The Radon-EDM Program

Tim Chupp

Funding: DOE

1. Brief motivation
2. Atomic EDMs
3. Octupole enhancements
4. Prospects

EDM $\longleftrightarrow$ $\not{C}\not{P}$ $\longleftrightarrow$ Baryon Asymmetry $\longleftrightarrow$ NEW PHYSICS

$\vec{d} = d\hat{J}$

A. Shakarov

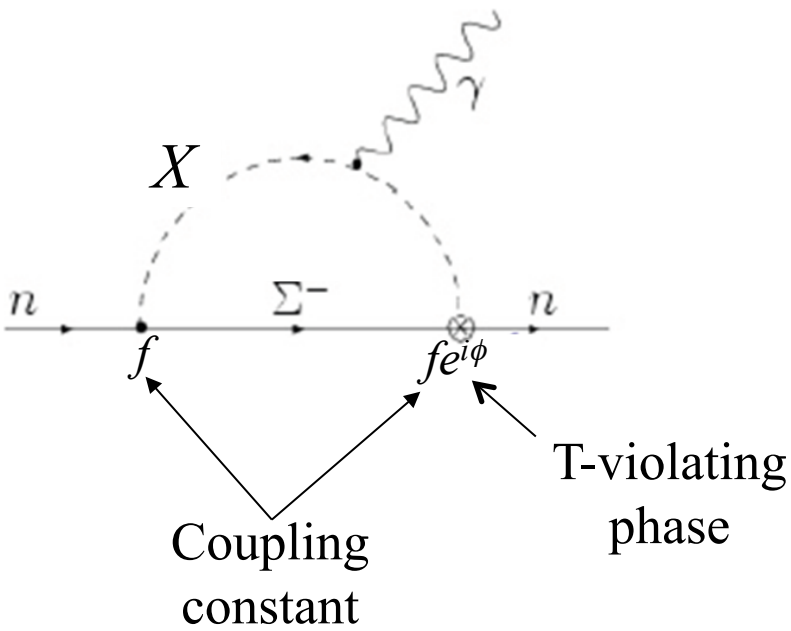
1) Baryon number violation

2) CP Violation

3) Rapid expansion (non-equilibrium)

Another possibility: CP violation in neutrinos + "seesaw"

NEW PHYSICS @ TeV (LHC)scale



$$\frac{d}{e} \approx \hbar c \alpha^N \frac{m_q}{\Lambda_x^2} \sin\phi$$

$m_q \approx 1\ MeV$

$e \approx 10^{-13}\ fm$

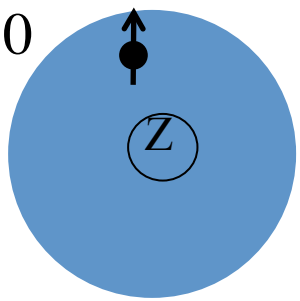
$$\Lambda_x \approx 10^7\ MeV = 10\ TeV$$

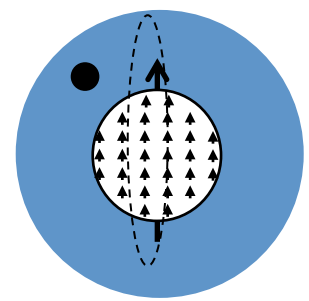
$$\sin\varphi \sim 1$$

Atomic EDMs

Particle Interactions Polarize Atoms

$\vec{E}(\vec{r}_e) \neq 0$





$\vec{E} \propto \vec{J}$

Paramagnetic atoms ($\vec{L} \cdot \vec{S}$ coupling)

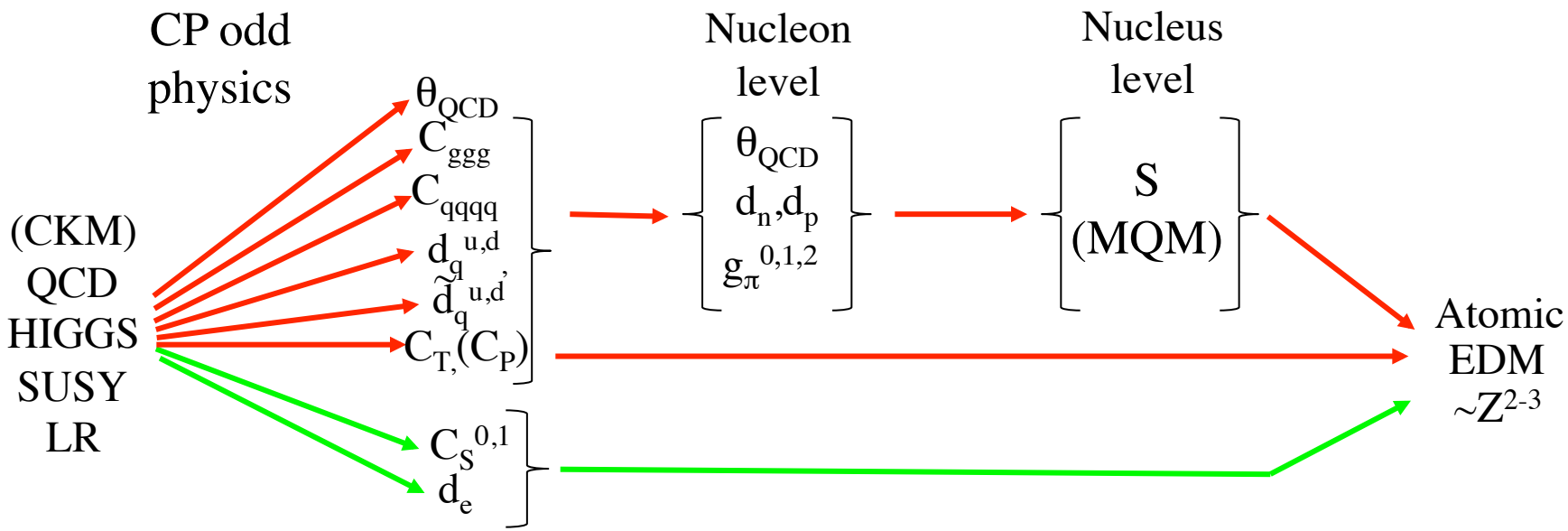
Diamagnetic atoms: Schiff moment

$$\vec{S} = S\vec{J} = \frac{1}{10}\left\langle r^2 \vec{r}_p \right\rangle - \frac{1}{6} Z \left\langle r^2 \right\rangle \left\langle \vec{r}_p \right\rangle$$

$$d_A = (k_T C_T + k_S C_S) + \eta_e d_e + \kappa_S S + \text{ h.o. } \text{(MQM)}$$

Atomic EDMs

Particle Interactions Polarize Atoms



13 Effective field-theory parameters

See Engel et al. arXiv:1303.2371

8 experiments (so far)

What can we learn?

Diagmagetic atoms and nucleons

T.C. & M. Ramsey-Musolf – in preparation

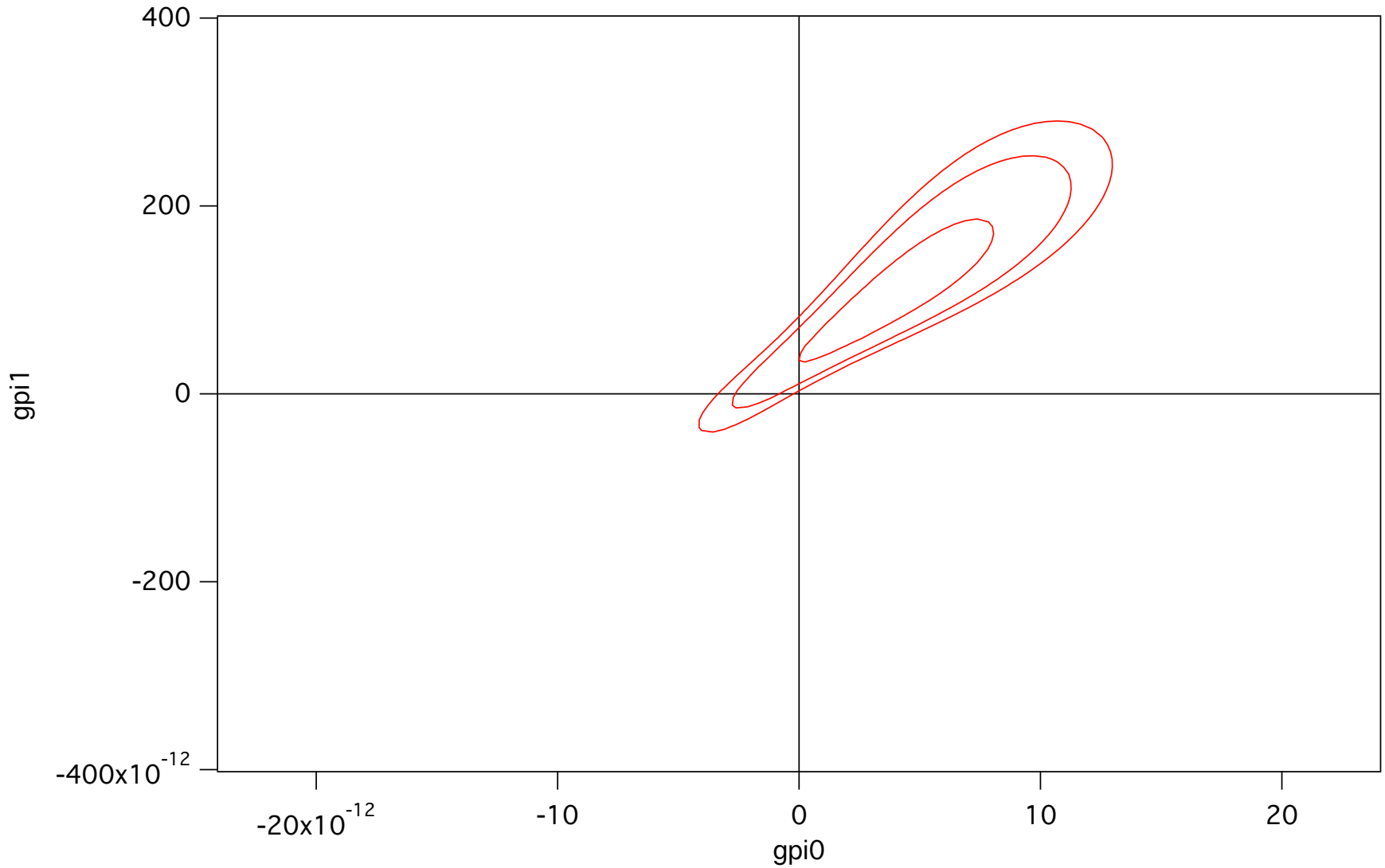
	θ_{QCD}	d_n^0	d_n^1	C_T	g_π^0	g_π^1
neutron	x	1	-1			
Xe, Hg, TlF	x			x	x	x
Ra, Rn	x			x	x	x
proton	x	1	+1			
d, ^{3}H, ^{3}He	x				x	x

