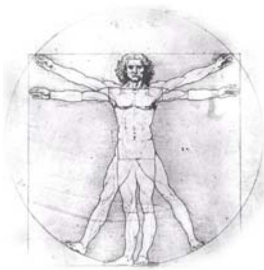
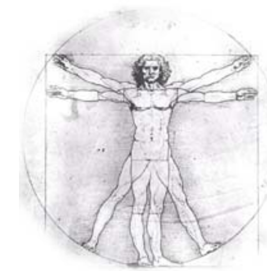
Radon-EDM Experiment

Eric Tardiff, Tim Chupp, Wolfgang Lorenzon (University of Michigan)
John Behr, Matt Pearson, Gordon Ball, Greg Hackman, Martin Smith (TRIUMF)
Carl Svensson, Andrew Phillips (Guelph) Mike Hayden (SFU)
Norbert Pietralla, Georgi Rainovsk, Gene Sprouse (SUNY Stony Brook)





TRIUMF E929

Spokesmen: Timothy Chupp & Carl Svensson

E-929 Collaboration (Guelph, Michigan, SFU, TRIUMF)
TRIUMF
Canada's National Laboratory for Particle and Nuclear Physics

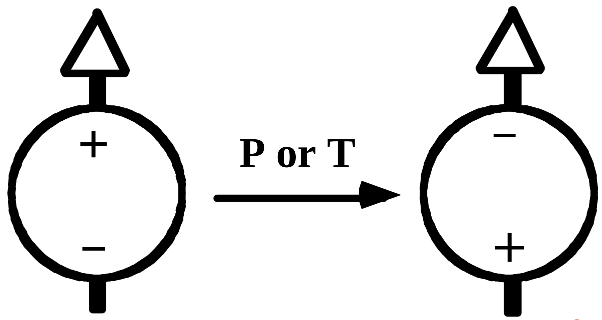
Funding: NSF-Focus Center, DOE, NRC (TRIUMF), NSERC

What I did on my Summer Vacation

I went backward in time and discovered Parity Violation.

Atomic Electric Dipole Moment

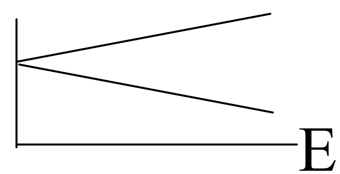
Separation of Charge along **J: $\langle d \rangle = g_d \langle J \rangle$**



$g_d > 0$ $g_d < 0$ if T symmetry, $g_d = -g_d$

$\langle \vec{d} \rangle = e \int \vec{r} \rho \, d^3r$ $\vec{d} \cdot \vec{E}$ is P&T even

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



EDM Motivations

Undiscovered

Study CP violation: mass scale

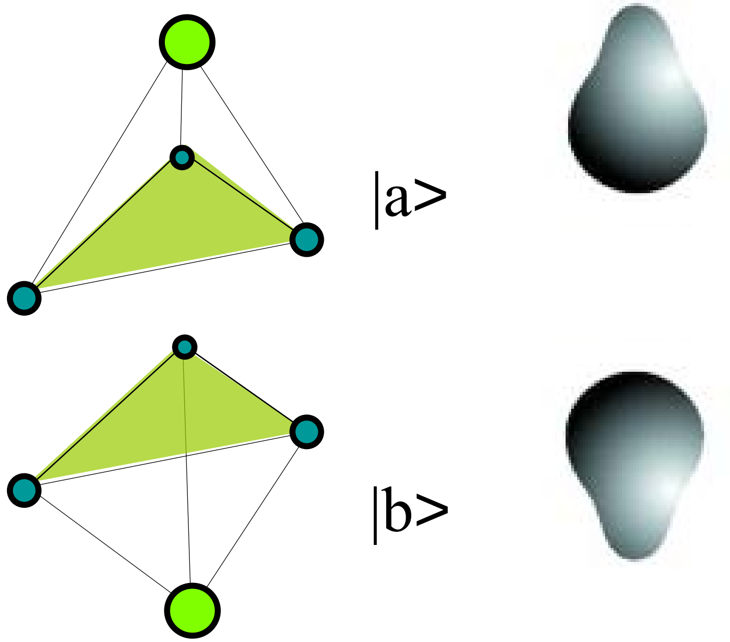
Signal of NEW PHYSICS (beyond SM - CKM)

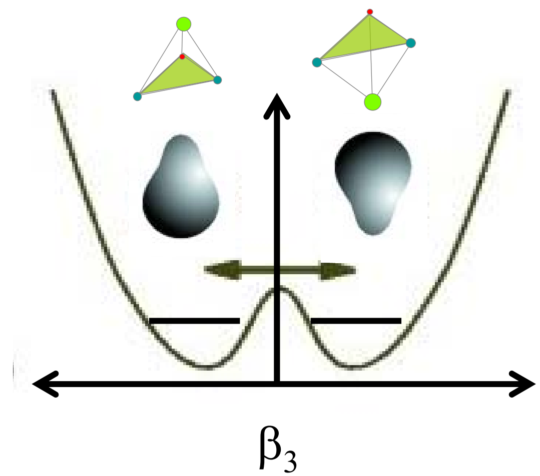
Cosmological Baryon Asymmetry

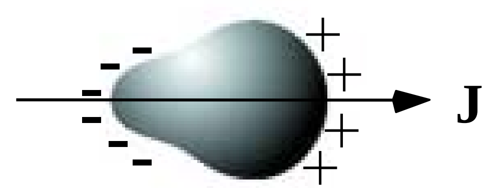
Octupole Deformation-Parity Doublets

(see Feynman vol 3.)

NH_3





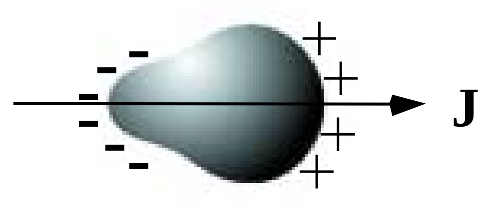


$$|\psi_\pm\rangle = \frac{1}{\sqrt{2}} \left(|a\rangle \pm |b\rangle \right) \qquad S \sim \frac{\langle +|\eta r^3 \cos\theta|-\rangle}{E_+ - E_-} \sim \frac{\eta \beta_2 \beta^2{}_3 Z A^{2/3} r_0{}^3}{E_+ - E_-}$$

Nuclei with Octupole Deformation/Vibration

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

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



	^{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:

Ocutpole Enhancements

Engel et al. agree with Flambaum et al.

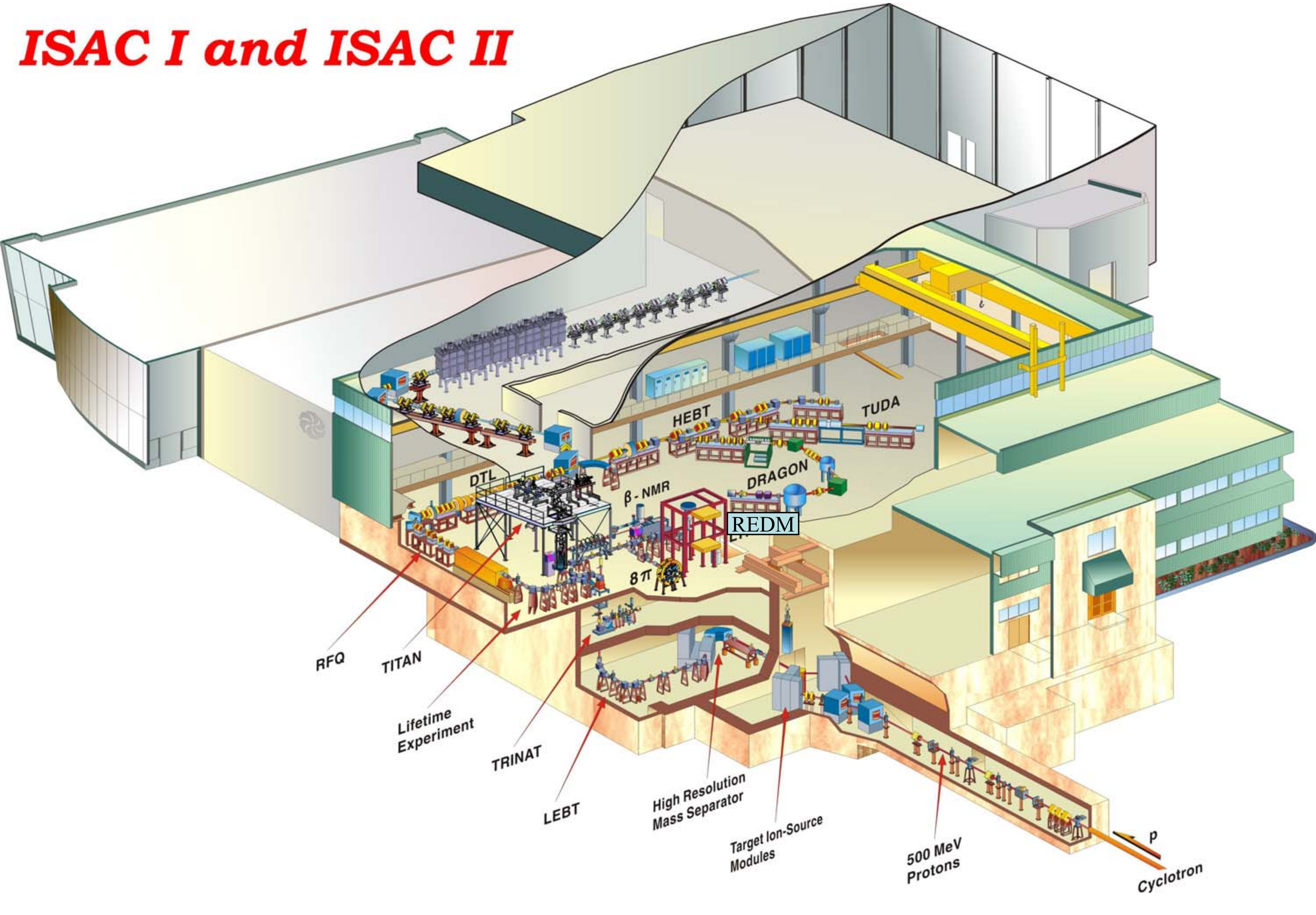
Even octupole vibrations enhance **S** (Engel…, Flambaum& Zelevinsky)

