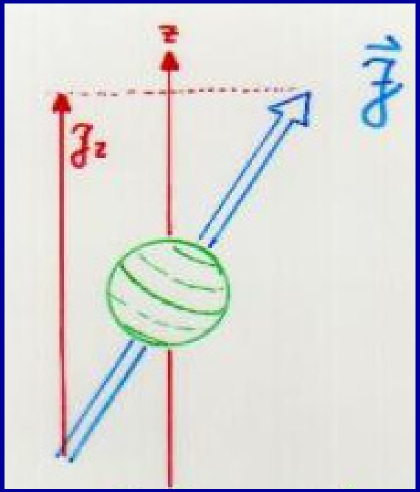

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Searches for permanent Electric Dipole Moments

- **Fundamental Symmetries and Forces**
- **Discrete Symmetries**
- **Fundamental Fermions**
- **Models Beyond Standard Theory**
- **Precision Experiments**
- **How to Compare Experiments**
- **Other approaches to same Physics Questions**

⇒ only scratching some examples

Klaus Jungmann, KVI, University of Groningen

3rd International Symposium on

LEPTON MOMENTS

Centerville, Cape Cod, MA
19 - 22 June 2006

Ramsey Price established:

Tuesday 20 June 2006

8:30	Ulrich Jentschura (MPI Heidelberg) (35)	The Bound-electron g-factor (pdf)
9:15	Wolfgang Quint (GSI) (35)	Bound state g-factors and the electron mass (pdf)
10:00	Coffee Break	
10:15	Adam Ritz (Victoria) (35)	Probing new CP-odd thresholds with EDMs (pdf)
11:00	Junji Hisano (Tokyo) (35)	EDMs and Lepton Flavor Violation (pdf)
11:45	Lunch	
1:15	Maxim Pospelov (Victoria) (35)	Breaking unbreakable: Lorentz, CPT violation, and the change of couplings in Time (pdf)
2:00	Jon Engel (North Carolina) (40)	Nuclear Physics of Atomic EDMs (pdf)
2:50	Coffee Break	
3:15	Ed Hinds (Imperial) (40)	Measurement of the electron EDM using cold YbF molecules (pdf)
4:05	David DeMille (Yale) (40)	The PbO Experiments at Yale (ppt)
4:55	Klaus Jungmann (KVI Groningen) (15)	TRImP: A new facility for fundamental symmetry research (ppt)
5:20	Break for the Day	

Wednesday 21 June 2006

8:45	David Weiss (Penn State) (25)	Update on Measuring the Electron EDM Using Cs and Rb in Optical Lattices(pdf)
9:20	Eric Cornell (JILA/Colorado) (35)	Searching for an Electron EDM in trapped molecular ions(pdf)
10:05	Coffee Break	
10:30	Neil Shafer-Ray (Oklahoma) (20)	Possible Measurement of the e-edm with g=0 Paramagnetic Molecules(ppt)
11:00	Jen-Chieh Peng (Illinois) (35)	The New Search for a neutron EDM at the SNS (pdf)
11:45	Lunch	
1:15	James Karamath (Sussex) (35)	The ILL Cryogenic- neutron EDM Experiment (ppt, pdf)
2:00	Klaus Kirch (PSI) (35)	Search for an EDM of the neutron at PSI(pdf)
2:40	Norval Fortson (Washington) (35)	Search for an EDM of the ^{199}Hg Atom (pdf)
3:30	Cofee Break	
3:45	Mike Romalis (Princeton) (35)	EDM experiments with Xenon (pdf)
4:30	Roy Holt (Argonne) (35)	Search for an EDM of ^{225}Ra(pdf)
5:15	Break for Day	

Thursday 22 June 2006

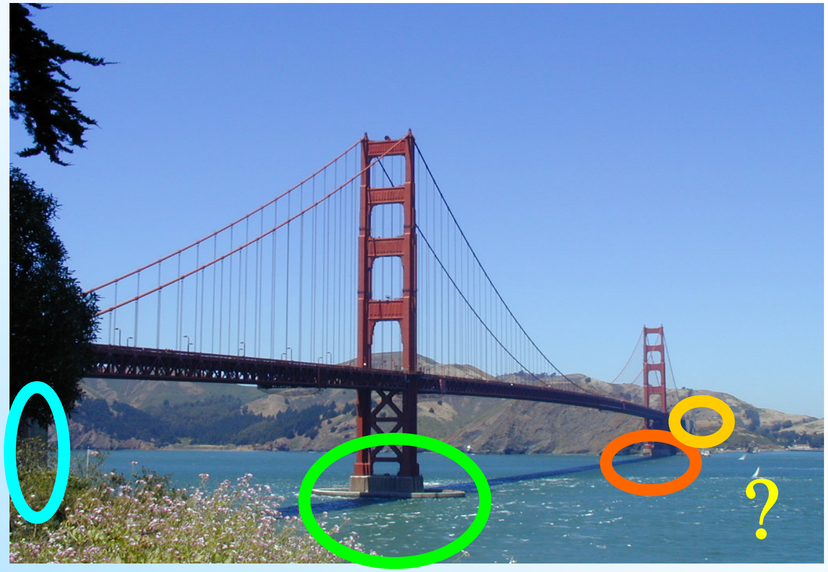
8:45	Gerco Onderwater (KVI Groningen) (30)	Search for EDMs in storage rings (pdf)
9:25	Yuri Orlov (Cornell) (15)	Systematic Errors for Measurements of EDMs in storage rings (pdf)
9:45	Coffee Break	
10:00	Yoshi Kuno (Osaka) (35)	Experimental Searches for Lepton Flavor Violation (49M pdf)
10:45	Andrzej Czarnecki (Alberta) (50)	Conference Summary and Outlook (pdf)

- Large fraction of all EDM experiments represented
- Plurality of
  - Old Approaches
  - New Experiments
  - Novel Ideas

  discussed

destillation ⟹

What are we concerned with ?



