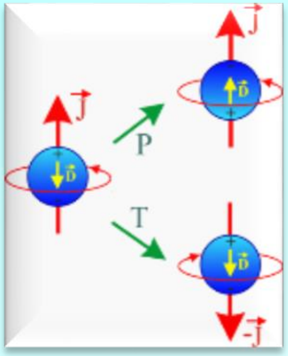
INTERNATIONAL CENTRE *for* THEORETICAL SCIENCES
ICTS
TATA INSTITUTE OF FUNDAMENTAL RESEARCH

CP VIOLATION IN ELEMENTARY PARTICLES AND COMPOSITE SYSTEMS
PCPV 2013, Mahabaleshwar, India February 2013

Radium Atoms to search for EDMs



- **Symmetries & Conservation Laws**
- **Standard Model and Beyond**
- **Search for New Interactions**
- **Questions : Matter-Antimatter Asymmetry ?**
- **Precision Experiments**

⇒ Field has many Experiments

⇒ here Focus on: Ra, Xe, μ

⇒ A few examples only

⇒ A few aspects of the full story

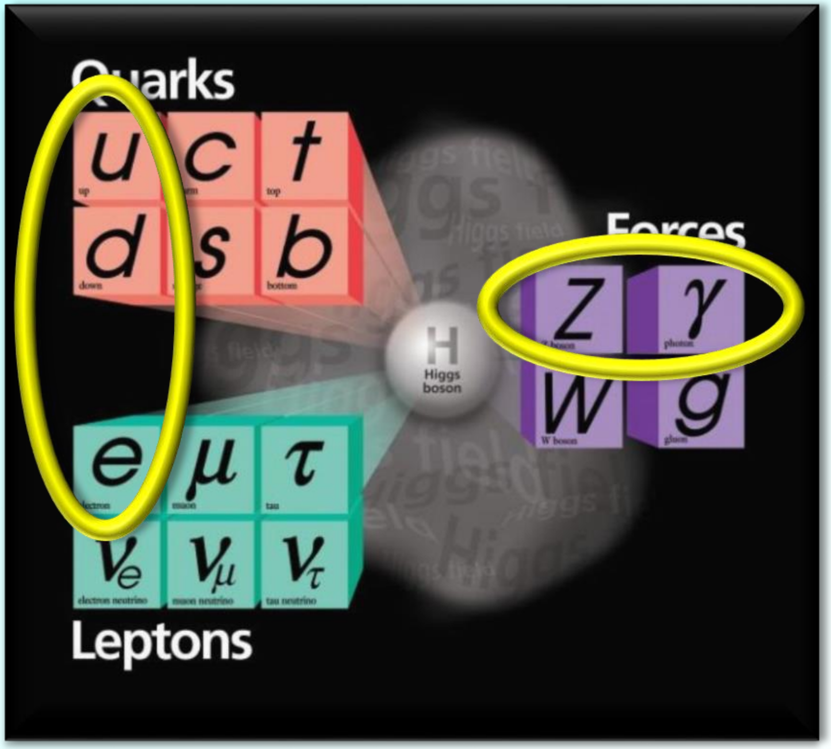
Klaus Jungmann*, KVI, University of Groningen, NL*

with many thanks to L. Willmann

university of groningen

FOM

Standard Model
&
Radium

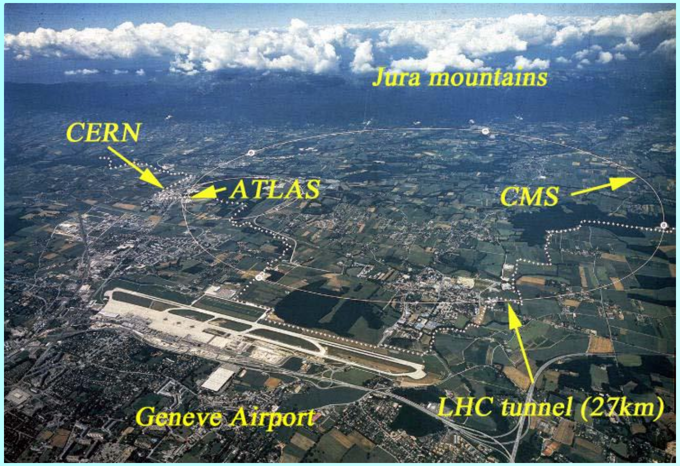


3 families of matter - 4 force carriers

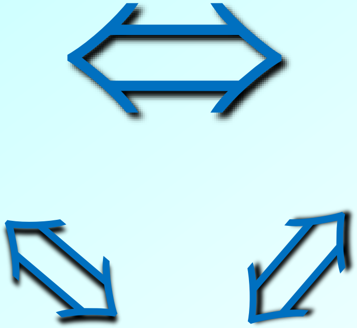
Experiments at the Frontiers of Standard Theory

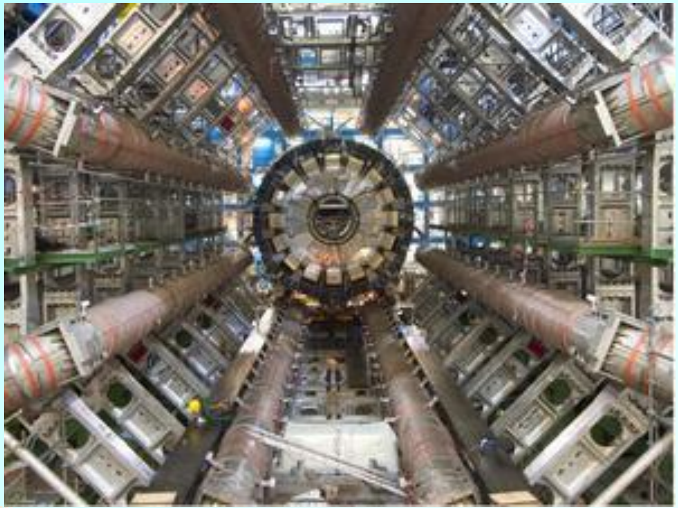
Direct Search Frontier

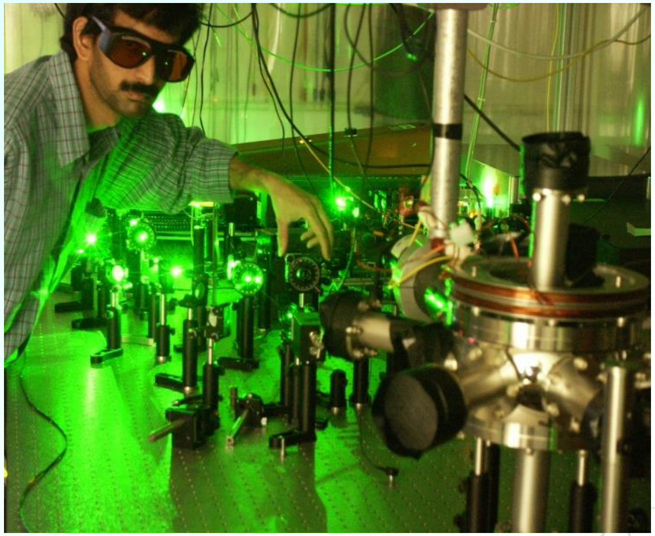
Precision Frontier



complementary
approaches







Intensity
Frontier

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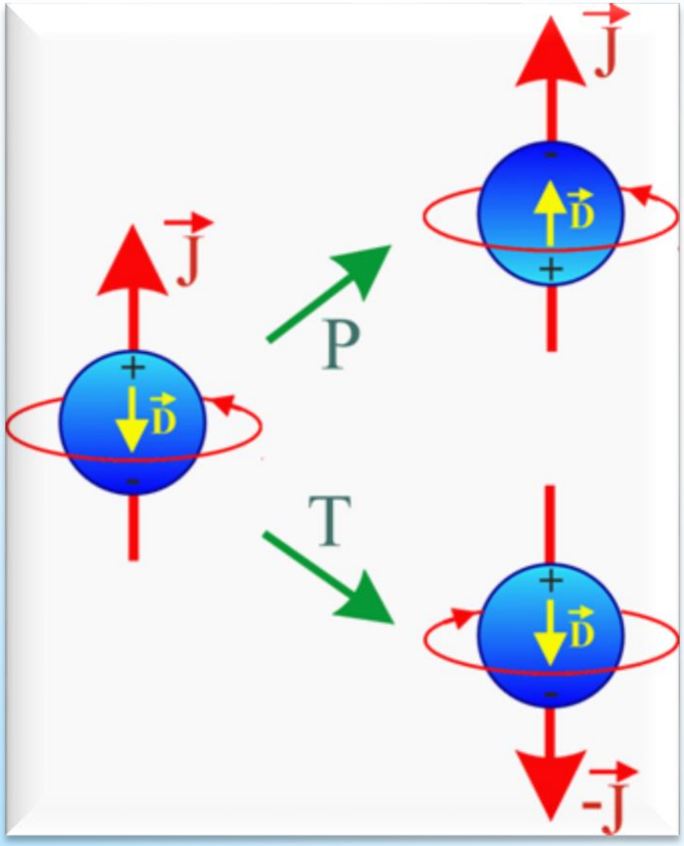
Permanent Electric Dipole Moment violates:



- Parity
- Time reversal
- CP- conservation

(if CPT conservation assumed)`

Standard Model value orders of magnitude below experimental limit:

⇒ **Window for**

New Physics

beyond

Standard Theory

Lines of attack towards an EDM

Free Particles

neutron
muon
proton
deuteron
bare nuclei ?
…

- → particle EDM
- → unique information
- → new insights
- → new techniques
- → challenging technology

Atoms

Hg Xe
Tl
Cs Rb
Ra Rn
…

- → electron EDM
- → nuclear EDM
- → enhancements
- → challenging technology

Electric
Dipole
Moment

goal:
new source of $\cancel{CP}$

Molecules

- → electron EDM
- → strong enhancements
- → new techniques
- → poor spectroscopic data

YbF
PbO
PbF ,ThO
HfF^+,ThF^+
WN^-…

Condensed State

- → electron EDM
- → strong enhancements
- → systematics ??

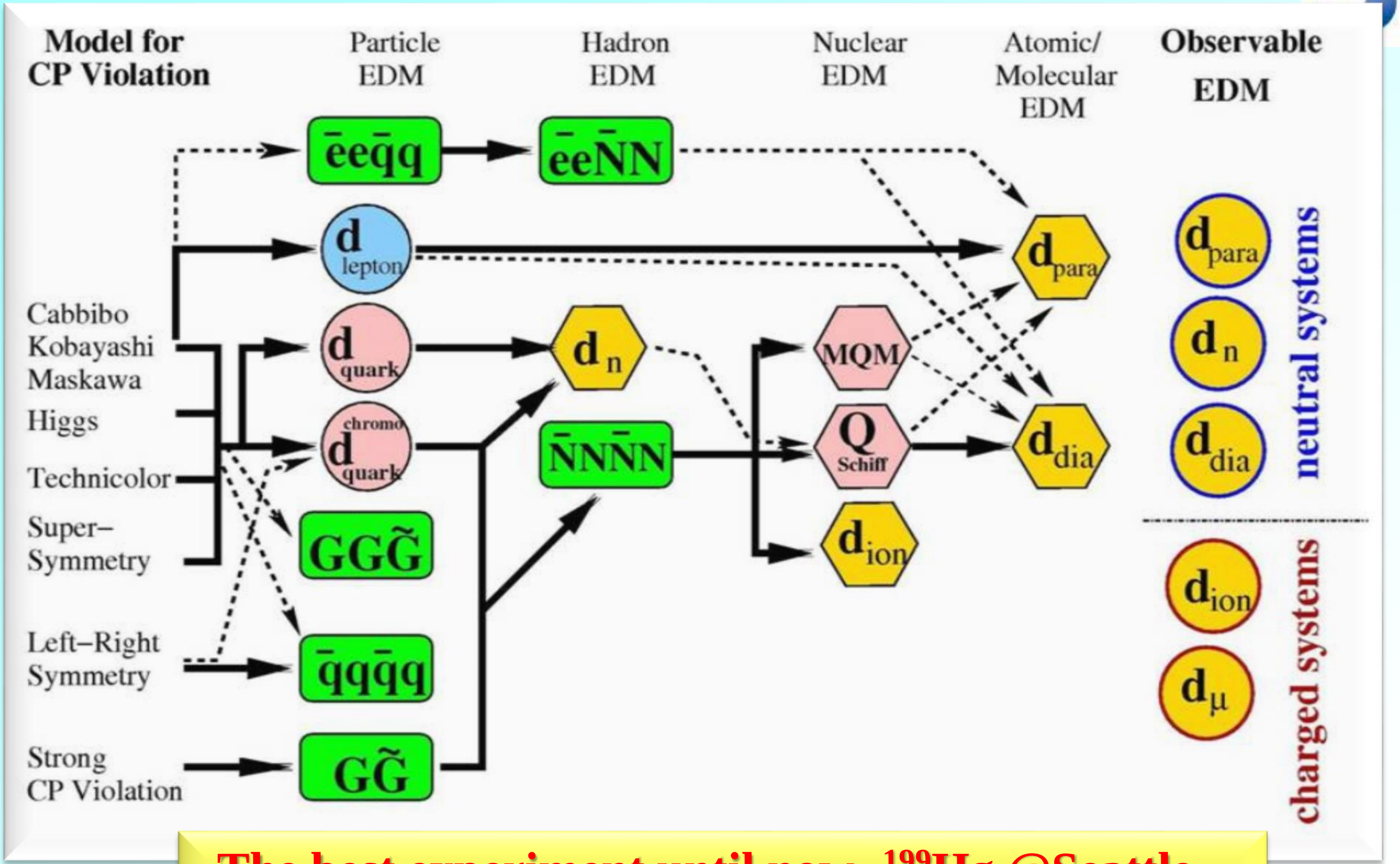
garnets
$(Gd_3Ga_5O_{12})$
$(Gd_3Fe_2Fe_3O_{12})$
solid He ?
liquid Xe

EDM Limits as of end 2012

Particle	Exp. Limit $[10^{-27}$ *e* cm$]$	SM [factor to go]	Possible New Physics [factor to go]
e (YbF)	< 0.15	10^{10}	$\lesssim 1$
μ	$< 1.8 * 10^{8}$	10^{8}	$\lesssim 200$
τ	$< 1.1 * 10^{10}$	10^{6}	$\lesssim 60^{(*!)}$
n	< 30	10^{4}	$\lesssim 10$
p (Hg)	$< 8 * 10^{2}$	10^{6}	$\lesssim 10^{5}$
Hg (odd n)	< 0.031	10^{4}	various
			*!) depending on type of EDM

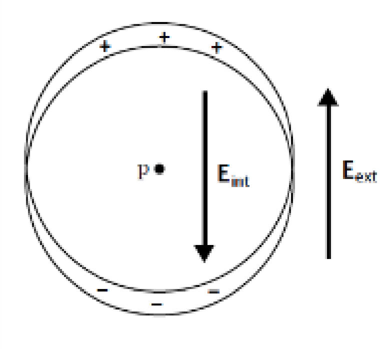
Theoretical Model	d_e [e cm]
Standard Model	$< 10^{-38}$
SUSY	$10^{-28} – 10^{-26}$
Multi Higgs	$10^{-28} – 10^{-26}$
LeftRight Symmetry	$10^{-28} – 10^{-26}$

Possible Sources of EDMs



The best experiment until now- ^{199}Hg @Seattle – Leaves somewhat restricted room for SUSY …

Enhancements of particle EDMs



$$\frac{d_{atom}}{d_e} \propto Z^3 \alpha^2 \chi$$

P. Sandars, 1968

$$d_{atom} = \sum_{n'} \frac{< n, l| - d_e(\beta - 1)\vec{\sigma} \cdot \vec{E}|n', l \pm \mathbf{1} >< n', l \pm \mathbf{1}| - e\vec{r}|n, l >}{E_{n,l} - E_{n',l\pm 1}} + h.c.$$

⇒ **go for heavy systems, where Z>>1, e.g. Hg, Xe**

⇒ **take advantage of enhancements, e.g. Ra**

⇒ **consider molecules such as YbF, RaF, …**

Atomic Enhancement Factors

for Electron EDM

Particle		Rb	Cs	Th	Fr	Ra	PbO	YbF
Enhancement		24	125	585	1 150	40 000	60 000	1 600 000

EDMs of atoms of experimental interest

Z	Atom	[*S*/(e fm3)]*e* cm	[10^{-25} η] *e* cm	Expt.
2	^{3}He	0.00008	0.0005	
KVI **54**	**^{129}Xe**	**0.38**	**0.7**	**Seattle, Ann Arbor, Princeton,Tokyo,** ***Mainz-PTB-HD-KVI***
70	^{171}Yb	-1.9	3	Bangalore,Kyoto
80	^{199}Hg	-2.8	4	Seattle
86	^{223}Rn	3.3	3300	TRIUMF
KVI 88	^{225}Ra	-8.2	2500	Argonne,KVI
88	^{223}Ra	-8.2	3400	

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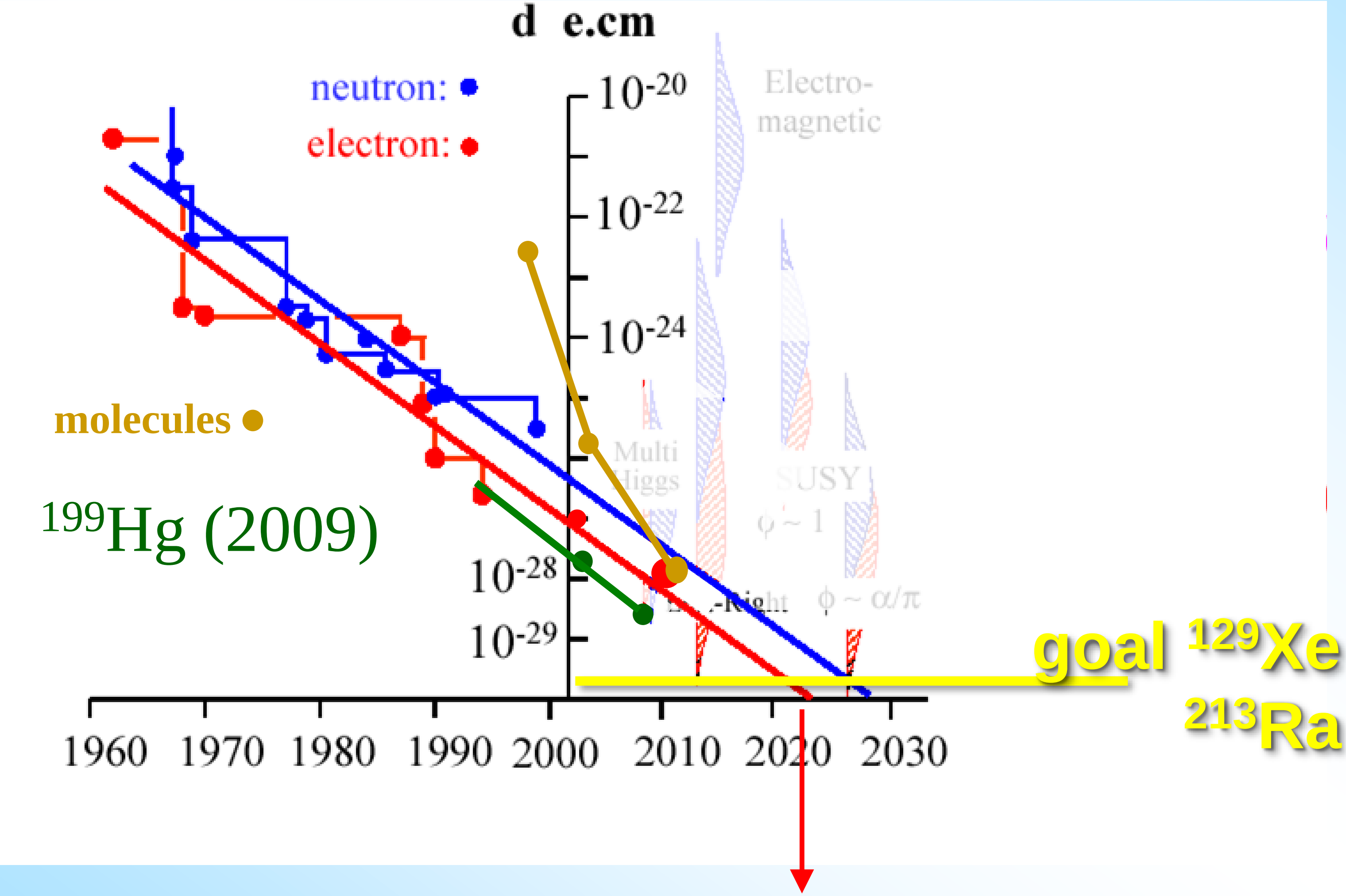
slide from Victor Flambaum