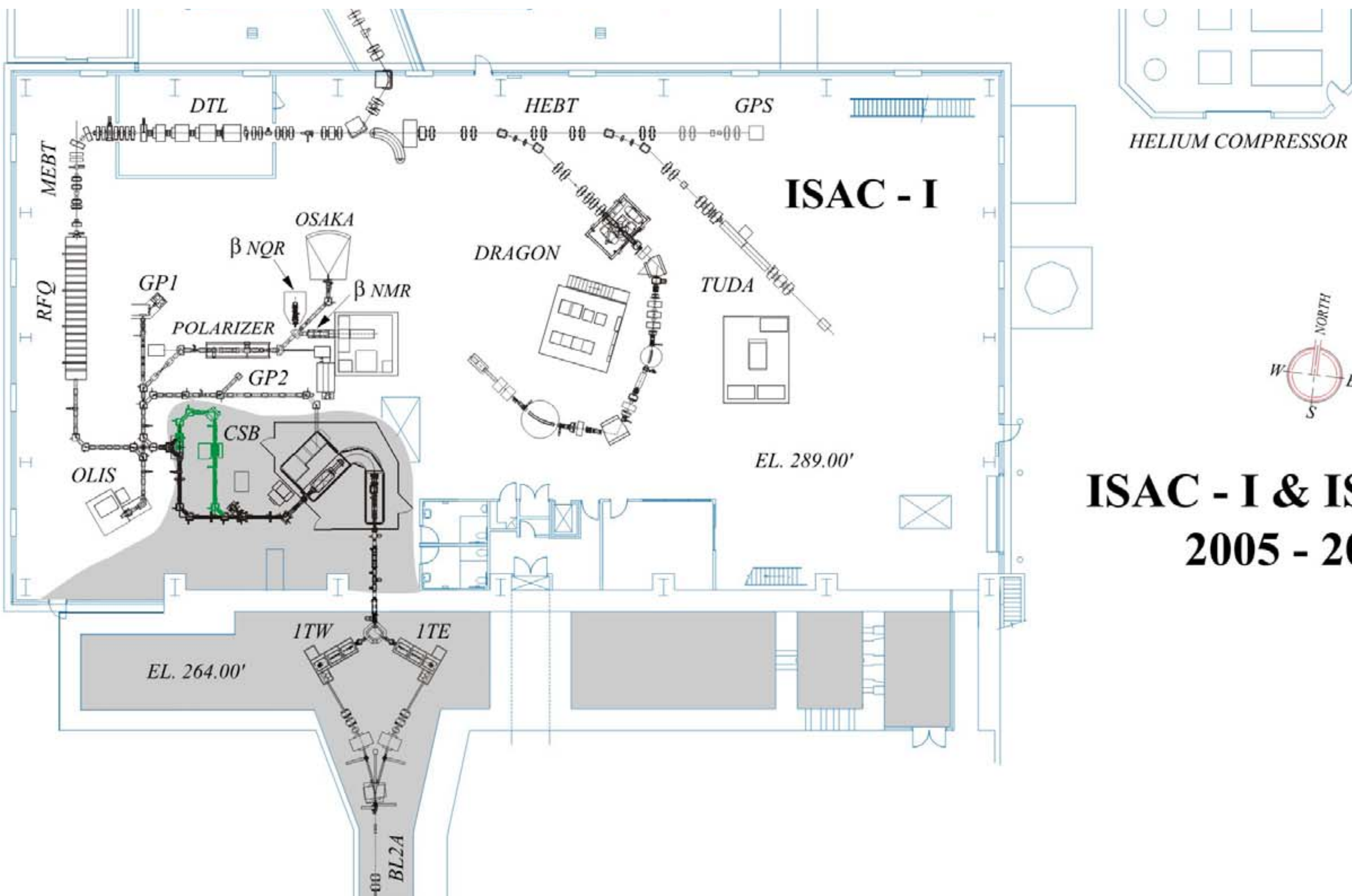
Radon EDM Experiment 929 at TRUMF (Vancouver BC)

Sarah Nuss-Warren, Eric Tardiff, W. Lorenzon, TC - UM
J Behr, M. Pearson, C. Svensson, A. Phillips, M. HaydenG. Hackman, G. Ball

QuickTime™ and a TIFF (Uncompressed) decompressor are needed to see this picture.

