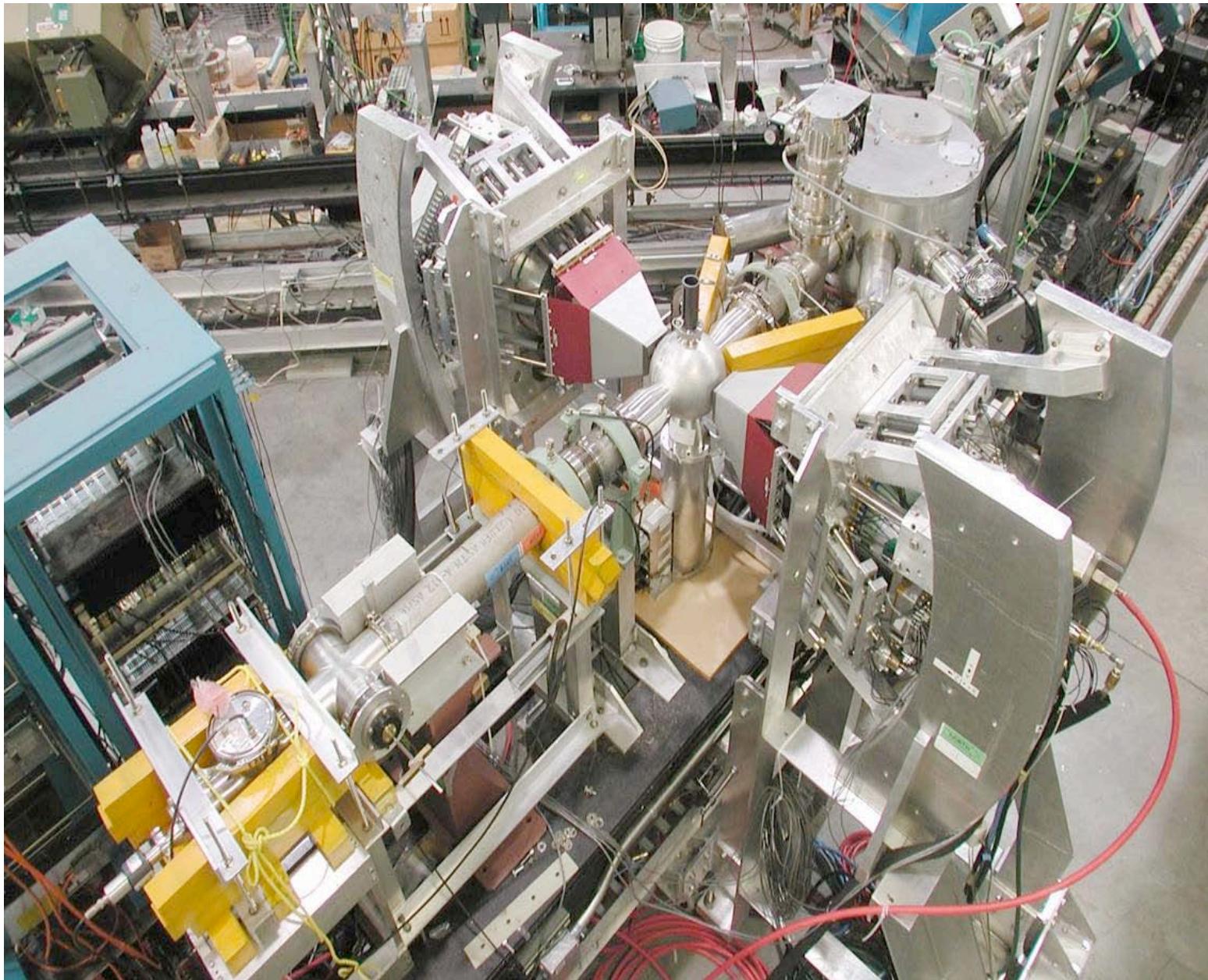
(Active + Passive)

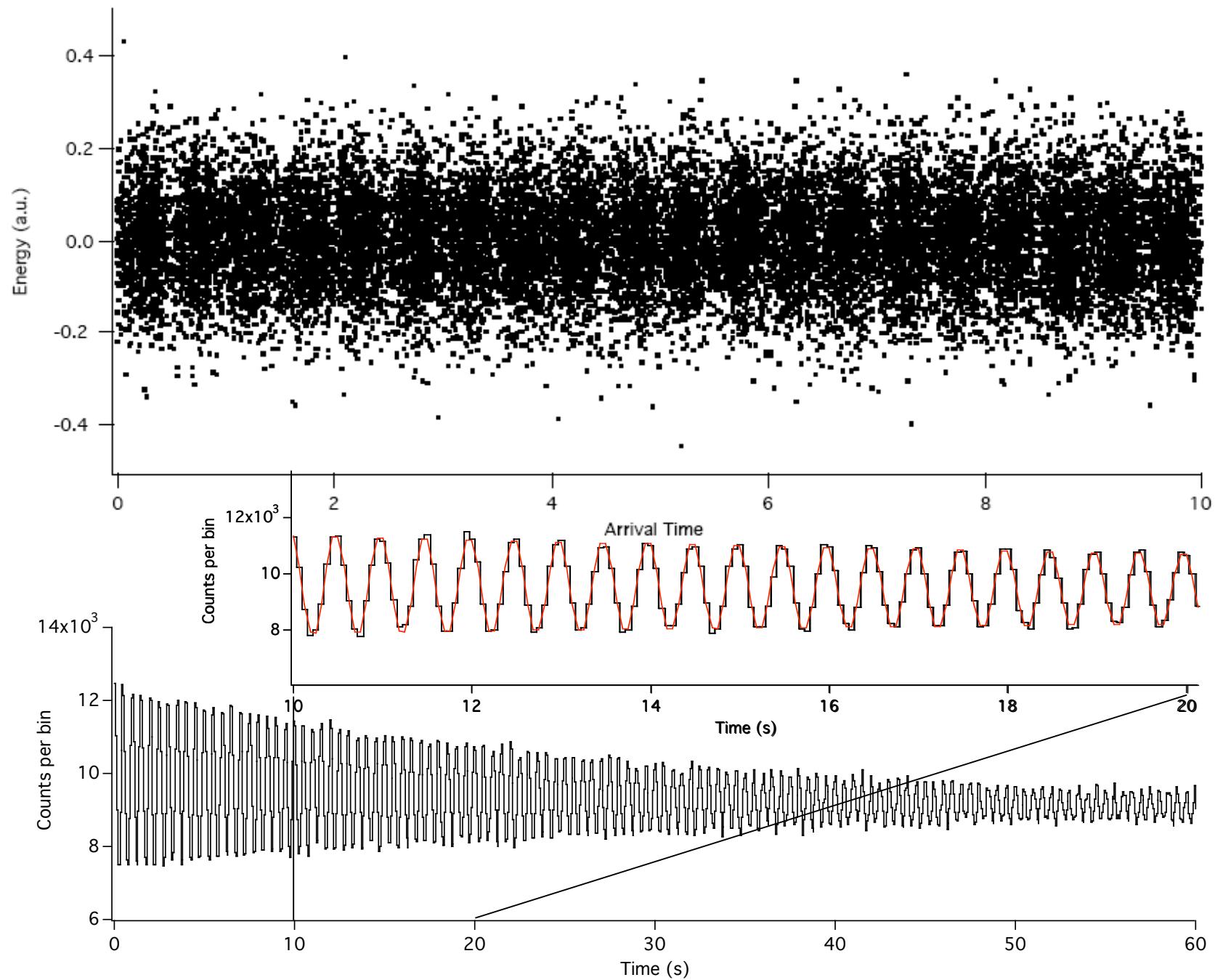


This shows schematically the scenario of pulling the detectors back.