Forces and Symmetries

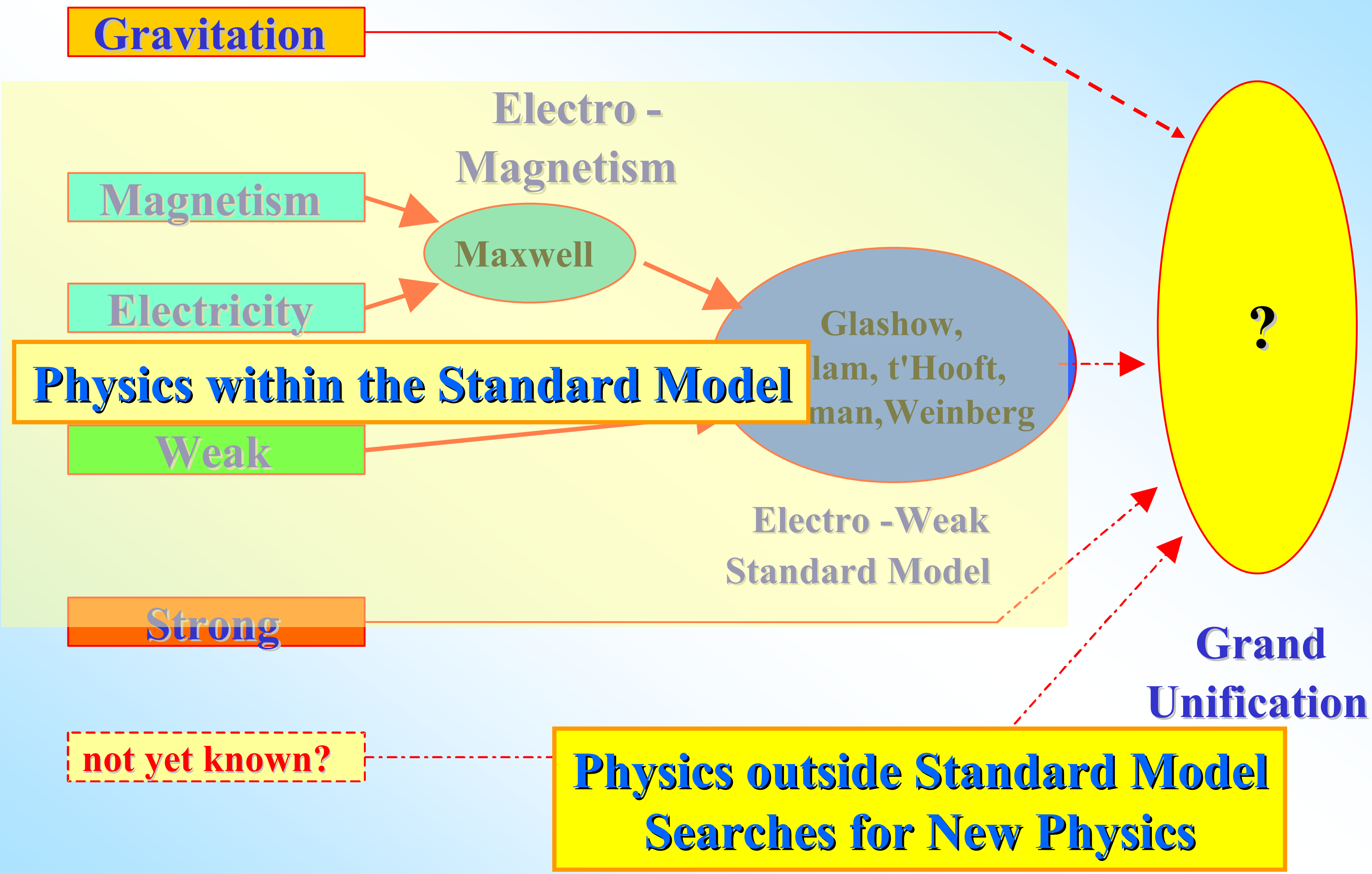
Local Symmetries ⇔ Forces

- fundamental interactions

Global Symmetries ⇔ Conservation Laws

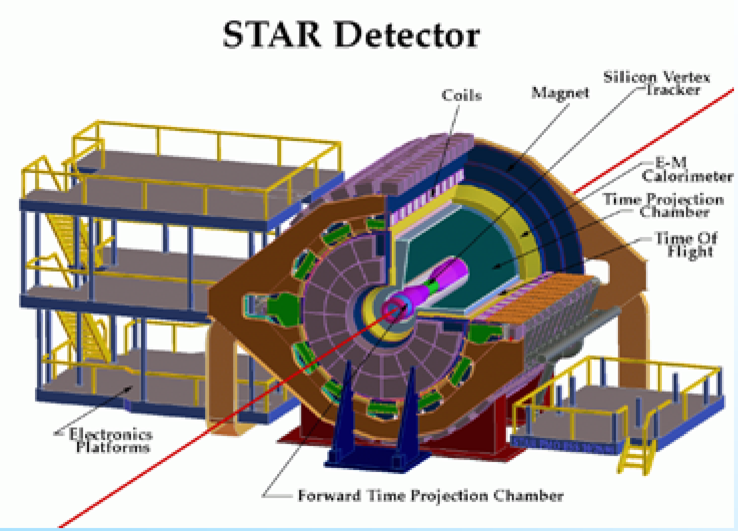
- energy
- momentum
- electric charge
- lepton number
- charged lepton family number
- baryon number
- …..

Fundamental Interactions – Standard Model

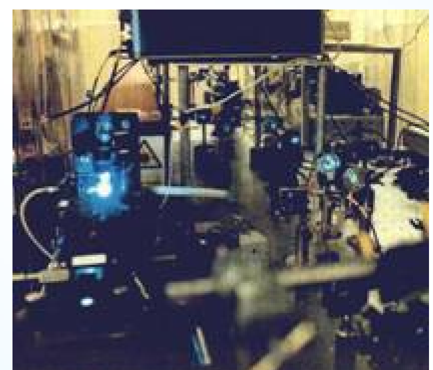


TRIμP

Possibilities to Test New Models



⇔



High Energies & direct observations

Low Energies & Precision Measurement

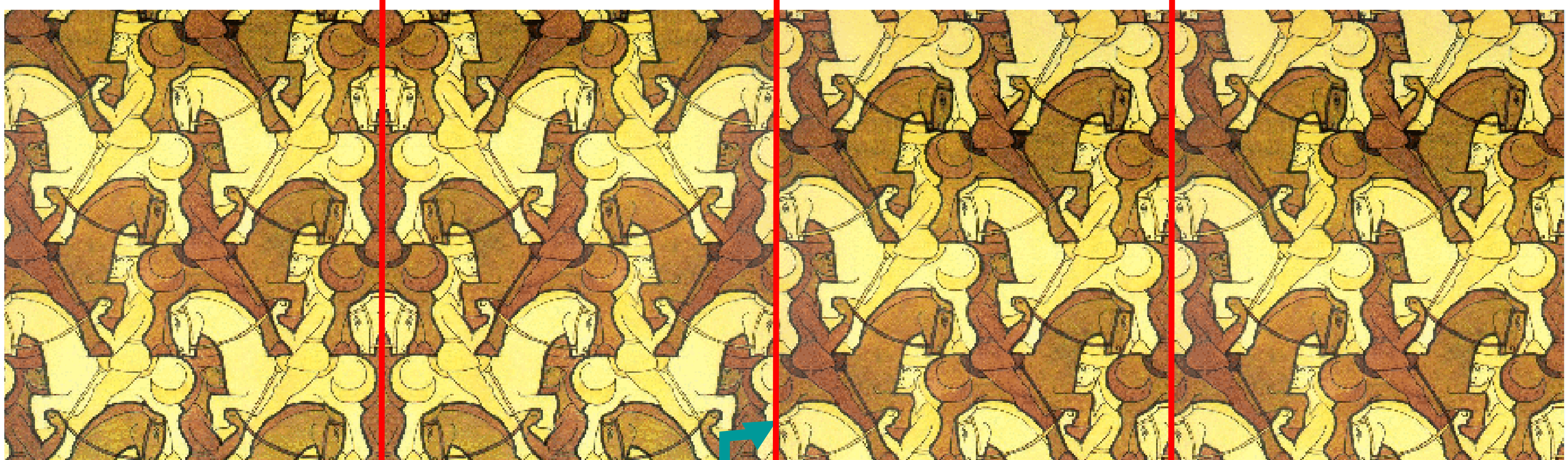
Discrete Symmetries

- Parity **P**
  - is violated
  - β-decay
- Time Reversal **T**
  - Reported violated directly in K-decay
- CPT Invariance **CPT**
  - No observed violation reported yet, searched for
  - Strong theorem
- Combined Charge Conjugation and Parity **CP**
  - K, B mesons
  - with **CPT** assumed **CP** violation implies **T** violation

The World according to Escher

P | C | T

start | matter | anti-matter | identical to start



mirror image | time → | ← time

Time Reversal Violation
can be measured at low energies

anti-particle e^+ | particle e^-

From H.W. Wilschut

Discrete Symmetries

At present we have activities in particular to study:

- **Parity**
  - Parity Nonconservation in Atoms
  - Nuclear Anapole Moments
  - Parity Violation in Electron-Scattering
- **Time Reversal and CP-Violation**
  - Electric Dipole Moments
  - R and D Coefficients in β-Decay
- **CPT Invariance**