FOM

Limit on EDMs vs Time



goal ^{129}Xe

^{213}Ra

d_e (SM) < 10^{-37}

Generic EDM Experiment

Preparation
of
“pure“ $\vec{J}$ **state**

→

Interaction
with
$\vec{E}$ **- field**

→

Analysis
of
state

Polarization

η contains all physics –
“e cm” values by themselves
not very helpful

$\mu_x = e\hbar/2m_x$

Electric Dipole Moment: $\vec{d} = \eta\ \mu_x\ c^{-1}\ \vec{J}$

Spin precession : $\vec{\omega}_e = \dfrac{\vec{d}\bullet\vec{E}}{\hbar}\ \dfrac{\vec{E}\times\vec{J}}{|\vec{E}\times\vec{J}|}$

Example: $d=10^{-24}$ e cm, E=100 kV/cm, J=1/2
$\omega_e = 15.2$ mHz

Generic EDM Experiment Sensitivity

P	***Polarization***
ε	***Efficiency***
N	***Average Trap Population***
T	***Measurement Time [s]***
τ	***Spin Coherence Time (≅ 1cycle) [s]***
E	***Electric Field [V/cm]***

~1
~1
10^6
10^6
10^5 V/cm

$< \sim 10^{-28}$ *e cm*

Need to understand systematics

$$P\varepsilon \sqrt{N * T * \tau}\ \ E$$

$d_x = d_{Ra}$ /enhancement

same physics sensitivity as ^{199}Hg due to enhancement factors

- **long Coherence Time**

⇒ one day gives more statistics than needed to reach previous experimental limits

Enhancements of particle EDMs

$$\frac{d_{atom}}{d_e} \propto Z^3 \alpha^2 \chi$$

$$d_{atom} = \sum_{n'} \frac{< n, l| - d_e(\beta - 1)\vec{\sigma} \cdot \vec{E} |n', l \pm \mathbf{1} >< n', l \pm \mathbf{1}| - e\vec{r} |n, l >}{E_{n,l} - E_{n',l\pm1}} + h.c.$$

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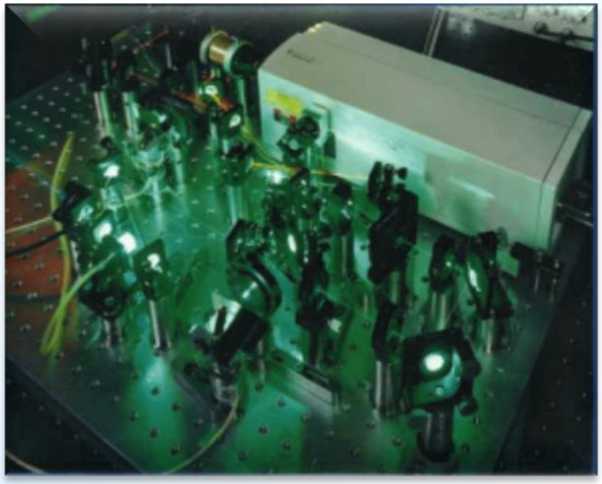
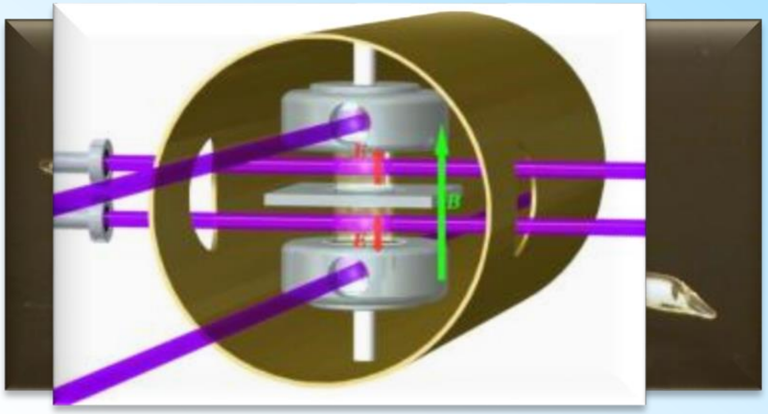
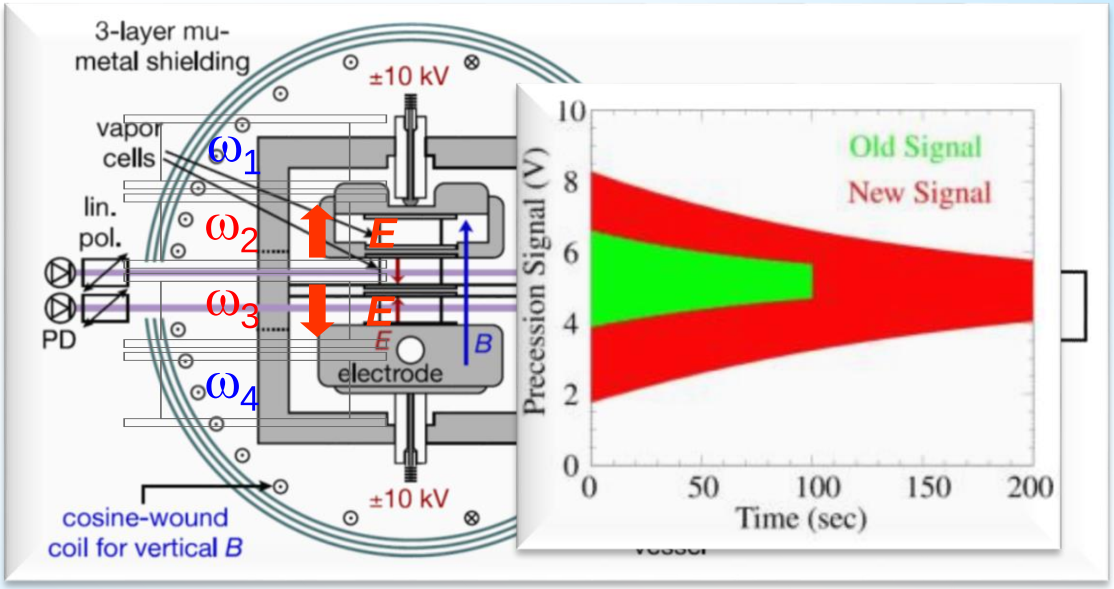
$d_n = 5 \times 10^{-24}\, e$ cm η, $d(^{3}\mathrm{He})/d_n = 10^{-5}$

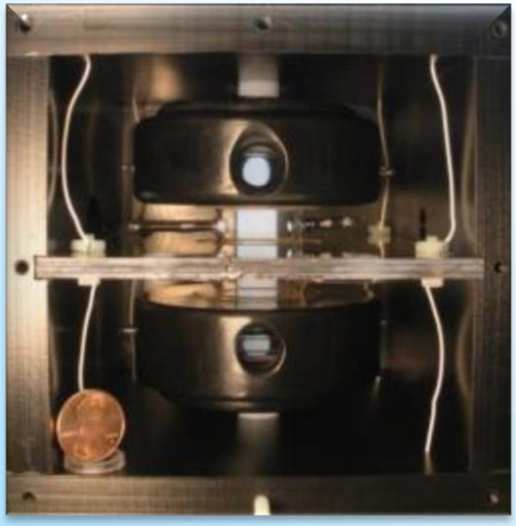
slide from Victor Flambaum

Hg EDM University of Washington, Seattle

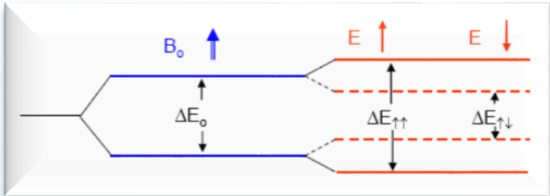




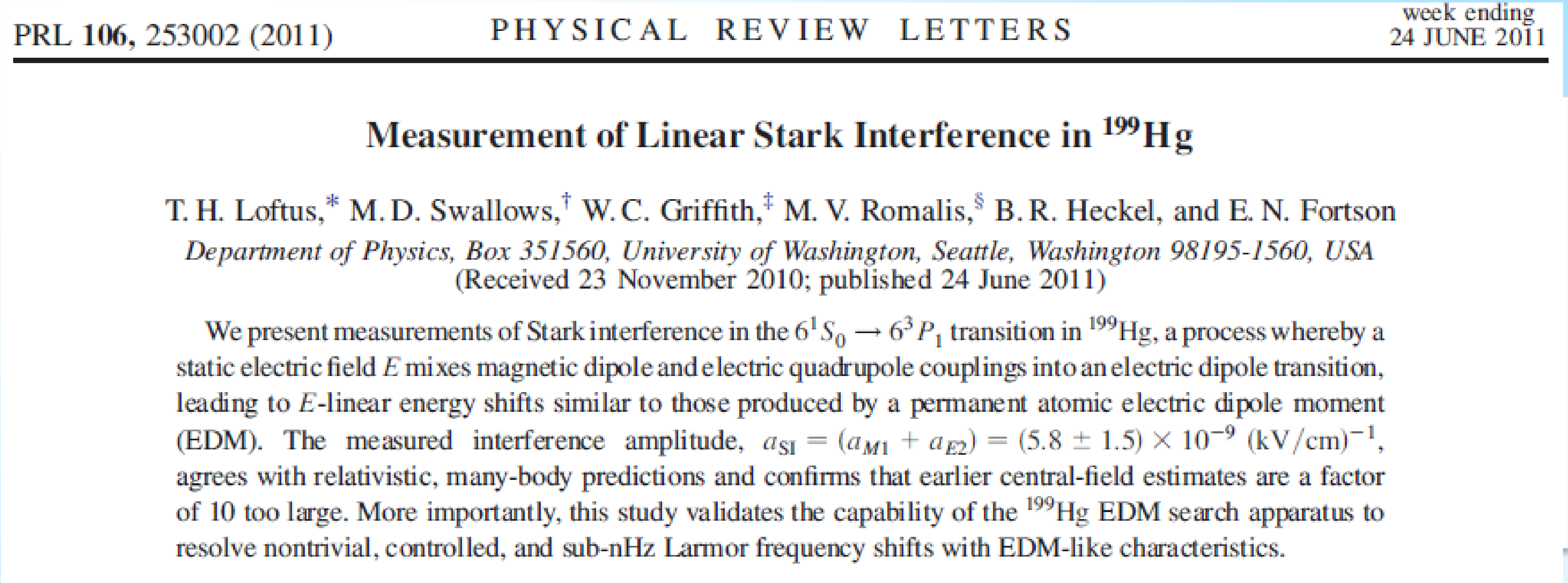




Spin coherence time: 300 sec
Electrical Resistance: 2×10^{16} Ω



Hg EDM University of Washington, Seattle II



PRL 106, 253002 (2011) PHYSICAL REVIEW LETTERS week ending 24 JUNE 2011

Measurement of Linear Stark Interference in ^{199}Hg

T. H. Loftus,* M. D. Swallows,† W. C. Griffith,‡ M. V. Romalis,§ B. R. Heckel, and E. N. Fortson
Department of Physics, Box 351560, University of Washington, Seattle, Washington 98195-1560, USA

(Received 23 November 2010; published 24 June 2011)

We present measurements of Stark interference in the $6^1S_0 \rightarrow 6^3P_1$ transition in ^{199}Hg, a process whereby a static electric field E mixes magnetic dipole and electric quadrupole couplings into an electric dipole transition, leading to E-linear energy shifts similar to those produced by a permanent atomic electric dipole moment (EDM). The measured interference amplitude, $a_{SI} = (a_{M1} + a_{E2}) = (5.8 \pm 1.5) \times 10^{-9}$ (kV/cm)$^{-1}$, agrees with relativistic, many-body predictions and confirms that earlier central-field estimates are a factor of 10 too large. More importantly, this study validates the capability of the ^{199}Hg EDM search apparatus to resolve nontrivial, controlled, and sub-nHz Larmor frequency shifts with EDM-like characteristics.

⇒ Going on in a structured way

translates into

$|d(^{199}\mathrm{Hg})| < 3.1\times10^{-29}$ e cm (95% C.L.)

Systematic limits expected factor of 5 further lower

W. C. Griffith, M. D. Swallows, T. H. Loftus, M. V. Romalis, B. R. Heckel, E. N. Fortson , Phys. Rev. Lett. **102**, 101601 (2009)

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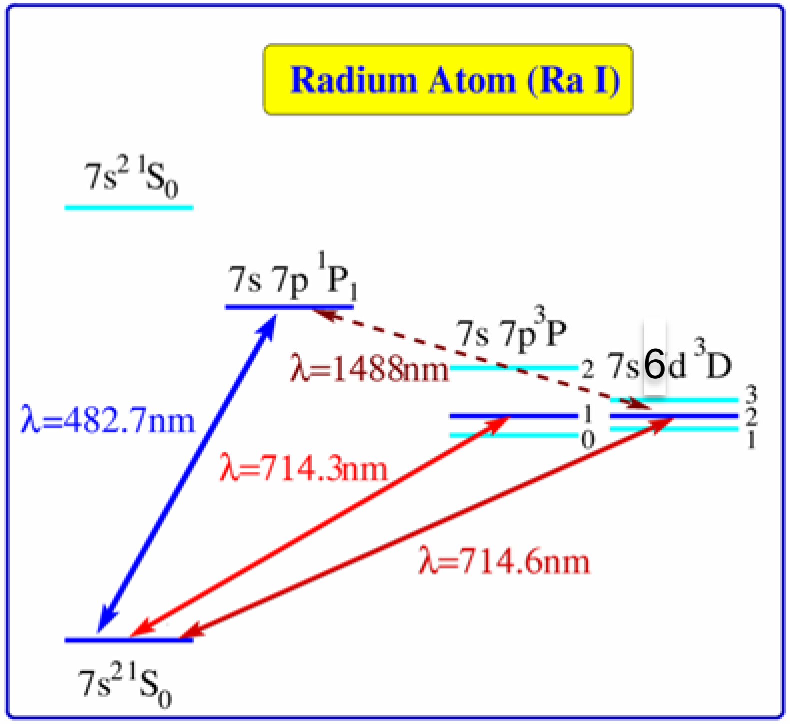
KVI

$d_n = 5 \times 10^{-24}\, e$ cm η, $d(^{3}\mathrm{He})/\, d_n = 10^{-5}$

slide from Victor Flambaum

Radium Permanent Electric Dipole Moment



Benefits of Radium

- **near degeneracy of $^3P_1$ and $^3D_2$**
  ⇒ ~ 40 000 enhancement

- **some nuclei strongly deformed**
  ⇒ nuclear enhancement
  50~1000 (?is Schiff operator correct?)

^3D : electron spins parallel

⇒ electron EDM

^1S : electron Spins anti-parallel

⇒ atomic / nuclear EDM

Ra also interesting for weak interaction effects
Anapole moment, weak charge
(Dzuba el al., PRA 6, 062509)

Deformed Nuclei

Enhancement of Dipole Moments

IS475 @ ISOLDE

Measurements of octupole collectivity in odd-mass Rn, Fr and Ra isotopes

CERN-ISOLDE (J. Pakarinen, T. Stora, D. Voulot, F.Wenander),*TU* ***Darmstadt*** (Th. Kröll),***GANIL*** (E. Clément), *U* ***Groningen KVI*** (K. Jungmann, J. Van de Walle, L. Willmann, H.W. Wilschut),*U* ***Jyväskylä*** (T. Grahn, P. T. Greenlees, R. Julin, P. Nieminen),*U* ***Kentucky*** (S.W. Yates),*U* ***Köln*** (A. Blazhev, N. Warr),***Lawrence Livermore*** *L* (E. Kwan, M. A. Stoyer, C.-Y. Wu),*KU* ***Leuven*** (M. Huyse, P. Van Duppen),*U* ***Liverpool*** (P.A. Butler, R.-D. Herzberg, D.T. Joss, R.D. Page, P. Papadakis, M.Scheck),*U* ***Lund*** (J. Cederkäll),*U* ***Michigan*** (T. Chupp, W. Lorenzon),*TU* ***München*** (V. Bildstein, R. Gernhäuser, R. Krücken, D. Muecher, N. Nowak, K.Wimmer),*U* ***Oslo*** (A.Bürger, M. Guttormsen, A.-C. Larsen, H.T.Nyhus, S. Siem, H.Toft, G. Tveten),*U* ***Rochester*** (D. Cline, A. Hayes),*HIL U* ***Warsaw*** (K. Hadynska-Klek, J. Iwanicki, P. Napiorkowski, D. Pietak, J. Srebrny, K. Wrzosek-Lipska, M. Zielinska),*U* ***West Scotland*** (A. Andreyev, J.F. Smith)

Spokesperson: **P.A.Butler** (***Liverpool***)

Abstract

It is proposed to study octupole correlations in odd-mass Rn, Fr and Ra isotopes using Coulomb excitation at 4.5-5 MeV.A. These data are necessary to interpret EDM measurements in terms of time-reversal violating interactions.

First Beamtime@ISOLDE 2012 on ^{221}Rn

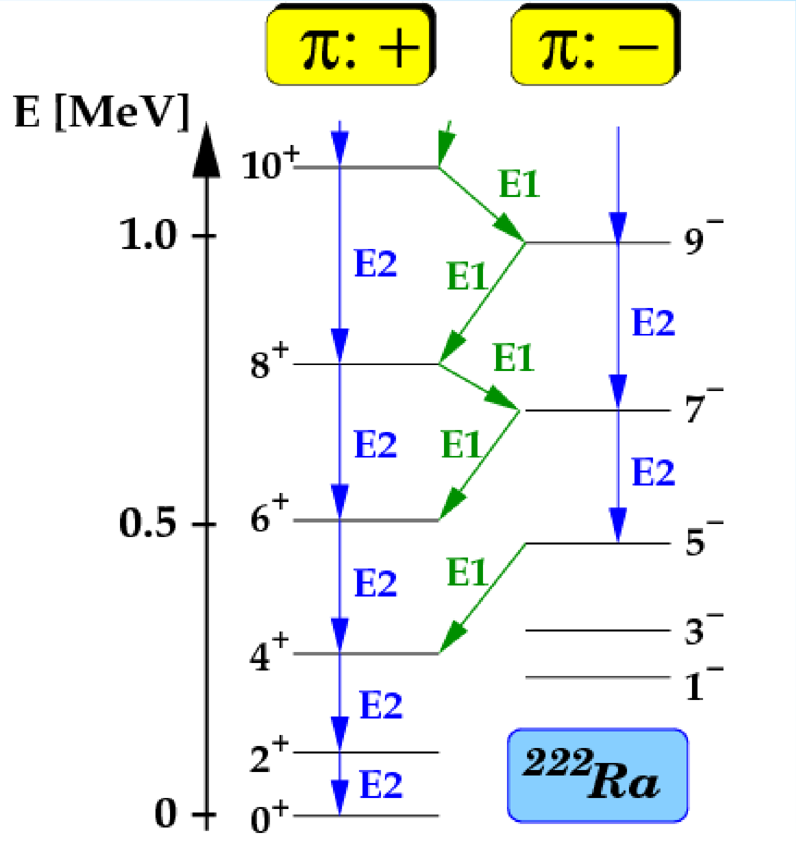
B(E3,$0^+ \mapsto 3^-$) in ^{224}Ra?
Octupole collectivity – Macroscopic

Multipole expansion of the shape:
2^L-pole and L=3 ⇒ Octupole

$B(E3, 0^+ \mapsto 3^-)$ in ^{224}Ra?
Octupole collectivity – Macroscopic

Multipole expansion of the shape:
2^L-pole and L=3 ⇒ Octupole

Reflection Asymmetric

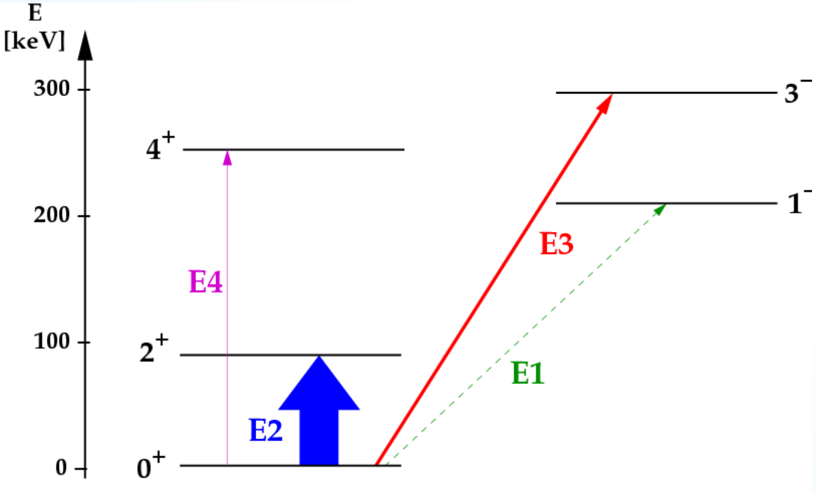


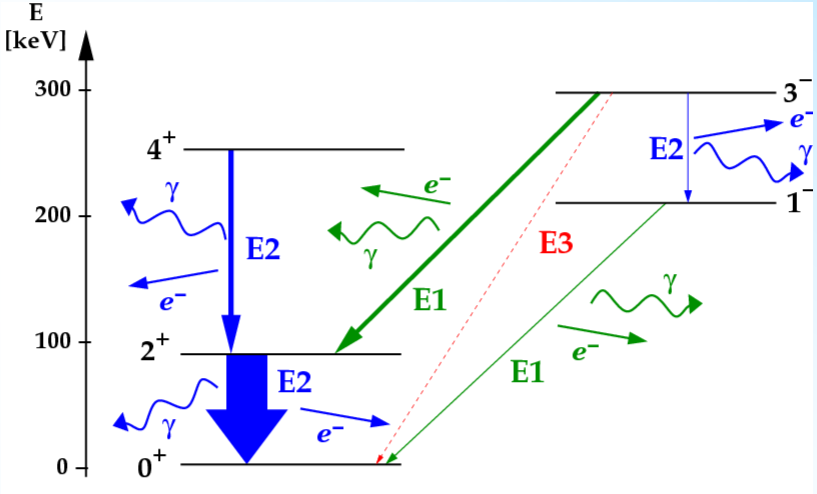
J.F.Cocks et al., PRL 78, 2920 (1997)

Measure $B(E3, 0^+ \mapsto 3^-)$ strengths
Why Coulomb excitation?