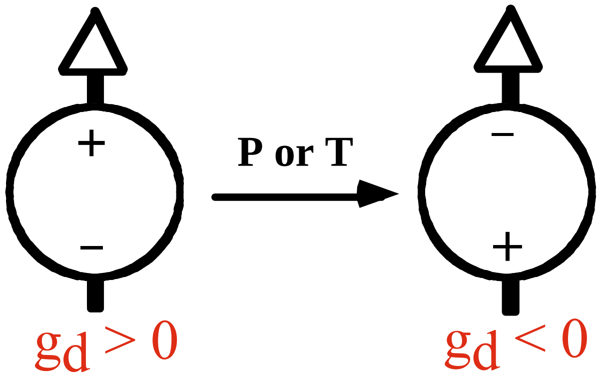
ISAC I and ISAC II

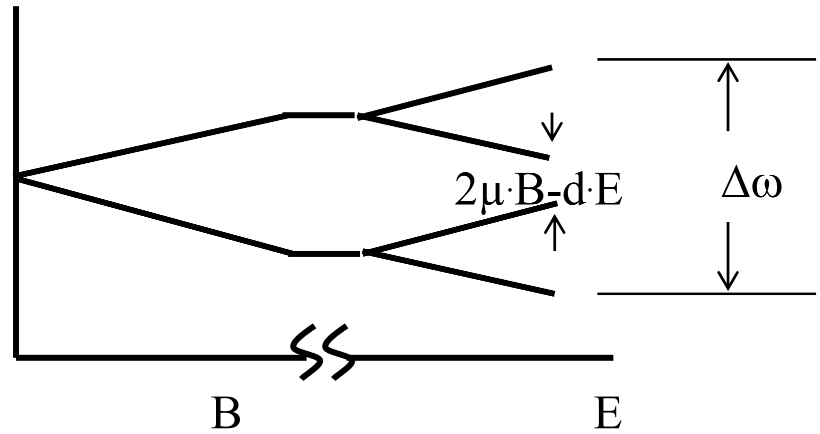


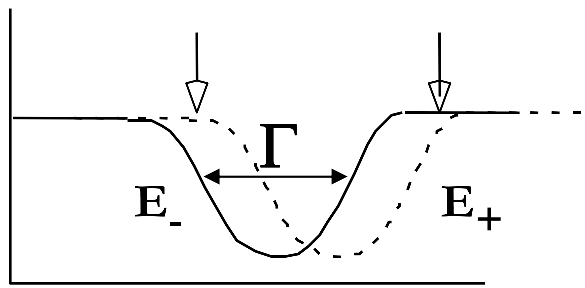


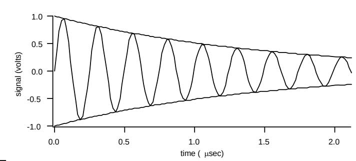
ISAC - I & ISAC - II
2005 - 2006

Atomic Electric Dipole Moment









T_2
RF power
B homogeneity

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

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

Analyzing power

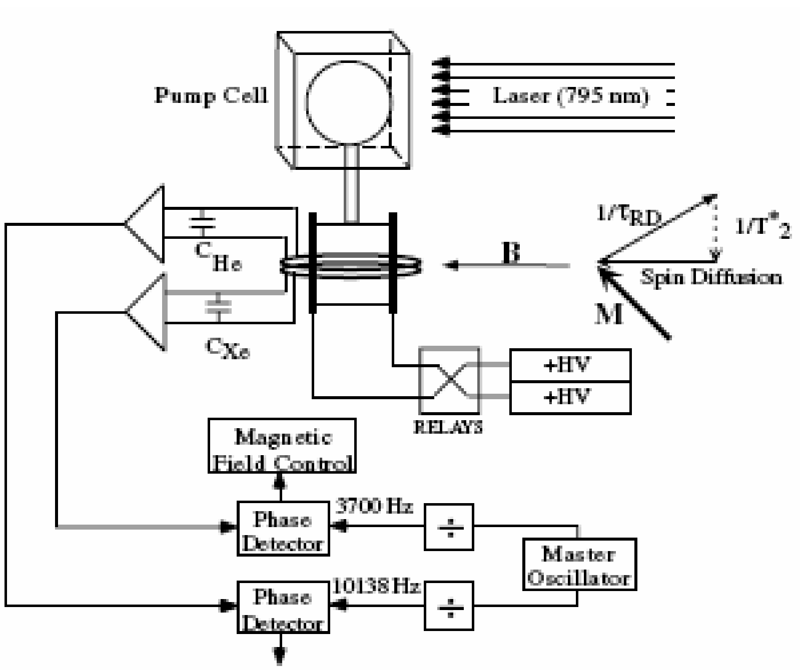
Need high radon polarization and long relaxation.

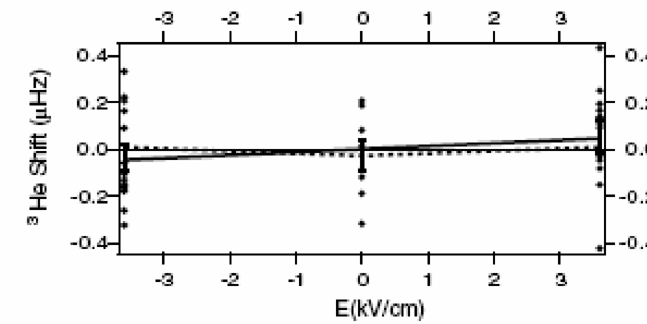
VOLUME 86, NUMBER 1 PHYSICAL REVIEW LETTERS 1 JANUARY 2001

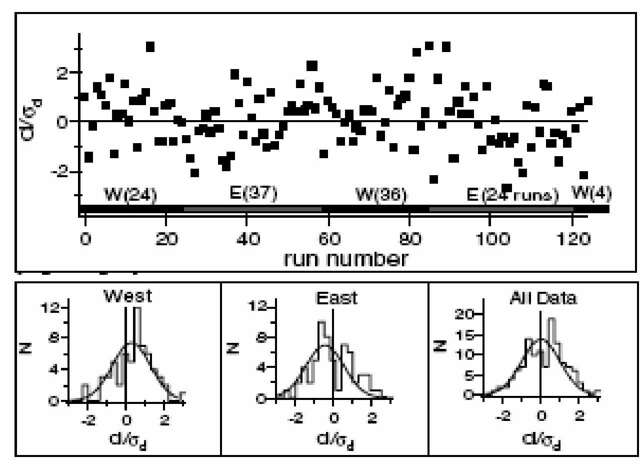
Atomic Electric Dipole Moment Measurement Using Spin Exchange Pumped Masers of ^{129}Xe and ^{3}He

M. A. Rosenberry* and T. E. Chupp
University of Michigan, Ann Arbor, Michigan 48109
(Received 1 August 2000)

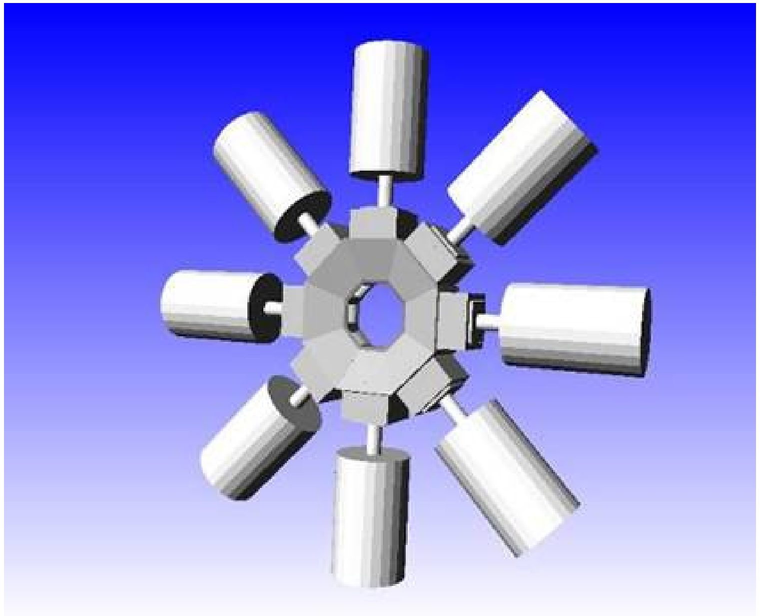
We have measured the T-odd permanent electric dipole moment of ^{129}Xe with spin exchange pumped masers and a ^{3}He comagnetometer. The comagnetometer provides a direct measure of several systematic effects that may limit electric dipole moment sensitivity, and we have directly measured the effects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

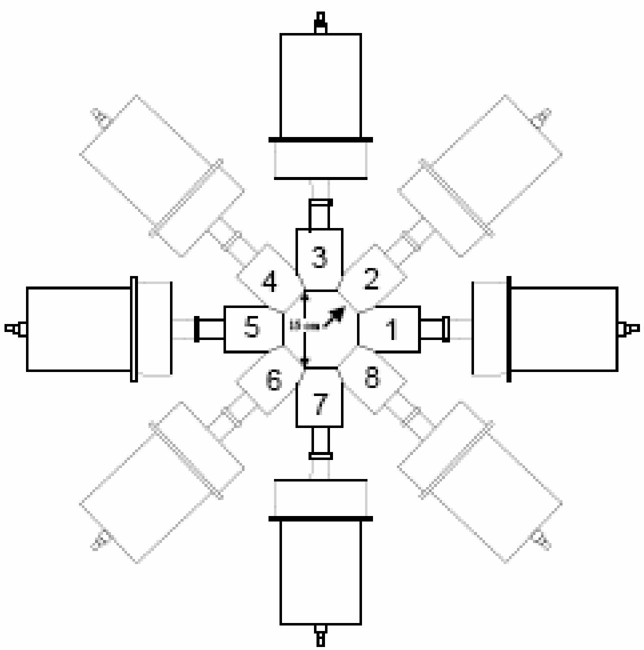


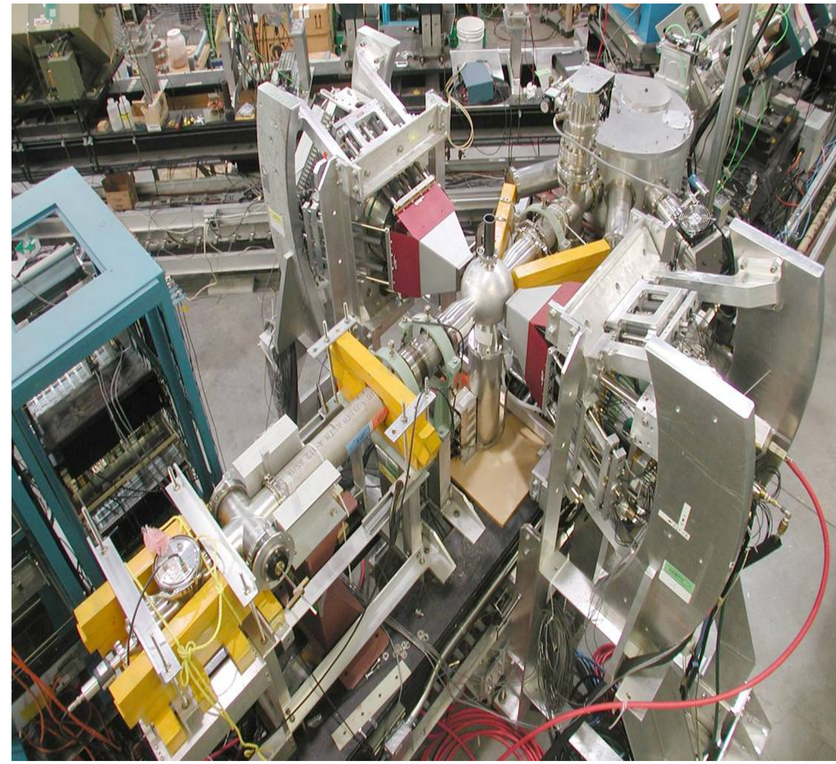




4th ~~3rd~~ ~~2nd~~ most sensitive EDM measurement.