Tigress



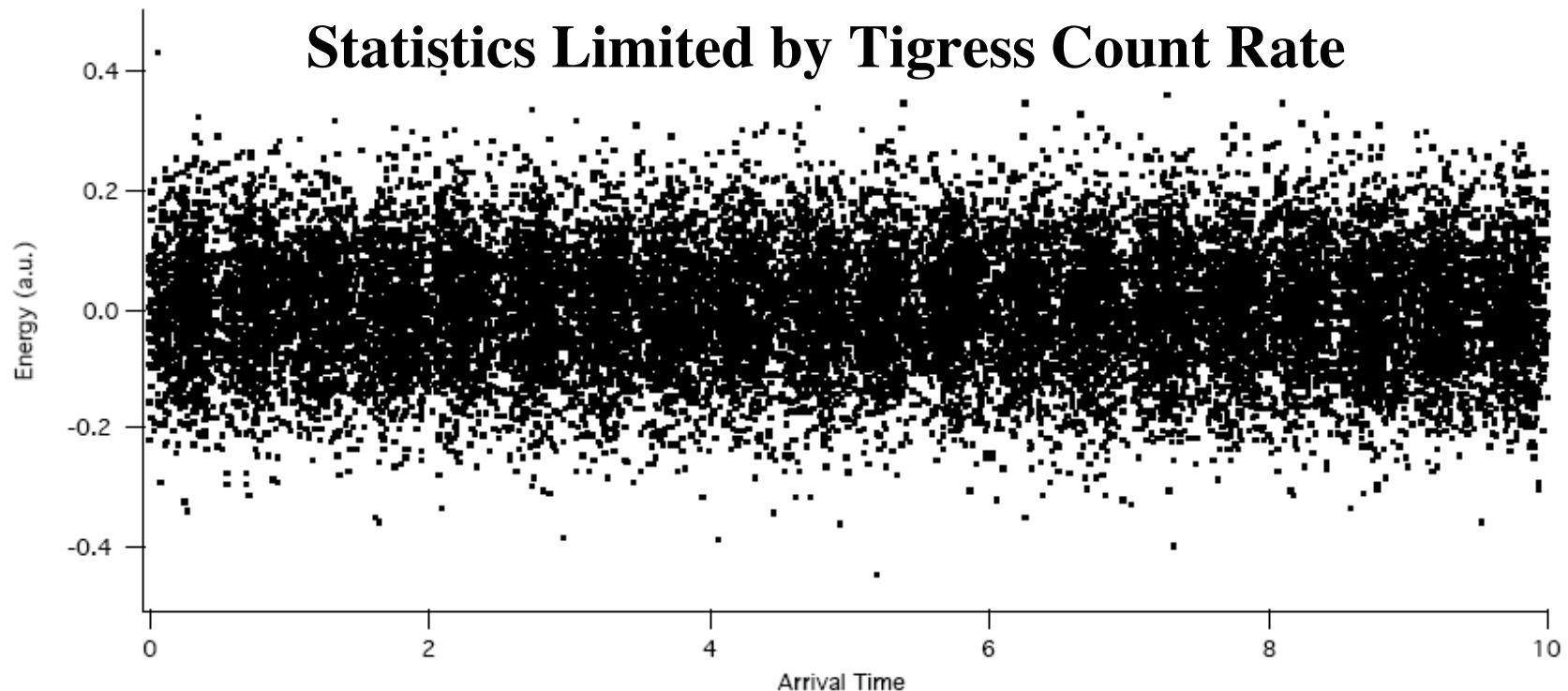


Gamma Anisotropy ($A=0.2$ 0.1)

$T_2 = 30$ s $E=5$ kV/cm

	Gamma Anisotropy
Count Rate (s^{-1})	1.2×10^5
A	0.2
Background	0.01
Total N (100 Days)	1×10^{12}
σ_{d_A} (e-cm)	1×10^{-26}

We only need beam 10%
of the time



Beta Asymmetry

$$R = R_0 \left(1 + \frac{p_e}{E_e} A_\beta \hat{J} \cdot \hat{r} \right)$$

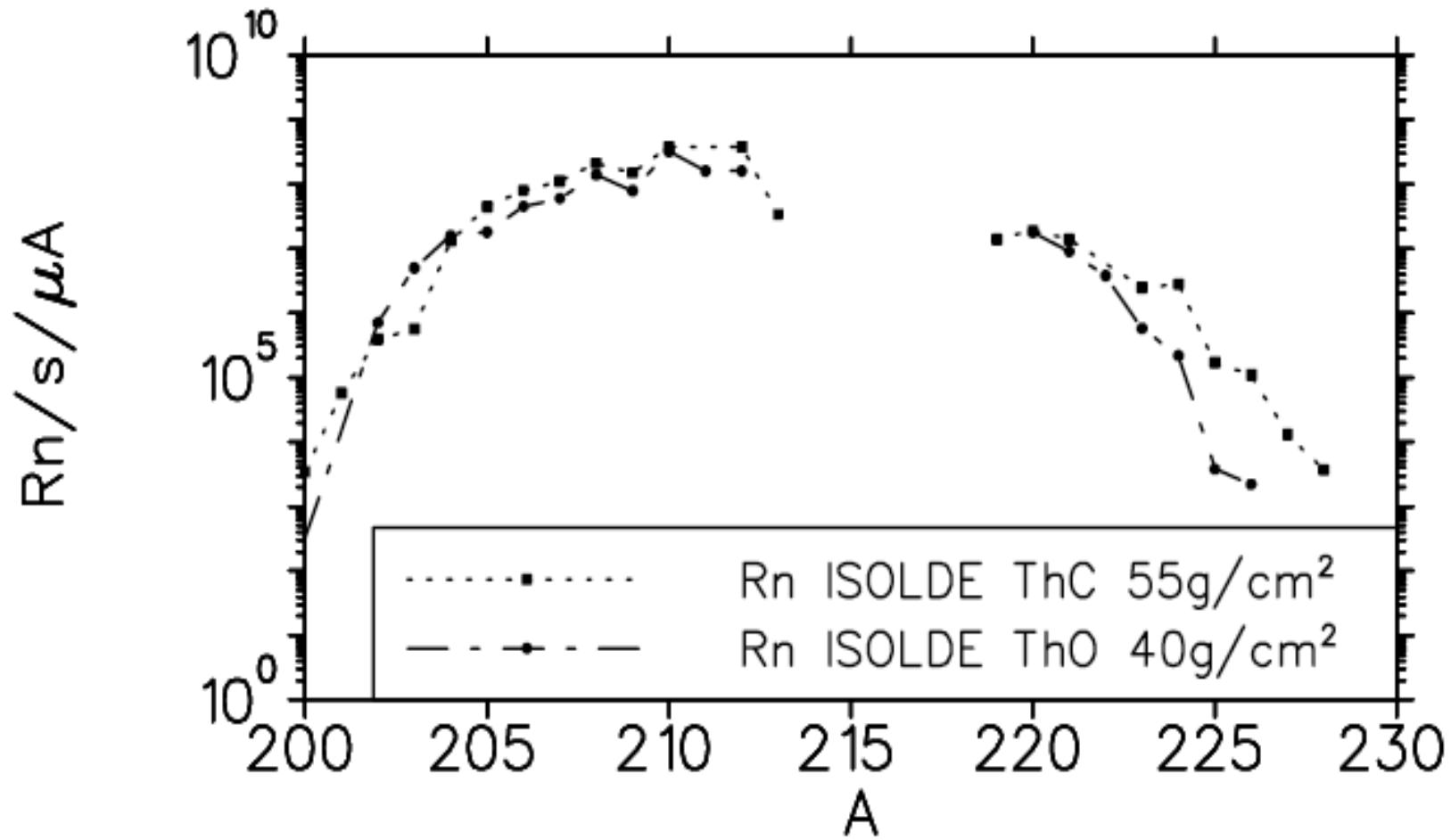
$$\xi A_\beta = \pm \kappa |g_A|^2 |\langle \sigma \rangle|^2 - (g_V g_A^* + g_A g_V^*) \langle 1 \rangle \langle \sigma \rangle \sqrt{\frac{J_i}{1 + J_1}}$$

J_i^π	J_f^π	A_β	note
7/2	9/2	+7/9	100% β^- decay; pure GT
	7/2	-2/9	not pure GT
	5/2	-1	pure GT

- No count rate limit (current detection mode)
- Discriminate species only by frequencies
- Scattered betas (lower effective A, Background)

	Gamma Anisotropy	beta asymmetry	
		ISAC	ISAC $\times 20$
Count Rate (s^{-1})	1.2×10^5	5×10^6	4×10^7
A	0.2	0.2	0.2
Background	0.01	0.3	0.3
Total N (100 Days)	1×10^{12}	4×10^{13}	8×10^{14}
σ_{d_A} (e-cm)	1×10^{-26}	4×10^{-27}	5×10^{-28}

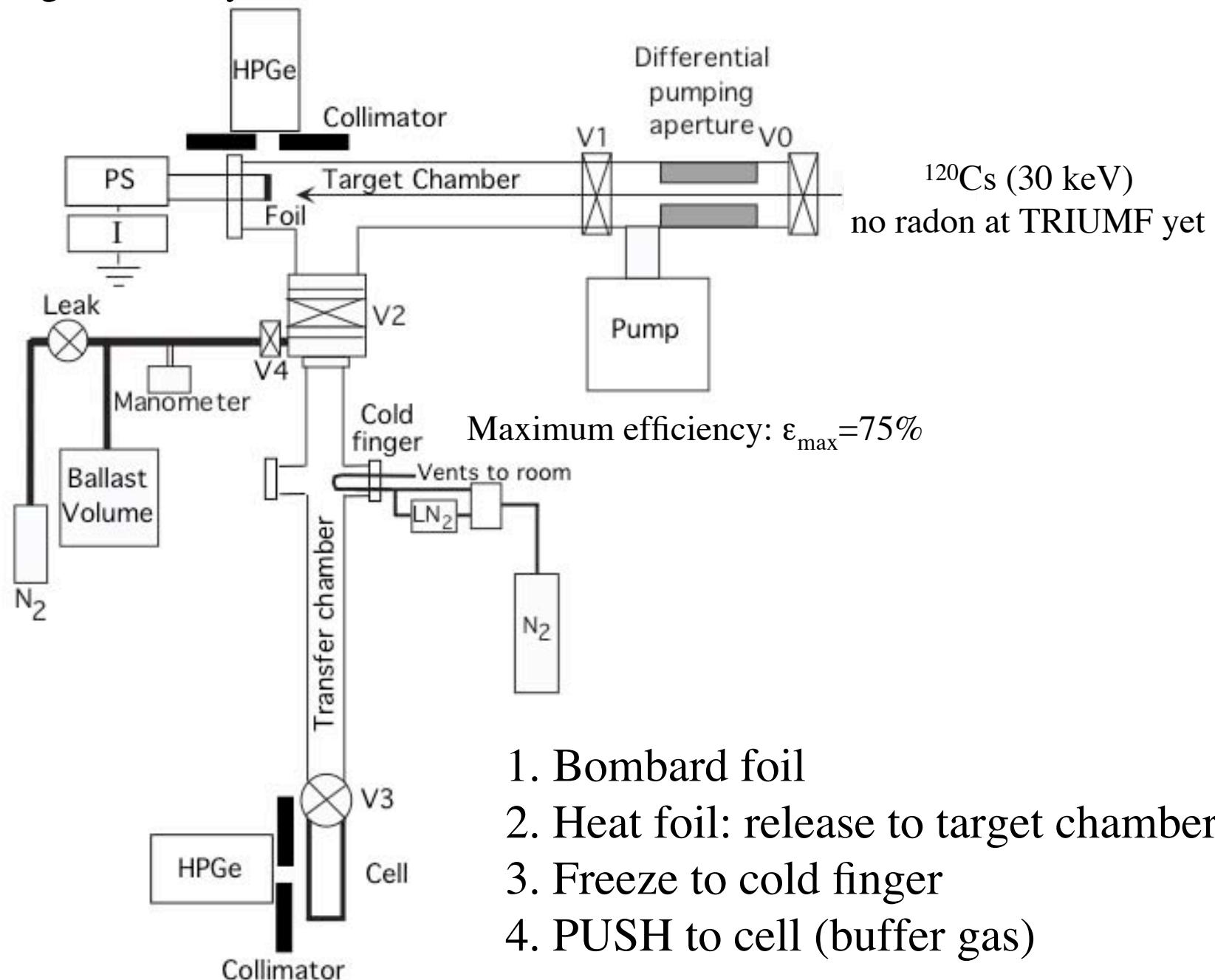
Rn Yields (extracted)