Excitation-process

Decay-process





E1 10^4-10^6x more probable

Principle:

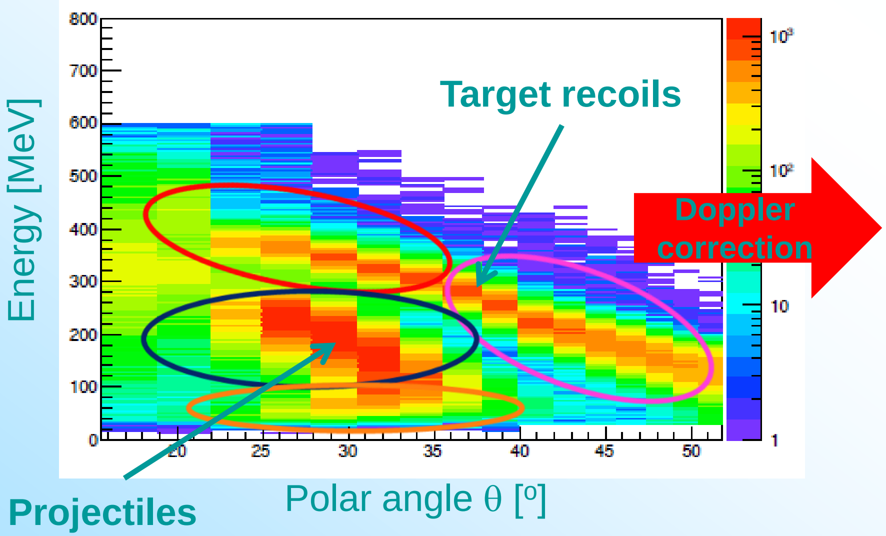
Populate 3^- level with E3 in Coulex ⇒ observe E1(and E2) decay γ ray(s)

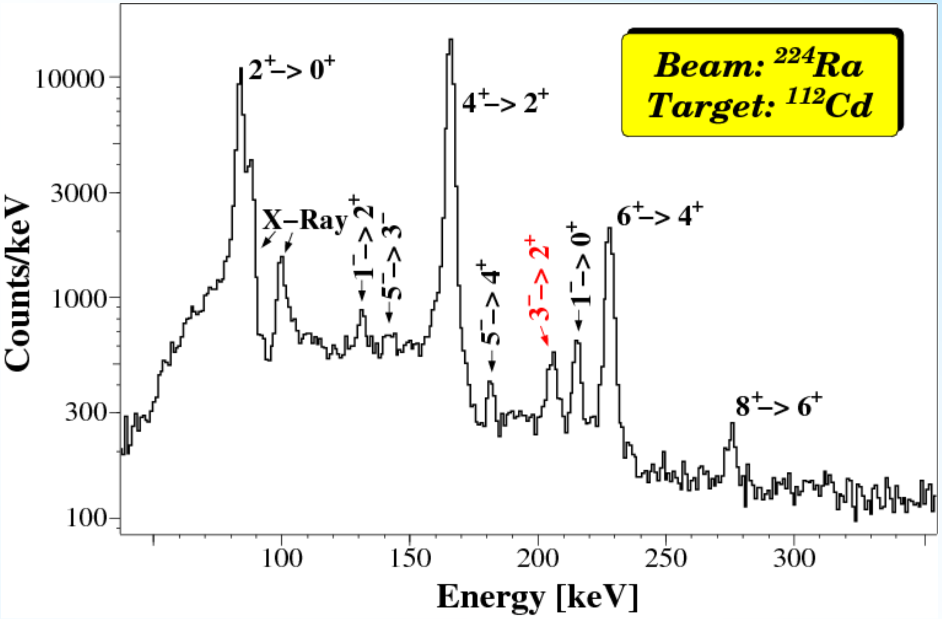
Kinematics and γ-ray spectra

Experimental Information

(Inverse) reaction kinematics

γ-ray Spectrum





Split in 4 angular ranges

4x 9 γ-ray yields

Radium Atom: Nuclear Structure

Partial Nuclear Level scheme

^{225}Ra

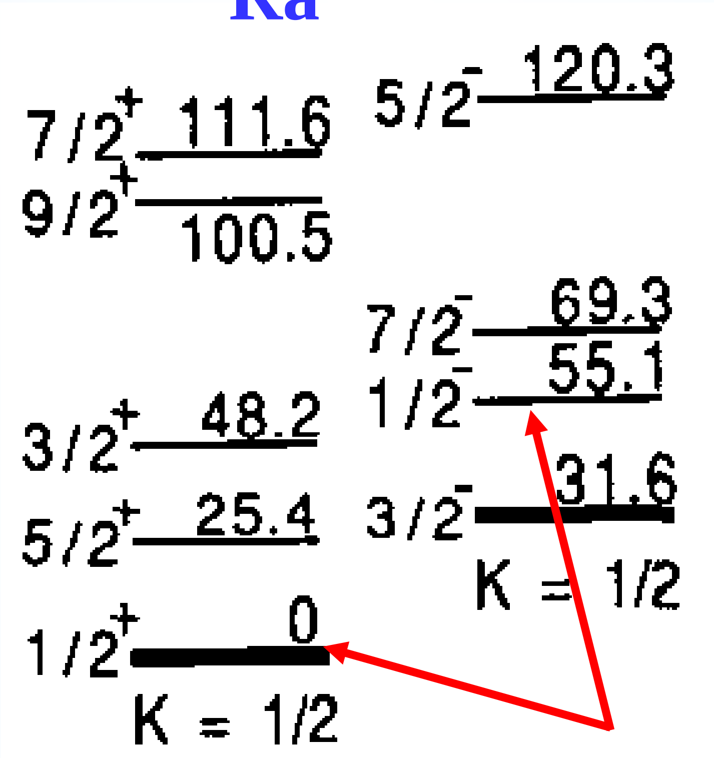


Figure from I. Ahmad & P. Butler, Ann. Rev. Nucl. Part.Sci.**43**,71(1993)

Enhancement due to

Octupole deformation

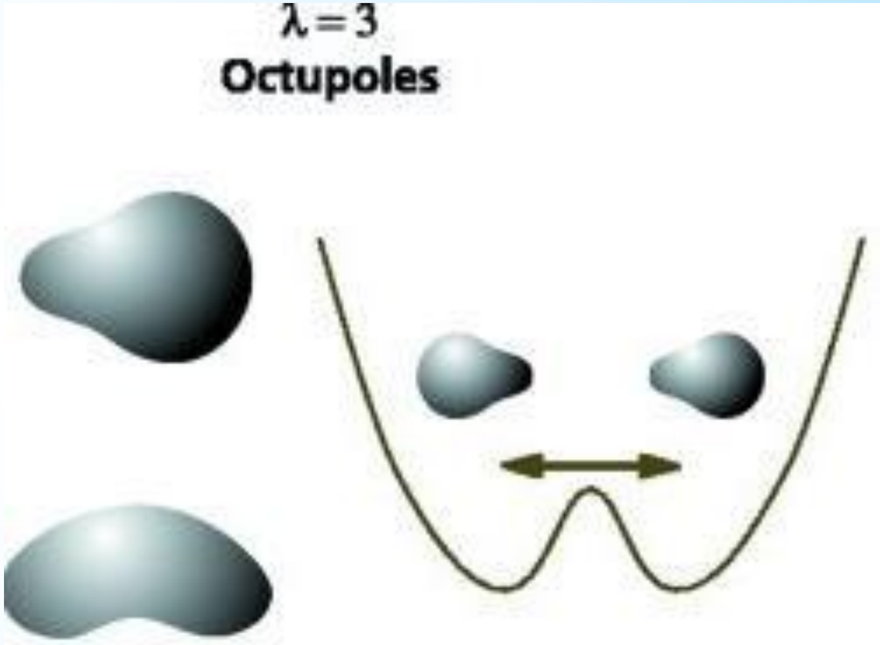


Figure from R. Lucas, Europhysics news **31**,71(2001)

Theory

J. Engel, J. Dobaczewski et al.

Nuclear enhancement: 50 - 500

EDM of ^{225}Ra enhanced

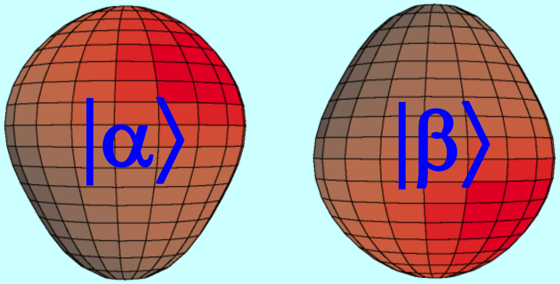
^{225}Ra:
I = ½
$t_{1/2}$ = 15 d

- 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)

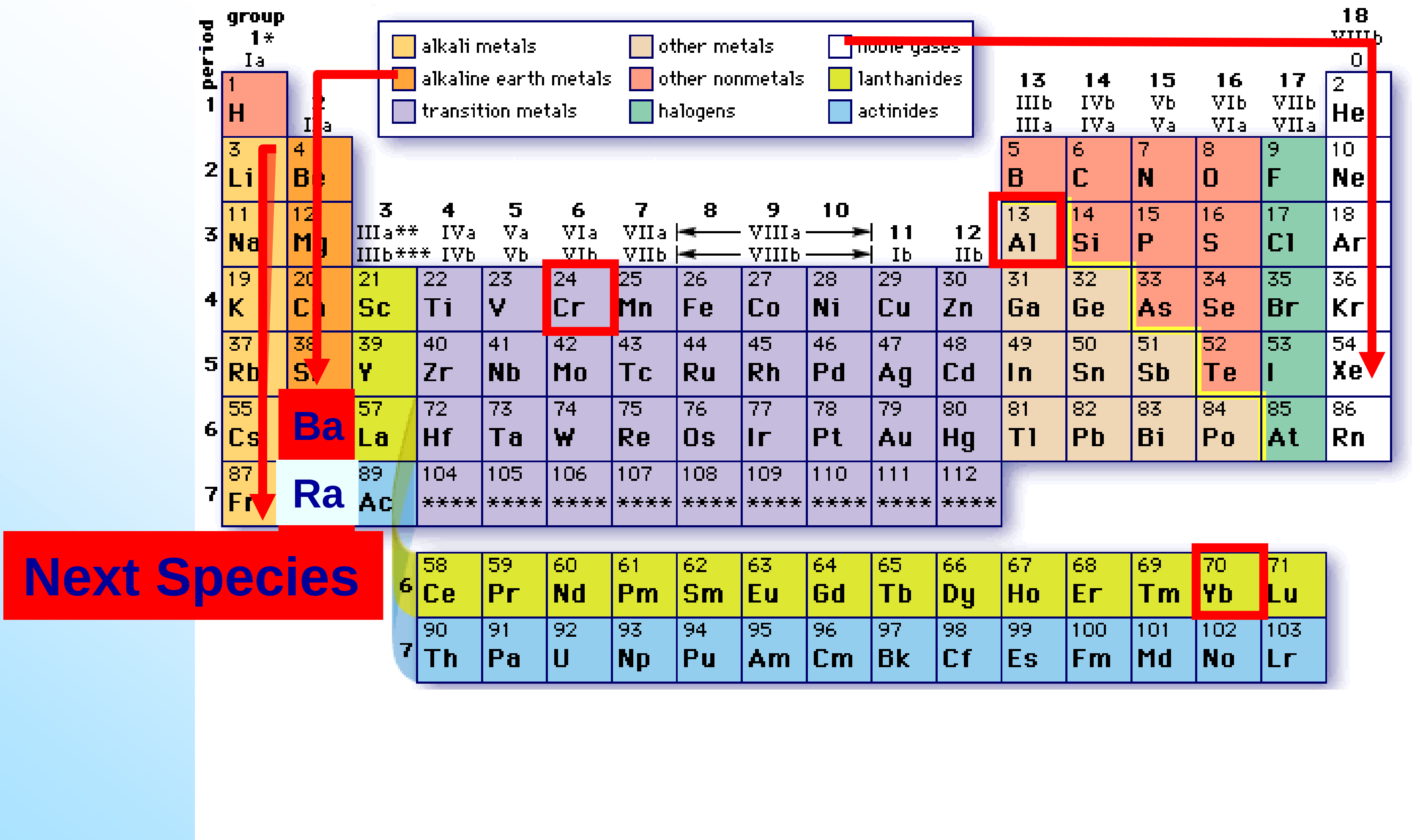
Skyrme Model	Isoscalar	Isovector	Isotensor
SIII	300	4000	700
SkM*	300	2000	500
SLy4	700	8000	1000

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

from Peter Mueller

TRIμP

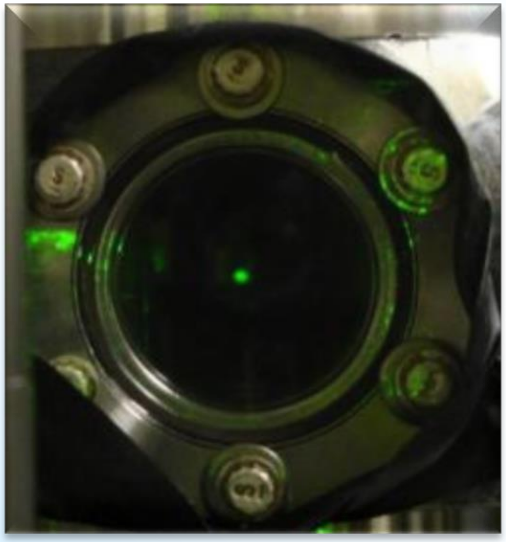
Laser Cooling Chart

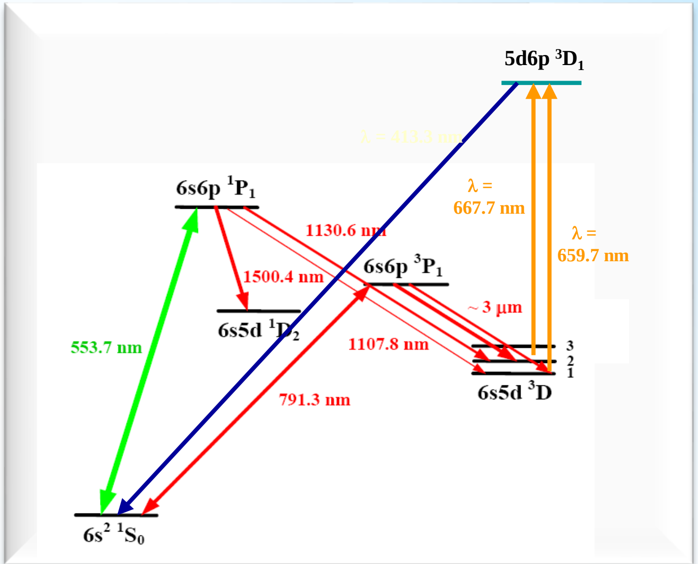


Next Species

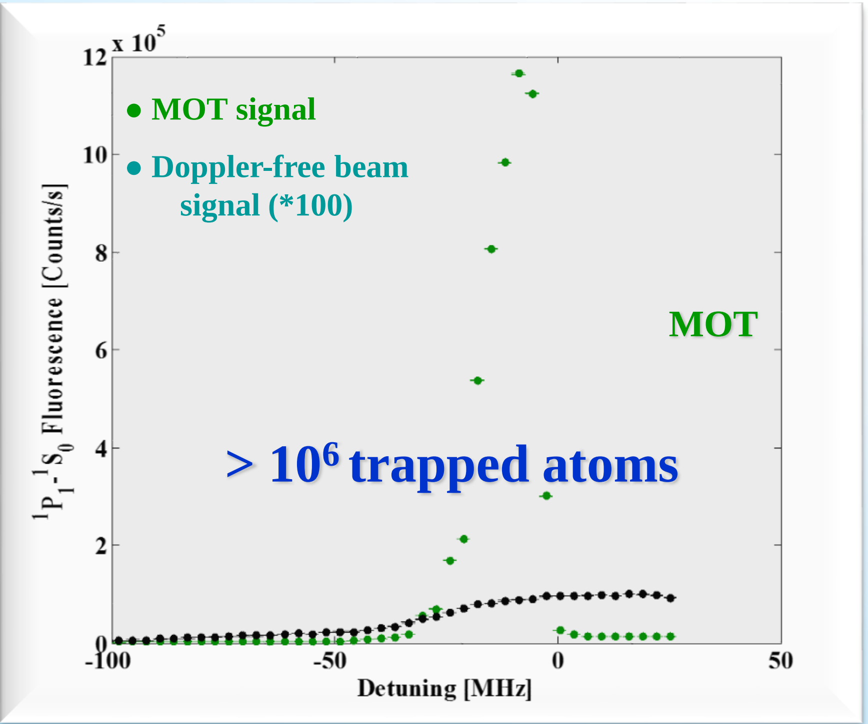
TRIμP

Efficient Trapping of Barium Atoms

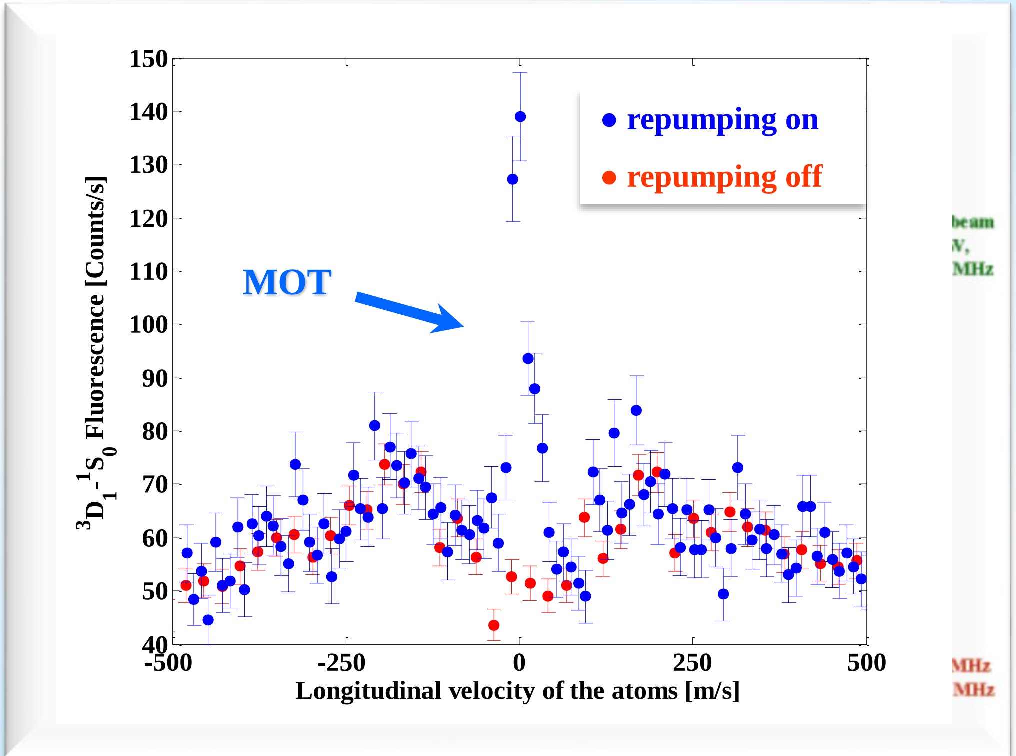




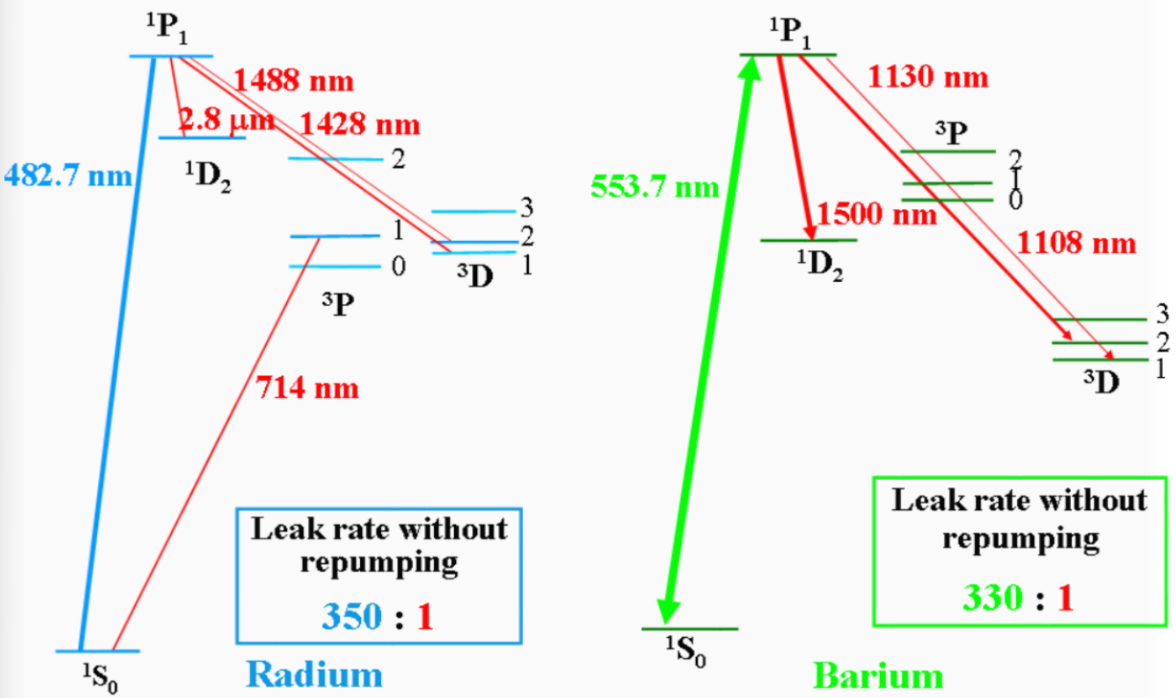
1 % trapping efficiency!