Discrete Symmetries

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  - **Parity Nonconservation in Atoms**
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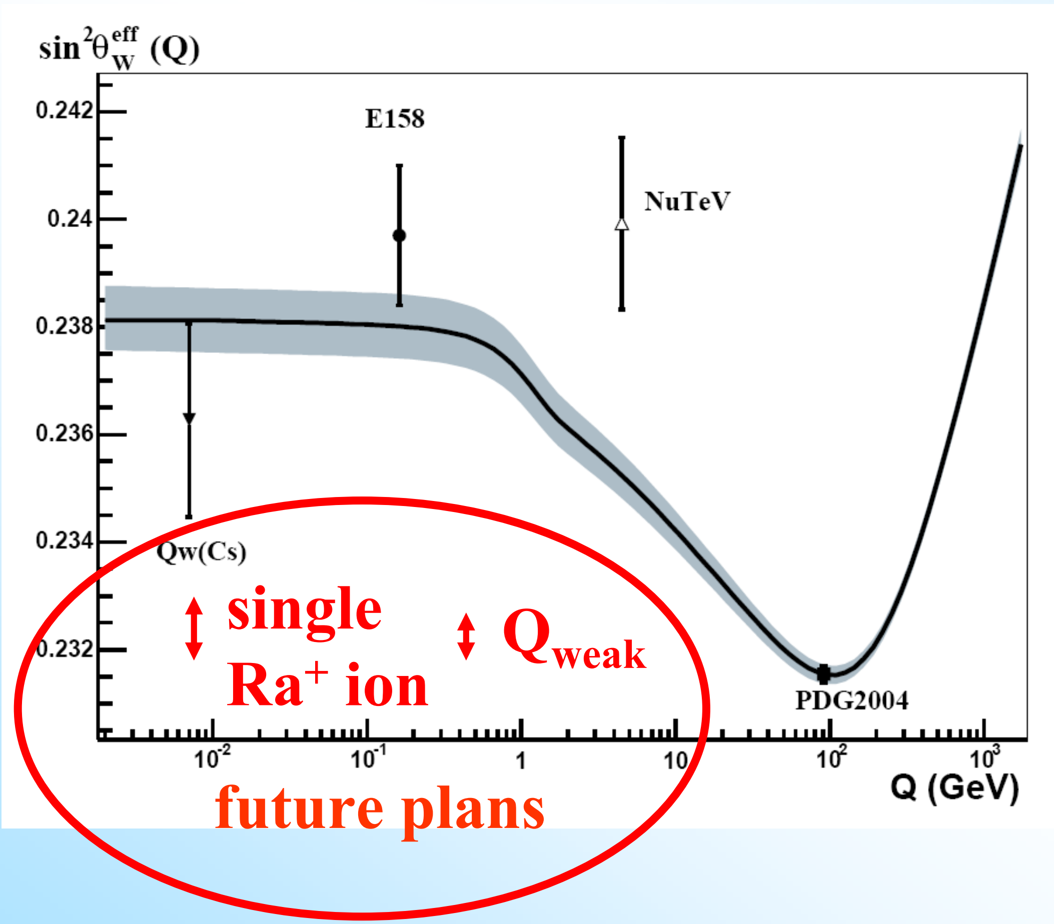
- **Time Reversal and CP-Violation**
  - **Electric Dipole Moments**
  - **R and D Coefficients in β-Decay**
- **CPT Invariance**

Possible Gains from Parity Violation Experiments



In past:
- excellent test of Standard Model

Now:
- running of weak mixing angle
- sensitivity to some leptoquark models, Z'
- s-quark content of nucleon
- neutron distributions in nuclei
- anapole moments
- Cs, Fr Atomic Parity Violation experiments are going on
- electron scattering & hadron forward scattering going on

Discrete Symmetries

At present we have activities in particular to study:

- Parity
  - Parity Nonconservation in Atoms
  - Nuclear Anapole Moments
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Discrete Symmetries

At present we have activities in particular to study:

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  - Parity Violation in Electron-Scattering
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  - **Electric Dipole Moments**
  - R and D Coefficients in β-Decay
- CPT Invariance

What's particular about CP-violation ?

Matter – Antimatter Asymmetry MAY be explained by (Sacharov)

- **Baryon number violation**
- **Thermal non - equilibrium**
- **CP- violation**

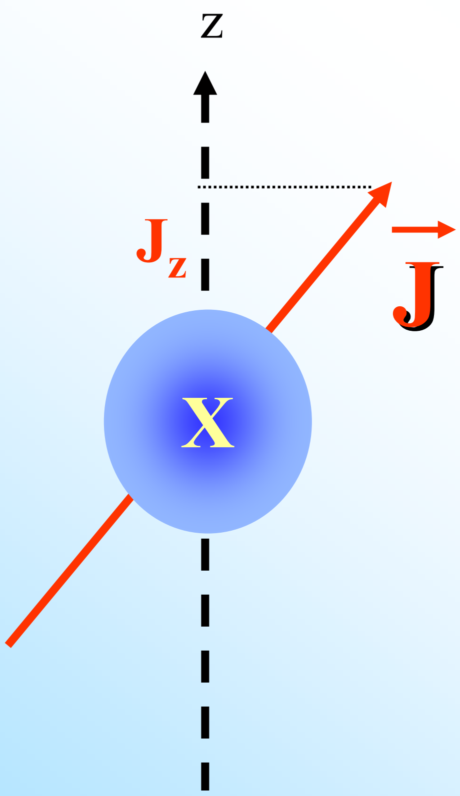
Beware: There are other routes!

e.g.