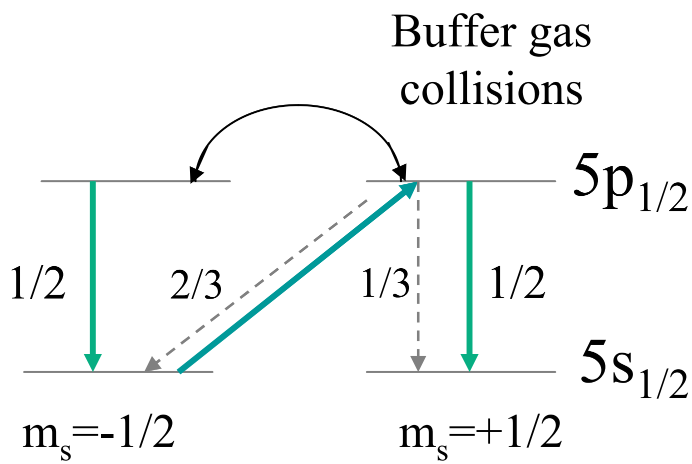


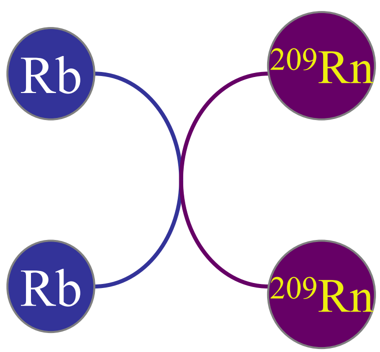

3
4
2
5
1
6
8
7



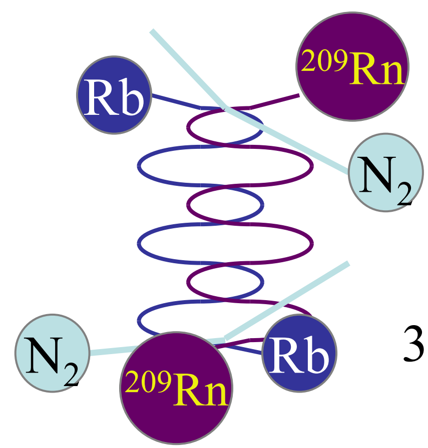
Spin-Exchange Optical Pumping

- 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.



van Der Waals
Molecule:
τ is dependent on
3rd body (N_2) pressure.

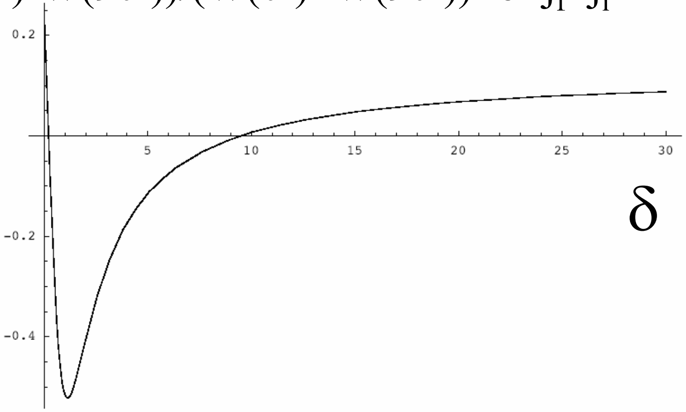
Gamma Ray Anisotropies

- Polarized nuclei emit gamma rays with calculable directional distributions.

j_f=j_i-1 pure dipole transition

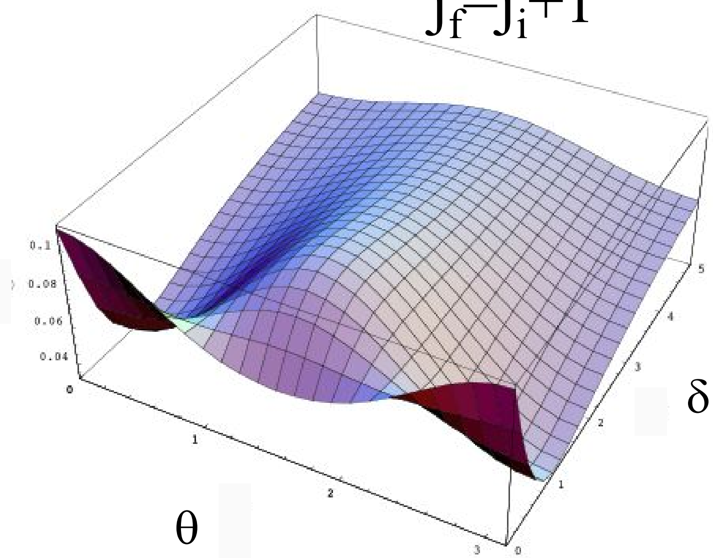
$$W(\theta) = \frac{1}{4\pi}\left\{1 + \frac{3}{2j_i(2j_i-1)}\left[\sum_{m_i} m_i^2 a_{m_i} - \frac{1}{3}j_i(j_i+1)\right]P_2(\cos\theta)\right\}$$

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



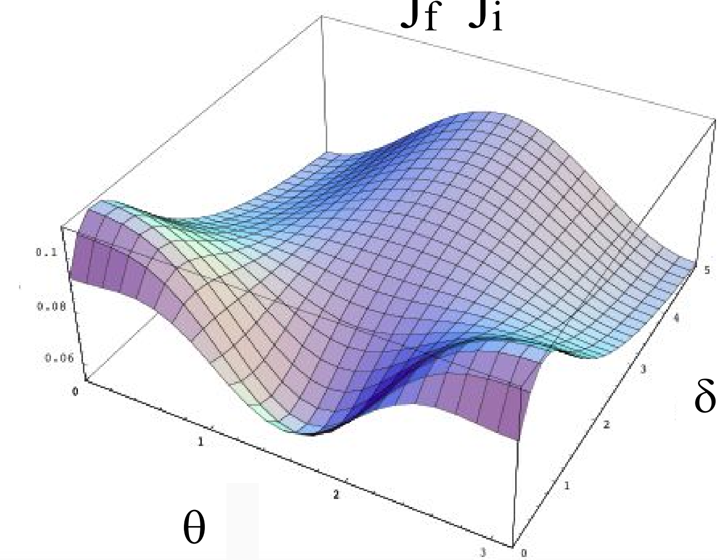
j_f=j_i+1

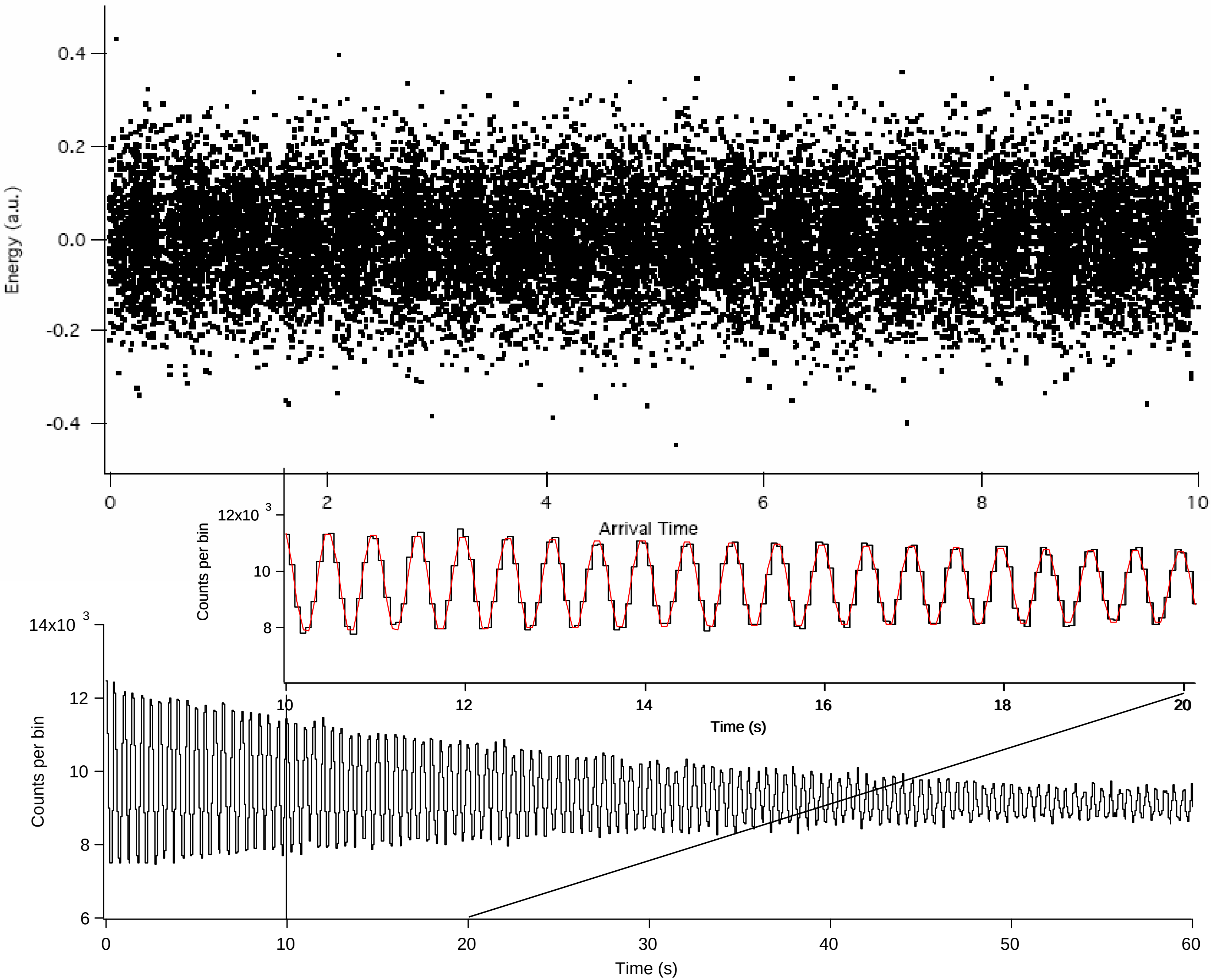
W(θ)