> 10^6 trapped atoms



Radium – Barium Optical Trapping



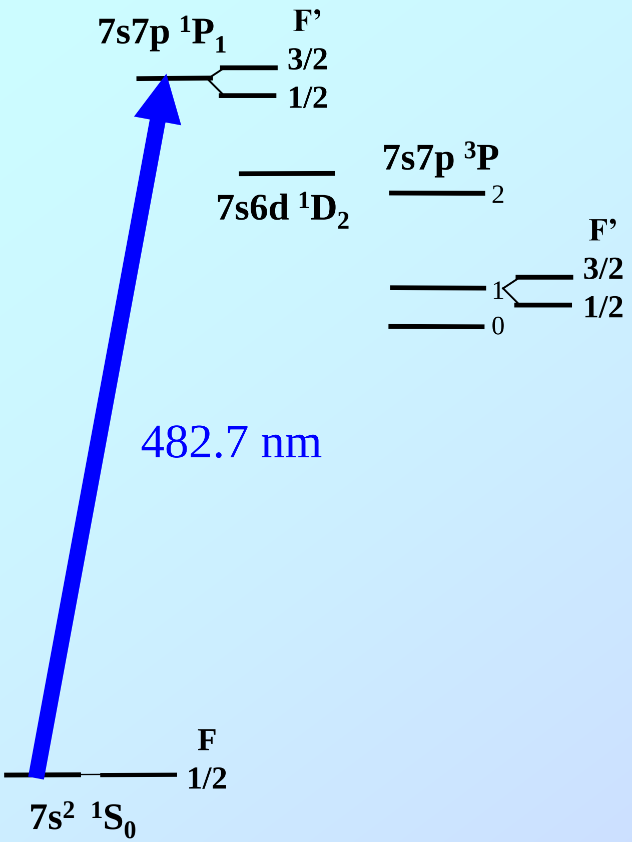
very similar level schemes – very similar leak rates

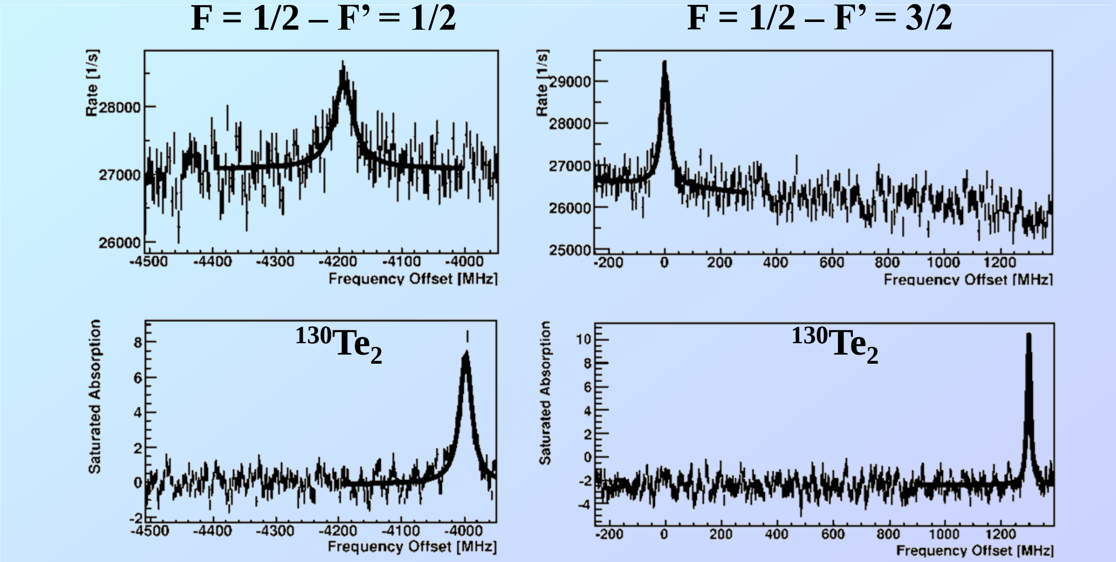
- ➢ Cooled and trapped on intercombination line with Zeeman slower
  (Argonne: Phys. Rev. Lett. 98, 093001, 2007)
- ➢ ~$7 \cdot 10^{-7}$ cooling & trapping efficiency from atomic beam
- ➢ ~20 ^{225}Ra (7000 ^{226}Ra) atoms trapped

- ➢ Cooled and trapped on resonance line with many laser repumping
  (KVI: S. De, L. Willmann et al., Phys.Rev. A79,41402(R) ,2009)
- ➢ ~10^{-2} cooling & trapping efficiency from atomic beam
- ➢ 10^6 Ba atoms trapped
- ➢ method transferrable to Radium

^{225}Radium Spectroscopy

$7s^2\ ^1S_0$ - $7s7p\ ^1P_1$: Strong transition, laser cooling




F = 1/2 – F' = 1/2

F = 1/2 – F' = 3/2

Accuracy of transition frequency:

4 MHz relative to $^{130}Te_2$,

F=1/2->F'=3/2 @ 20715.7210(1)cm^{-1}

2100 MHz (0.03cm^{-1}) Rasmussen, Z.Phys 87, 607 (1934)

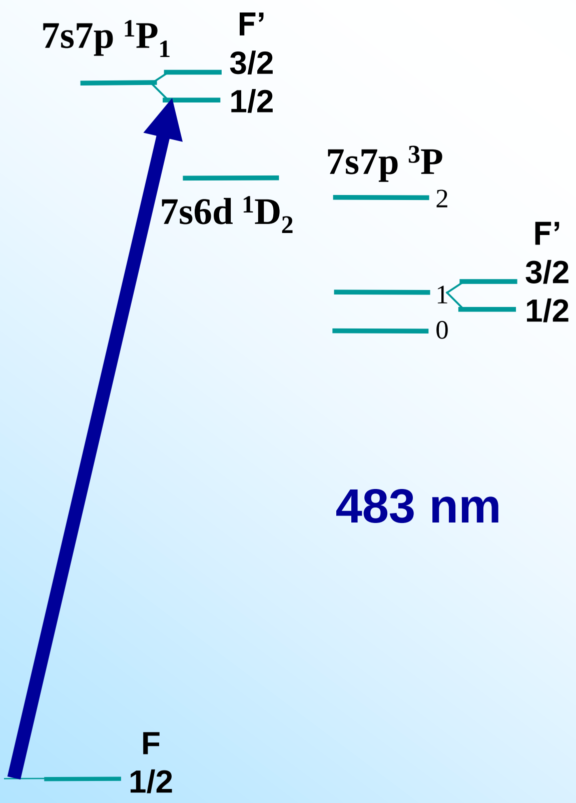
Hyperfine Structure:

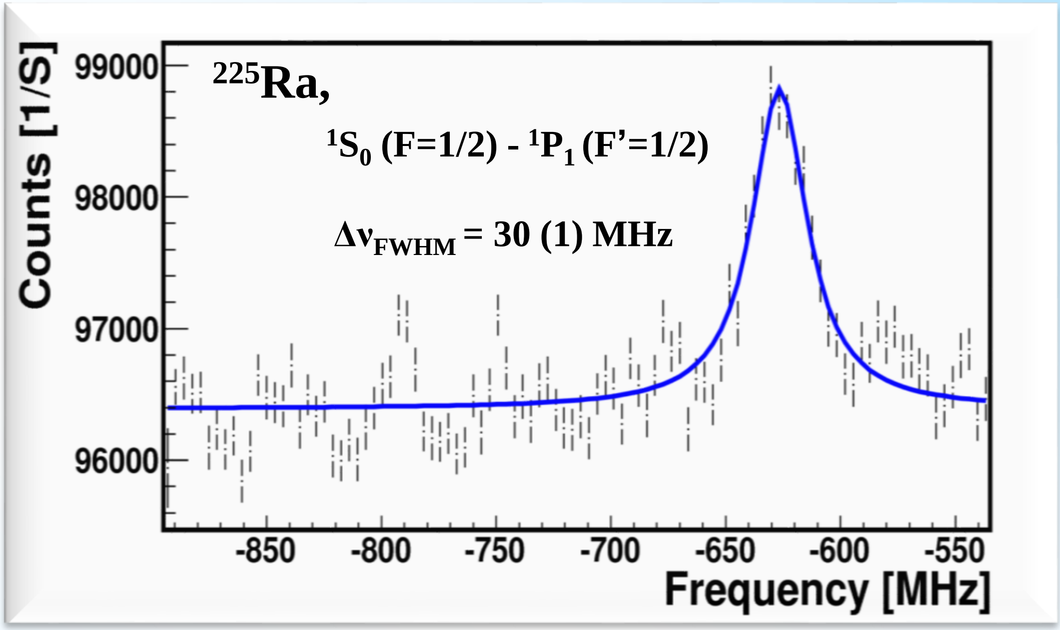
4198(4) MHz

4195(4)MHz (Wendt et al. Z. Phys. D4, 227 (1987))

^{225}Radium Spectroscopy

7s^2 $^1S_0$ - 7s7p $^1P_1$: strong transition, first stage cooling

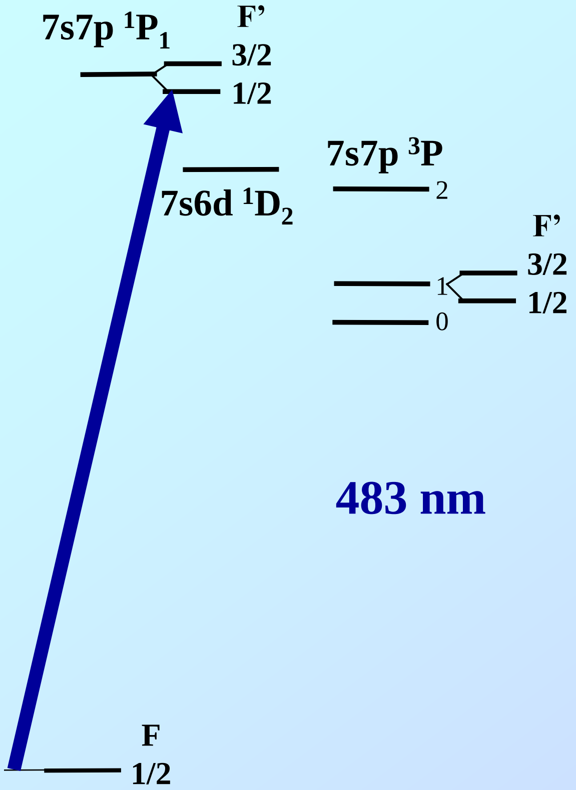




Absolute Frequency:
Offset from a $^{130}Te_2$ line

627(5) MHz (L. Willlmann et al., KVI (2010)

→ **Relevant input for atomic theory**



7s7p $^1P_1$

F'

3/2

1/2

7s7p ^3P

2

1

0

F'

3/2

1/2

7s6d $^1D_2$

483 nm

F

1/2

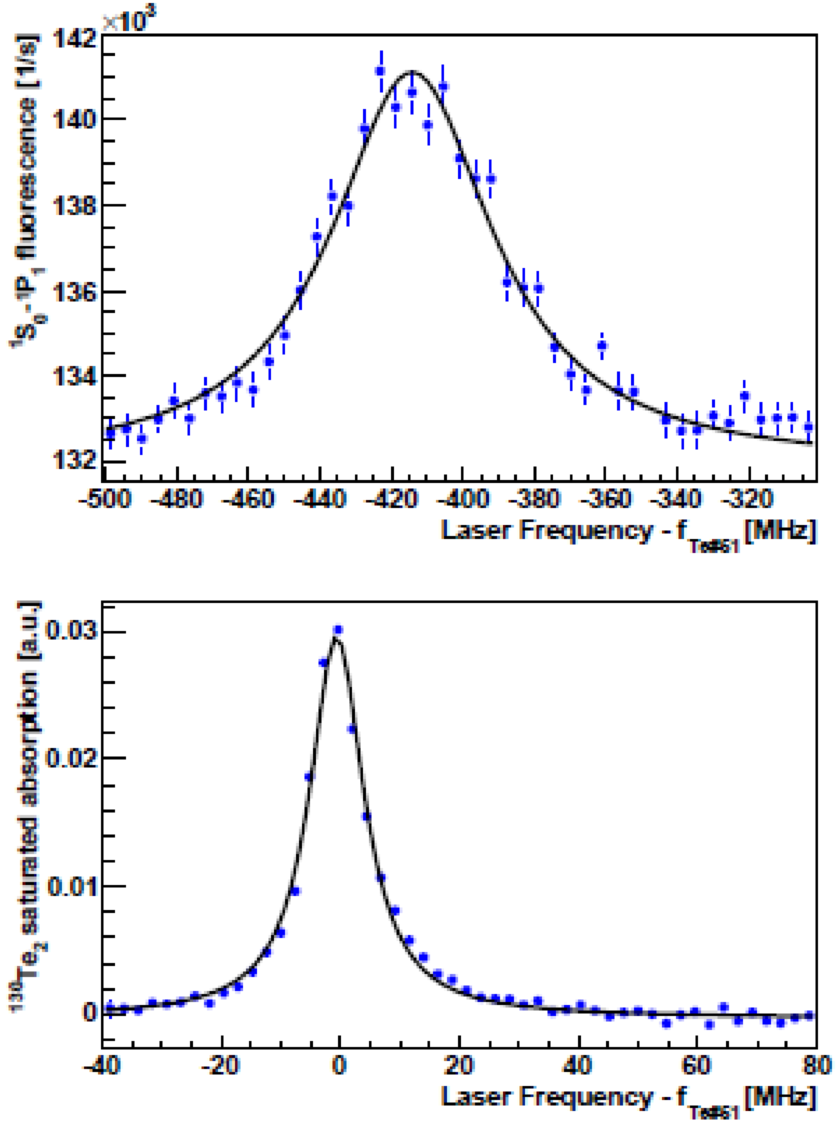
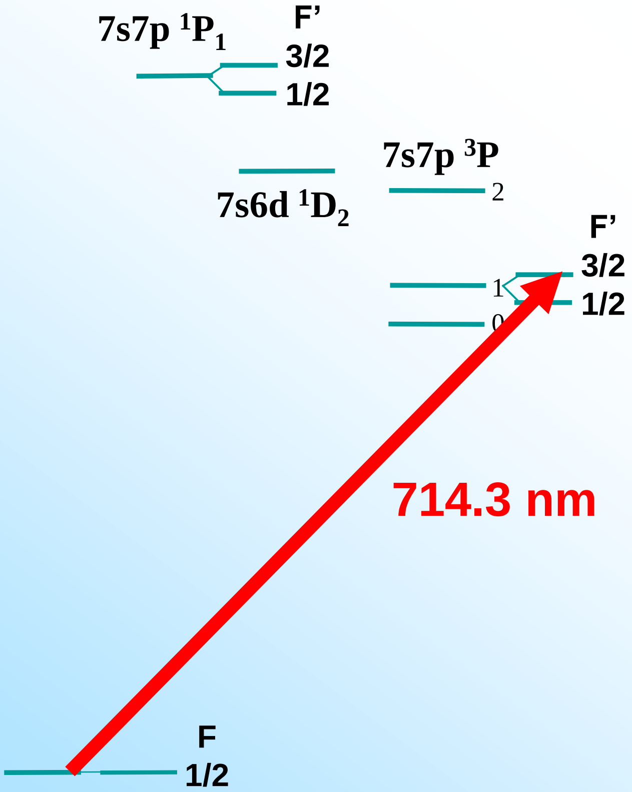


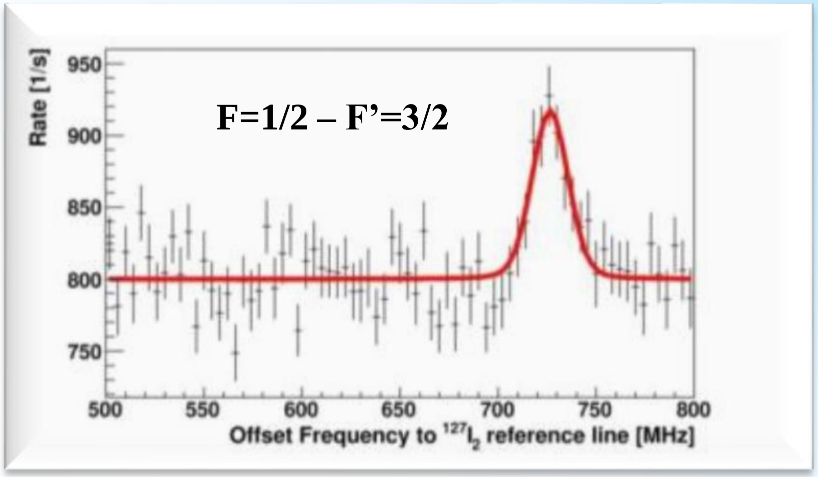
FIG. 6.6: (Top) Fluorescence from the $^1S_0(F=1/2)$-$^1P_1(F=3/2)$ transition in ^{225}Ra. (Bottom) Saturated absorption line no.51 in $^{130}Te_2$. The frequency of the transition in radium is 418(1) MHz lo ie reference line #51 (Sec-

from B.Santra, PhD thesis, KVI (2012)

^{225}Radium Spectroscopy

$7s^2\ ^1S_0$ - $7s7p\ ^3P_1$: weak transition, second stage cooling





Absolute Frequency:
Offset from a $^{127}I_2$ line

726(5) MHz (L. Willlmann et al., KVI (2010)

702(30) MHz (N. D. Scielzo et al., PRA 73, 010501(R) (2006))