Matter – Antimatter Asymmetry MAY be also explained by (Kostelecky et al.):

- **Baryon number violation**
- **CPT - violation**

Fundamental Particles



$\vec{J}$ is the only vector characterizing a non-degenerate quantum state

magnetic moment:

$$\vec{\mu}_x = g\, \mu_x\, c^{-1}\, \vec{J}$$

electric dipole moment:

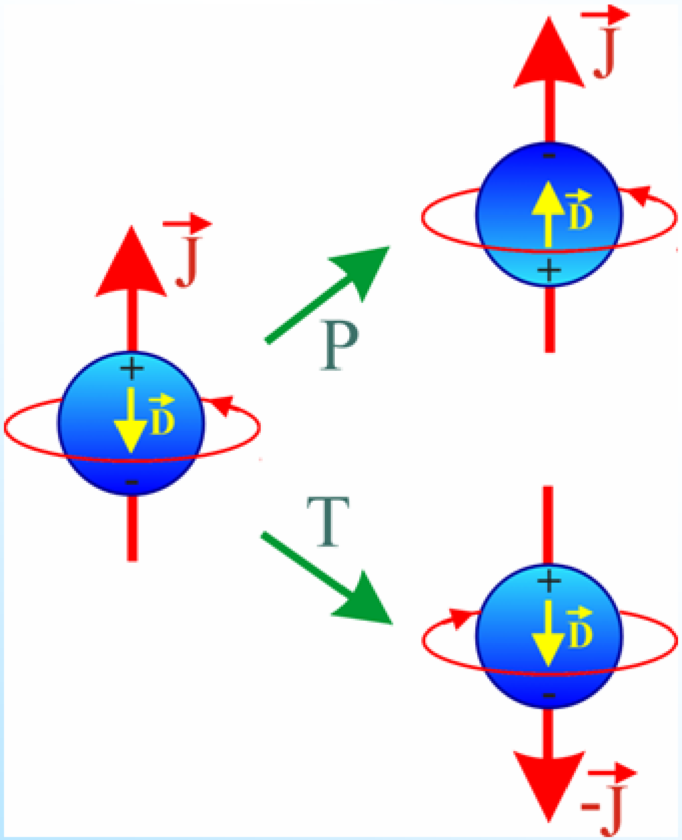
$$\vec{d}_x = \eta\, \mu_x\, c^{-1}\, \vec{J}$$

magneton:

$$\mu_x = e\hbar / (2m_x)$$

$$\mu_x\, c^{-1}\, J = \begin{cases} 9.7 \cdot 10^{-12} \text{ e cm (electron)} \\ 5.3 \cdot 10^{-15} \text{ e cm (nucleon)} \end{cases}$$

Permanent Electric Dipole Moments Violate Discrete Fundamental Symmetries



$$H = -(\vec{d}\,\vec{E} + \vec{\mu}\,\vec{B})\,\vec{J}/J$$

d - electric dipole moment
μ - magnetic dipole mom
J - Spin

EDM violates:

- **Parity**
- **Time reversal**
- **CP- conservation**

(if **CPT** conservation assumed)

Standard Model values are tiny, hence:

An observed EDM would be Sign of New Physics beyond Standard Theory

Permanent Electric Dipole Moments are predicted by the Standard Model

and

a variety of Models Beyond Standard Theory

- **Strong CP Violation**
- **LeftRight Symmetry**
- **Supersymmetry**
- **Higgs Models**
- **Technicolor**
- **. . .**

} **No status in Physics , yet**

"Not even wrong"

There is no indication whatsoever given by nature, yet, which would justify to prefer any of these possibilities

Schiff Theorem - introduced by Ramsey and Purcell

- A neutral system composed of charged objects re-arranges in an external electric field such that the net force on it cancels on average.
- This may give rise to
  - significant shielding of the field at the location of the particle of interest
  - (strong) enhancement of the EDM effect
- "Schiff corrections" need to be looked at very carefully – there is a need for theoretical support

Enhancement of EDM in Atomic Shell

- Heavy Atoms

  $d_A/d_e \approx 10\, Z^3 \alpha^2$

- Induced Dipol Moment

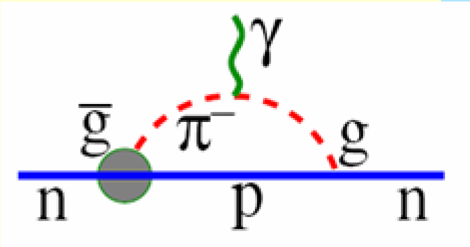
  → Polarizability
  in nucleus as well as atomic shell

$$d_A = \sum_{n'} \frac{< nl \,|\, -d_e\, (\beta-1)\, \vec{\sigma}\, \vec{E} \,|\, n'(l+1) > < n'\, (l+1) \,|\, -e\vec{r} \,|\, nl >}{E_{nl} - E_{n'(l+1)}} + c.c.$$