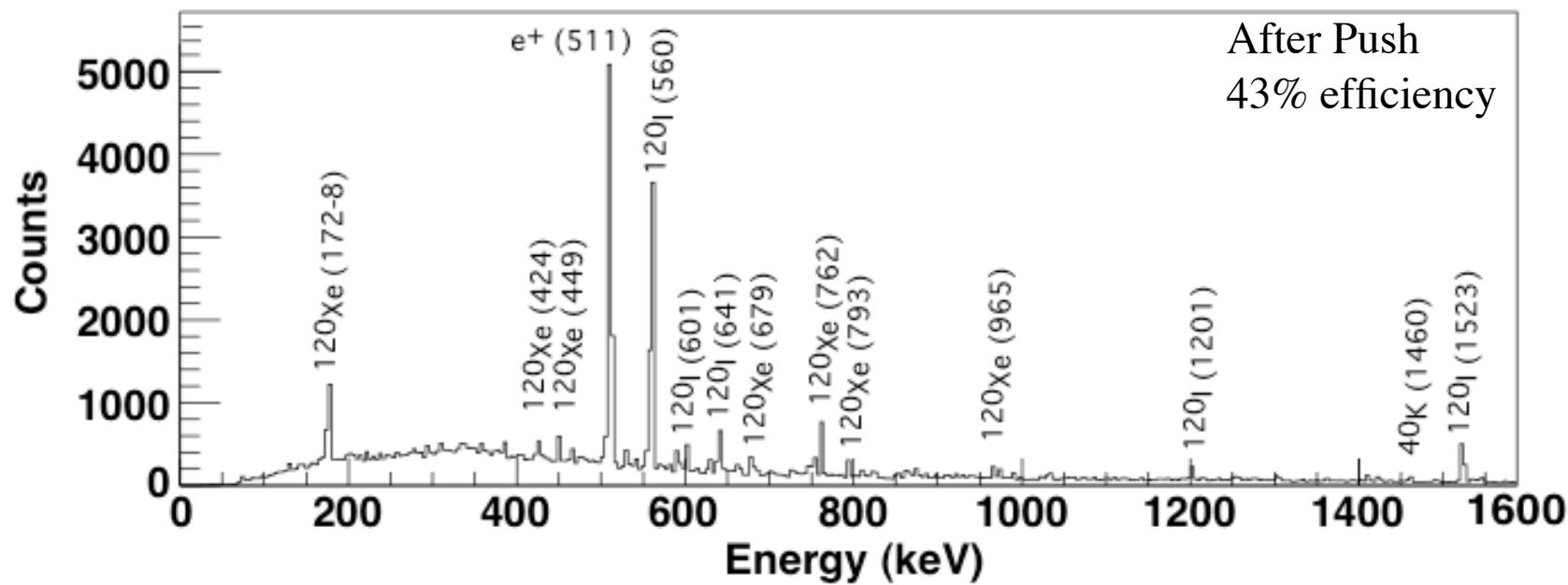
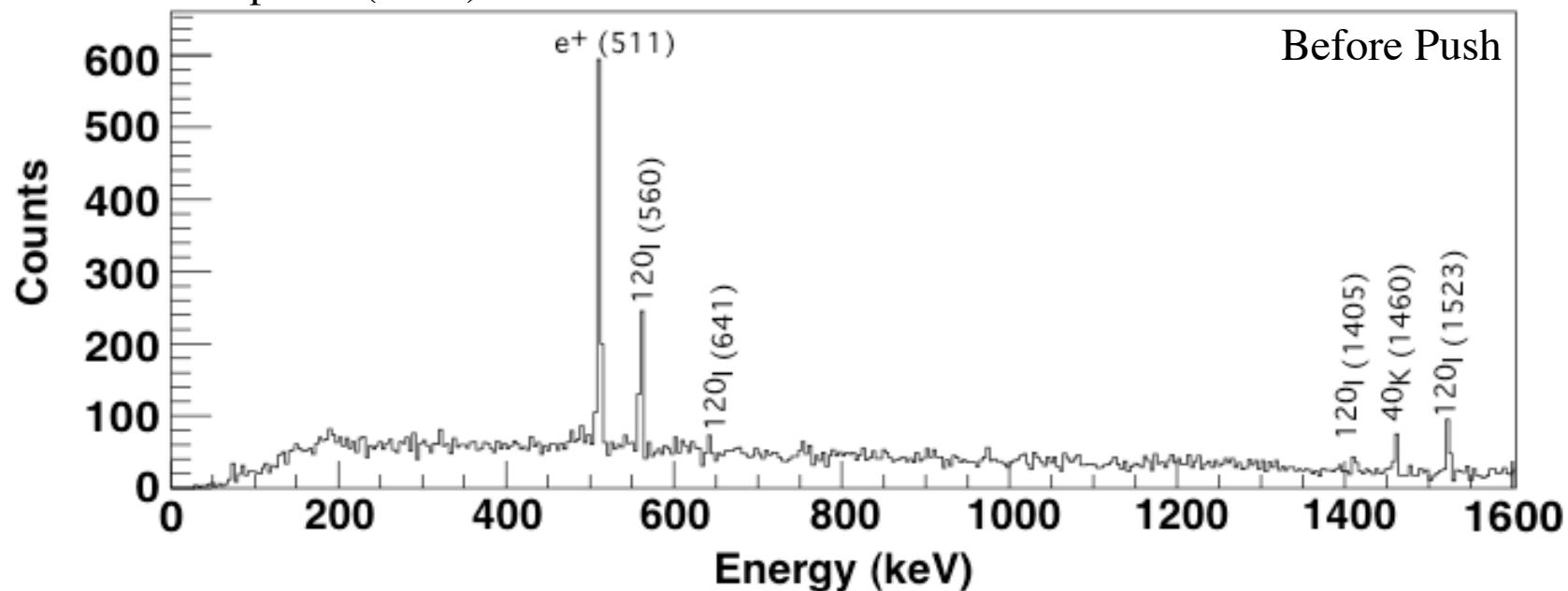