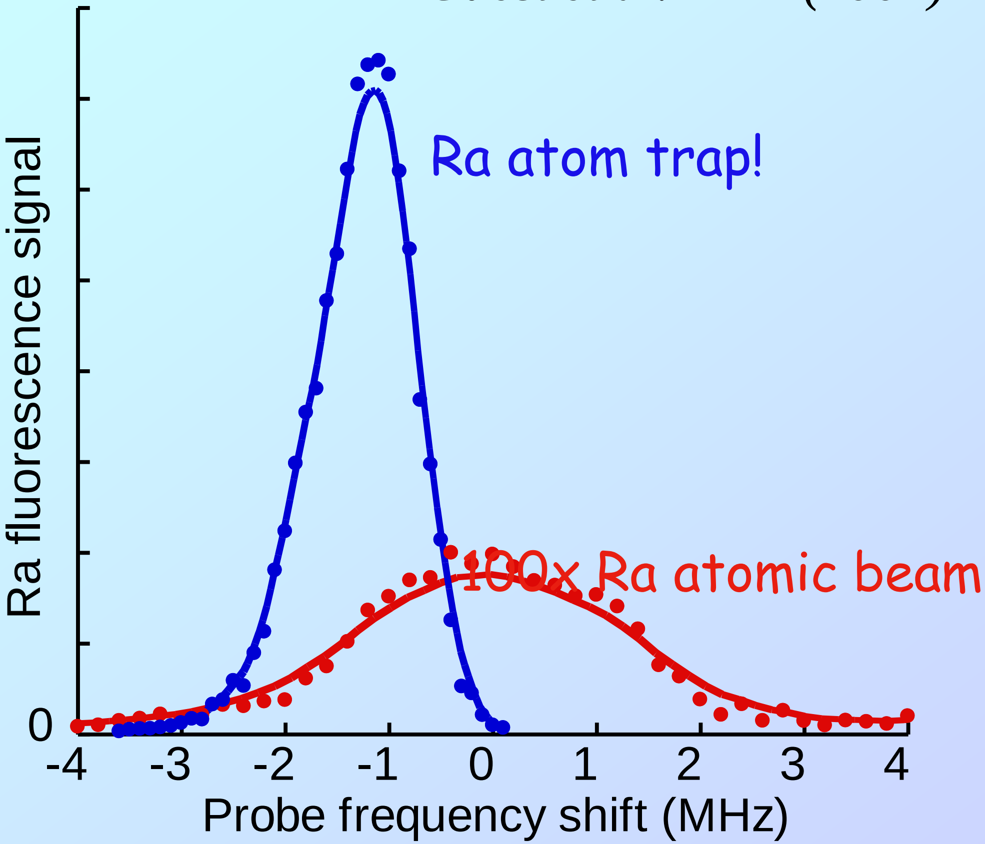
→ **Relevant input for atomic theory**

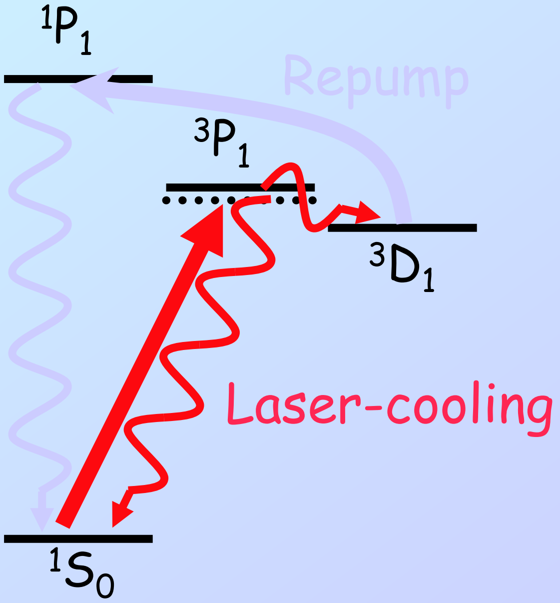
Τραππινγ οφ ^{225}Ρα ανδ ^{226}Ρα Ατομσ

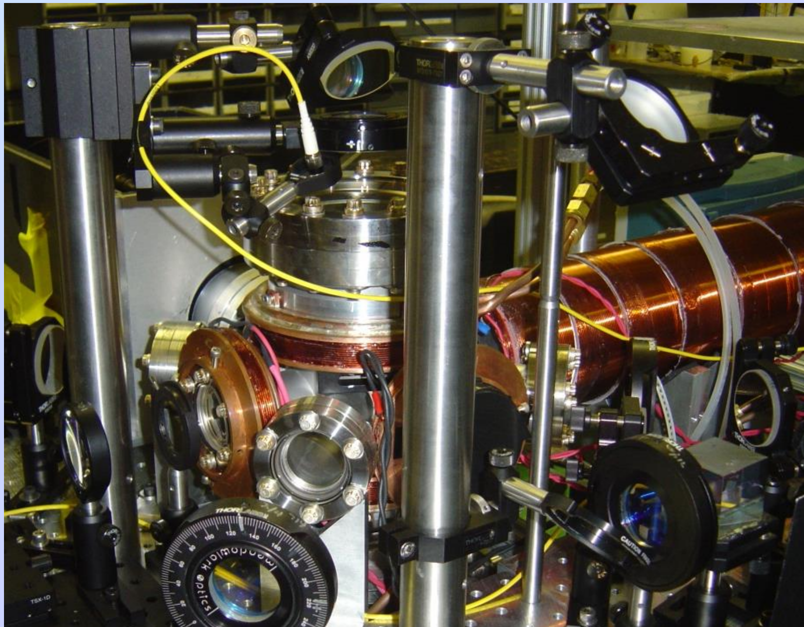
- **Key ^{225}Ra frequencies, lifetimes measured**

  Scielzo et al. PRA (2006)
- **^{225}Ra laser cooled and trapped!**

  Guest et al. PRL (2007)

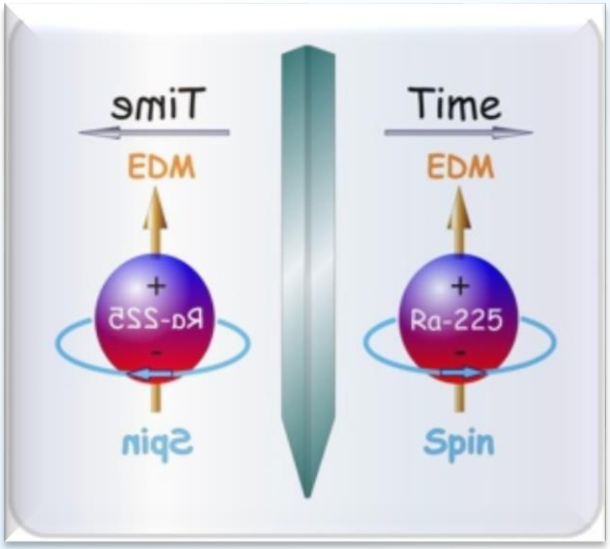


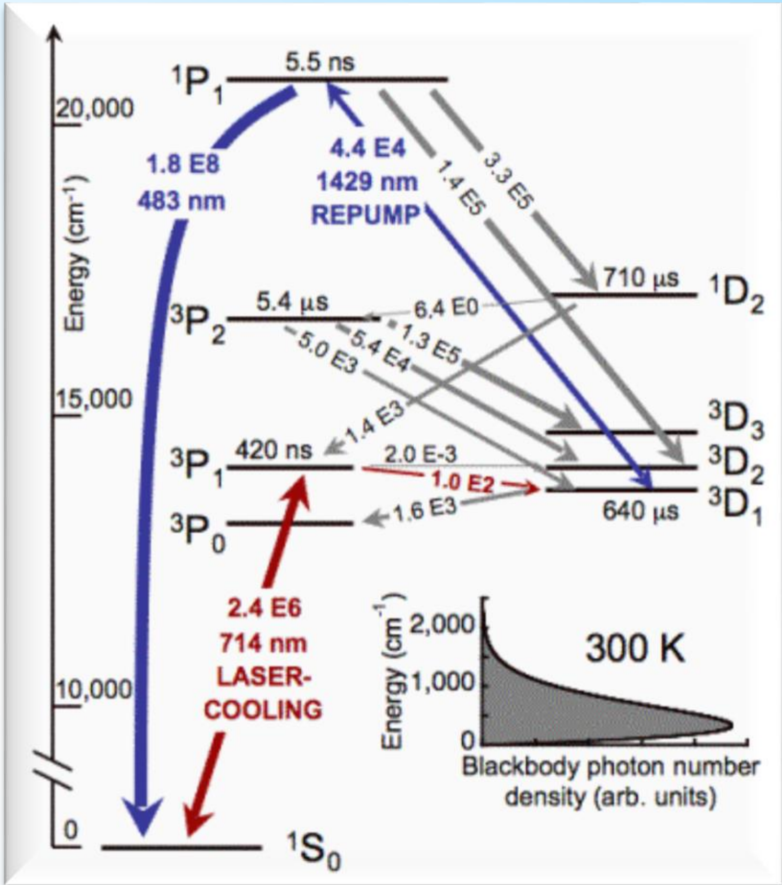


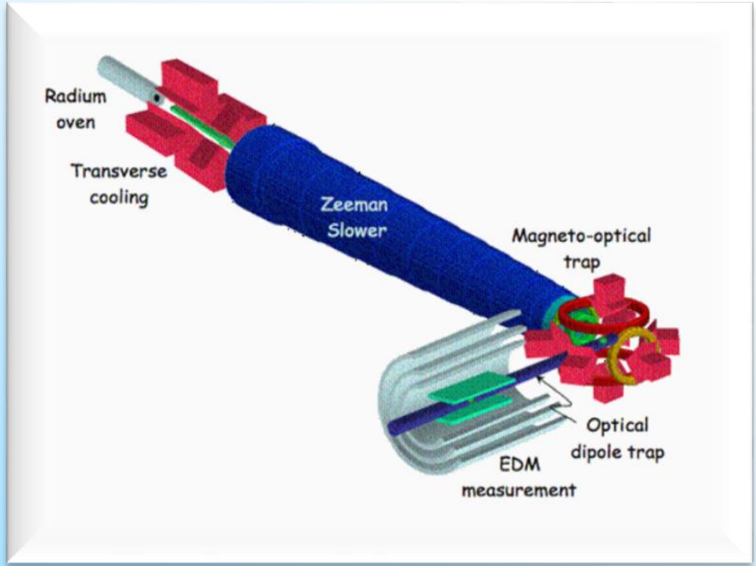


From Peter Mueller, ANL

Argonne Radium EDM







Radium EDM Setup @ Argonne

E=100 kV/cm

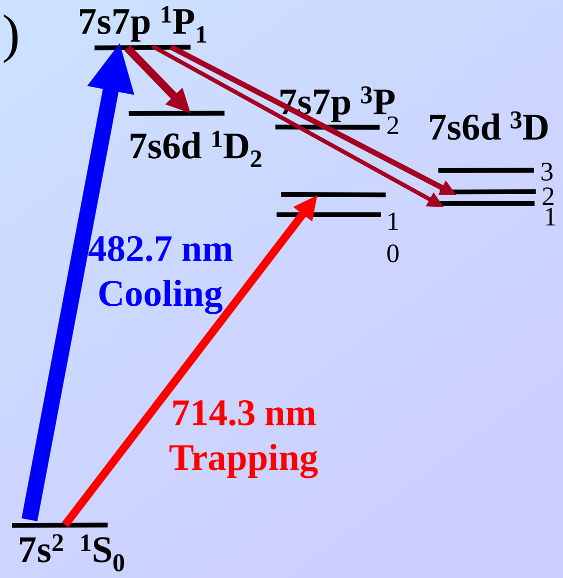
(from P. Mueller)

Key Issues for Ra

- Sources of Radium Isotopes
- Efficient laser cooling on strong transition: 483 nm
  - Close leaks with additional lasers
  - demonstrated with Ba

    S.De et al., PRA **79**, 041402(R) (2009)
- Magneto-optical trapping: 714 nm

  J.R. Guest et al., PRL 98, 093001(2007)
  - Lower trap temperatures
  - Efficient loading to an optical dipole trap
- Optical Dipole trapping



Sources & Isotopes

^{225}**Radium** (from sources)

Electrochemical extraction from ^{229}Th source (ANL)
regular filling required

Long lived ^{229}Th source in an oven (TRIμP@KVI)

Argonne
National Lab

Experiment seems feasible with modest (< 10 mCi) ^{225}Ra sources.

Special thanks to our health physicists Paul Niquette and Lee Sprouse.

Once filled with
^{229}Th 10μCi

Isotope Production Facilities

ISOLDE, CERN (flux ~ 10^9/s)
FRIB, MI, USA (flux ~ 10^9/s)
ISOL@MIRRHA even higher

Isotope	Half life ($\tau_{1/2}$)	Nuclear spin (I)
^{225}Ra	14.9 days	1/2
^{223}Ra	11.4 days	3/2
^{213}Ra	2.74 min	1/2

Radium cooling

Parameter	**483 nm**	**714 nm**
Maximum deceleration (a)	**330 x 10^3 m/s^2**	**3 x 10^3 m/s^2**
Distance to stop 300 m/s (d)	**0.14 m**	**15 m**
Doppler cooling limit (T_D)	**700 μK**	**9 μK**
Recoil limit (T_R)	**180 nK**	**83 nK**

- transition leak rate 1:350
- indispensible repumping
- 0.1 m slowing section

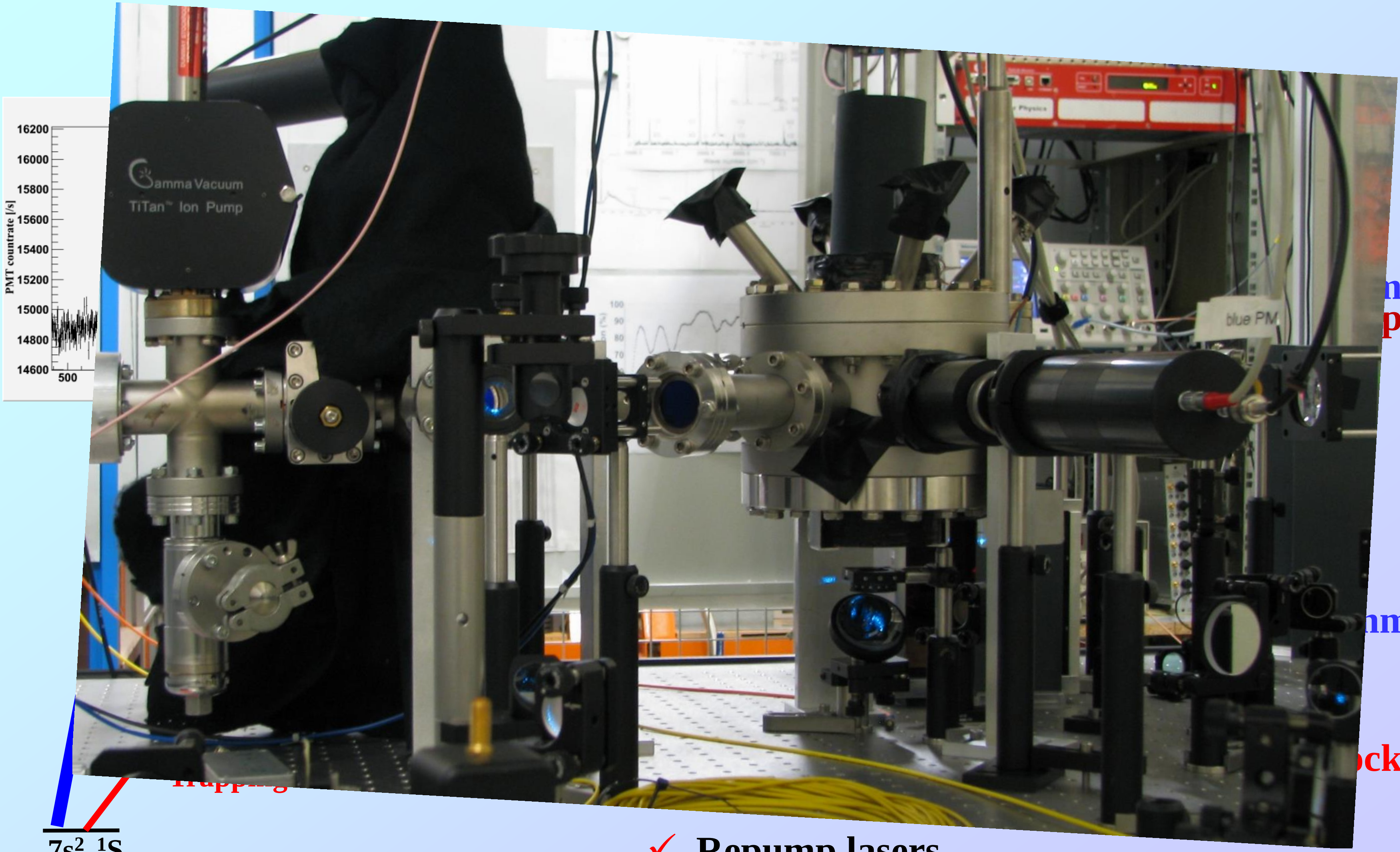
  60 % of all atoms

- transition leak rate 1:25000
- 1 m slowing section

  0.06% of all atoms

  0.6% with repumping

Towards an experiment



n +

pers

nm

ck

$7s^2\ ^1S_0$

✓ **Repump lasers**

EDMs of atoms of experimental interest

Z	Atom	[*S*/(e fm3)]*e* cm	[$10^{-25}\ \eta$] *e* cm	Expt.
2	^{3}He	0.00008	0.0005	
54	**^{129}Xe**	**0.38**	**0.7**	**Seattle, Ann Arbor,** **Princeton,Tokyo,** ***Mainz-PTB-HD-KVI***
70	^{171}Yb	-1.9	3	Bangalore,Kyoto
80	^{199}Hg	-2.8	4	Seattle
86	^{223}Rn	3.3	3300	TRIUMF
88	^{225}Ra	-8.2	2500	Argonne,KVI
88	^{223}Ra	-8.2	3400	

$d_n = 5 \times 10^{-24}\ e\ \mathrm{cm}\ \eta$, $d(^{3}\mathrm{He})/\,d_n = 10^{-5}$