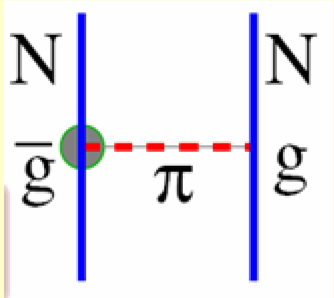
- Example: Tl ~ -585, Fr ~ 1150, Ra ~ 40.000

A Nucleus is more that the sum of Nucleons

- **Neutron has EDM of the Nucleon e.g.**



- **Nucleus carries Nucleon EDM *plus* EDM from CP-odd Nucleon-Nucleon Forces**



- **Nucleus may induce EDM into Atom**
  - **screening**
  - ~~**dipole operator** $\vec{d} \equiv \sum_p \vec{r}_p$~~ **Schiff operator** $\vec{S} \approx \sum_p r_p^2 \vec{r}_p$

Mercury

VOLUME 86, NUMBER 12 PHYSICAL REVIEW LETTERS 19 MARCH 2001

New Limit on the Permanent Electric Dipole Moment of ^{199}Hg

M. V. Romalis, W. C. Griffith, J. P. Jacobs,* and E. N. Fortson
Department of Physics, University of Washington, Seattle, Washington 98195
(Received 21 November 2000)

We present the first results of a new search for a permanent electric dipole moment of the ^{199}Hg atom using a UV laser. Our measurements give $d(^{199}\mathrm{Hg}) = -(1.06 \pm 0.49 \pm 0.40) \times 10^{-28} e$ cm. We interpret the result as an upper limit $|d(^{199}\mathrm{Hg})| < 2.1 \times 10^{-28} e$ cm (95% C.L.), which sets new constraints on $\bar{\theta}_{QCD}$, chromo-EDMs of the quarks, and CP violation in supersymmetric models.

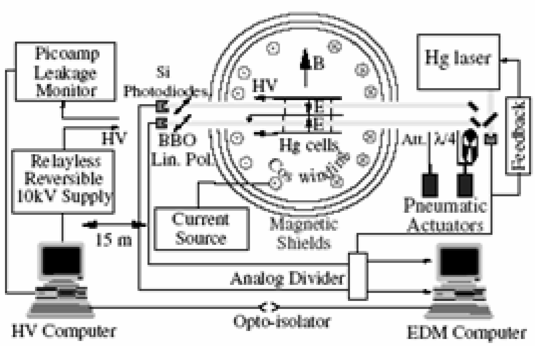


FIG. 1. Schematic of the apparatus used to search for a permanent EDM of ^{199}Hg atoms.

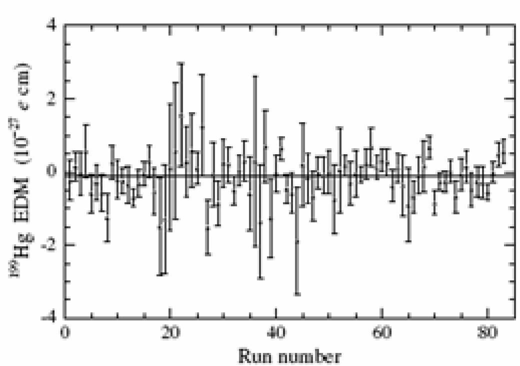


FIG. 2. ^{199}Hg EDM signal as a function of run number. The solid line shows the average of the data. Runs with larger errors were done in nonoptimal configurations.

arXiv:hep-ex/0407008 v1 1 Jul 2004

Electron

VOLUME 88, NUMBER 7 PHYSICAL REVIEW LETTERS 18 FEBRUARY 2002

New Limit on the Electron Electric Dipole Moment

B. C. Regan,* Eugene D. Commins,† Christian J. Schmidt,‡ and David DeMille§
Physics Department, University of California, Berkeley, California 94720
and Lawrence Berkeley National Laboratory, Berkeley, California 94720
(Received 8 August 2001; published 1 February 2002)

We present the result of our most recent search for T violation in ^{205}Tl, which is interpreted in terms of an electric dipole moment of the electron d_e. We find $d_e = (6.9 \pm 7.4) \times 10^{-28} e$ cm, which yields an upper limit $|d_e| \leq 1.6 \times 10^{-27} e$ cm with 90% confidence. The present apparatus is a major upgrade of the atomic beam magnetic-resonance device used to set the previous limit on d_e.

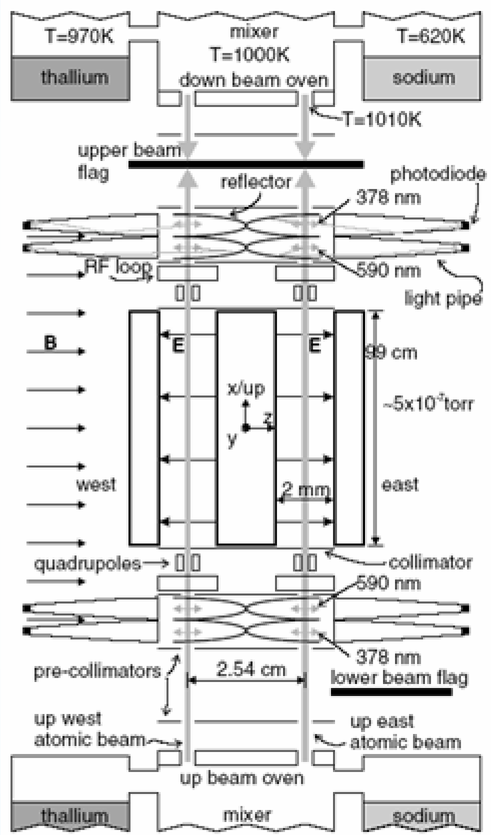


FIG. 1. Schematic diagram of the experiment; not to scale.