Schiff Moment

$$S = g_{\pi NN}(a_0\bar{g}^0_{CP} + a_1\bar{g}^1_{CP} + a_2\bar{g}^2_{CP})$$

$$d_n \approx \bar{d}_n + (1.44 \times 10^{-14} g_\pi^{(0)} - 8.3 \times 10^{-16} g_\pi^{(1)})\ \mathrm{e-cm}$$

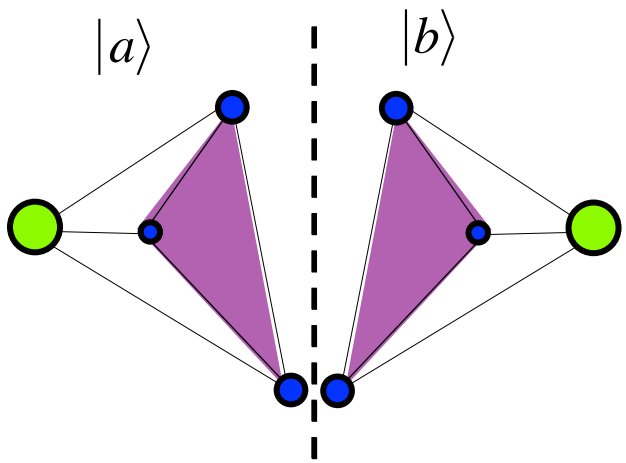
$$\bar{g}^0_{CP} \approx 0.027\ \theta_{QCD}$$


400
200
0
-200
-400x10^-12
gpi1
-20x10^-12
-10
0
10
20
gpi0

Octupole Enhancements

Intrinsic (body-frame) moment
Polarizabitliy

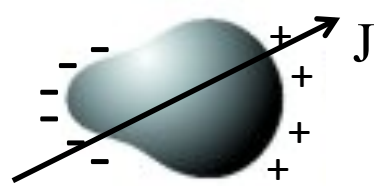
NH_3 (see Feynman vol 3.)

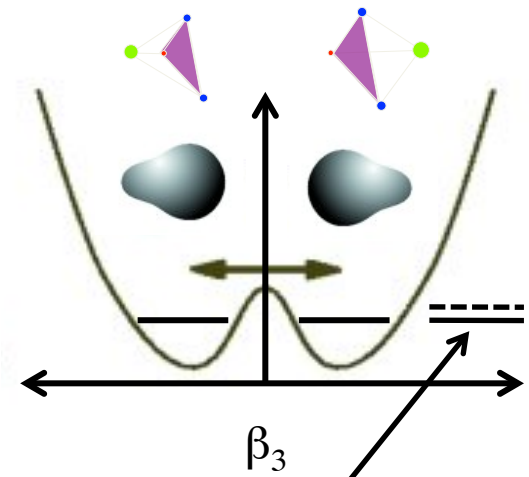


Reflection Symmetry

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

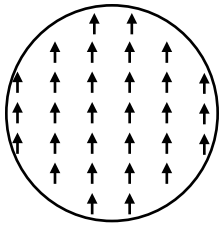
$$|\psi_-\rangle = \frac{1}{\sqrt{2}}\left(|a\rangle - |b\rangle\right)$$





Small splitting (tunnel frequency)
Large electric polarizability

$$\vec{S} = \frac{1}{10}\left\langle r^2 \vec{r}_p \right\rangle - \frac{1}{6} Z \left\langle r^2 \right\rangle \left\langle \vec{r}_p \right\rangle$$



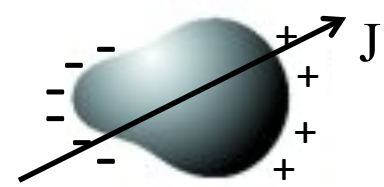
$\vec{E} \propto \vec{J}$

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

Nuclei with Octupole Deformation/Vibration

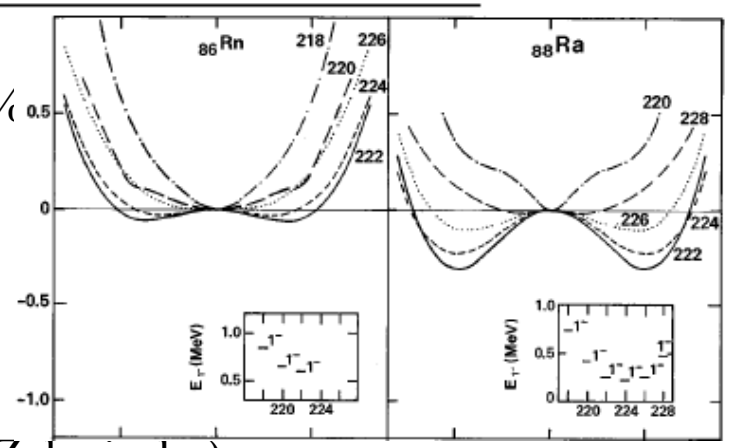
(Haxton & Henley; Auerbach, Flambaum, Spevak; Engel et al., Hayes & Friar, etc.)

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



	^{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

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



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

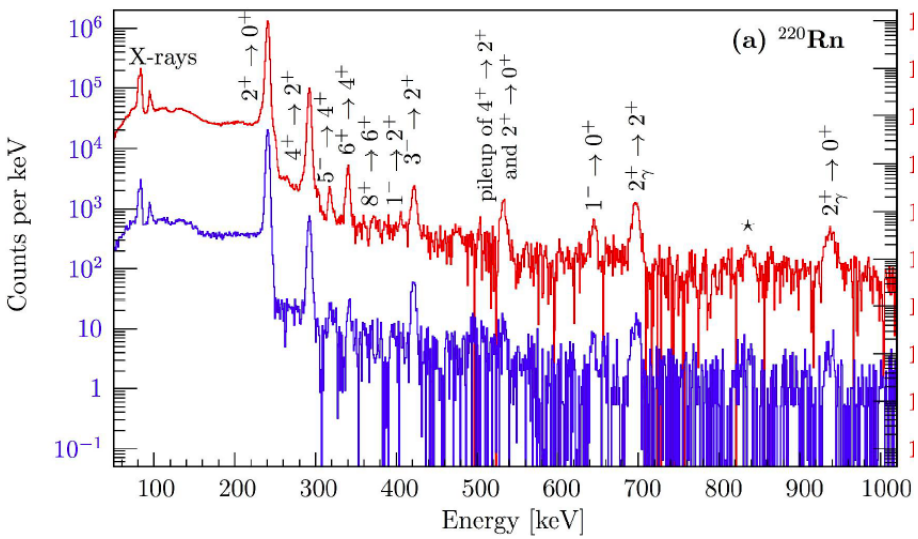
*Based on Woods-Saxon Potential

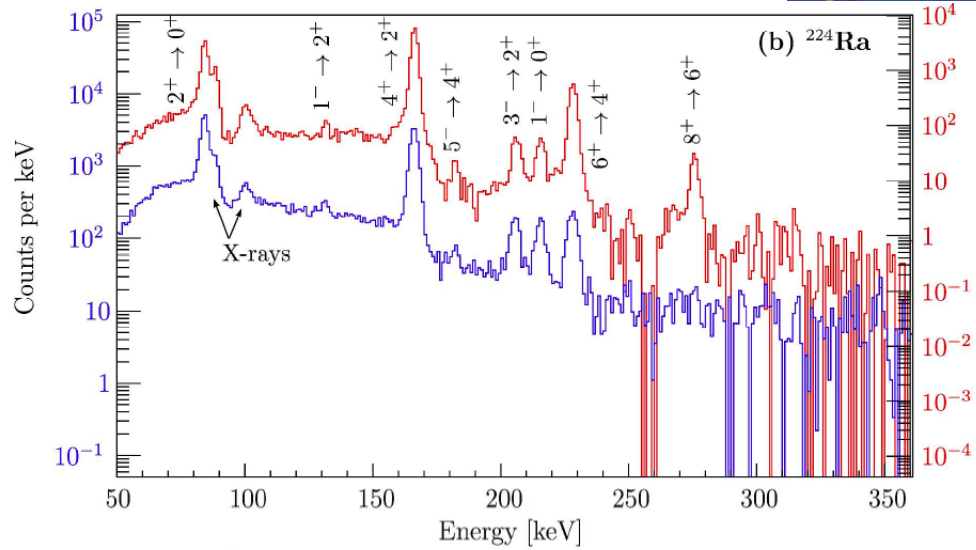
† Nilsson Potential Prediction is 137 keV

NOTES:
Ocutpole Enhancements
Engel et al. agree with Flambaum et al.
Even octupole vibrations enhance S (Engel, Flambaum& Zelevinsky)

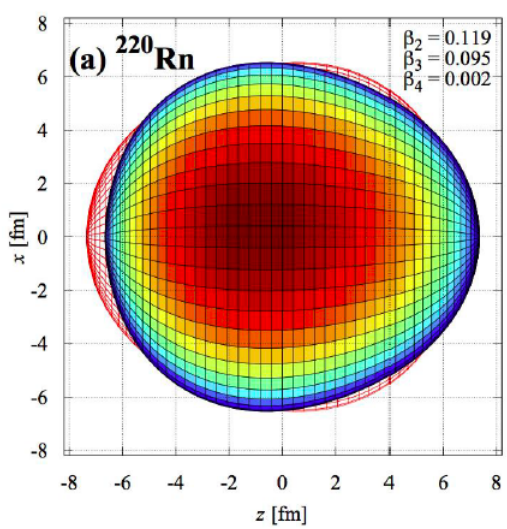
Measurement of Deformation Parameters of Rn, Ra

Liam Gaffney et al. (Nature v 407, p 199, 2013)