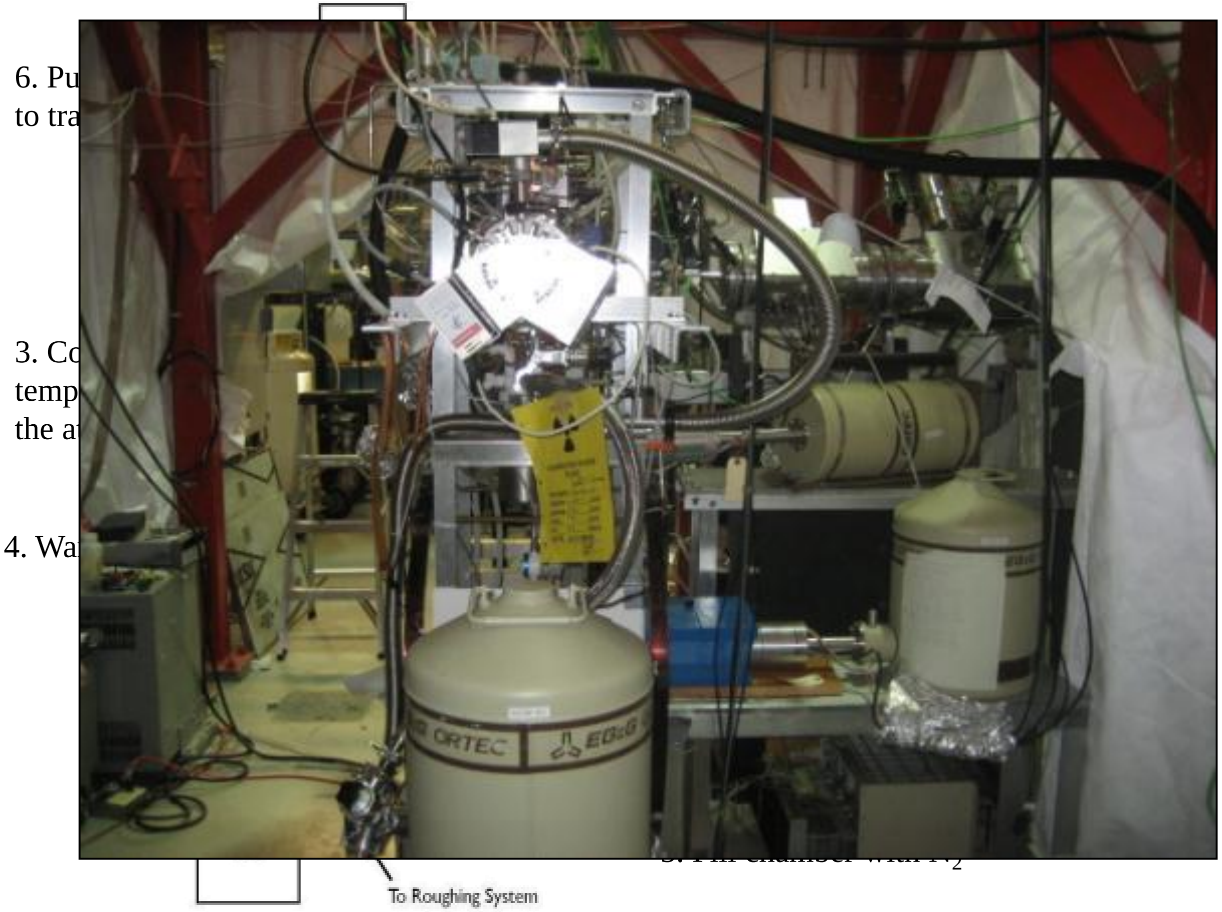
slide from Victor Flambaum

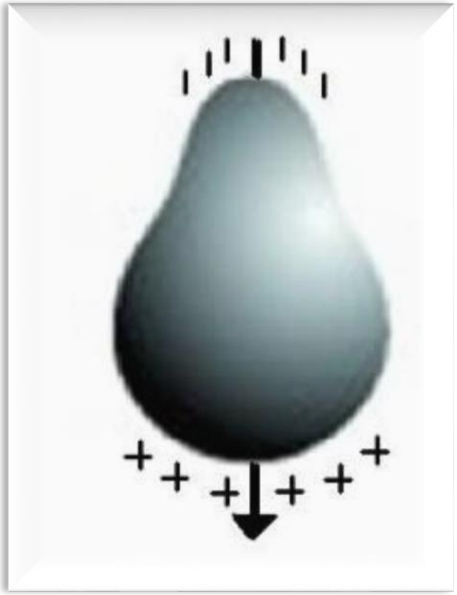
Towards a Rn EDM Experiment at TRIUMF

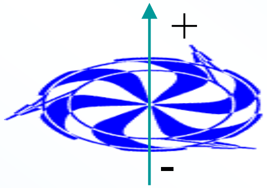
T. Chupp and C. Svensson

- **Magnitude of EDM ~ Z^3**
- **Radon isotopes possibly octupole deformed**

- Rn is predicted to be ~ 600 times more sensitive than ^{199}Hg





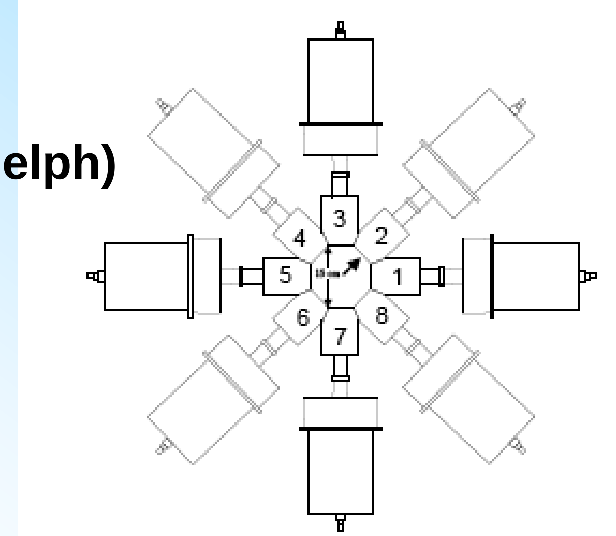


Radon-EDM Experiment

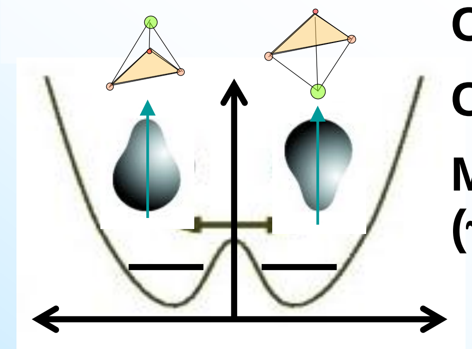
TRIUMF E929

T. Chupp (Michigan) & C. Svensson (Guelph)

Funding: NSF, DOE, NRC, NSERC



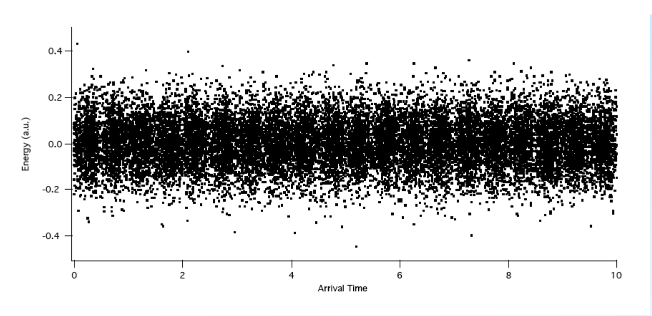
TRIUMF



β_3

- **Produce rare ion radon beam**
- **Collect in cell**
- **Comagnetometer**
- **Measure free precesion (γ anisotropy/β asymmetry)**

$$\sigma_d \approx \frac{\hbar}{AET_2\sqrt{N}}$$



$^{221/223}$Rn EDM projected sensitivity

Facility	Detection	S_d (100 d)
ISAC	γ anisotropy	2×10^{-26} e-cm
ISAC	β asymmetry	1×10^{-27} e-cm
FRIB	β asymmetry	2×10^{-28} e-cm

→ ~ 5×10^{-30} for ^{199}Hg

Courtesy of Tim Chupp

EDMs of atoms of experimental interest

Z	Atom	[*S*/(e fm3)]*e* cm	$[10^{-25}\,\eta]$ *e* cm	Expt.
2	^{3}He	0.00008	0.0005	
KVI **54**	**^{129}Xe**	**0.38**	**0.7**	**Seattle, Ann Arbor, Princeton,Tokyo, *Mainz-PTB-HD-KVI***
70	^{171}Yb	-1.9	3	Bangalore,Kyoto
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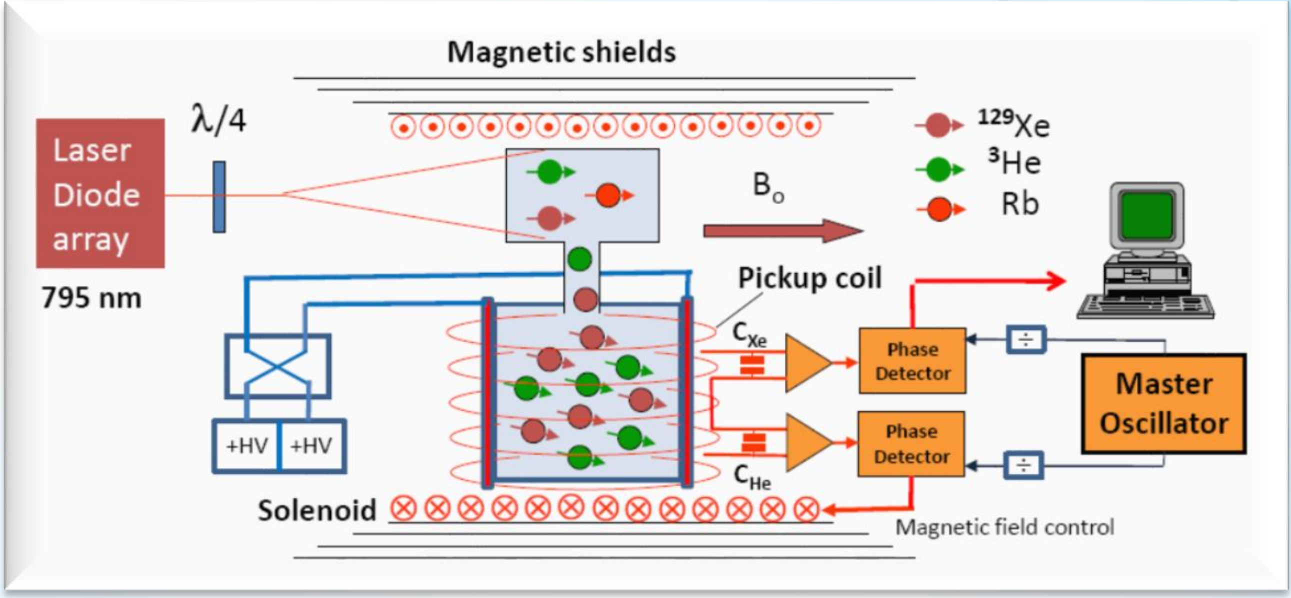
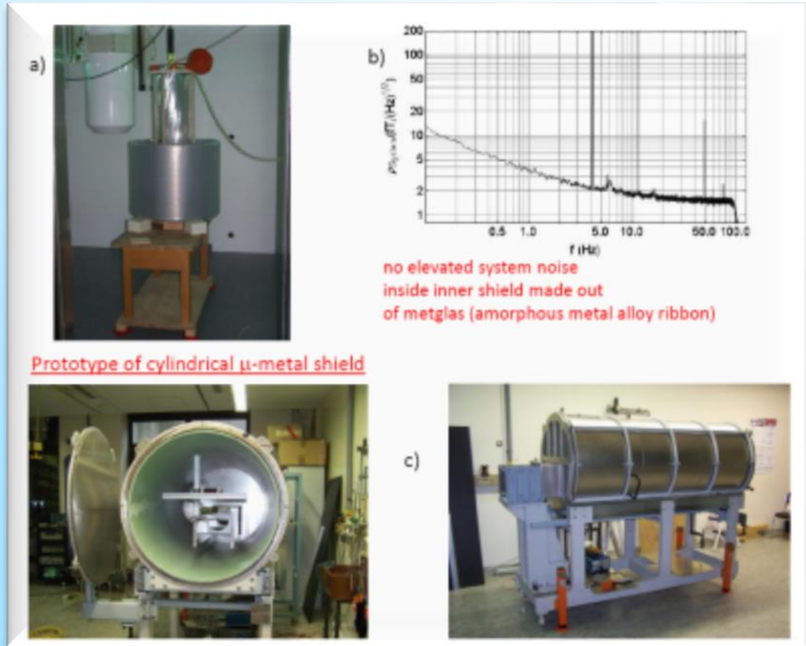
88	^{225}Ra	-8.2	2500	Argonne,KVI
88	^{223}Ra	-8.2	3400	

slide from Victor Flambaum

Future EDM Search from ^{3}He/^{129}Xe Clock Comparison

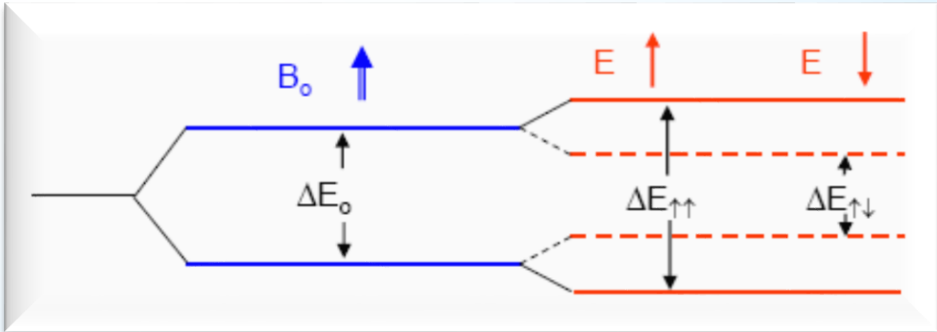
W.Heil, U. Schmidt, L. Willmann et al. ***Mainz –Heidelberg - Groningen***





no elevated system noise inside inner shield made out of metglas (amorphous metal alloy ribbon)

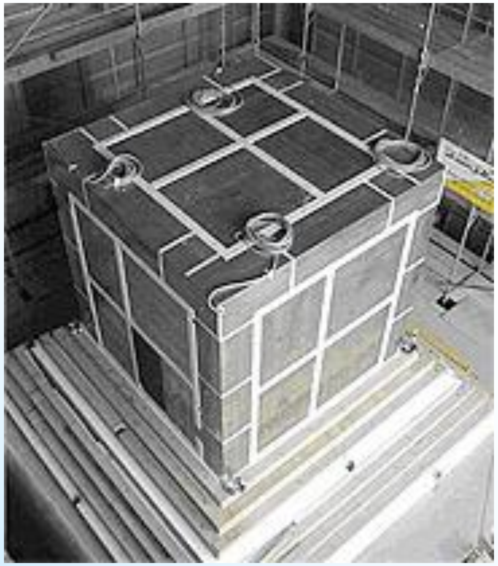
Prototype of cylindrical µ-metal shield



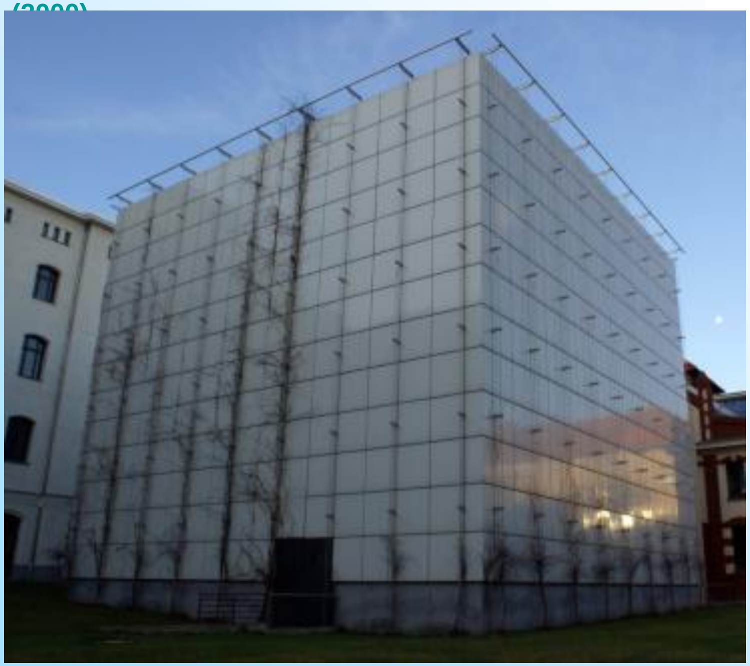
- ➢**present limit** $d_{Xe} < 3\times10^{-27}$ ecm
- ➢**goal** gain 3 orders of magnitude
- ➢**note** $d_{Hg} < 3{,}1\times10^{-29}$ ecm

Magnetic Field Shielded Room at PTB Berlin

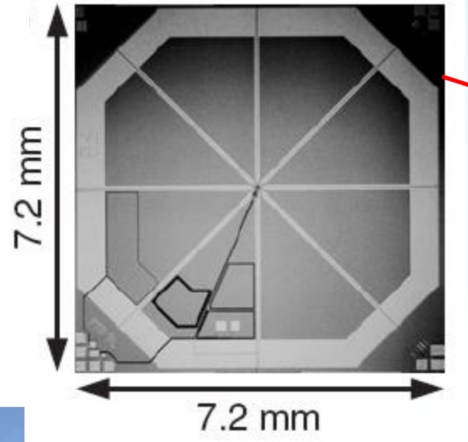
7 layers of magnetic shielding ⇒ residual field < 2nT



J. Bork, et al., Proc. Biomag 2000, 970 (2000)



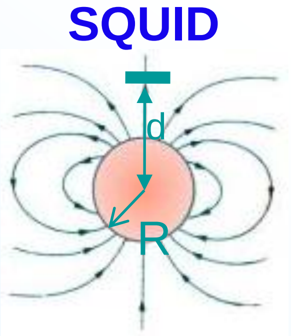
LT$_c$- SQUID



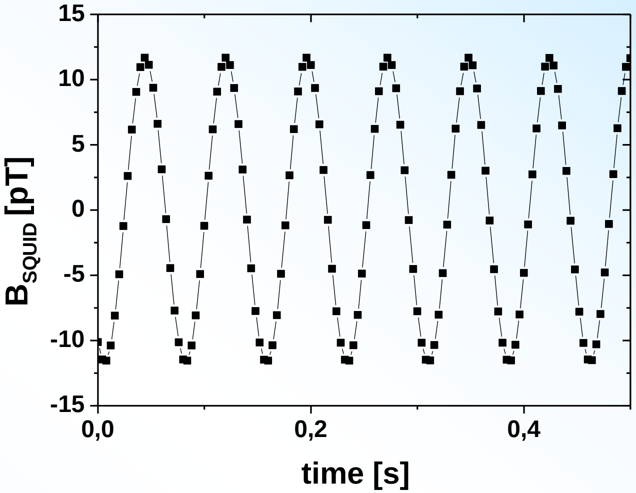
^{3}He (4.5 mbar)

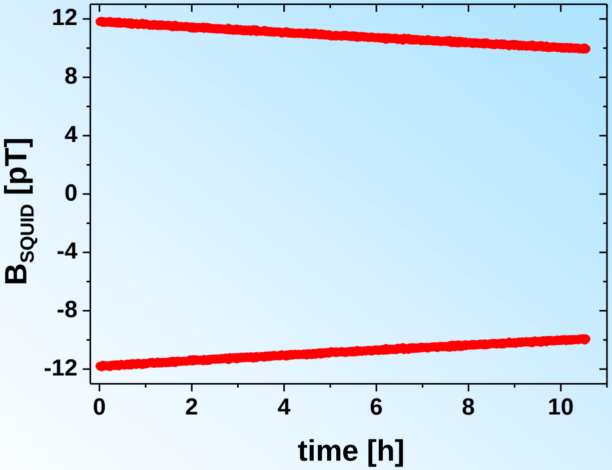
magnetic guiding field
≈ 0.4 μT (Helmholtz-coils)

^{3}He Free Spin-Precession Signal



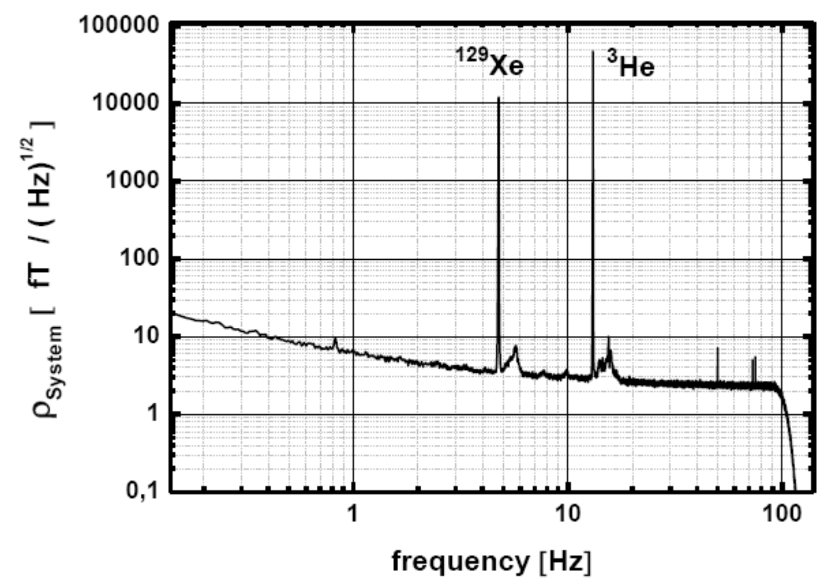
p_{He}= 4.5 mbar
P_{He}= 15%
R =2.9 cm
d = 6 cm





$$\Delta B[pT] \approx 220 \cdot p[mbar] \cdot P \cdot \left(\frac{R}{d}\right)^3$$

^{3}He: $T_2^* = (60.2 \pm 0.1)h$

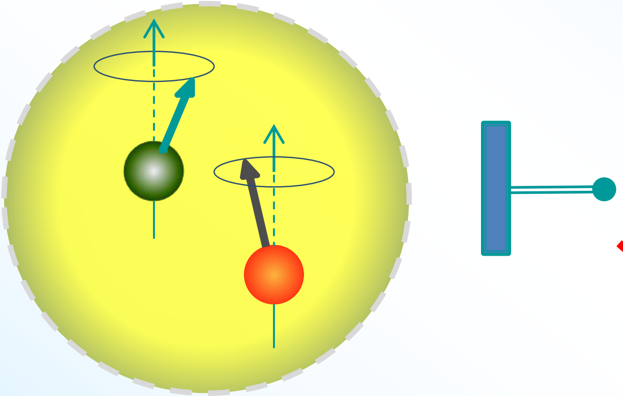


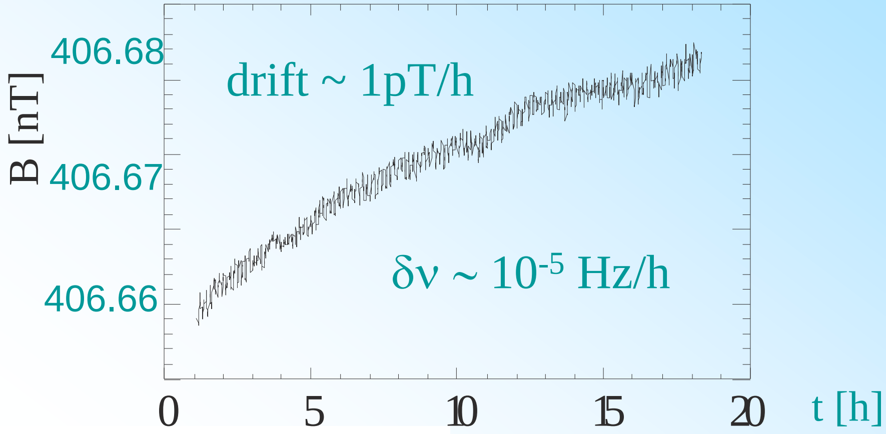
^{129}Xe: $4h < T_2^* < 6h$

→ wall relaxation
→ limiting factor

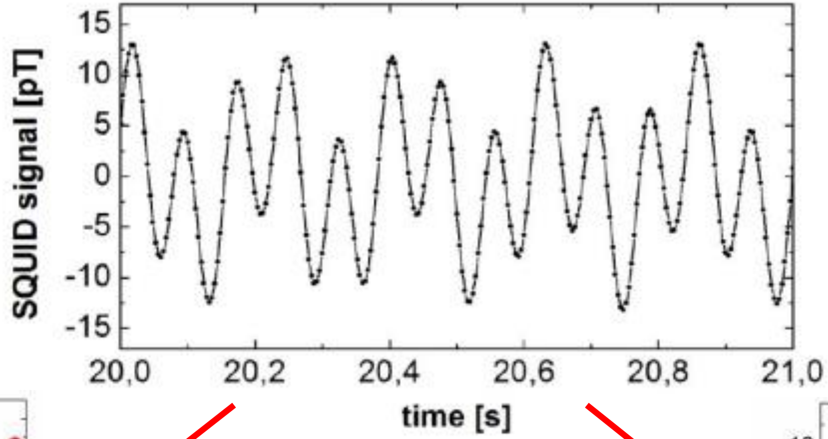
C. Gemmel et al., Eur.Phys.Jour. D57,303 (20