j_f=j_i

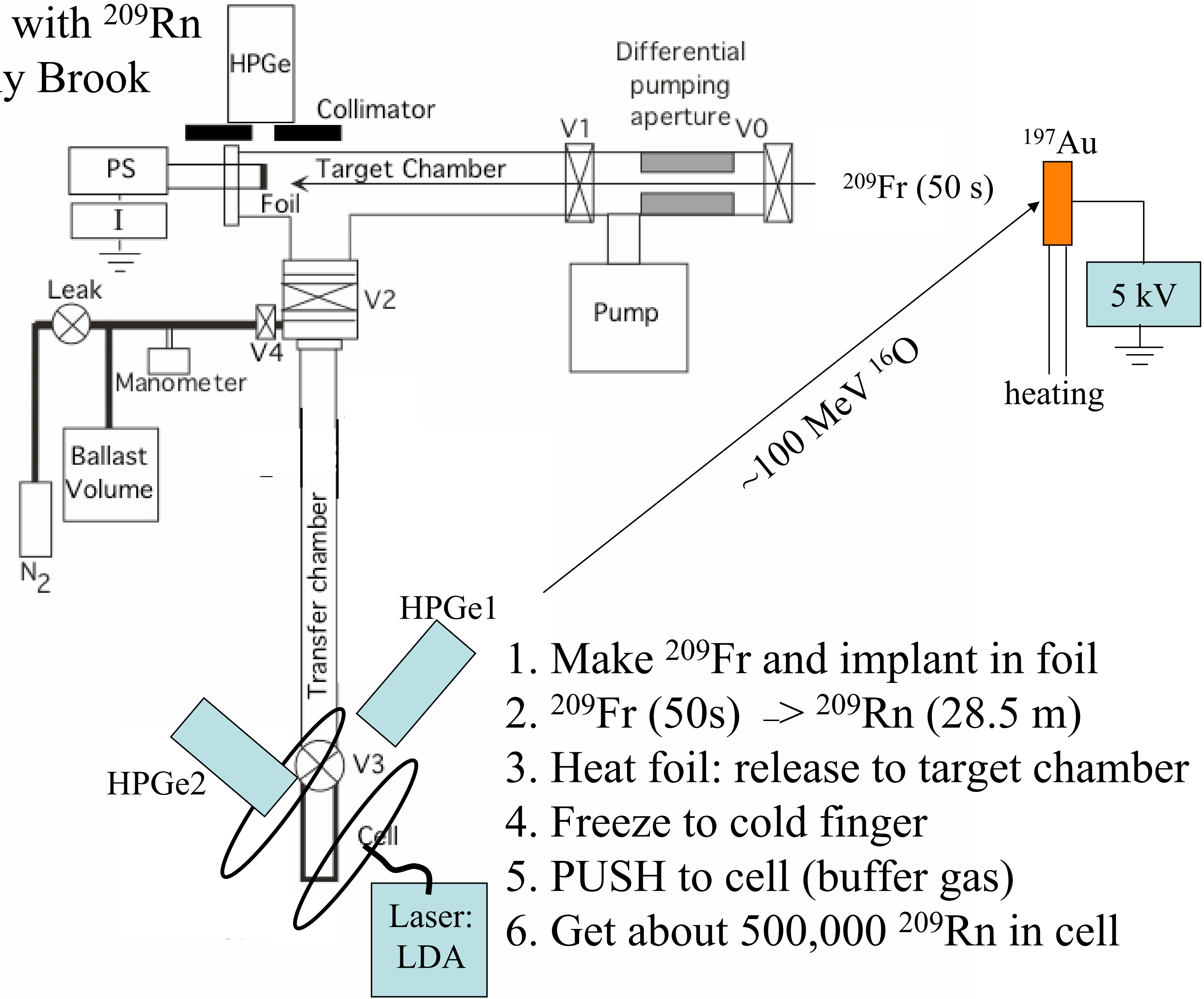
W(θ)



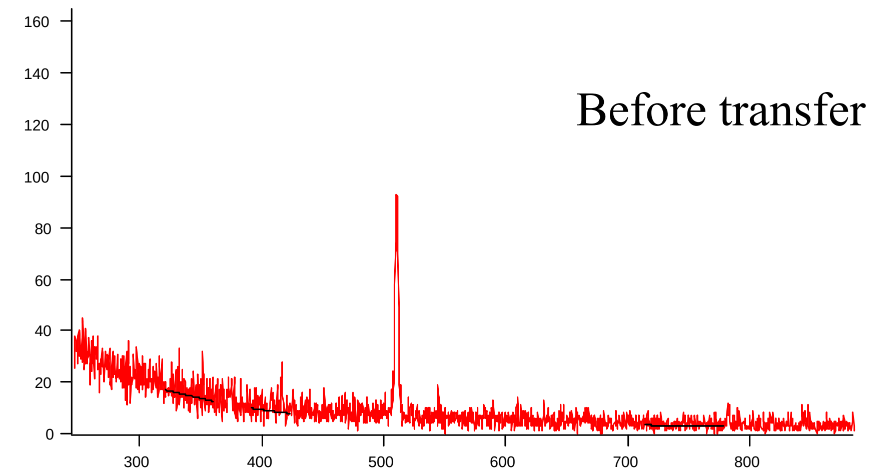


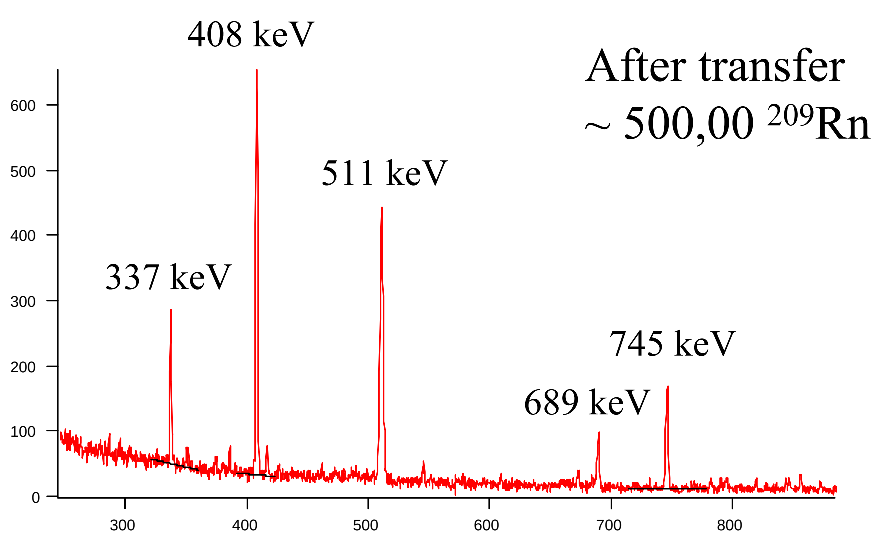
Energy (a.u.)
0.4
0.2
0.0
-0.2
-0.4
0
2
4
6
8
10
Arrival Time
12x10 3
10
8
Counts per bin
10
12
14
16
18
20
Time (s)
14x10 3
12
10
8
6
Counts per bin
0
10
20
30
40
50
60
Time (s)