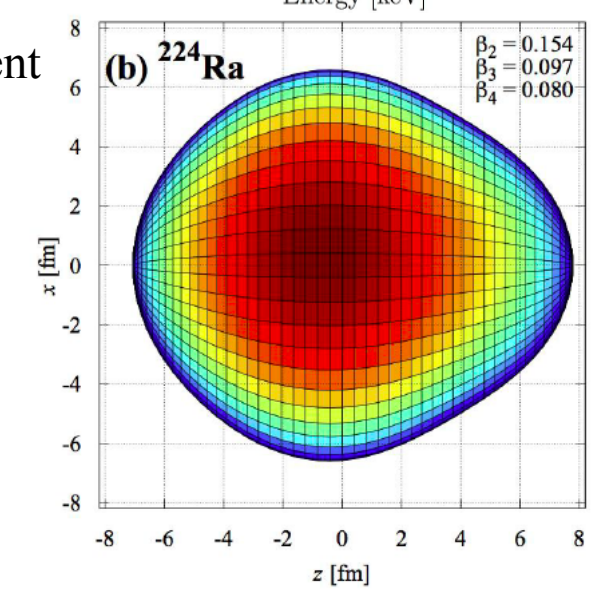




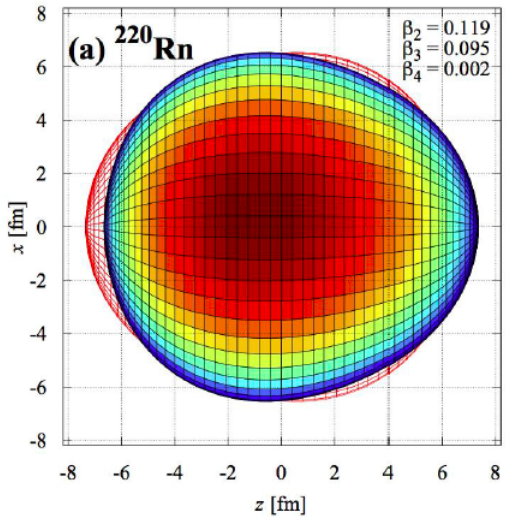
Vibrator

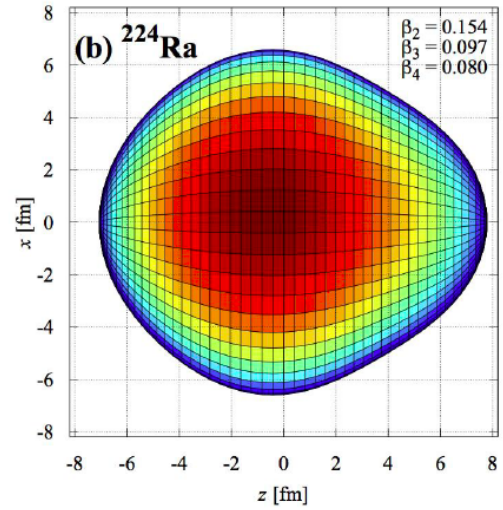


Permanent



Estimate of ^{221}Rn Enhancement





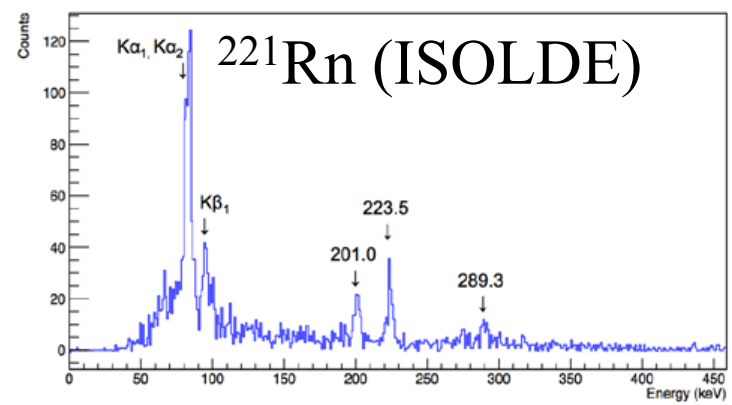
$$S \propto \frac{\eta \beta_2 \beta_3^2 A^{2/3} r_0^3}{E_+ - E_-}$$

$$\frac{S_{Rn}}{S_{Hg}} = \frac{S_{Ra}}{S_{Hg}} \frac{S_{Rn}}{S_{Ra}} \approx 1000 \frac{\beta_2}{\beta_2} \frac{\beta_3^2}{\beta_3^2} \frac{\Delta E_{Ra}}{\Delta E_{Rn}} \approx 50 - 100$$

50 keV

400 keV

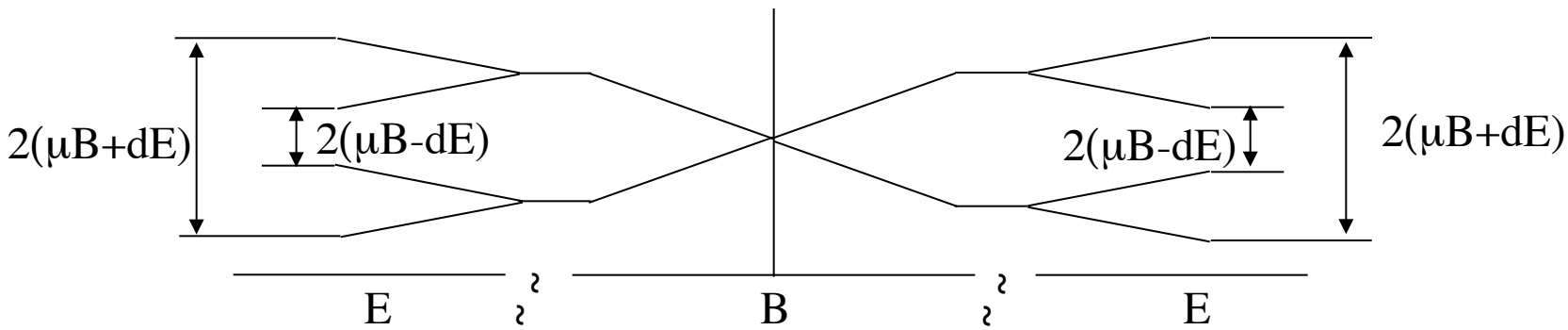
500-1000
(J. Engel et al.)



^{223}Rn: TBD

Measurement Principle

$$H=\mu \bullet B+d \bullet E=(g_\mu B+g_d E)\bullet J$$



Measure frequencies

$$\sigma_d \approx \frac{1}{2E}\frac{\hbar}{AT_2}\frac{1}{S/N}$$

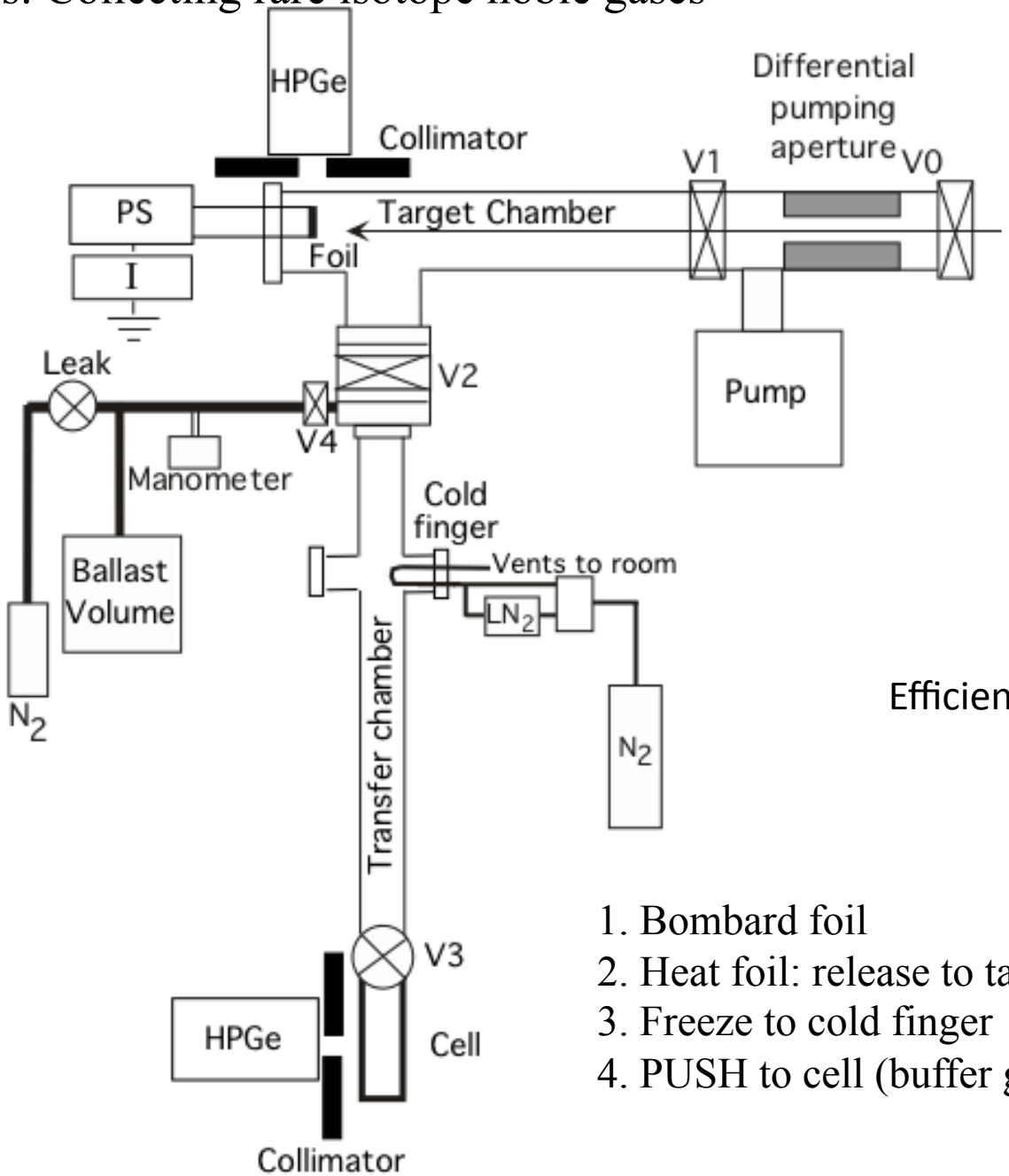
"Analyzing power"

$$\frac{1}{2E}\frac{\hbar}{AT_2}\frac{1}{\sqrt{\varphi_n T_2}}$$ Phase-noise limit

$$\boxed{\frac{1}{2E}\frac{\hbar}{AT_2}\frac{1}{\sqrt{N_\gamma}}}$$ Count-rate limit

Need to measure B (co)magnetometry

Techniques: Collecting rare isotope noble gases



Efficiency~100% (Mike Hayden)