Apparent progress in Mercury

⇒ Systematics is ~~an~~ THE issue

Overview of EDM data after November 2005

- About 120 runs thus far
- Blind analysis instituted about half-way through
- Result of first half (before blind analysis):
  - $d(^{199}Hg) = [-5.4 \pm 4.1_{stat.} \pm ??_{syst.}] \times 10^{-29}\ e$ cm
  - Compare with 2001 result: $[-10.6 \pm 4.9_{stat.} \pm 4.0_{syst.}] \times 10^{-29}\ e$ cm
- Statistical sensitivity per run has improved in recent months
  - Total statistical error thus far: $\pm 2.9_{stat.} \times 10^{-29}\ e$ cm
  - Projected after 6 more months: $\pm 1.5_{stat.} \times 10^{-29}\ e$ cm
- Major remaining issue: Systematics!
  - Aiming for $\pm 1.5_{syst} \times 10^{-29}\ e$ cm

From: N. Fortson, Lepton Moments 2006

Neutron

PRL 97, 131801 (2006) PHYSICAL REVIEW LETTERS week ending 29 SEPTEMBER 2006

Improved Experimental Limit on the Electric Dipole Moment of the Neutron

C. A. Baker,[1] D. D. Doyle,[2] P. Geltenbort,[3] K. Green,[1,2] M. G. D. van der Grinten,[1,2] P. G. Harris,[2] P. Iaydjiev,[1,*] S. N. Ivanov,[1,†] D. J. R. May,[2] J. M. Pendlebury,[2] J. D. Richardson,[2] D. Shiers,[2] and K. F. Smith[2]
[1]*Rutherford Appleton Laboratory, Chilton, Didcot, Oxon OX11 0QX, United Kingdom*
[2]*Department of Physics and Astronomy, University of Sussex, Falmer, Brighton BN1 9QH, United Kingdom*
[3]*Institut Laue-Langevin, BP 156, F-38042 Grenoble Cedex 9, France*
(Received 9 February 2006; revised manuscript received 29 March 2006; published 27 September 2006)

An experimental search for an electric dipole moment (EDM) of the neutron has been carried out at the Institut Laue-Langevin, Grenoble. Spurious signals from magnetic-field fluctuations were reduced to insignificance by the use of a cohabiting atomic-mercury magnetometer. Systematic uncertainties, including geometric-phase-induced false EDMs, have been carefully studied. The results may be interpreted as an upper limit on the neutron EDM of $|d_n| < 2.9 \times 10^{-26}\,e$ cm (90% C.L.).

DOI: 10.1103/PhysRevLett.97.131801 PACS numbers: 13.40.Em, 07.55.Ge, 11.30.Er, 14.20.Dh

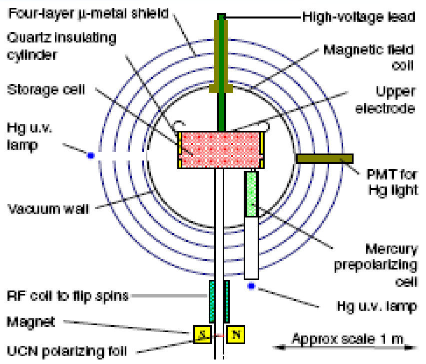


FIG. 1 (color online). Experimental apparatus.

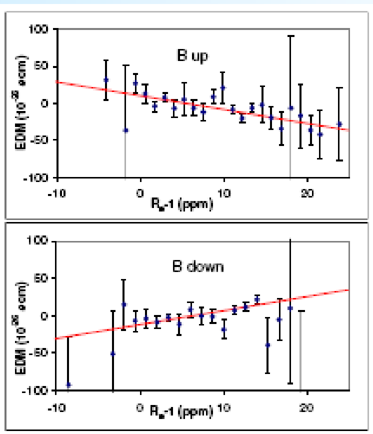


FIG. 2 (color online). Measured EDM (binned data) as a function of the relative frequency shift of neutrons and Hg.

Muon

An Improved Limit on the Electric Dipole Moment of the Muon

Ronald McNabb
(for the Muon g-2 collaboration)
Dept. of Physics, University of Illinois at Urbana-Champaign
1110 W Green St., Urbana, IL 61801, USA.

arXiv:hep-ex/0407008 v1 1 Jul 2004

Data from the muon g-2 experiment at Brookhaven National Lab has been analyzed to search for a muon electric dipole moment(EDM), which would violate parity and time reversal symmetries. An EDM would cause a tilt in the spin precession plane of the muons, resulting in a vertical oscillation in the position of electrons hitting the detectors. No signal has been observed. Based on this analysis, an improved limit of 2.8×10^{-19} e-cm(95% CL) is set on the muon EDM.