^{3}He / ^{129}Xe clock comparison to get rid of magnetic field drifts

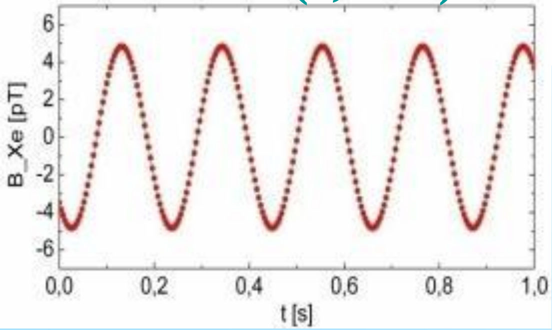




$$\omega_L = 2\pi\nu_L = \gamma\left|\vec{B}\right|$$

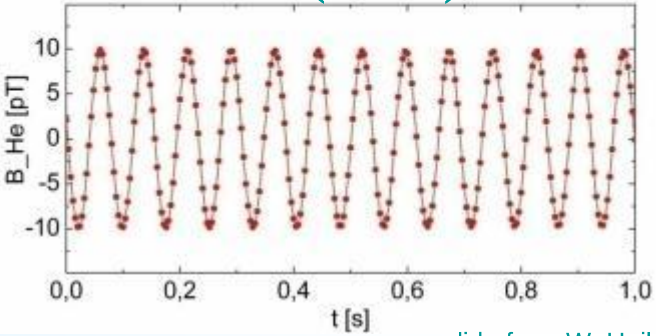


^{129}Xe **(4,7 Hz)**



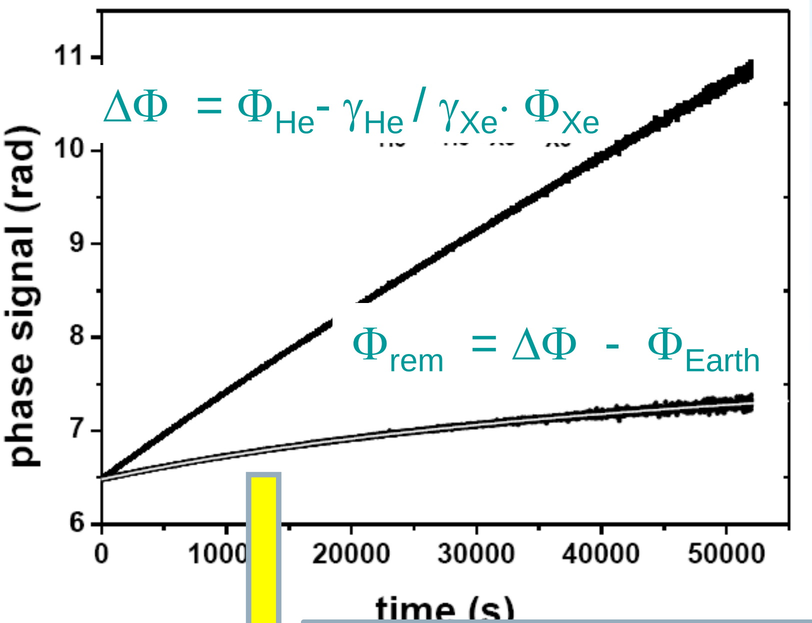
$$\Delta\Phi = \Phi_{He} - \frac{\gamma_{He}}{\gamma_{Xe}}\cdot\Phi_{Xe} \overset{!}{=} const.$$

^{3}He **(13 Hz)**



slide from W. Heil

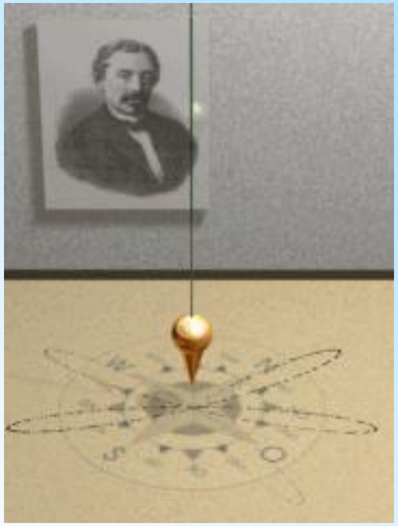
Subtraction of deterministic phase shifts



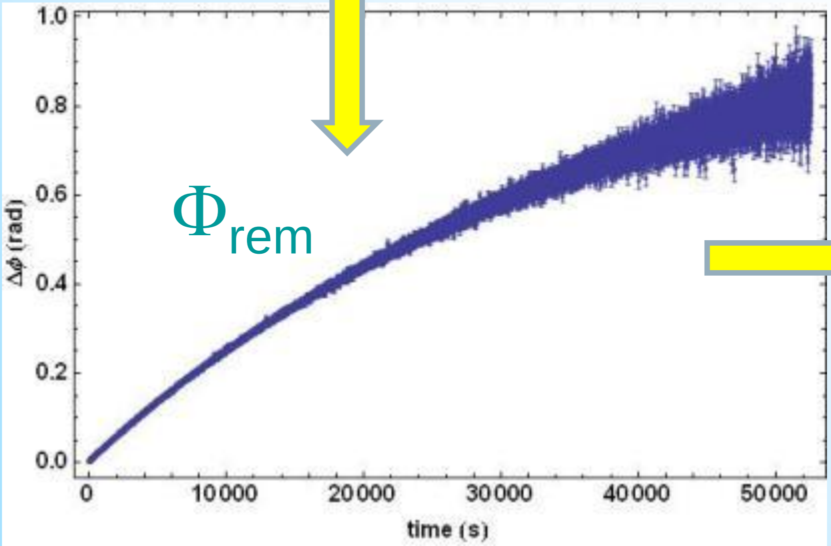
$\Delta\Phi = \Phi_{He} - \gamma_{He} / \gamma_{Xe} \cdot \Phi_{Xe}$

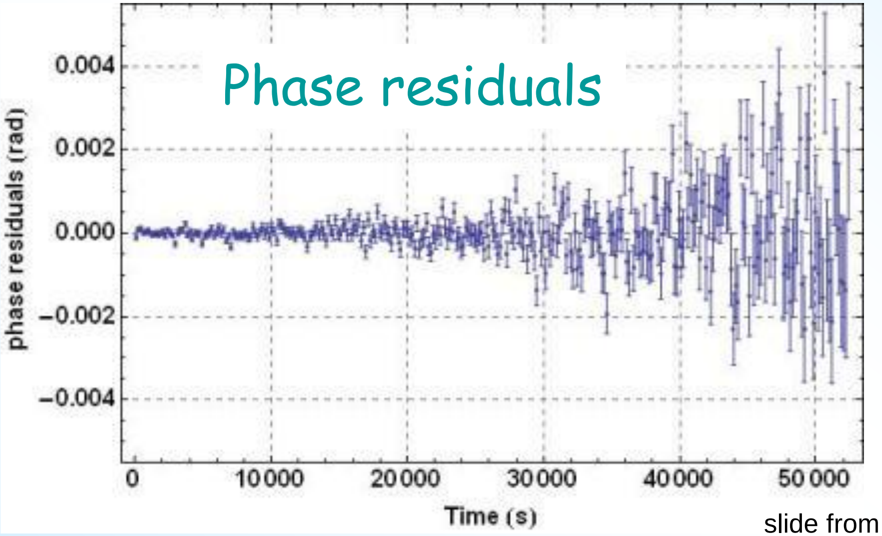
$\Phi_{rem} = \Delta\Phi - \Phi_{Earth}$

I. Earth‘s rotation

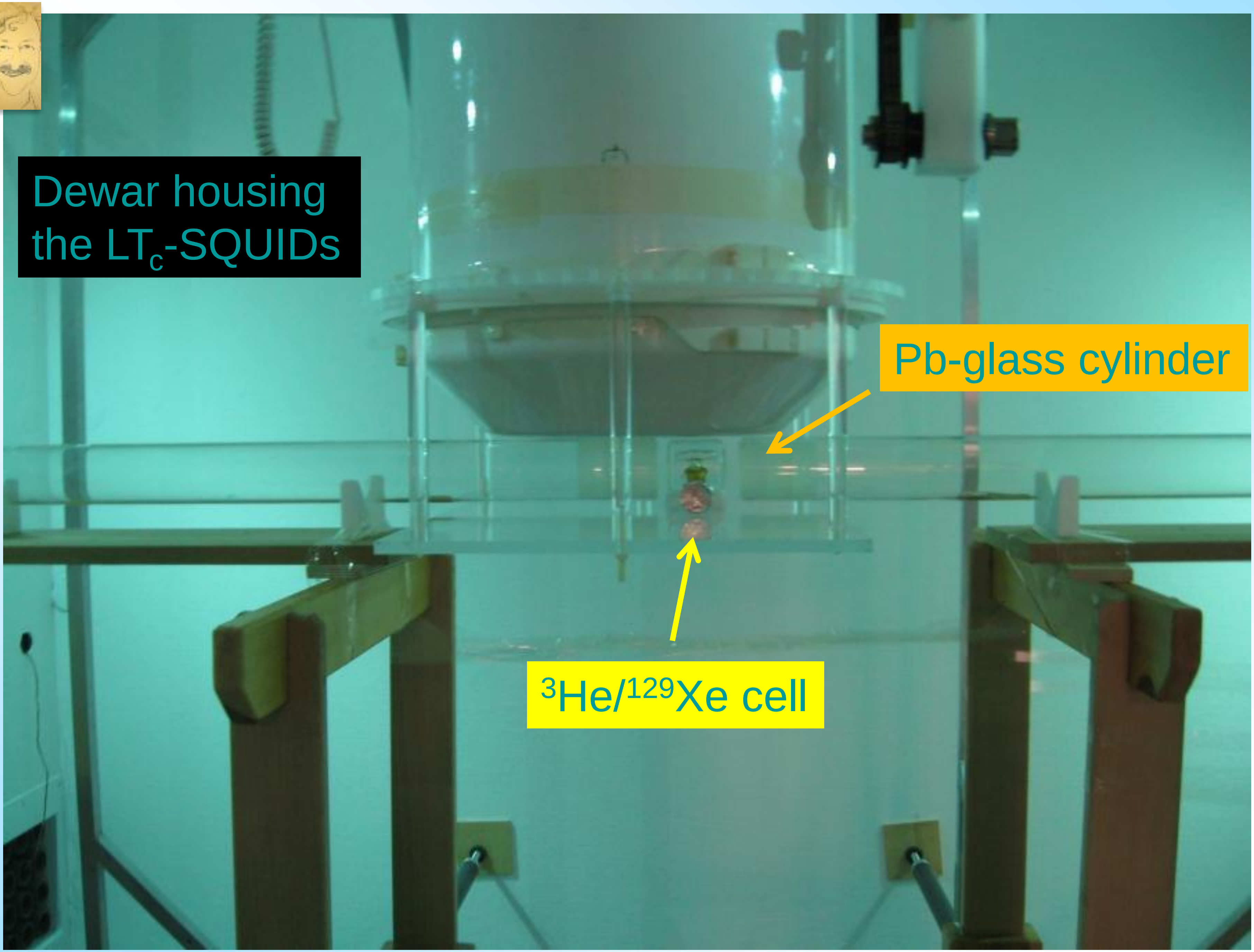


II. $Fit = c + a_{lin} \cdot t + a_{He} \cdot e^{-t/T^*_{2,He}} + a_{Xe} \cdot e^{-t/T^*_{2,Xe}} + \Phi(t)_{spin\text{-}coupling}$





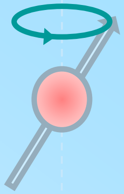
slide from W. Hei



Dewar housing the LT$_c$-SQUIDs

Pb-glass cylinder

^{3}He/^{129}Xe cell



^{3}He , ^{129}Xe clocks based on free spin precession yield best limit due to long spin coherence times

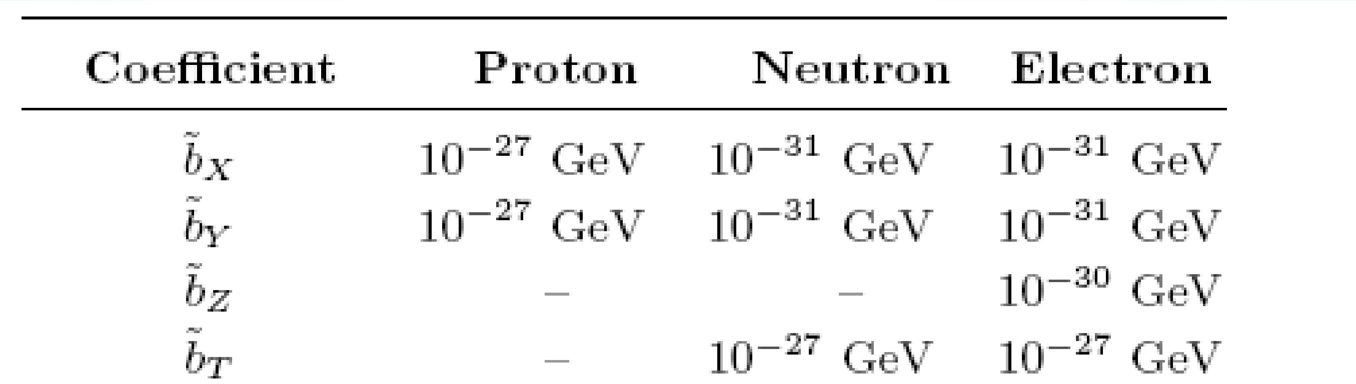
$$T^*_{2,He} > 60\,hours$$

$$\boxed{T^*_{2,Xe} = 4-6\ hours}$$

limiting parameter
for experiment

in Lorentz violating Standard Model extension (Kostelecky)

$$V = -\vec{\tilde{b}}\cdot\vec{\sigma}$$



Coefficient	Proton	Neutron	Electron
$\tilde{b}_X$	10^{-27} GeV	10^{-31} GeV	10^{-31} GeV
$\tilde{b}_Y$	10^{-27} GeV	10^{-31} GeV	10^{-31} GeV
$\tilde{b}_Z$	–	–	10^{-30} GeV
$\tilde{b}_T$	–	10^{-27} GeV	10^{-27} GeV

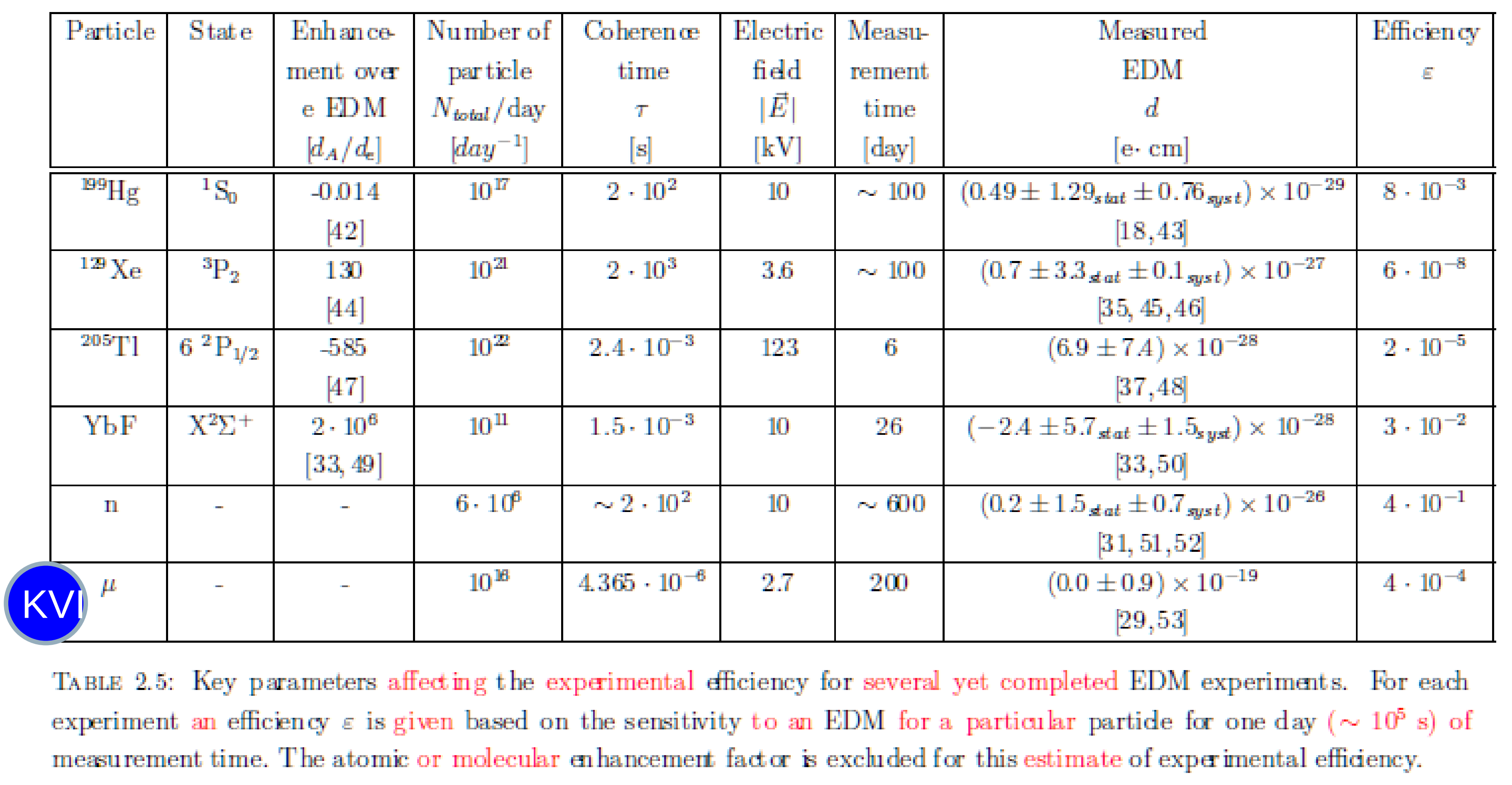
$$\tilde{b}^n_\perp = \leq 3.72\cdot 10^{-32}\ GeV\quad (95\%\quad C.L.\ )$$