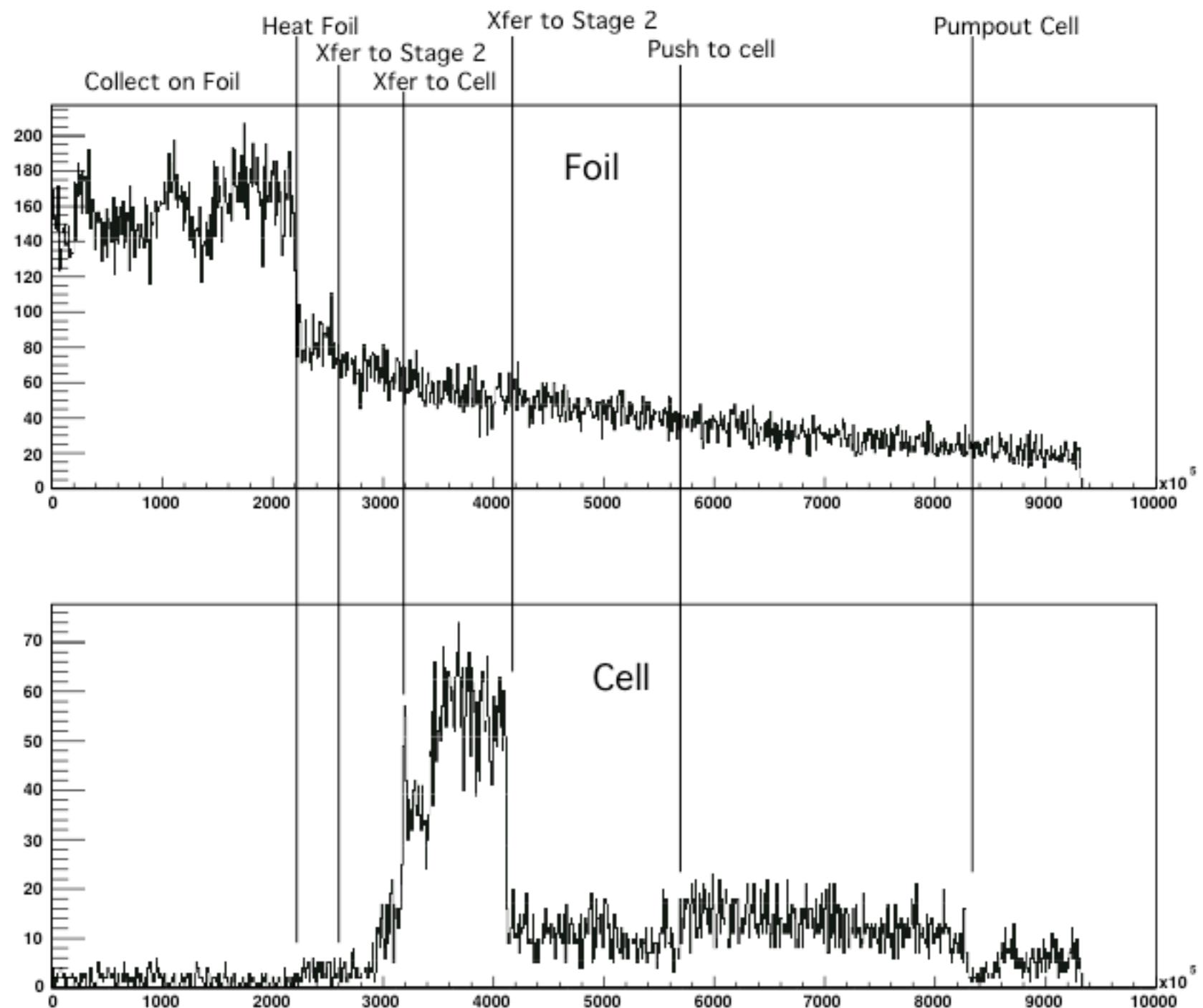
Progress

- Noble gas collection with ^{120}Xe
- ^{209}Rn polarization and relaxation at Stony Brook
- ISAC Floor space
- EDM cell development
- Tigress delivery
- Increasing work-load and collaboration

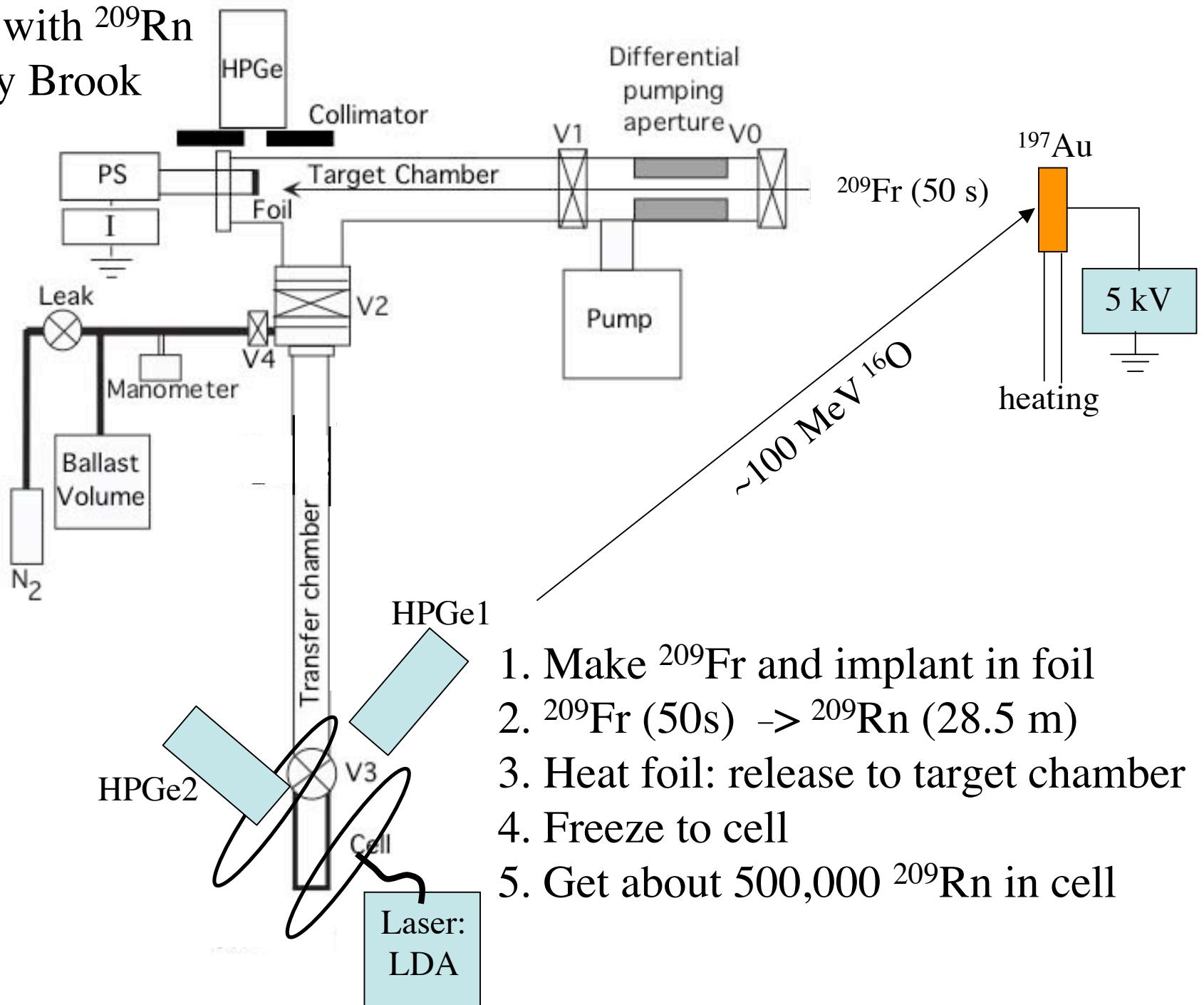
Progress: High efficiency tranfer of ^{120}Xe at TRIUMF: from millstones to milestones



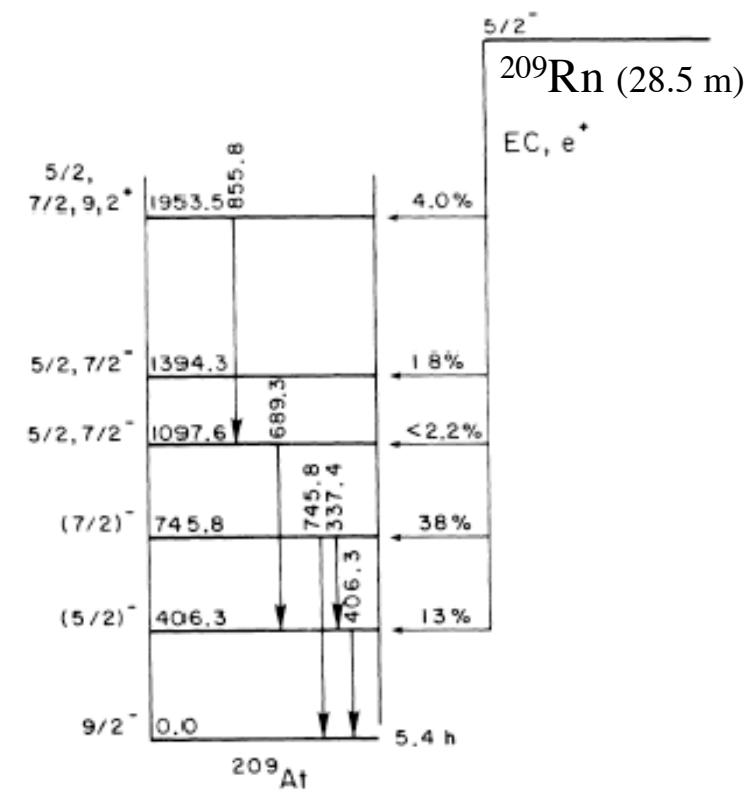
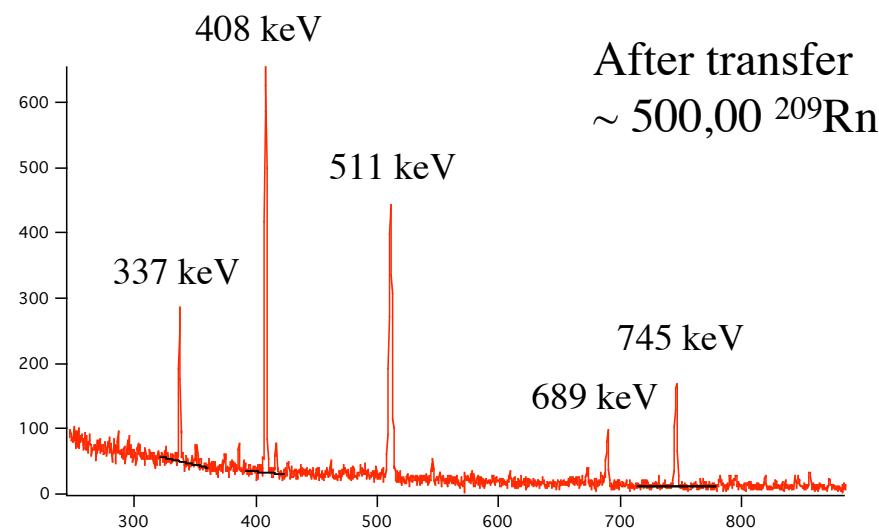
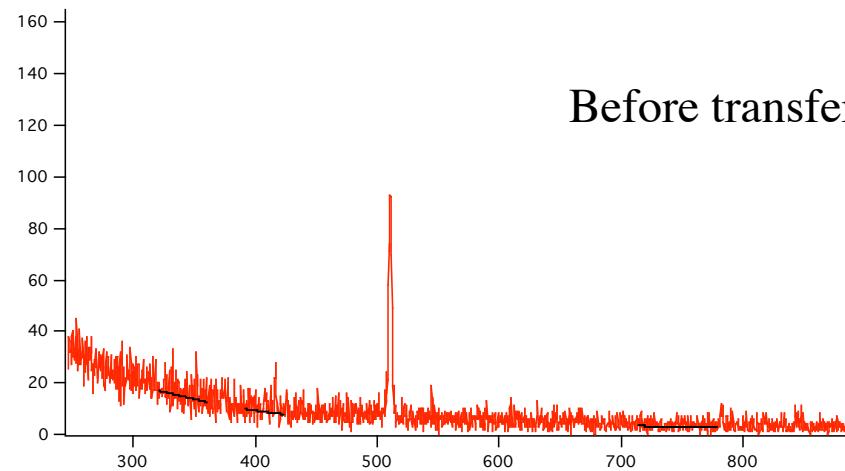