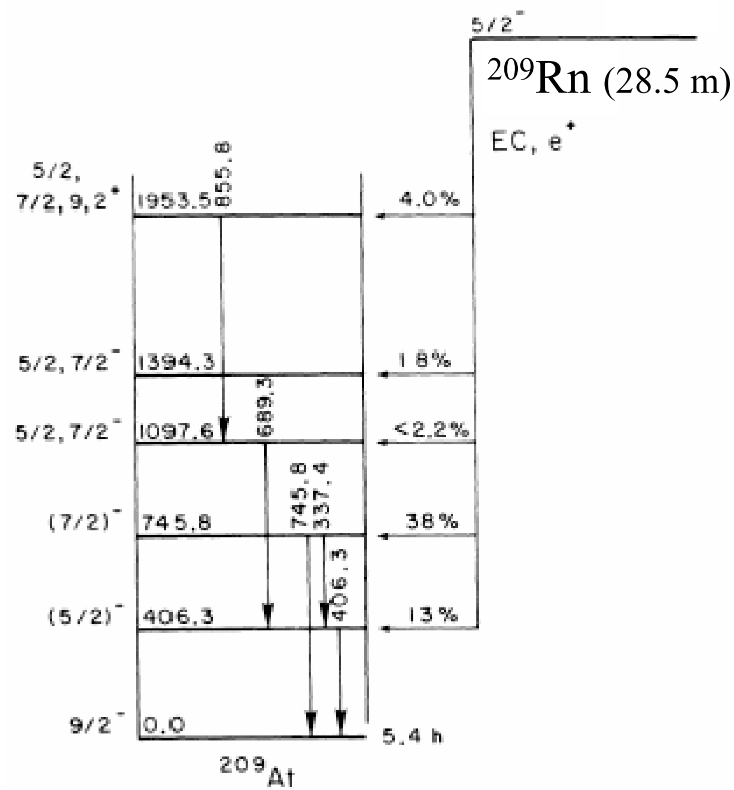
Studies with ^{209}Rn @ Stony Brook



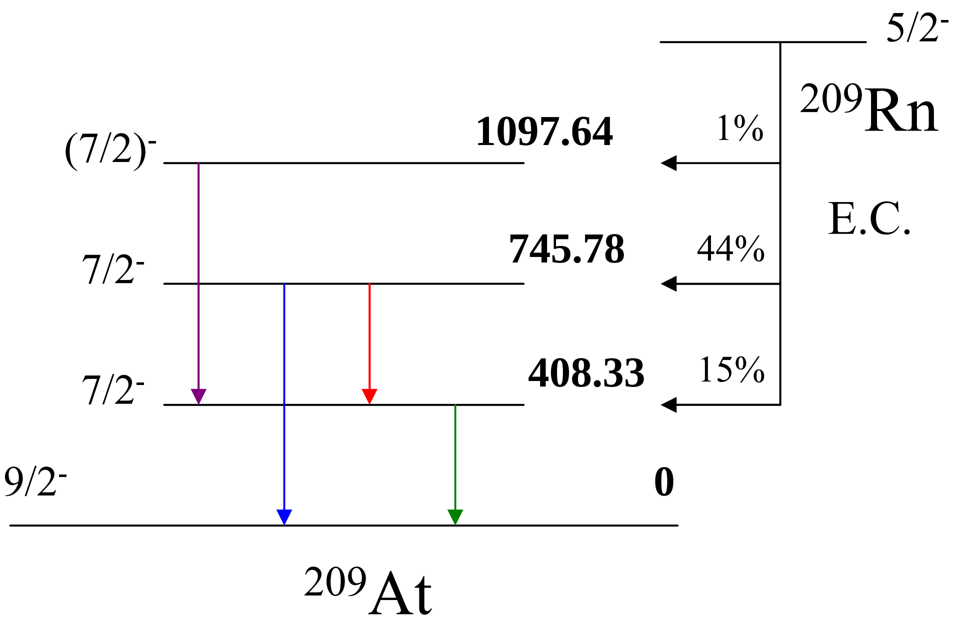
1. Make ^{209}Fr and implant in foil
2. ^{209}Fr (50s) –> ^{209}Rn (28.5 m)
3. Heat foil: release to target chamber
4. Freeze to cold finger
5. PUSH to cell (buffer gas)
6. Get about 500,000 ^{209}Rn in cell


Before transfer
160
140
120
100
80
60
40
20
0
300
400
500
600
700
800


408 keV
After transfer
~ 500,00 ^{209}Rn
511 keV
337 keV
745 keV
689 keV
600
500
400
300
200
100
0
300
400
500
600
700
800


5/2⁻
^{209}Rn (28.5 m)
EC, e⁺
5/2,
7/2, 9, 2⁺
1953.5
855.8
4.0%
5/2, 7/2⁻
1394.3
18%
689.3
5/2, 7/2⁻
1097.6
<2.2%
745.8
337.4
(7/2)⁻
745.8
38%
406.3
(5/2)⁻
406.3
13%
9/2⁻
0.0
5.4 h
^{209}At

The ^{209}Rn Decay Scheme



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

$a_1 = 1 \Rightarrow$ pure dipole

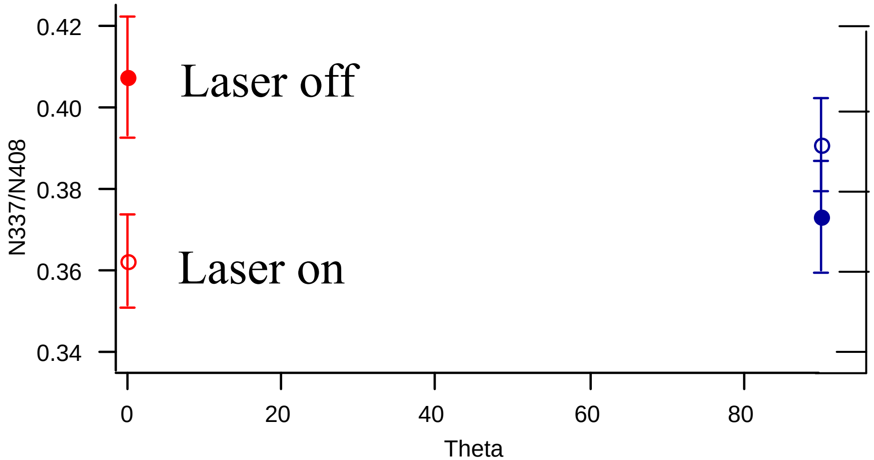
$a_2 = 1 \Rightarrow$ pure quadrupole

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

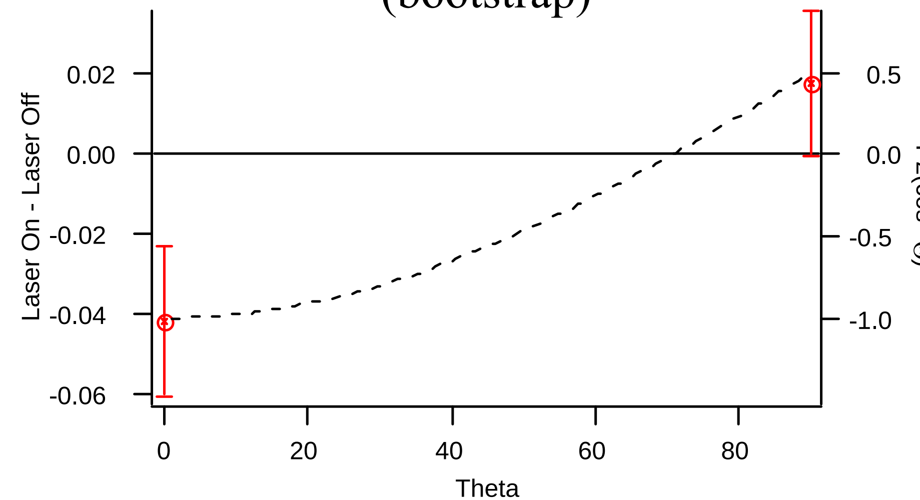
γ-ray Energy	Intensity	δ (Mixing Ratio)
337.45	14.5	∞
408.32	50.3	0
689.26	9.7	>3.57
745.78	22.8	>2.86

from Table of Isotopes

Normalize 337 keV to 408 keV
T=130° C Uncoated Pyrex



Alignment≈20%
of maximum
(bootstrap)