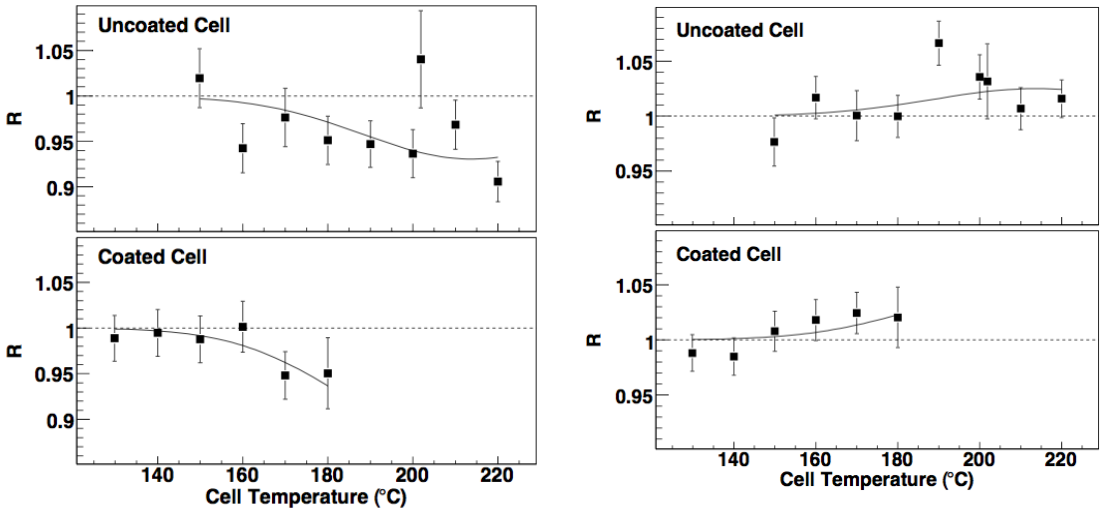
1. Bombard foil
2. Heat foil: release to target chamber
3. Freeze to cold finger
4. PUSH to cell (buffer gas)

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 (uncoated);
0.03 Hz (coated)
Use 2.5×10^{-21} cm^2

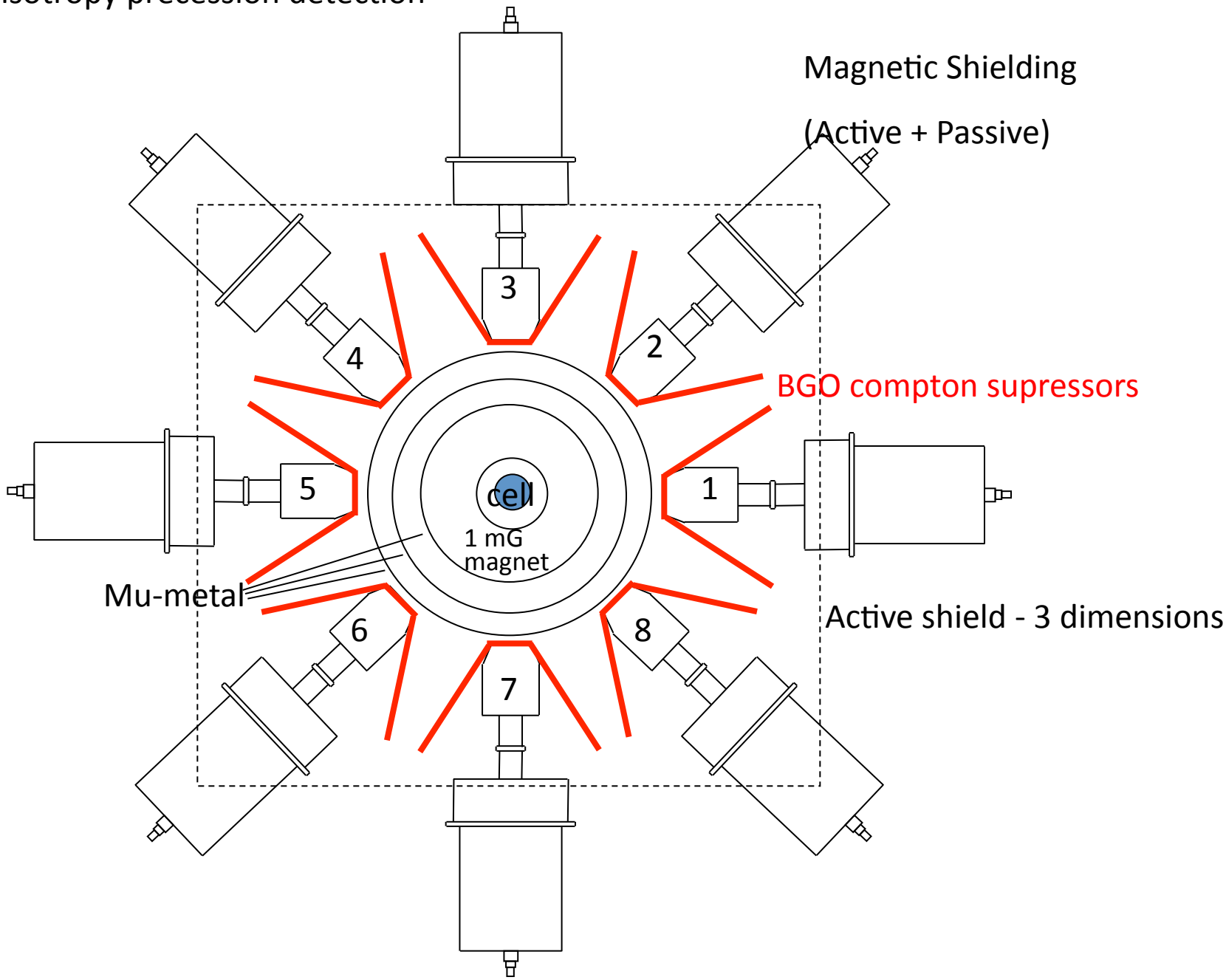
VOLUME 60, NUMBER 21 PHYSICAL REVIEW LETTERS 23 MAY 1988

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
G. Ulm[(b)] and K. Wendt[(c)] T. Chupp J. Bonn, R. Neugart, and E. Otten H. T. Duong

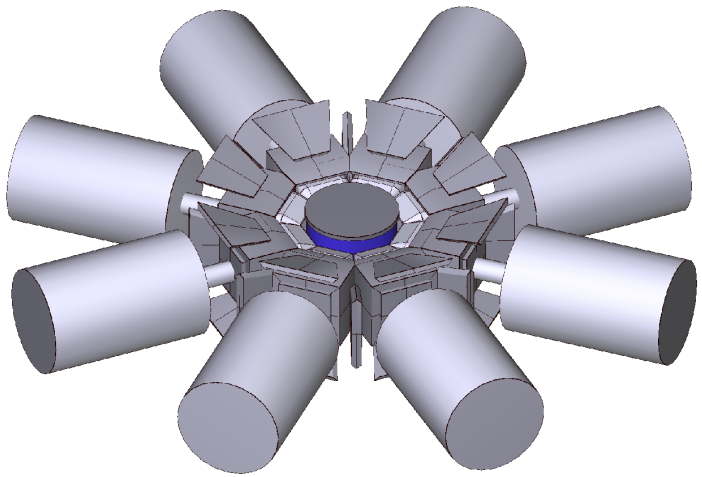
E_γ (keV)	Spin sequence	Anisotropy R	$R-1$ (%)
337	$(\frac{7}{2}^-)$-$(\frac{5}{2}^-)$	0.903(14)	-9.7 ± 1.4
408	$(\frac{5}{2}^-)$-$\frac{9}{2}^-$	1.009(7)	$+0.9\pm0.7$
689	$\frac{5}{2}, \frac{7}{2}^-$-$\frac{5}{2}^-$	1.079(22)	$+7.9\pm2.2$
745	$(\frac{7}{2}^-)$-$\frac{9}{2}^-$	1.129(14)	$+12.9\pm1.4$

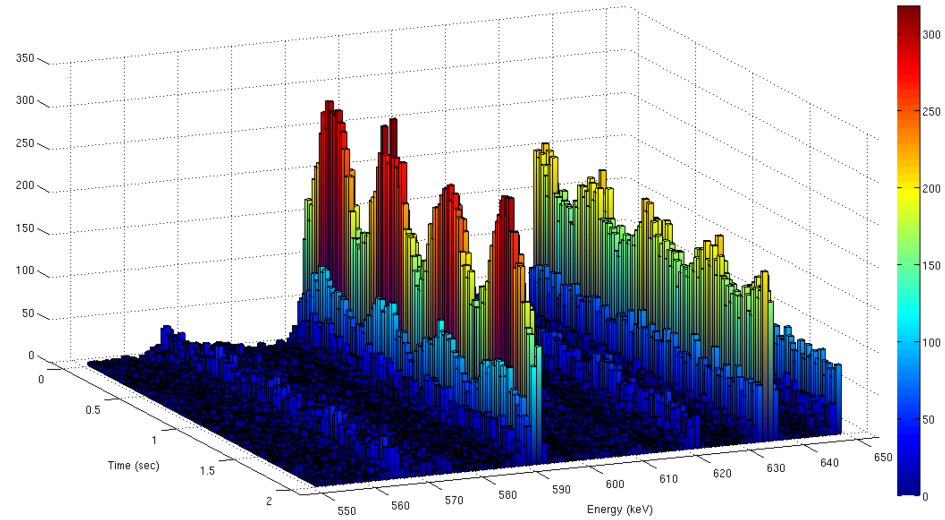
Gamma-anisotropy precession detection



Genat-4 simulations by Evan Rand

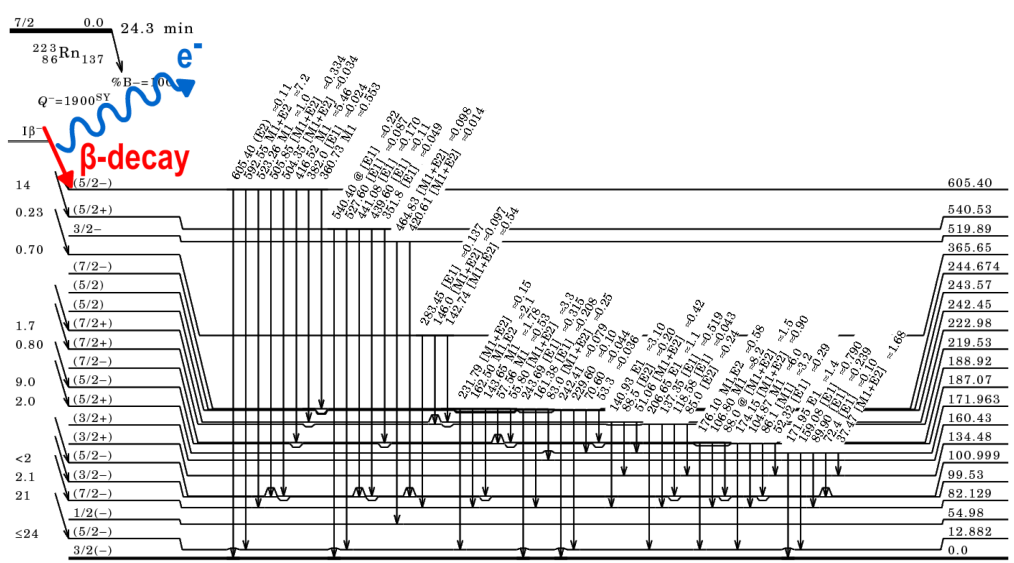
γ-ray energy-time matrix from the β decay of 1.2 billion ^{223}Rn nuclei from an initial 8×10^{10} nuclei located in the EDM cell surrounded by a ring of eight GRIFFIN detectors in the forward position.