M. Burghoff et al., arXiv 1008.0579

⇒ new limit on the bound neutron

muon EDM

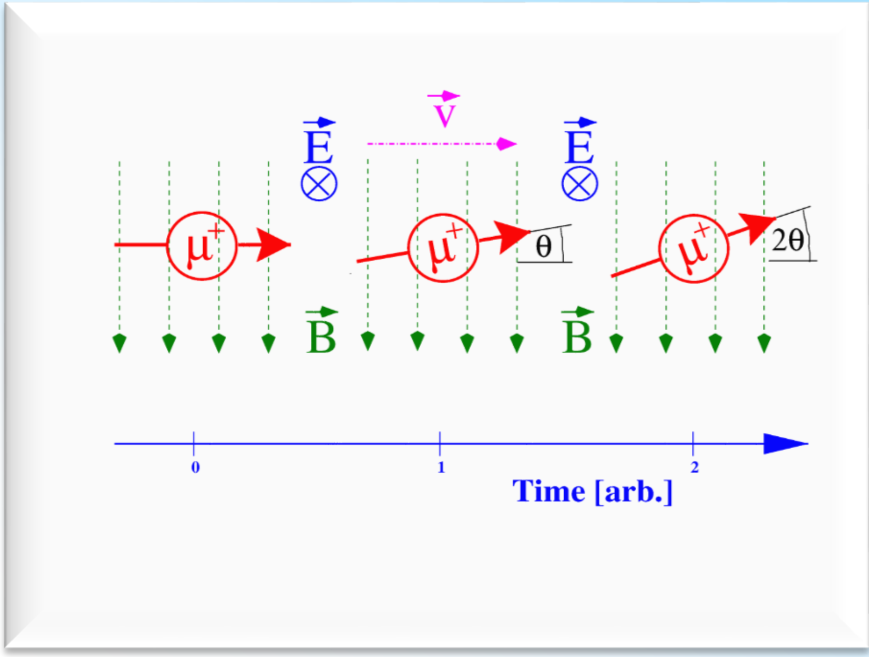
method for charged particles



Particle	State	Enhancement over e EDM $[d_A/d_e]$	Number of particle N_{total}/day $[day^{-1}]$	Coherence time τ [s]	Electric field $\lvert\vec{E}\rvert$ [kV]	Measurement time [day]	Measured EDM d [e· cm]	Efficiency ε
^{199}Hg	$^1S_0$	-0.014 [42]	10^{17}	$2 \cdot 10^2$	10	~ 100	$(0.49 \pm 1.29_{stat} \pm 0.76_{syst}) \times 10^{-29}$ [18,43]	$8 \cdot 10^{-3}$
^{129}Xe	$^3P_2$	130 [44]	10^{21}	$2 \cdot 10^3$	3.6	~ 100	$(0.7 \pm 3.3_{stat} \pm 0.1_{syst}) \times 10^{-27}$ [35,45,46]	$6 \cdot 10^{-8}$
^{205}Tl	$6\ ^2P_{1/2}$	-585 [47]	10^{22}	$2.4 \cdot 10^{-3}$	123	6	$(6.9 \pm 7.4) \times 10^{-28}$ [37,48]	$2 \cdot 10^{-5}$
YbF	$X^2\Sigma^+$	$2 \cdot 10^6$ [33,49]	10^{11}	$1.5 \cdot 10^{-3}$	10	26	$(-2.4 \pm 5.7_{stat} \pm 1.5_{syst}) \times 10^{-28}$ [33,50]	$3 \cdot 10^{-2}$
n	-	-	$6 \cdot 10^6$	$\sim 2 \cdot 10^2$	10	~ 600	$(0.2 \pm 1.5_{stat} \pm 0.7_{syst}) \times 10^{-26}$ [31,51,52]	$4 \cdot 10^{-1}$
μ	-	-	10^{16}	$4.365 \cdot 10^{-6}$	2.7	200	$(0.0 \pm 0.9) \times 10^{-19}$ [29,53]	$4 \cdot 10^{-4}$

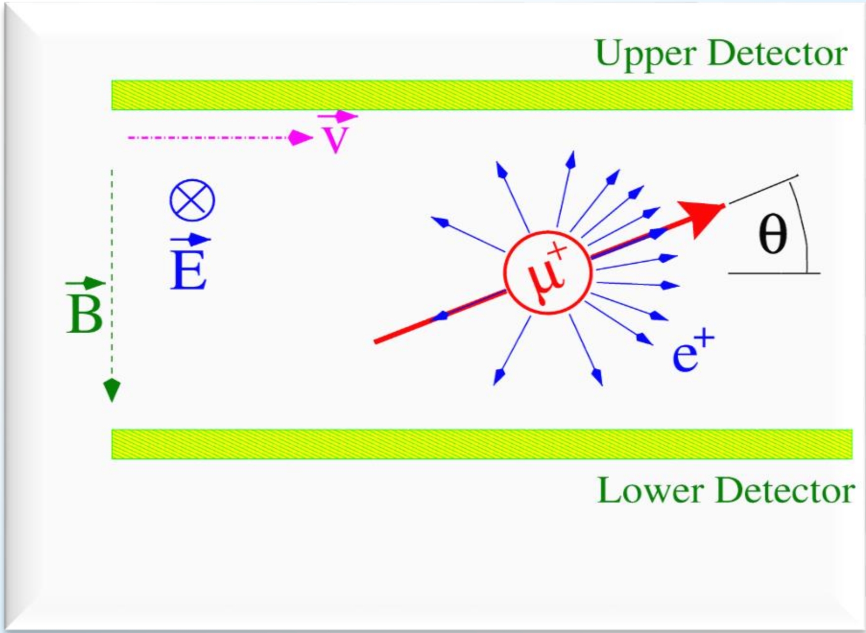
TABLE 2.5: Key parameters affecting the experimental efficiency for several yet completed EDM experiments. For each experiment an efficiency ε is given based on the sensitivity to an EDM for a particular particle for one day (~ 10^5 s) of measurement time. The atomic or molecular enhancement factor is excluded for this estimate of experimental efficiency.

Permanent Electric Dipole Moment in a Ring

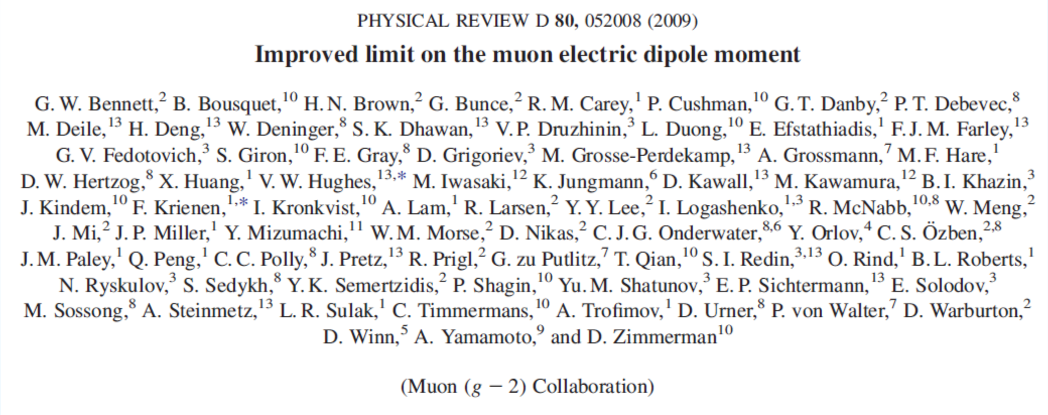


Spin precession in (electro-) magnetic field

$$\vec{\omega} = \frac{e}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right] + \frac{e}{m}\left[\frac{\eta}{2}\left(\frac{\vec{E}}{c} + \vec{\beta}\times\vec{B}\right)\right]$$



Muon EDM – A Parasitic Measurement



PHYSICAL REVIEW D **80,** 052008 (2009)

Improved limit on the muon electric dipole moment

G. W. Bennett,[2] B. Bousquet,[10] H. N. Brown,[2] G. Bunce,[2] R. M. Carey,[1] P. Cushman,[10] G. T. Danby,[2] P. T. Debevec,[8] M. Deile,[13] H. Deng,[13] W. Deninger,[8] S. K. Dhawan,[13] V. P. Druzhinin,[3] L. Duong,[10] E. Efstathiadis,[1] F. J. M. Farley,[13] G. V. Fedotovich,[3] S. Giron,[10] F. E. Gray,[8] D. Grigoriev,[3] M. Grosse-Perdekamp,[13] A. Grossmann,[7] M. F. Hare,[1] D. W. Hertzog,[8] X. Huang,[1] V. W. Hughes,[13,*] M. Iwasaki,[12] K. Jungmann,[6] D. Kawall,[13] M. Kawamura,[12] B. I. Khazin,[3] J. Kindem,[10] F. Krienen,[1,*] I. Kronkvist,[10] A. Lam,[1] R. Larsen,[2] Y. Y. Lee,[2] I. Logashenko,[1,3] R. McNabb,[10,8] W. Meng,[2] J. Mi,[2] J. P. Miller,[1] Y. Mizumachi,[11] W. M. Morse,[2] D. Nikas,[2] C. J. G. Onderwater,[8,6] Y. Orlov,[4] C. S. Özben,[2,8] J. M. Paley,[1] Q. Peng,[1] C. C. Polly,[8] J. Pretz,[13] R. Prigl,[2] G. zu Putlitz,[7] T. Qian,[10] S. I. Redin,[3,13] O. Rind,[1] B. L. Roberts,[1] N. Ryskulov,[3] S. Sedykh,[8] Y. K. Semertzidis,[2] P. Shagin,[10] Yu. M. Shatunov,[3] E. P. Sichtermann,[13] E. Solodov,[3] M. Sossong,[8] A. Steinmetz,[13] L. R. Sulak,[1] C. Timmermans,[10] A. Trofimov,[1] D. Urner,[8] P. von Walter,[7] D. Warburton,[2] D. Winn,[5] A. Yamamoto,[9] and D. Zimmerman[10]

(Muon ($g-2$) Collaboration)

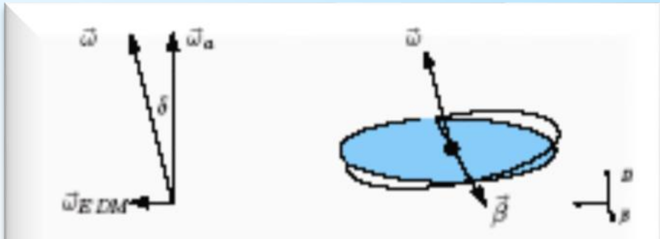


Figure 1: A muon EDM would tilt the spin precession plane.

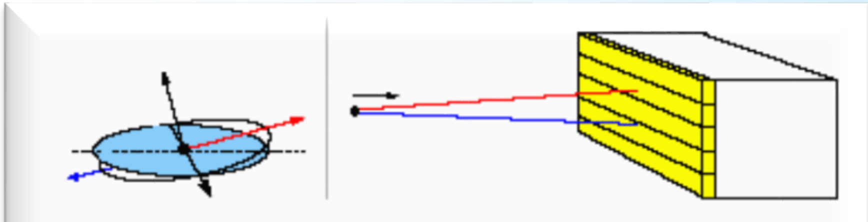


Figure 2: A tilt in the precession plane results in a vertical oscillation of hits on the detector face.

3 methods for analysis:

$d\mu < 1.8 \cdot 10^{-19}$ ecm (95% C.L.)

Fermilab: factor ~100

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G. W. Bennett,[2] B.
M. Deile,[13] H. Den
G. V. Fedotovich
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N. Ryskulov,[3] S
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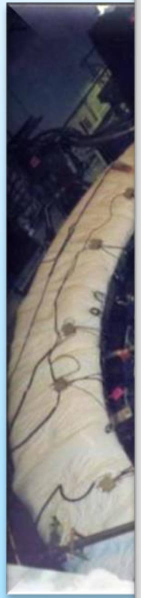

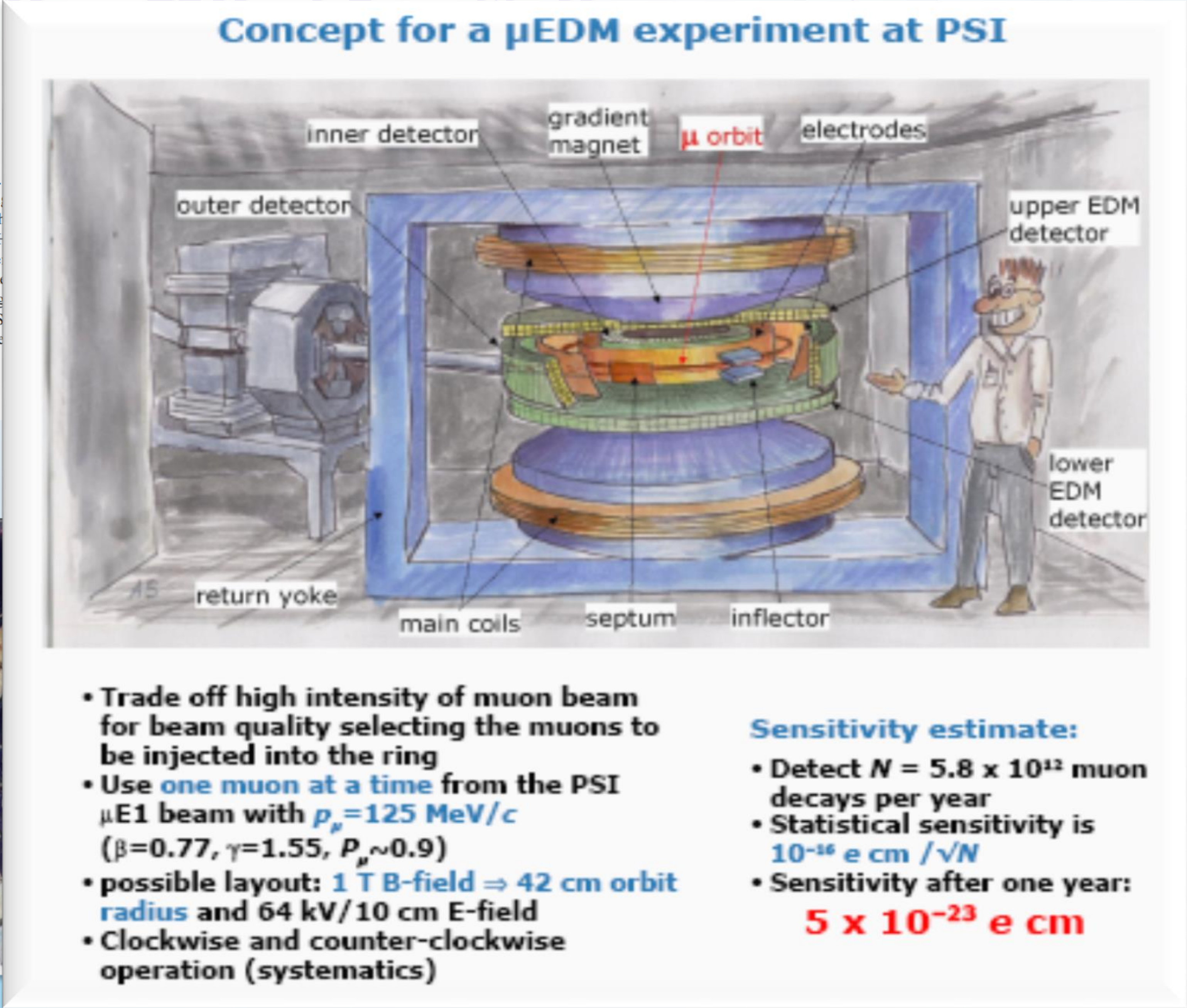

Concept for a μEDM experiment at PSI

- Trade off high intensity of muon beam for beam quality selecting the muons to be injected into the ring
- Use one muon at a time from the PSI μE1 beam with p_μ=125 MeV/c (β=0.77, γ=1.55, P_μ~0.9)
- possible layout: 1 T B-field ⇒ 42 cm orbit radius and 64 kV/10 cm E-field
- Clockwise and counter-clockwise operation (systematics)

Sensitivity estimate:

- Detect $N = 5.8 \times 10^{12}$ muon decays per year
- Statistical sensitivity is 10^{-16} e cm $/\sqrt{N}$
- Sensitivity after one year:

5×10^{-23} e cm

C.L.)

Adelmann, Kirch, Onderwater, J. Phys. G: Nucl. Part. Phys. 37 085001 (2010)

- Transport coils to and from barge via Sikorsky aircrane
- Ship through St Lawrence -> Great Lakes -> Calumet SAG
- Subsystems can be transported overland, but probably more cost effective to ship steel on barge as well.

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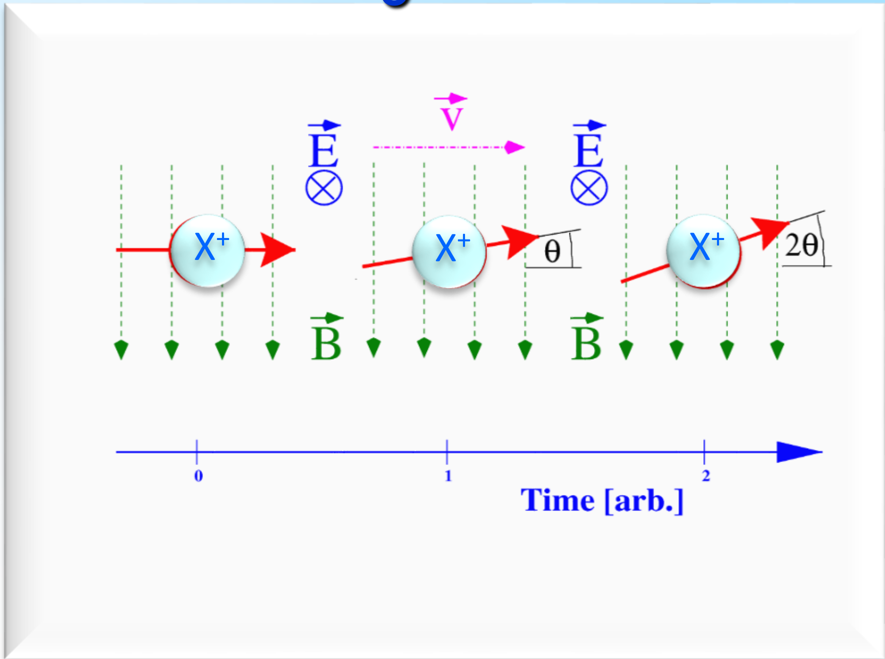
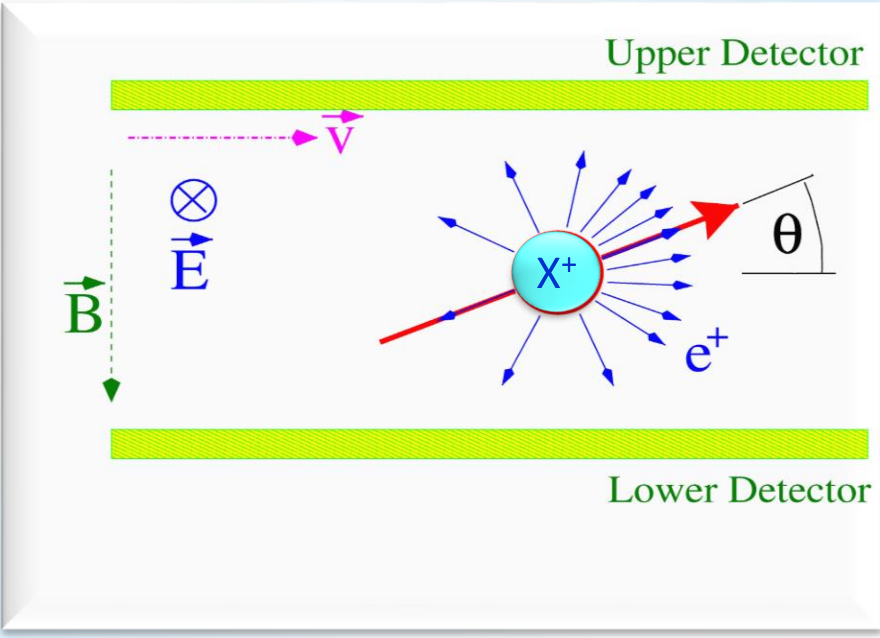
Permanent Electric Dipole Moment in a Ring



Spin precession
in (electro-)
magnetic field

$$\vec{\omega} = \frac{e}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right]$$

$$+ \frac{e}{m}\left[\frac{\eta}{2}\left(\frac{\vec{E}}{c} + \vec{\beta}\times\vec{B}\right)\right]$$



Some Candidate Nuclei for EDM in Ring Searches

Nucleus	Spin J	μ/μ_N	Reduced Anomaly a	$T_{1/2}$
$^{139}_{57}$La	7/2	+2.789	-0.0305	
$^{123}_{51}$Sb	7/2	2.550	-0.1215	
$^{137}_{55}$Cs	7/2	+2.8413	0.0119	30y
$^{223}_{87}$Fr	3/2	+1.17	<0.02	22 min
$^{6}_{3}$Li	1	+0.8220	-0.1779	
$^{2}_{1}$H	1	+0.8574	-0.1426	
$^{75}_{32}$Ge	1/2	+0.510	+0.195	82.8 m
$^{157}_{69}$Tm	1/2	+0.476	0.083	3.6 m

Method works also for highly charged ions

More complete lists:
I.B. Khriplovich, K. Jungmann
GSI EDM Workshop, 1999

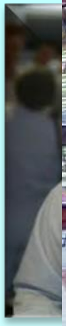
The Importance of Informal Meals

International Symposiua on

LEPTON MOMENTS

Heidelberg, Germany
1: 08 - 12 June 1999
Centerville, Cape Cod, MA
2: 09 - 12 June 2003
3: 19 - 22 June 2006
4: 1 9- 22 July

ECT* works
Many, ma



Ring EDM experimenst can work for ALL ions

Up to now mostly in THEORY

It's time for an after conference party

@ Mahabaleshwar !

Summary

- Atomic EDMs are experimentally accessible
- Atomic Physics technology
- EDM sensitivity scales approx. with Z^3
- Relatively easy to interpret
- High potential : Ra, Xe …
- Stay tuned

$\Rightarrow$ Work in progress :

Atoms Still yield the Best Limits !

university of groningen

FOM