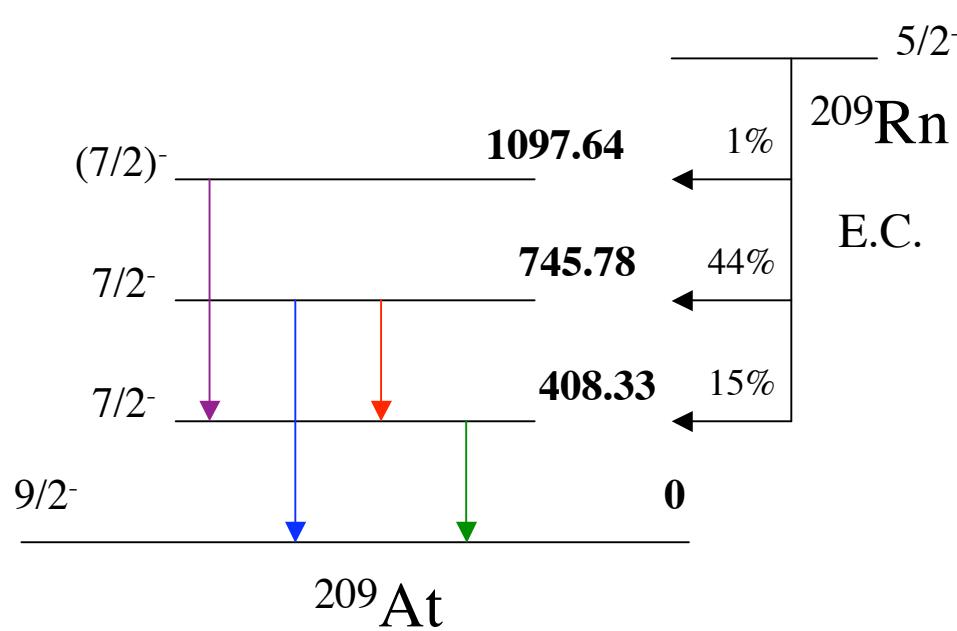
Studies with ^{209}Rn @ Stony Brook



1. Make ^{209}Fr and implant in foil
2. ^{209}Fr (50s) $\rightarrow ^{209}\text{Rn}$ (28.5 m)
3. Heat foil: release to target chamber
4. Freeze to cell
5. Get about 500,000 ^{209}Rn in cell



The ^{209}Rn Decay Scheme



$$\delta^2 = \frac{a_1^2}{a_2^2}$$

$a_1 = 1 \Rightarrow$ pure dipole

$a_2 = 1 \Rightarrow$ pure quadrupole

require : $a_1^2 + a_2^2 = 1$

γ -ray Energy Intensity δ (Mixing Ratio)

337.45 14.5 ∞

408.32 50.3 0

689.26 9.7 >3.57

745.78 22.8 >2.86

from Table of Isotopes

Polarization and relaxation of radon

E. R. Tardiff,¹ J. A. Behr,³ T. E. Chupp,¹ K. Gulyuz,⁴ R. S. Lefferts,⁴ W. Lorenzon,² S. R. Nuss-Warren,¹ M. R. Pearson,³ N. Pietralla,⁴ G. Rainovski,⁴ J. F. Sell,⁴ and G. D. Sprouse⁴

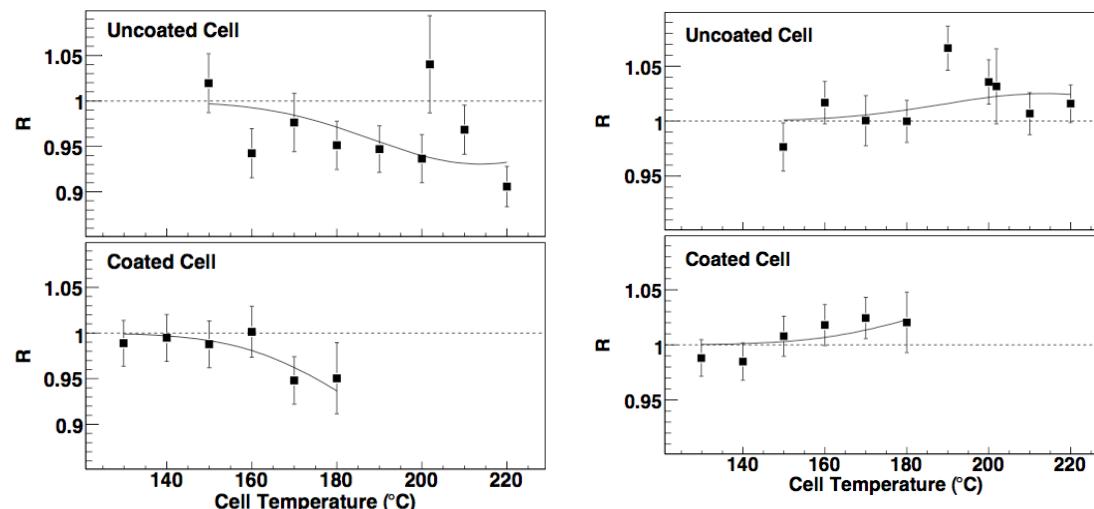
¹FOCUS Center, University of Michigan Physics Department, 450 Church St., Ann Arbor 48109-1040, USA

²University of Michigan Physics Department, 450 Church St., Ann Arbor 48109-1040, USA

³TRIUMF, 4004 Westbrook Mall, Vancouver V6T 2A3, Canada

⁴SUNY Stony Brook Department of Physics and Astronomy, Stony Brook 11794-3800, USA

(Dated: December 6, 2006)



Fit for Γ_2 ($T_a = 300^\circ\text{K}$):
 0.05 Hz (uncoated);
 0.03 Hz (coated)
 Use $2.5 \times 10^{-21} \text{ cm}^2$

VOLUME 60, NUMBER 21

PHYSICAL REVIEW LETTERS

23 MAY 1988

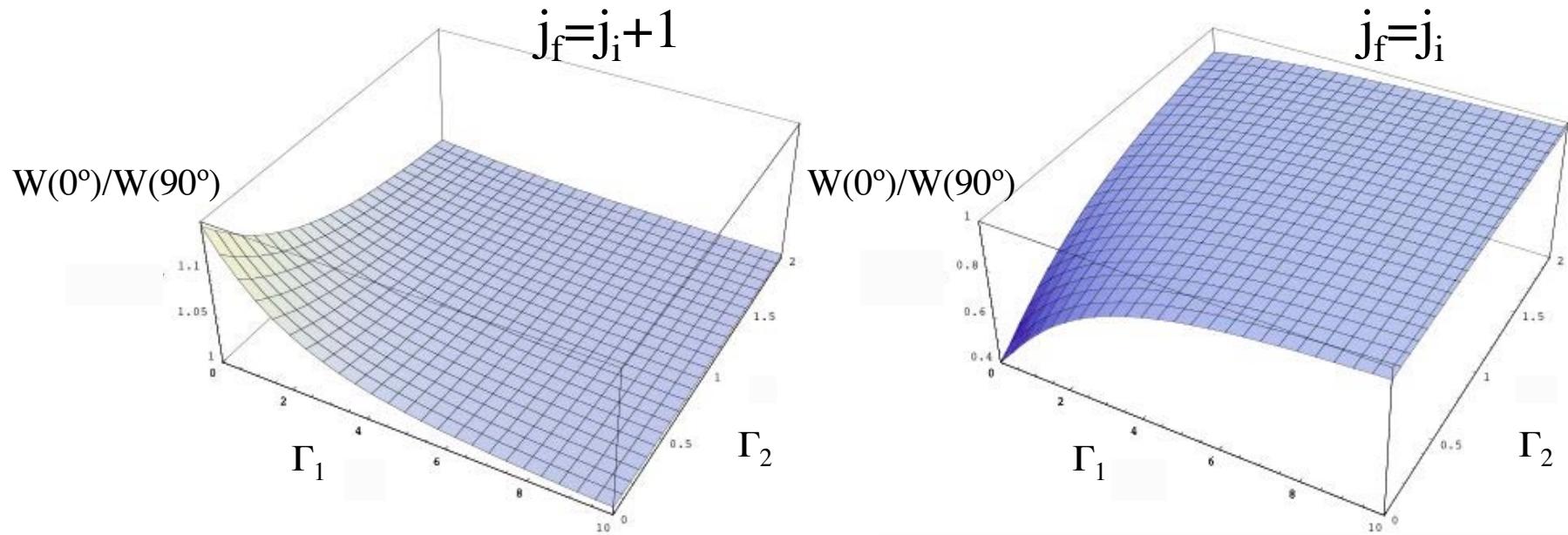
Nuclear Orientation of Radon Isotopes by Spin-Exchange Optical Pumping