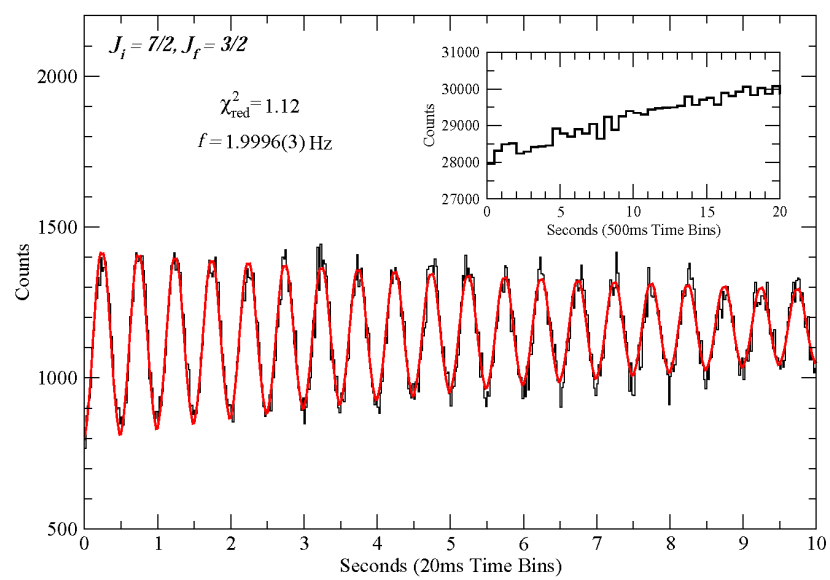




Known Level Structure of ^{223}Fr

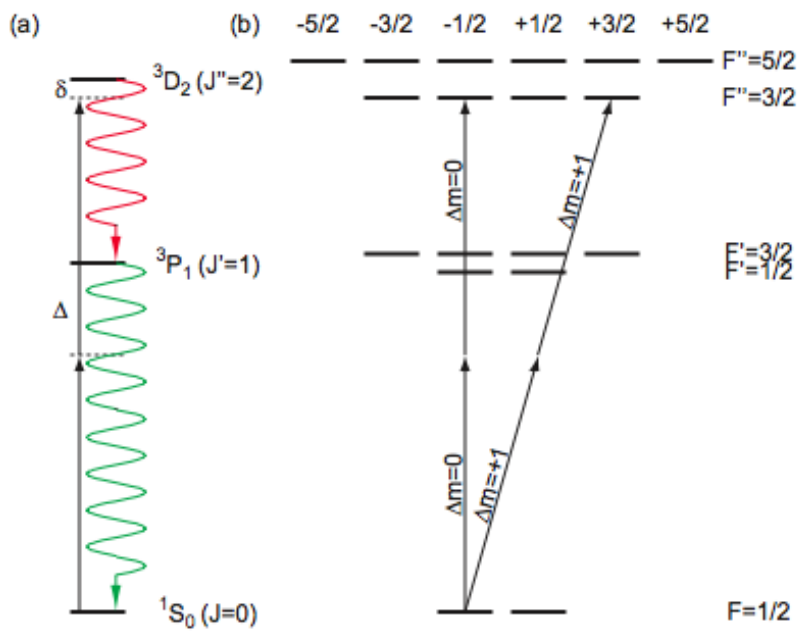
- *Nuclear Data Sheets (2001)*

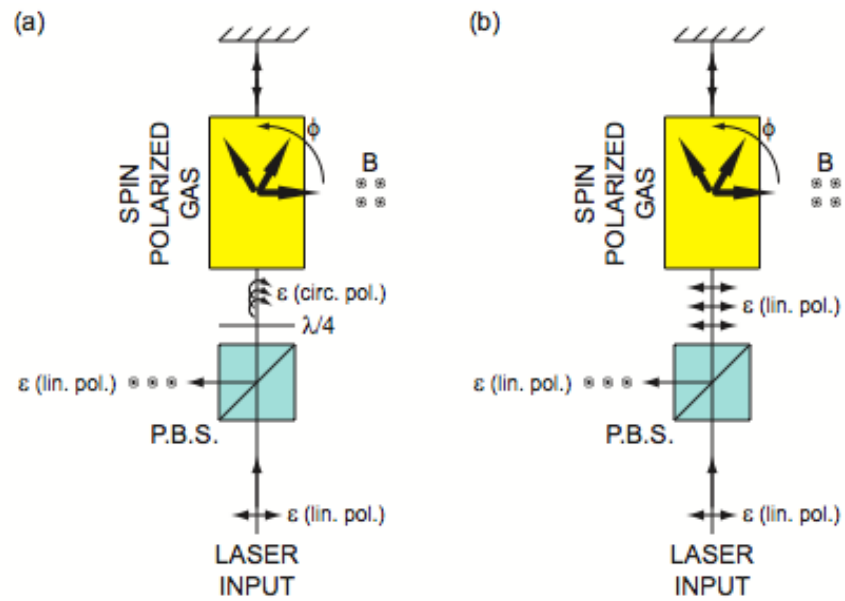




Other detection techniques

- Beta asymmetry
- 2-photon laser magnetometry developed for ^{129}Xe/nEDM





$$\mathcal{R}(\delta) \approx \rho V \frac{|\mu_{01}|^2 |\mu_{12}|^2}{\hbar^4 \Delta^2 \Gamma} \left(\frac{I}{\epsilon_0 c}\right)^2 \frac{1}{1+\left(\frac{\delta}{\Gamma}\right)^2},$$

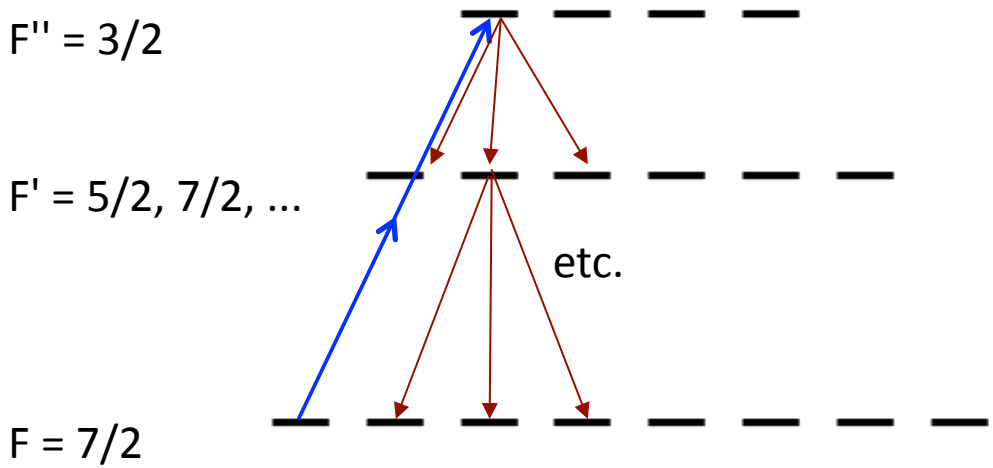
scattering rate (transmission)

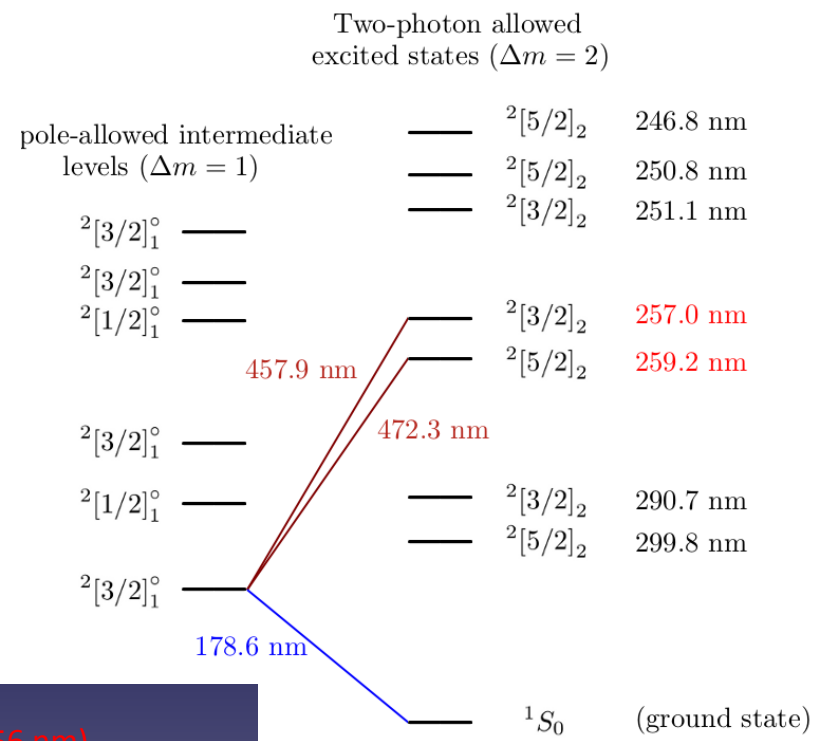
$$n(\delta) \approx 1 + \frac{\rho}{\epsilon_0} \frac{|\mu_{01}|^2 |\mu_{12}|^2}{\hbar^3 \Delta^2 \Gamma} \frac{I}{\epsilon_0 c} \frac{\frac{\delta}{\Gamma}}{1+\left(\frac{\delta}{\Gamma}\right)^2},$$