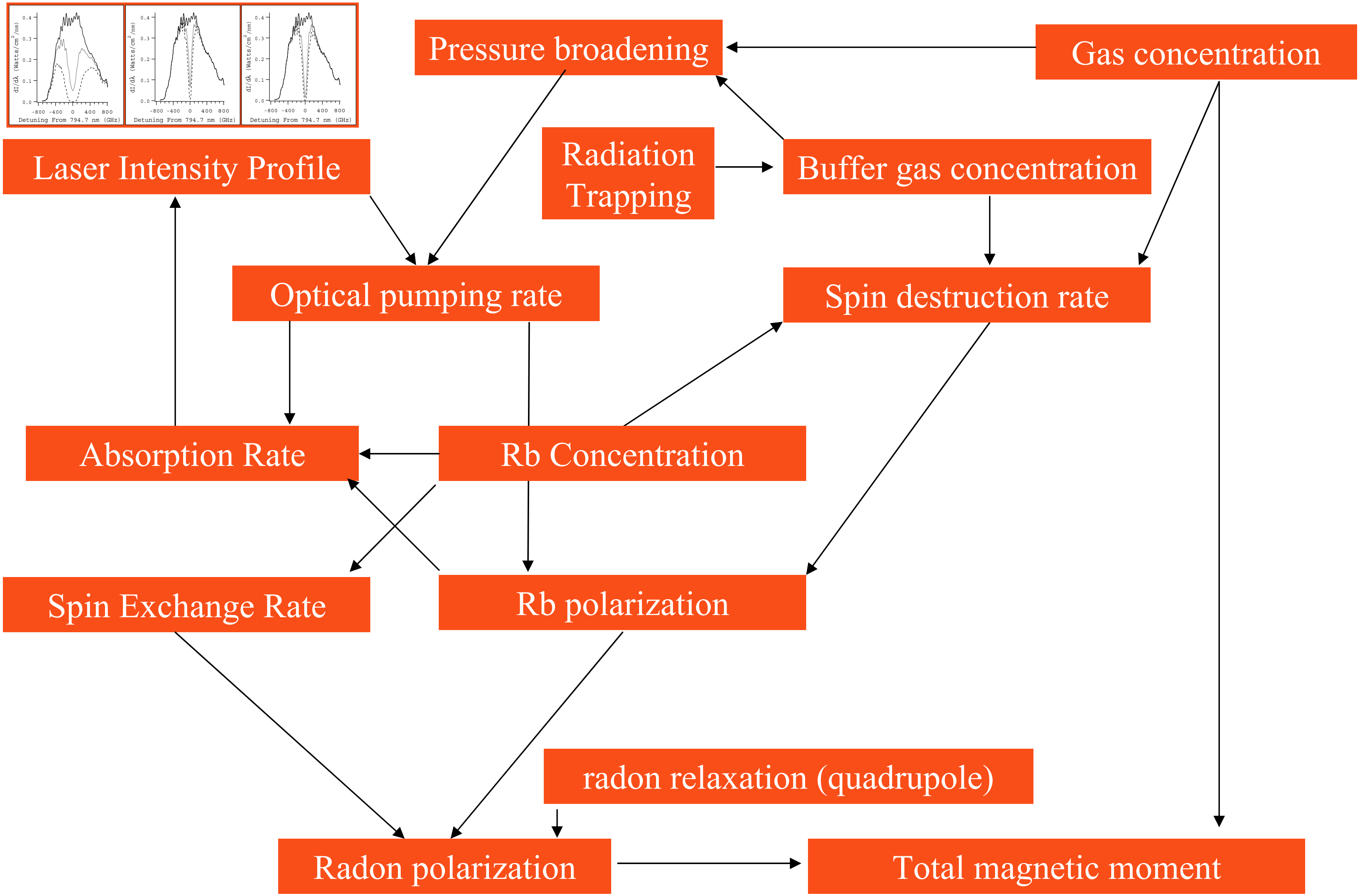
VOLUME 60, NUMBER 21 PHYSICAL REVIEW LETTERS 23 MAY 1988

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
Department of Physics, Princeton University, Princeton, New Jersey 08544

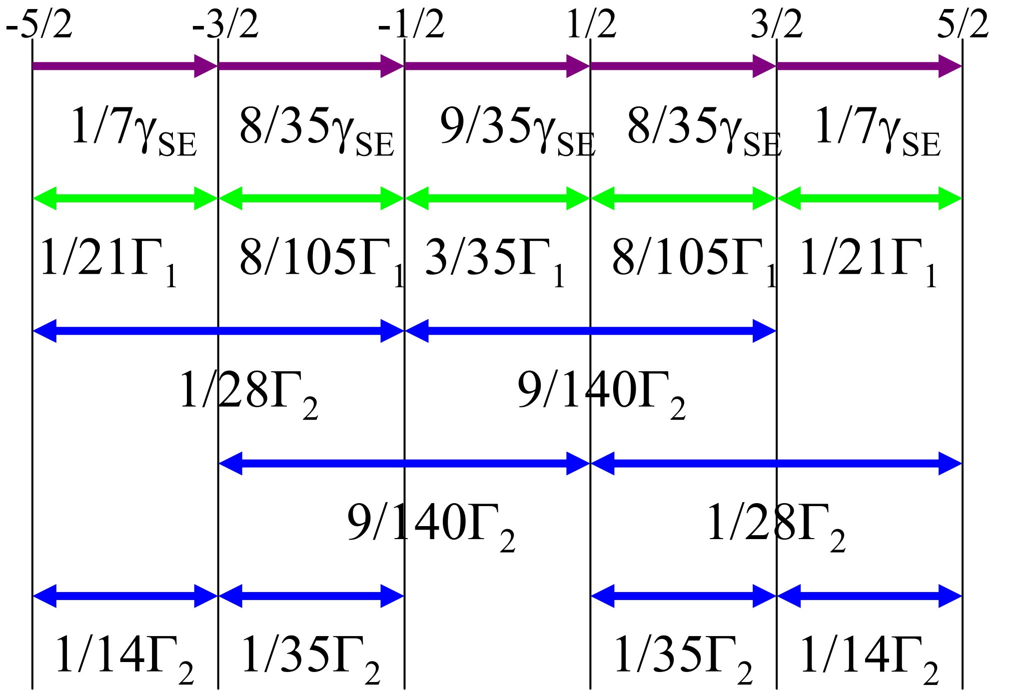
E_γ (keV)	Spin sequence	Anisotropy R	$R-1$ (%)
337	$(\frac{7}{2}^-)$-$(\frac{5}{2}^-)$	0.903(14)	-9.7 ± 1.4
408	$(\frac{5}{2}^-)$-$\frac{9}{2}^-$	1.009(7)	$+0.9\pm0.7$
689	$\frac{5}{2}$, $\frac{7}{2}^-$-$\frac{5}{2}^-$	1.079(22)	$+7.9\pm2.2$
745	$(\frac{7}{2}^-)$-$\frac{9}{2}^-$	1.129(14)	$+12.9\pm1.4$

Spin Exchange Pumping



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.