M. Kitano,^(a) F. P. Calaprice, M. L. Pitt, J. Clayhold, W. Happer, M. Kadar-Kallen, and M. Musolf

E_γ (keV)	Spin sequence	Anisotropy R	$R - 1$ (%)
337	$(\frac{1}{2}^-) - (\frac{5}{2}^-)$	0.903(14)	-9.7 ± 1.4
408	$(\frac{1}{2}^-) - (\frac{9}{2}^-)$	1.009(7)	$+0.9 \pm 0.7$
689	$\frac{5}{2}^+, \frac{7}{2}^-, \frac{5}{2}^-$	1.079(22)	$+7.9 \pm 2.2$
745	$(\frac{1}{2}^-) - (\frac{9}{2}^-)$	1.129(14)	$+12.9 \pm 1.4$

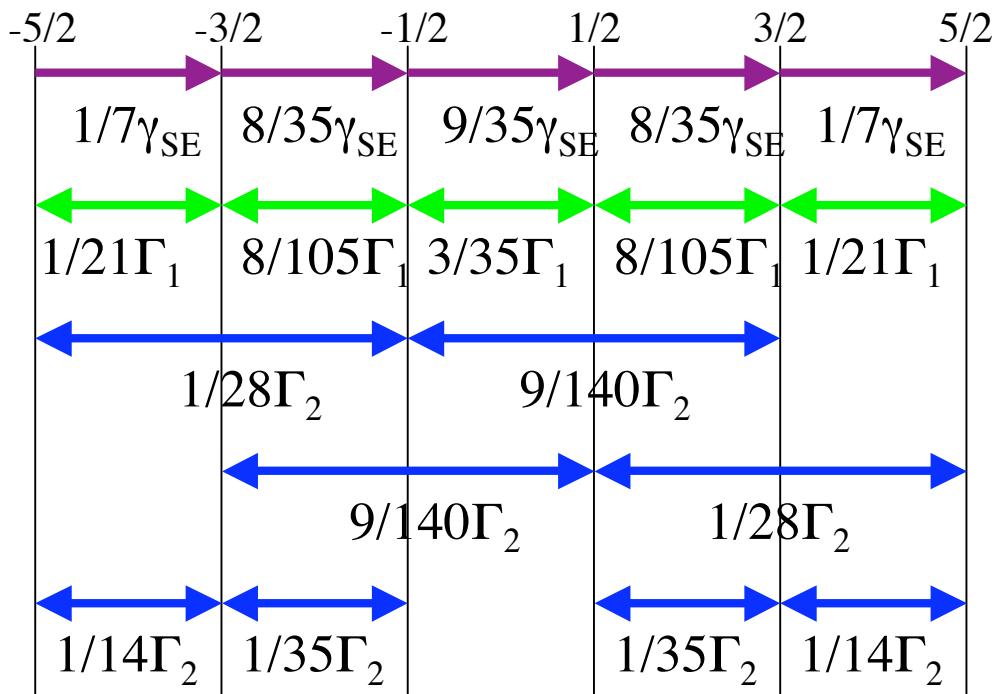
Modeling Polarization

- Quadrupole relaxation should be the dominant mechanism.
- As a first approximation, set $\Gamma_1=0$, calculate γ_{SE} for a given T , and calculate the expected anisotropies.



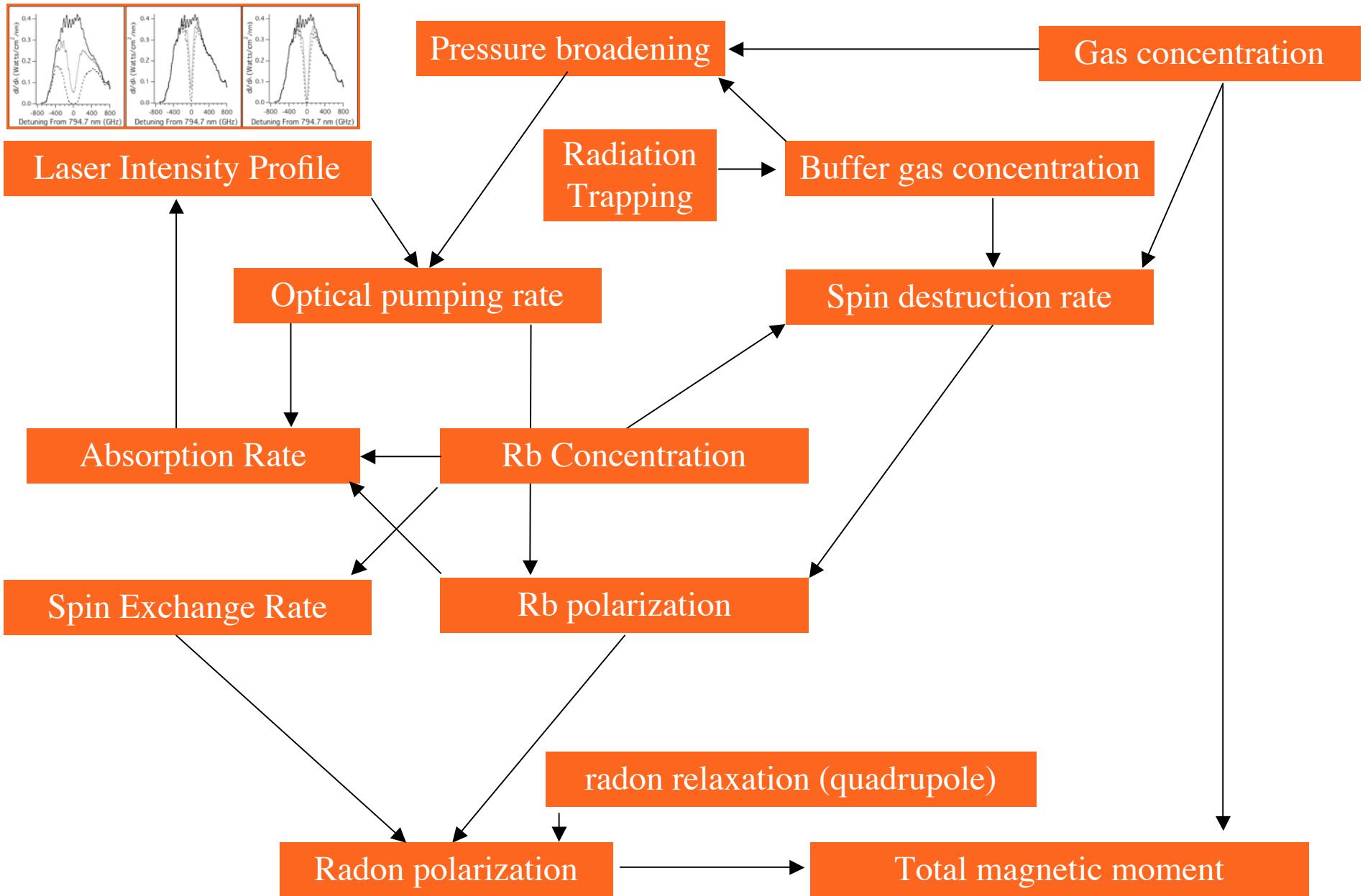
Modeling Polarization

- 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.
- The dipole and quadrupole relaxation rates, Γ_1 and Γ_2 , must be determined from data.