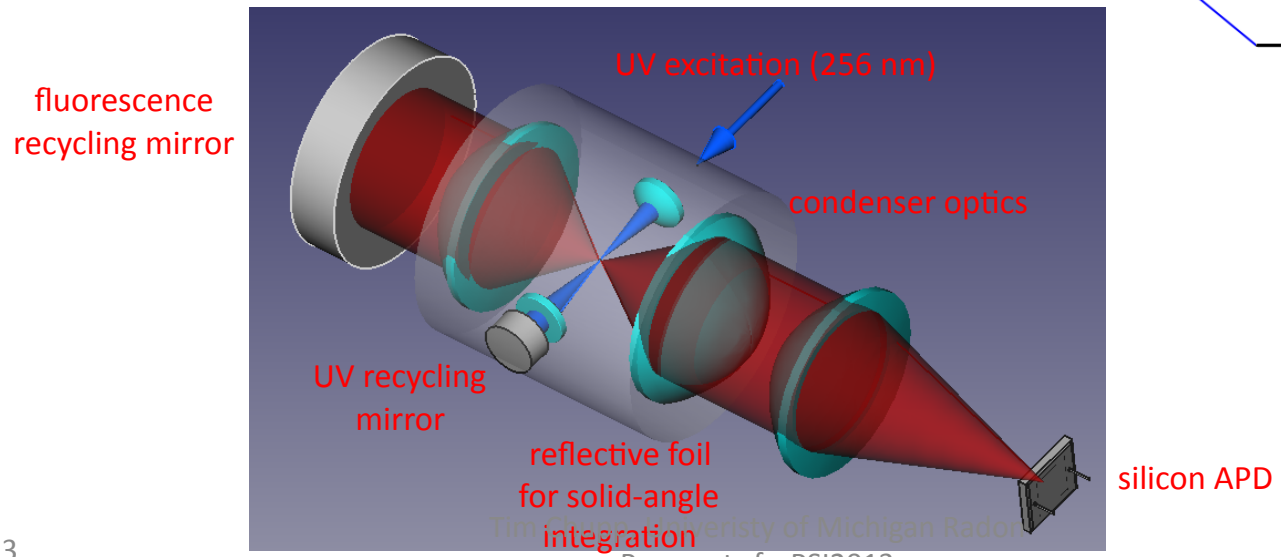
index of refraction (Faraday rotation)

Two-photon magnetometry with $^{221/223}$Rn (J=7/2)

S. Degenkolb







Radon-EDM Prospects

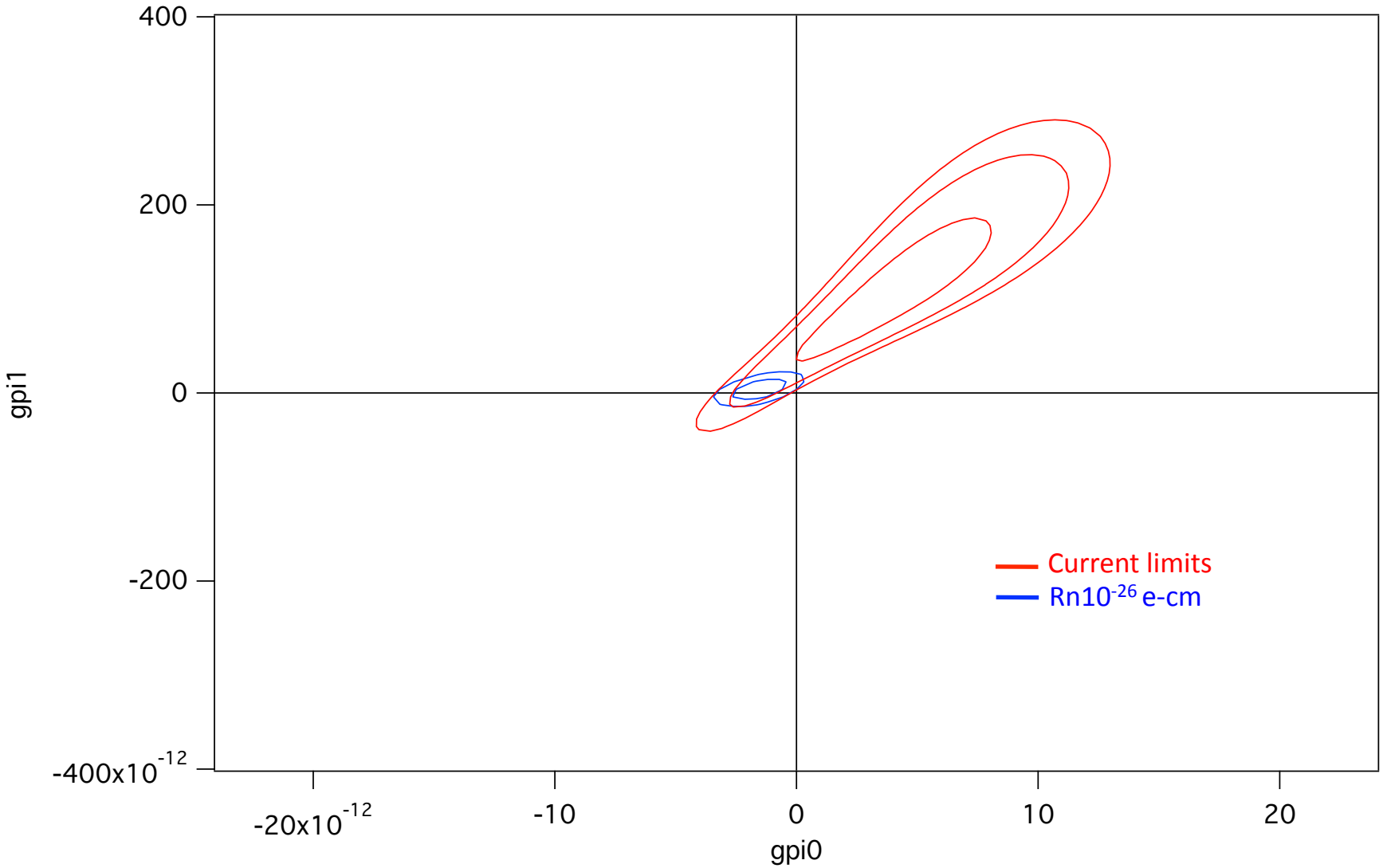
Compare to ^{199}Hg: d<3x10^{-29} e-cm (90%)

Facility	TRIUMF-ISAC	FRIB(^{223}Th)	Project X
Rate	2.5x10^{7} s^{-1}	1x10^{9} s^{-1}	3x10^{10} s^{-1}
# atoms	3.5x10^{10}	1.4x10^{12}	4.2x10^{13}
σ_{EDM} (100 d)	2x10^{-27} e-cm	3x10^{-28} e-cm	5x10^{-29} e-cm
^{199}Hg equivalent	4x10$^{-28/29}$ e-cm	6x10$^{-29/30}$ e-cm	1x10$^{-30/31}$ e-cm A future?

Assumptions: E=10 kV/cm, T_2=15 s, A=0.2, 25% duty factor

$$\sigma_d \approx \frac{1}{2E}\frac{\hbar}{AT_2}\frac{1}{\sqrt{N_\gamma}}$$

Impact: Relevance … Discovery



Elements of the EDM measurement

Need	Status
Radon production	Nearly there @ TRIUMF
Collection/transfer	✓
EDM Cells	✓ but new ideas
Polarization/lasers	✓
HV	OK (10kv/cm)
Detection	Under development
Gamma anisotropy	OK
Beta asymmetry	To be developed
Laser (2 photon)	Under development
Magnetic shielding	Needed

Thank you!

Extra Slides

Yields of Enhancer Isotopes: Ra, Rn, Fr

Presently available

- Decay daughters of ^{229}Th, National Isotope Development Center, ORNL
  - ^{225}Ra: 10^8 /s

Projected rates at FRIB (B. Sherrill, MSU)

- Beam dump recovery with a ^{238}U beam
  - Parasitic operation, available ~ 150 days per year
  - ^{225}Ra: 6 x 10^9 /s ; ^{223}Rn: 8 x 10^7 /s; $^{208\text{-}220}$Fr: 10^9 -10^{10} /s.

- Dedicated running with a ^{232}Th beam
  - ^{225}Ra: 5 x 10^{10} /s ; ^{223}Rn: 1 x 10^9 /s; $^{208\text{-}220}$Fr: 10^{10} /s;

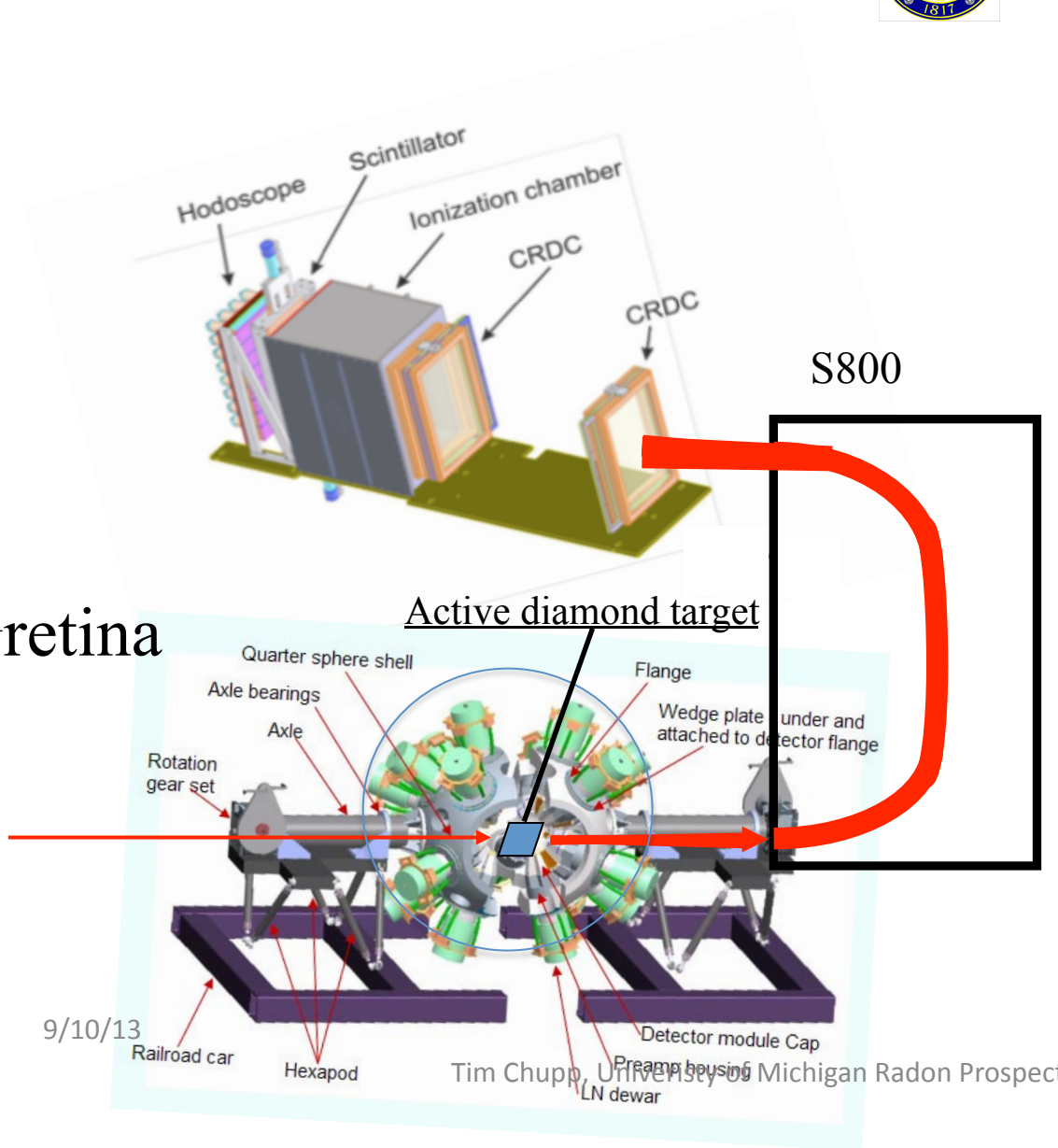
^{238}U fragmentation-in beam $^{221/223}$Rn* spectroscopy