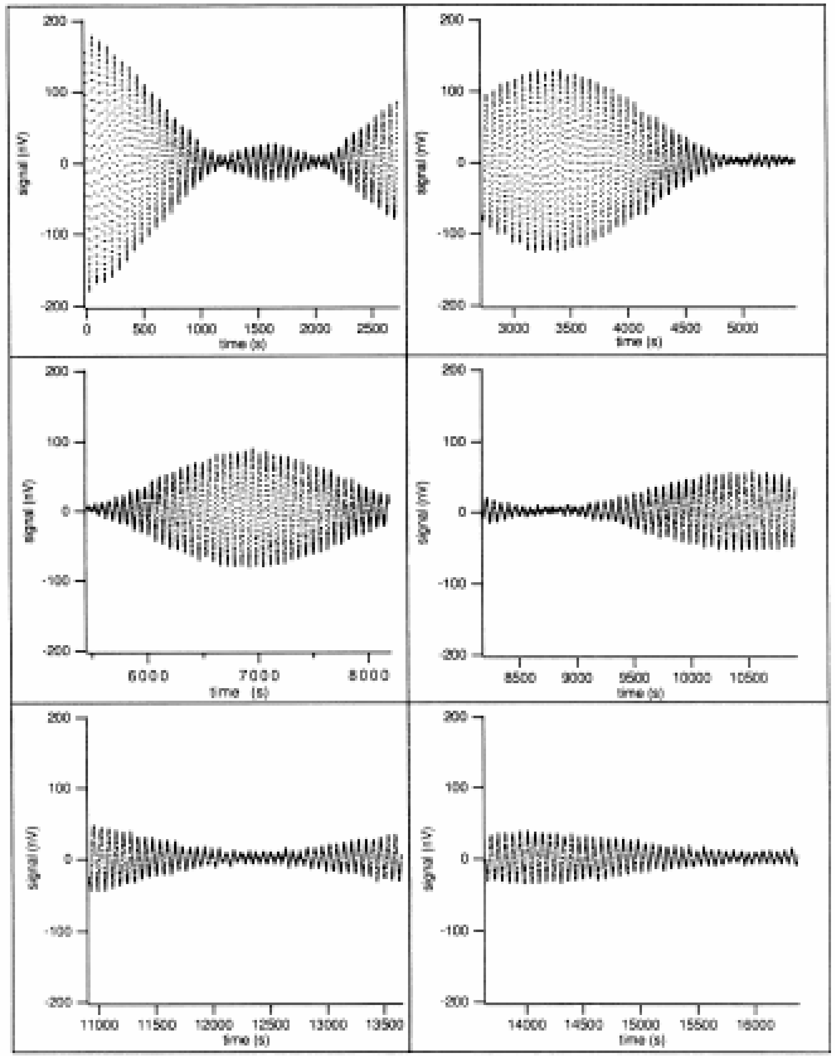


$$\Gamma_2(\mathrm{T}) = \Gamma_2^{\infty} e^{\Delta \mathrm{E} / k\mathrm{T}}$$

VOLUME 64, NUMBER 19 PHYSICAL REVIEW LETTERS 7 MAY 1990

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

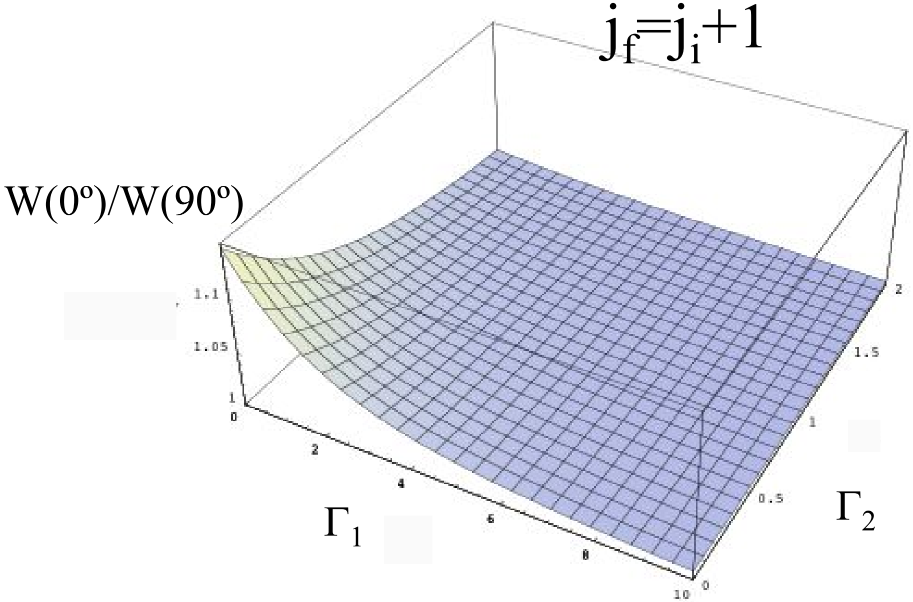
T. E. Chupp and R. J. Hoare
The Physics Laboratories, Harvard University, Cambridge, Massachusetts 02138
(Received 28 February 1990)

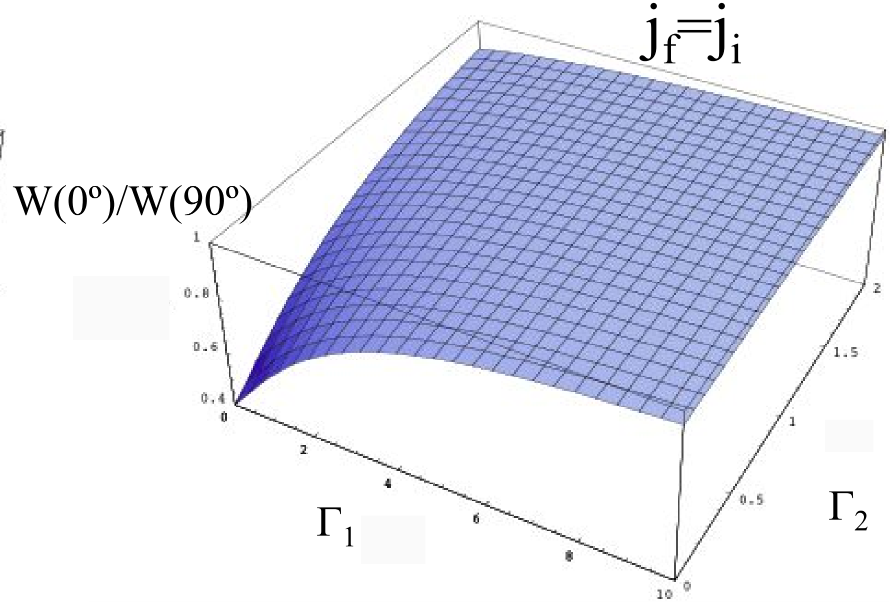


Shows T2~4.5 h, dominated by Quadrupole Interactions ($\Gamma_2 >> \Gamma_1$)

Modeling Polarization

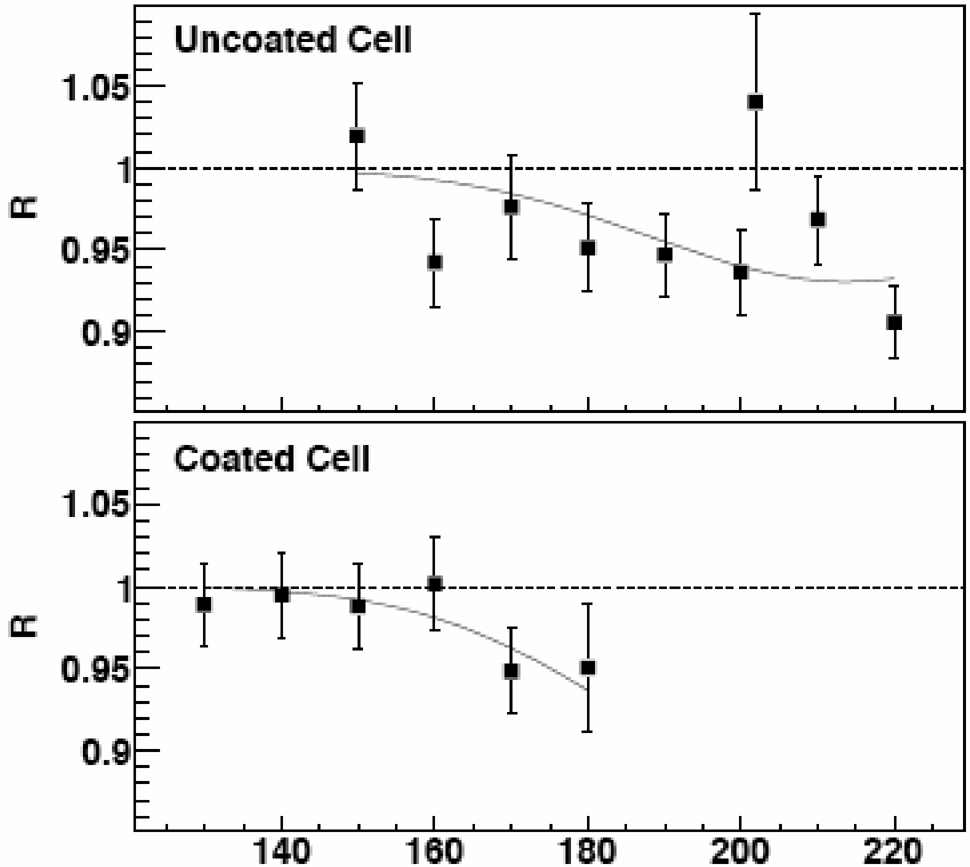
- Quadrupole relaxation should be the dominant mechanism.
- As a first approximation, set $\Gamma_1=0$, calculate γ_{SE} for a given T, and calculate the expected anisotropies.





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. Sprouse[4]
[1] *FOCUS Center, University of Michigan Physics Department, 450 Church St., Ann Arbor 48109-1040, USA*
[2] *University of Michigan Physics Department, 450 Church St., Ann Arbor 48109-1040, USA*
[3] *TRIUMF, 4004 Westbrook Mall, Vancouver V6T 2A3, Canada*
[4] *SUNY Stony Brook Department of Physics and Astronomy, Stony Brook 11794-3800, USA*
(Dated: December 6, 2006)



Fit for Γ_2 (T_a=300°K)

0.05 Hz for uncoated
0.03 Hz for coateds

Use 2.5×10^{-21} cm^2

Backgrounds

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

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 $\langle v_x \mathbf{E} \rangle$ (negligible in gas cells)

What's next?

We're done at Stony Brook

Cell characterization with natural xenon:
- 27% ^{129}Xe (J=1/2); 21% ^{131}Xe (J=3/2)

Cell development: coatings/electrodes/temperatures
Laser studies (LDA light absorption by Rb)

TRIUMF
set up measurements with xenon isotopes

Measure Rn nuclear structure (8-π)

Build up to EDM measurements (~ 3 years)

Beta Asymmetry

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

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

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)

Radon EDM Summary

Progresss - but a lot remains to be done.

^{209}Rn work at Stony Brook Productive

Move to TRIUMF beginning summer 2007

^{223}Rn EDM projections

Gamma Anisotropy (A=0.2 *0.1*)
T_2 = 30 s E=5 kV/cm

	Gamma Anisotropy	beta asymmetry ISAC	beta asymmetry 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}