$$\Gamma_2(T) = \Gamma_2^\infty e^{\Delta E / kT}$$

Spin Exchange Pumping

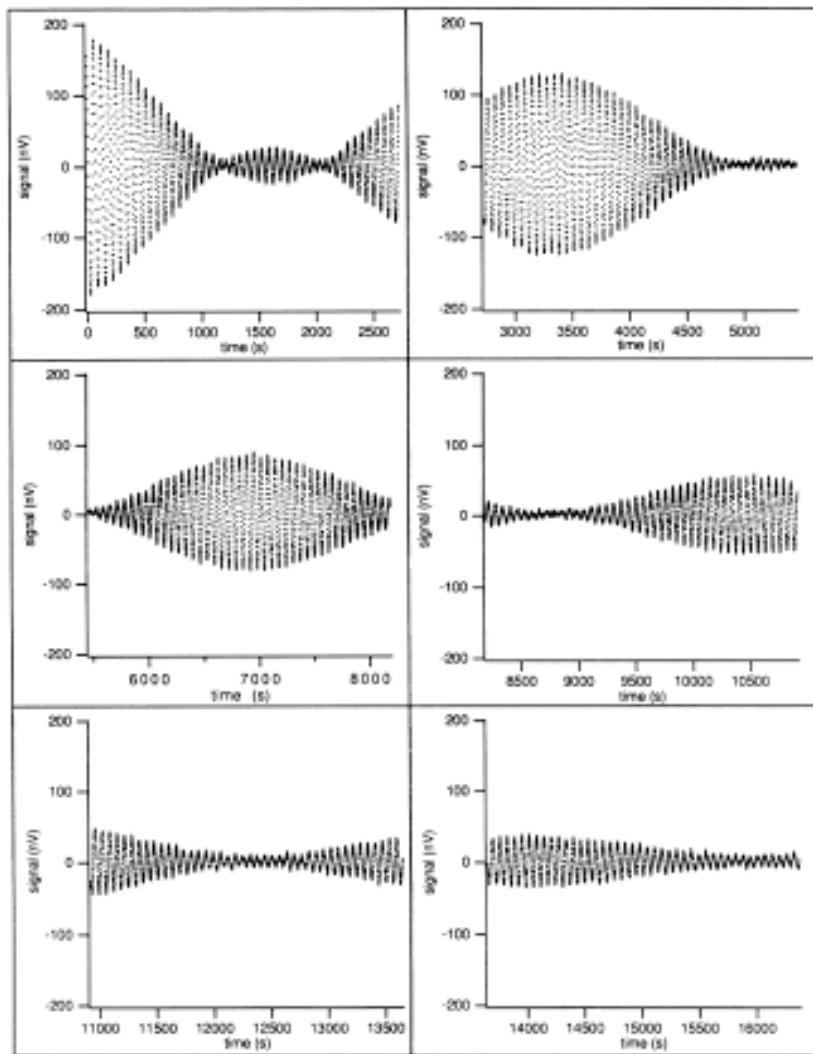


Coherence in Freely Precessing ^{21}Ne and a Test of Linearity of Quantum Mechanics

T. E. Chupp and R. J. Hoare

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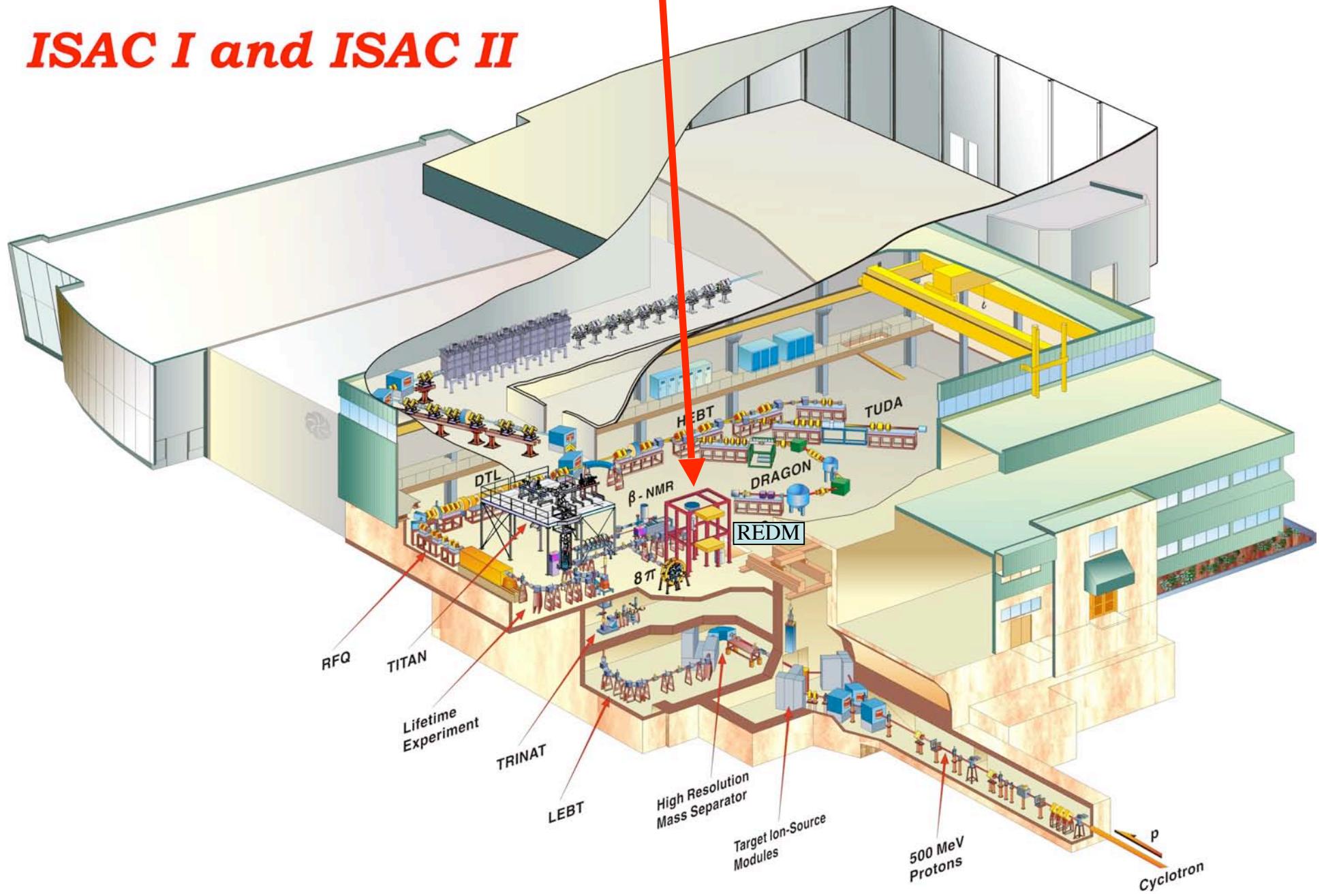
(Received 28 February 1990)



Shows $T_2 \sim 4.5$ h, dominated by Quadrupole Interactions ($\Gamma_2 \gg \Gamma_1$)

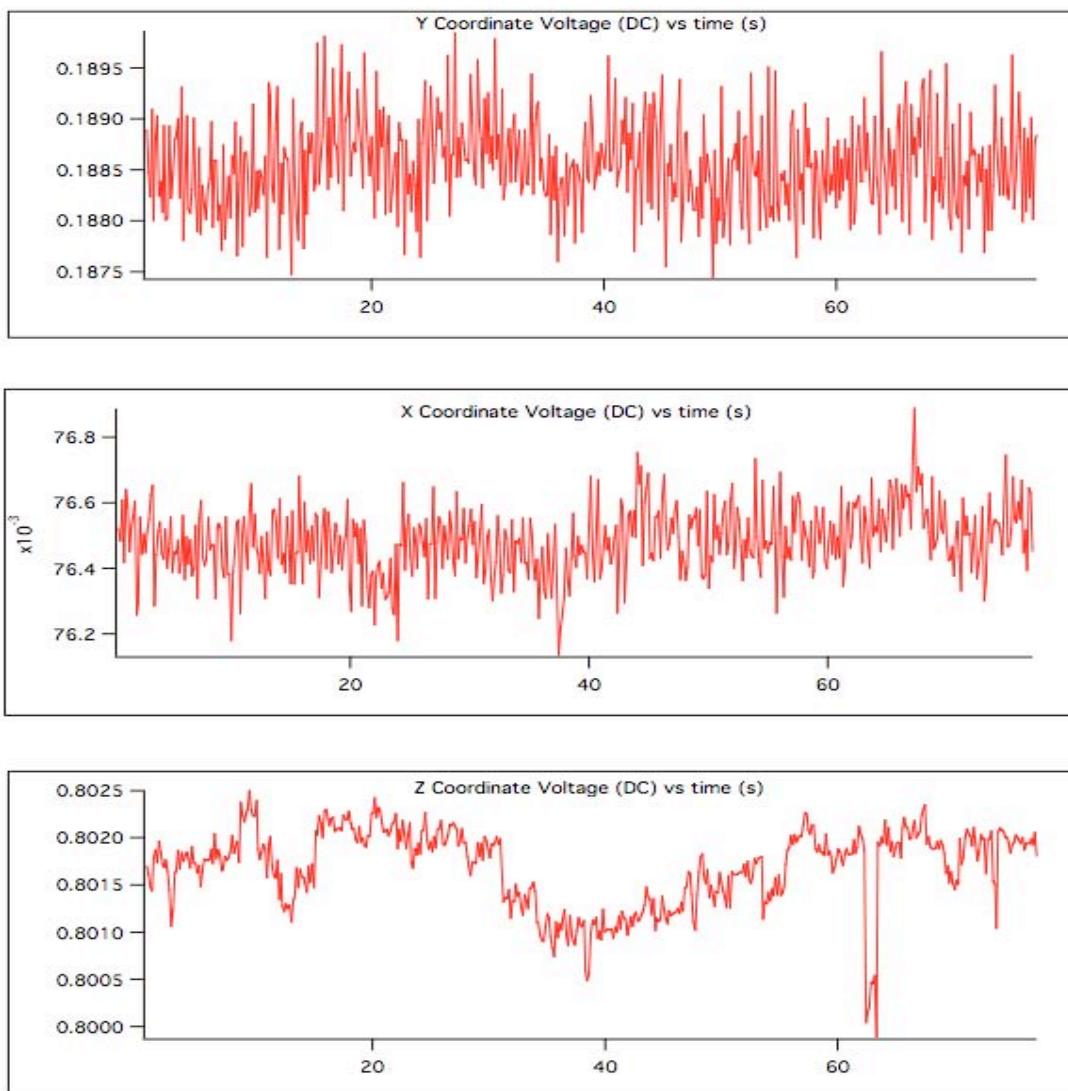
We've started setting up at TIRUMF

ISAC I and ISAC II



Remote Tracking of Laboratory Fields:

(magnetometer at TRIUMF, Control in Michigan)



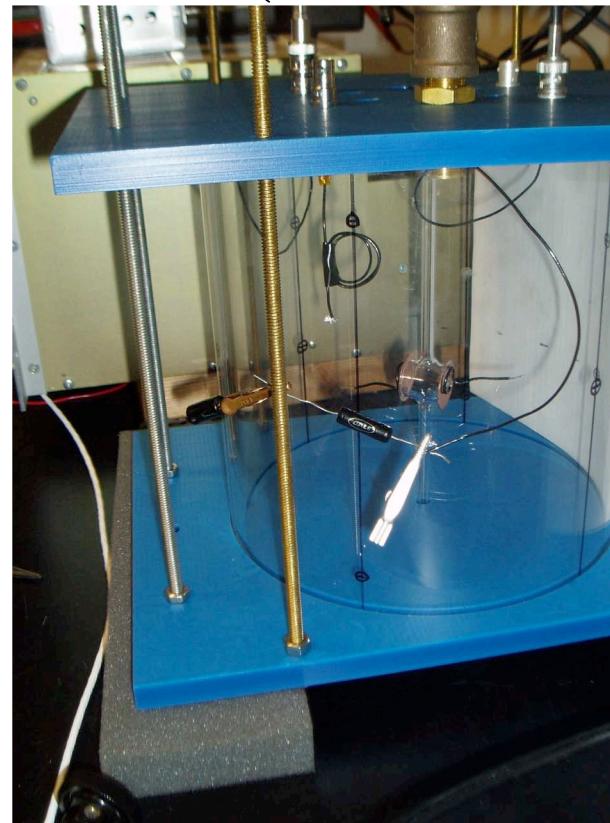
EDM Cell Development

We want a single cell @ 200C

Problems: leakage currents, materials

Silica (Fused Quartz) or Sapphire

IN PROGRESS (Celia Cunningham)



Backgrounds

$$\sigma_{\omega} = \frac{2}{T_2} \frac{1}{(S/N)} = \frac{2}{T_2} \sqrt{\frac{1}{A^2(1-B)^2 N \gamma}}$$

Build-up of decay products for γ -anistropy probe

 Change cells (weekly?) - good for systematics

Scattered betas (beta asymmetry detection)

Systematics

Leakage currents -- must be minimized: **Multiple species**

Electric quadrupole moment (gradients/walls)

Change cells, cell shape/orientation: **Multiple species**

Electric field effects on shields, electronics, etc.

Check and measure with $E=0$

∇E^2 and $|E|$ effects (Stark shifts)

Multiple Species: $J=1/2, 3/2$, etc.

Motional effects $\langle v_x E \rangle$ (negligible in gas cells)

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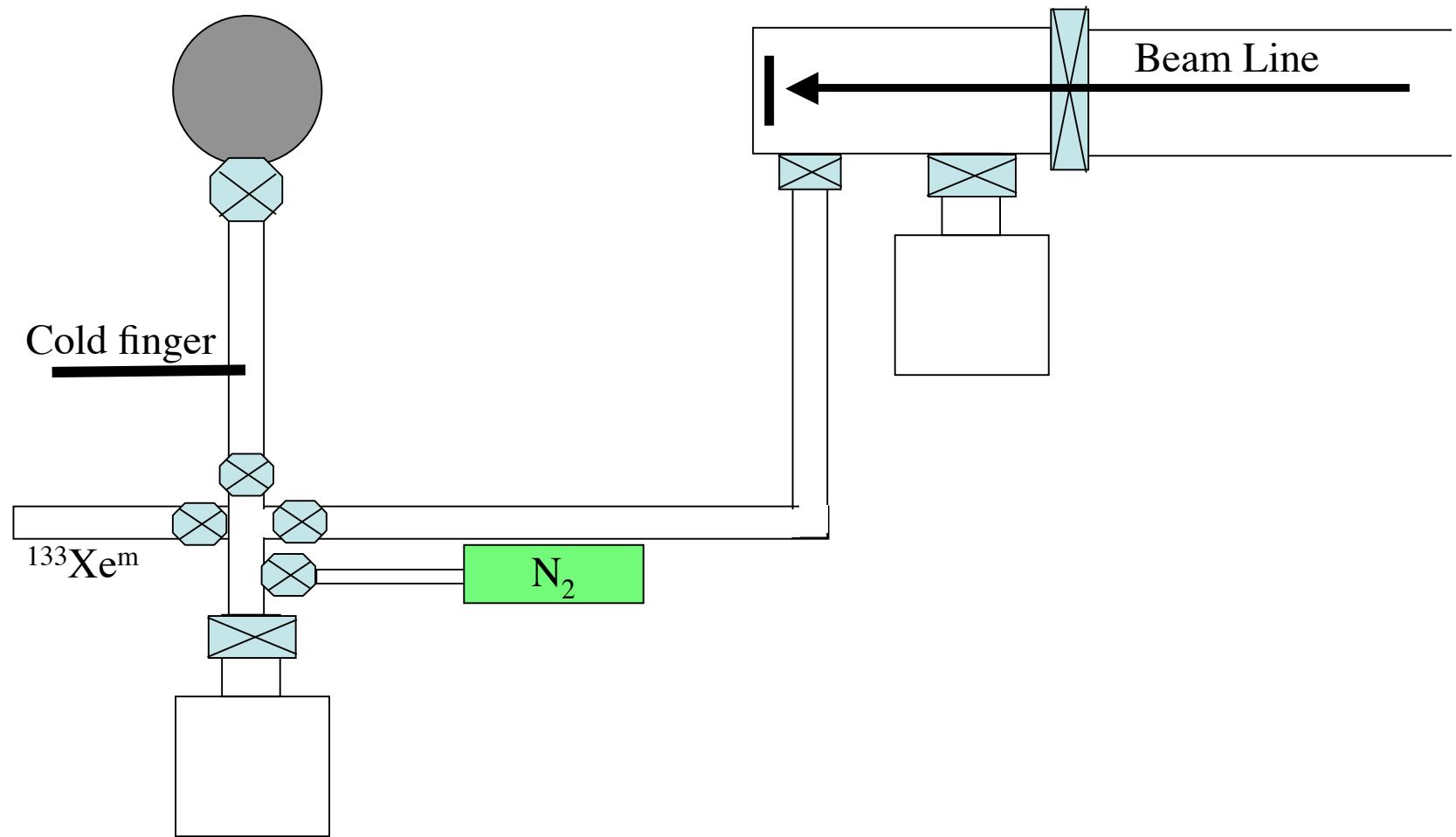
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Comagnetometers

$$\hbar\omega = 4(dE + \mu B) \cdot J + Q \nabla E J^2 + \dots$$

- Long lived; produced in gobs; noble gas



Schedule

32 shifts approved for 2008-9+

August 1-4 (8 shifts): Collect and polarize $^{121,123}\text{Xe}$ (from $^{121,123}\text{Cs}$) ($J_{121}=5/2$; $J_{123}=1/2$)
Laser, simple magnet (ala Stony Brook)

+ 6-12 months (8+ shifts): Measure free precession
(DAQ, good magnet, 2+ Tigress modules)

+ 6-12 months (16 shifts): EDM trial run with ^{121}Xe (EDM cell, laser development)

2010: Actinide Target

Measure Rn nuclear structure (8- π)
First RADON EDM measurements 2011

Radon EDM Summary

^{223}Rn EDM projections

Gamma Anisotropy (A=0.2 0.1)

T₂=30 s E=5 kV/cm

	Gamma Anisotropy	beta asymmetry	
		ISAC	ISAC \times 20
Count Rate (s^{-1})	1.2×10^5	5×10^6	4×10^7
A	0.2	0.2	0.2
Background	0.01	0.3	0.3
Total N (100 Days)	1×10^{12}	4×10^{13}	8×10^{14}
σ_{d_A} (e-cm)	1×10^{-26}	4×10^{-27}	5×10^{-28}

Production rates: 1×10^7 (1 μA @ ISAC)

TABLE II. γ -ray anisotropies of ^{223}Fr from the decay of oriented ^{223}Rn .

E_γ (keV)	Anisotropy R	$R - 1$ (%)
159.9	0.958(18)	-4.2 ± 1.8
171.8	1.082(24)	$+8.2 \pm 2.4$
206.3	0.990(25)	-1.0 ± 2.5
416.0	0.933(14)	-6.7 ± 1.4
491.4	1.092(39)	$+9.2 \pm 3.9$
591.8	1.014(12)	$+1.4 \pm 1.2$
621.5	0.936(40)	-6.4 ± 4.0
635.2	1.011(15)	$+1.1 \pm 1.5$
723.2	1.054(33)	$+5.4 \pm 3.3$