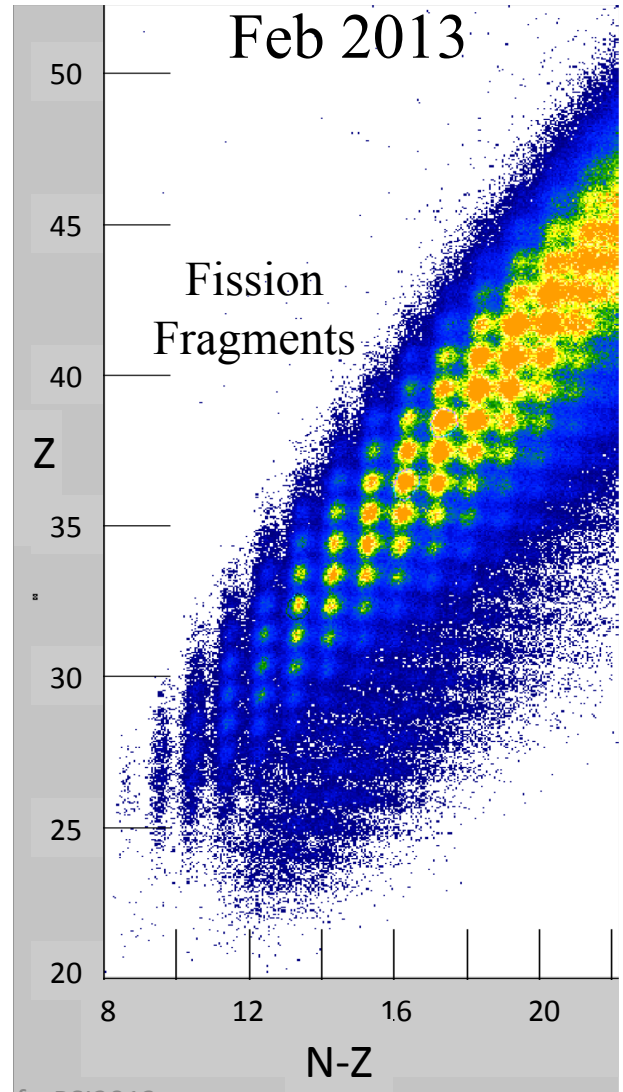
J. Berryman*, A. Gade, B. Sherrill, **TC*** et al. (***spokespersons**)

MSU

Data analysis underway

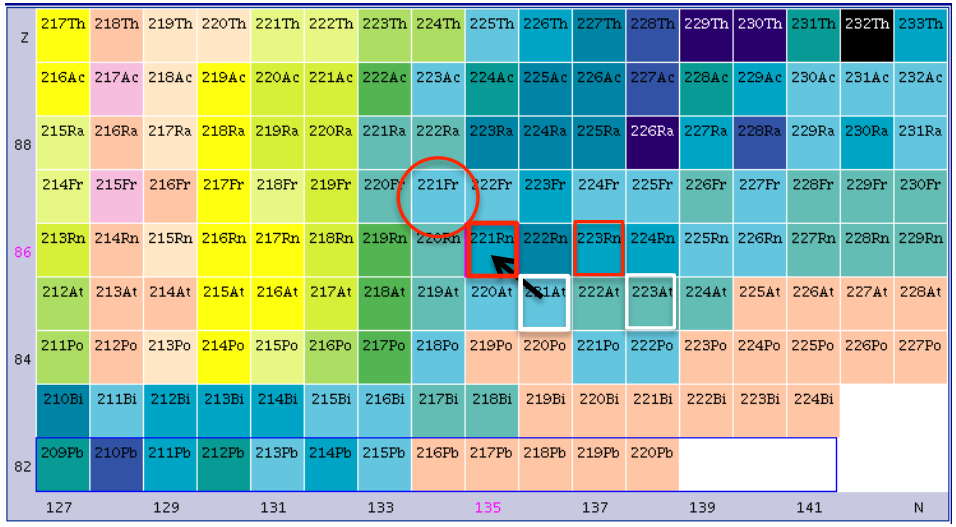
Feb 2013





TRIUMF

Canada's National Laboratory for Particle and Nuclear Physics
S-929 Radon-EDM Collaboration (Guelph, Michigan, SFU, TRIUMF)
Spokesmen: T. Chupp, C. Svensson



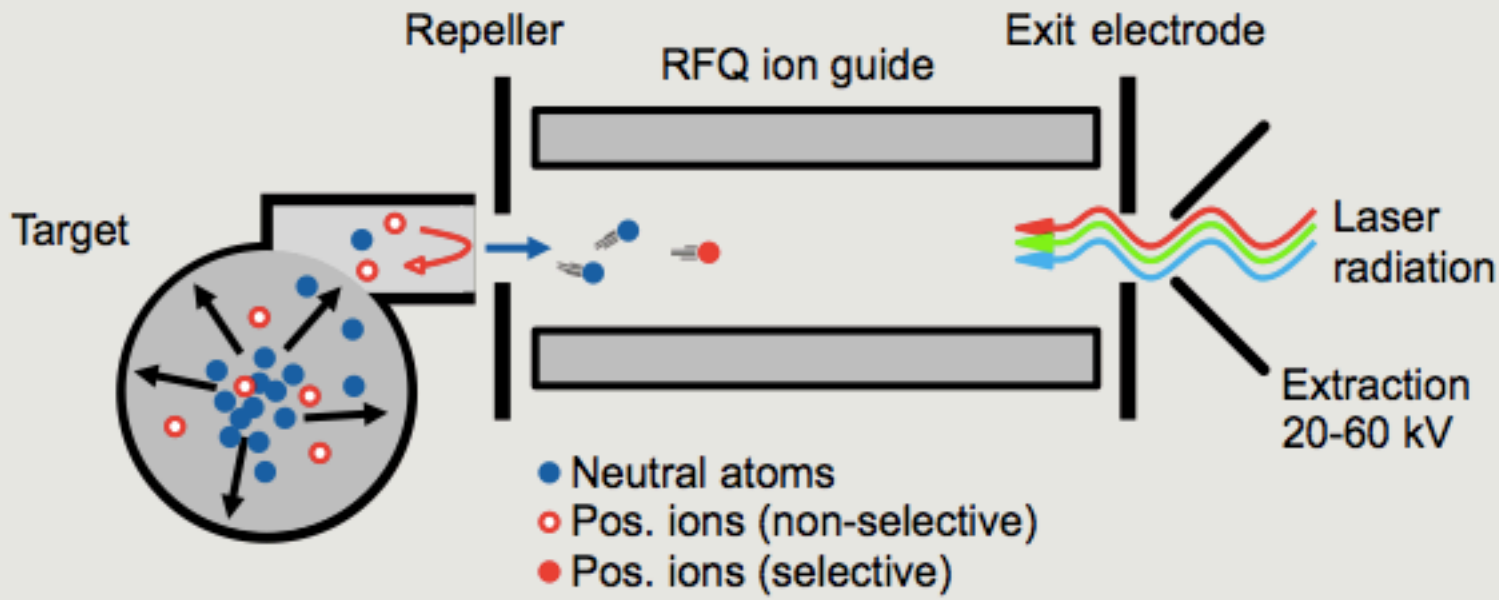
Populate ^{221}Rn levels from ^{221}At @ ISAC – December 2013

TRIUMF

Henning Heggen M.Sc. I Grad. Research Assistant TRILIS

Concept IG-LIS

- Decoupling of evaporation processes and laser ionization
  - Suppression of surface ions from target
  - Laser ionization in "cold" environment



- **Isobar suppression** of up to **10^6** demonstrated (Na)
- **Yield reduction seen** typically **< 50**
- **7 RIBs** successfully **delivered** to experiment

Proposed by:
K. Blaum, C. Geppert and H.-J. Kluge et al.,
***Nucl. Instr. Meth. Phys. Res.* B, 204, 2003**

^{225}Ra EDM Prospects

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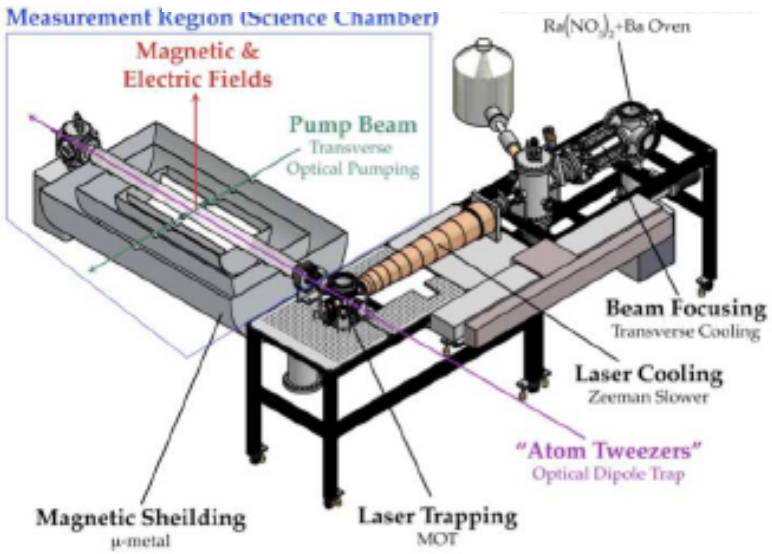
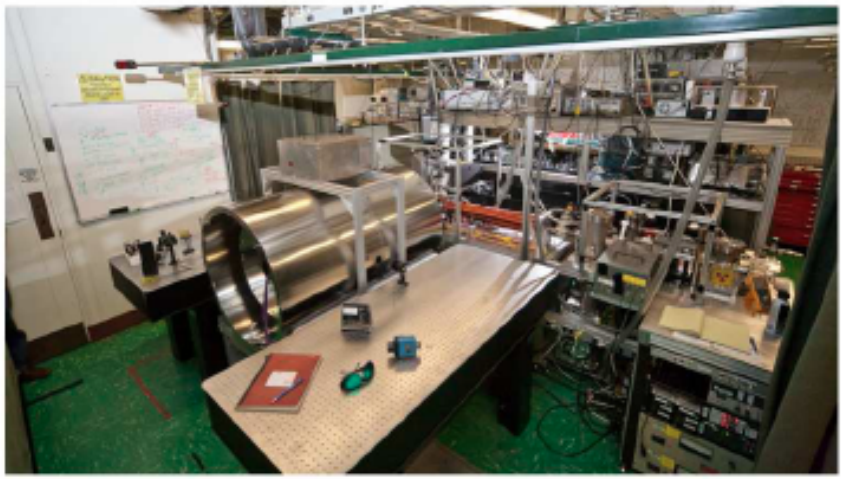




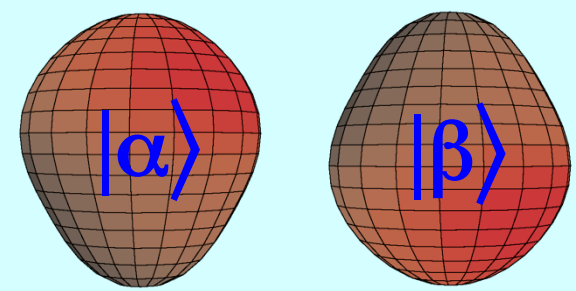
Phase	Phase 1	Phase 2 (upgrade)	Project X
Ra (mCi)	1-10	10	> 1000
Sens. ^{225}Ra (10^{-28} e cm)	100	10	0.1-1
Sens. ^{199}Hg (10^{-30} e cm)	10	1	0.01-0.1

EDM of ^{225}Ra enhanced

^{225}Ra:
I = ½
$t_{1/2}$ = 15 d

- Closely spaced parity doublet – *Haxton & Henley (1983)*
- Large intrinsic Schiff moment due to octupole deformation
  – *Auerbach, Flambaum & Spevak (1996)*
- Relativistic atomic structure (^{225}Ra / ^{199}Hg ~ 3)
  – *Dzuba, Flambaum, Ginges, Kozlov (2002)*

Parity doublet



$\Psi^- = (|\alpha\rangle - |\beta\rangle)/\sqrt{2}$

55 keV

$\Psi^+ = (|\alpha\rangle + |\beta\rangle)/\sqrt{2}$

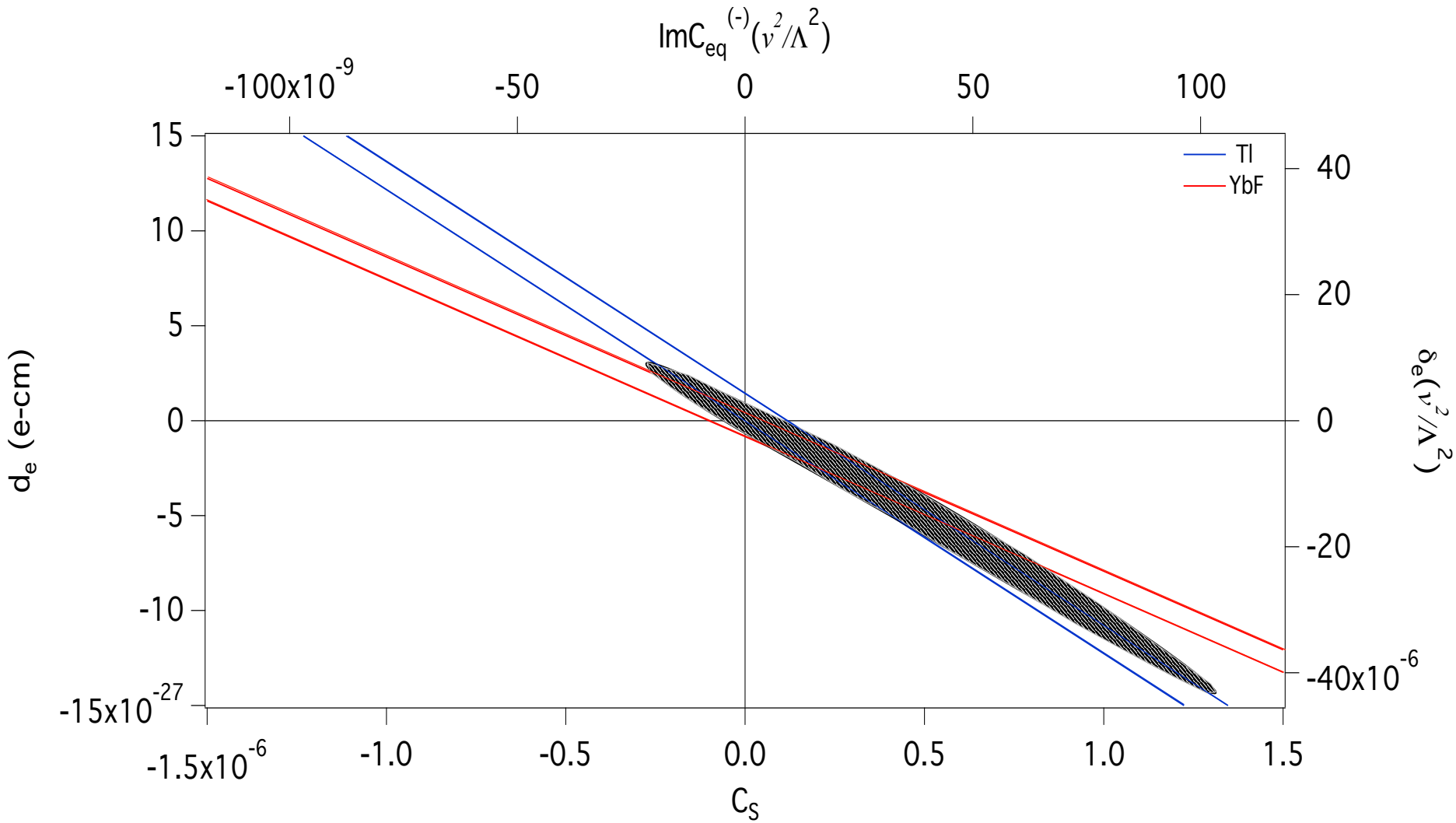
$$S \equiv \langle \psi_0 | \hat{S}_z | \psi_0 \rangle = \sum_{i \neq 0} \frac{\langle \psi_0 | \hat{S}_z | \psi_i \rangle \langle \psi_i | \hat{H}_{PT} | \psi_0 \rangle}{E_0 - E_i} + c.c.$$

Enhancement Factor: EDM (^{225}Ra) / EDM (^{199}Hg)

Skyrme Model	Isoscalar	Isovector	Isotensor
SIII	300	4000	700
SkM*	300	2000	500
SLy4	700	8000	1000

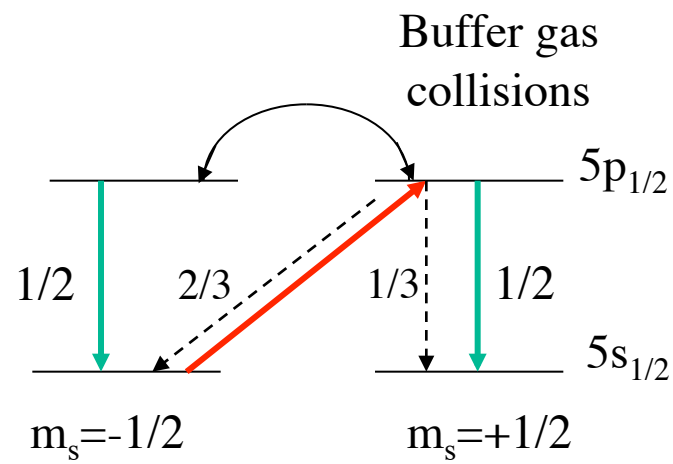
Schiff moment of ^{225}Ra, Dobaczewski, Engel (2005)
Schiff moment of ^{199}Hg, Ban, Dobaczewski, Engel, Shukla (2010)

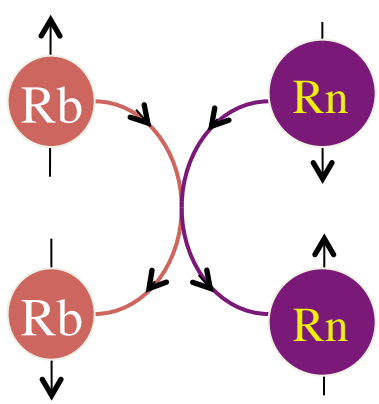
Paramagnetic atoms: d_e and C_S



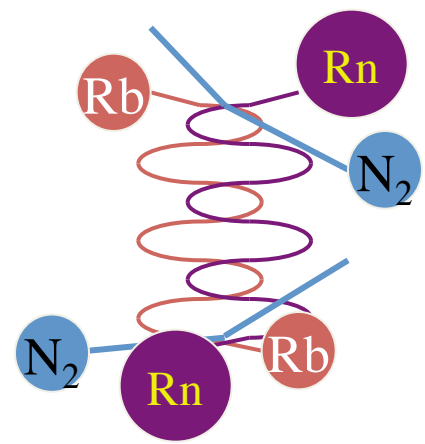
Spin-Exchange Optical Pumping

- Optically pump the Rb with circularly polarized laser light.
- Spin-exchange collisions transfer the polarization to the ^{3}He, ^{129}Xe, radon nuclei.





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



van Der Waals Molecule