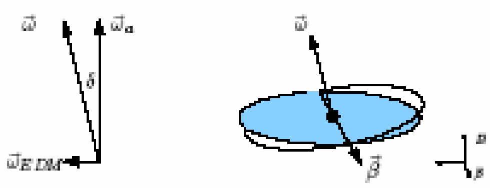


Figure 1: A muon EDM would tilt the spin precession plane.

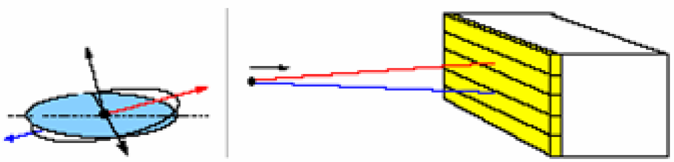


Figure 2: A tilt in the precession plane results in a vertical oscillation of hits on the detector face.

Theoretical work close to Experiment …

VOLUME 89, NUMBER 13 PHYSICAL REVIEW LETTERS 23 SEPTEMBER 2002

Enhancement of the Electric Dipole Moment of the Electron in PbO

M. G. Kozlov*
Petersburg Nuclear Physics Institute, Gatchina, 188300, Russia

D. DeMille†
Physics Department, Yale University, New Haven, Connecticut 06520
(Received 23 May 2002; published 4 September 2002)

The $a(1)$ state of PbO can be used to measure the electric dipole moment of the electron d_e. We discuss a semiempirical model for this state, which yields an estimate of the effective electric field on the valence electrons in PbO. Our final result is a lower limit on the measurable energy shift, which is significantly larger than was anticipated earlier: $2|W_d|d_e \gtrsim 2.4 \times 10^{25}$ Hz$[\frac{d_e}{e\ \mathrm{cm}}]$.

A new method of measuring electric dipole moments in storage rings

F.J.M. Farley[7], K. Jungmann[4], J.P. Miller[2], W.M. Morse[3], Y.F. Orlov[5], B.L. Roberts[2], Y.K. Semertzidis[3], A. Silenko[1], E.J. Stephenson[6]

…sian State University, Belarus; [2]Physics Department, Boston University, Boston, MA 02215; …haven National Laboratory, Upton, NY 11973; [4]Kernfysisch Versneller Instituut, Groningen; …oratory, Cornell University, Ithaca, NY 14853; [6]IUCF, Indiana University, Bloomington, IN 47408; [7]Department of Physics, Yale University, New Haven, CT 06520.

(Dated: July 10, 2004)

…w highly sensitive method of looking for electric dipole moments of charged particles in … rings is described. The major systematic errors inherent in the method are addressed and … minimize them are suggested. It seems possible to measure the muon EDM to levels that …eculative theories beyond the standard model

…and more in Speculative Spheres

Available online at www.sciencedirect.com
SCIENCE @ DIRECT
Physics Letters B 633 (2006) 319–324
PHYSICS LETTERS B
www.elsevier.com/locate/physletb

…apolation formulas for neutron EDM calculations in lattice QCD

Donal O'Connell [a,*], Martin J. Savage [b]

[a] Department of Physics, California Institute of Technology, Pasadena, CA 91125, USA
[b] Department of Physics, University of Washington, Seattle, WA 98195-1560, USA

Received 1 October 2005; accepted 19 November 2005
Available online 29 November 2005
Editor: H. Georgi

VOLUME 89, NUMBER 10 PHYSICAL REVIEW LETTERS 2 SEPTEMBER 2002

Electric Dipole Moments in the Limit of Heavy Superpartners

Oleg Lebedev and Maxim Pospelov
Centre for Theoretical Physics, University of Sussex, Brighton BN1 9QJ, United Kingdom
(Received 30 April 2002; published 15 August 2002)

Supersymmetric loop corrections induce potentially large CP-violating couplings of the Higgs bosons to nucleons and electrons that do not vanish in the limit of heavy superpartners. The Higgs-mediated CP-odd four-fermion operators are enhanced by $\tan^3\beta$ and induce electric dipole moments of heavy atoms which exceed the current experimental bounds for the electroweak scale Higgs masses and $\tan\beta \geq 10$. If only the first two sfermion generations are heavy, the Higgs-mediated contributions typically dominate over the Barr-Zee type two-loop diagrams at $\tan\beta > 30$.

DOI: 10.1103/PhysRevLett.89.101801 PACS numbers: 12.60.Jv, 11.30.Er, 13.40.Em

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Physics Letters B 624 (2005) 239–249
PHYSICS LETTERS B
www.elsevier.com/locate/physletb

Hadronic EDM constraints on orbifold GUTs

Junji Hisano, Mitsuru Kakizaki, Minoru Nagai
ICRR, University of Tokyo, Kashiwa 277-8582, Japan
Received 6 June 2005; received in revised form 17 July 2005; accepted 3 August 2005

VOLUME 84, NUMBER 24 PHYSICAL REVIEW LETTERS 12 …

VOLUME 84, NUMBER 24 PHYSICAL REVIEW LETTERS 12 JUNE 2000

Erratum: Electric Dipole Moments and the Mass Scale of New T-Violating, P-Conserving Interactions [Phys. Rev. Lett. 83, 3997 (1999)]

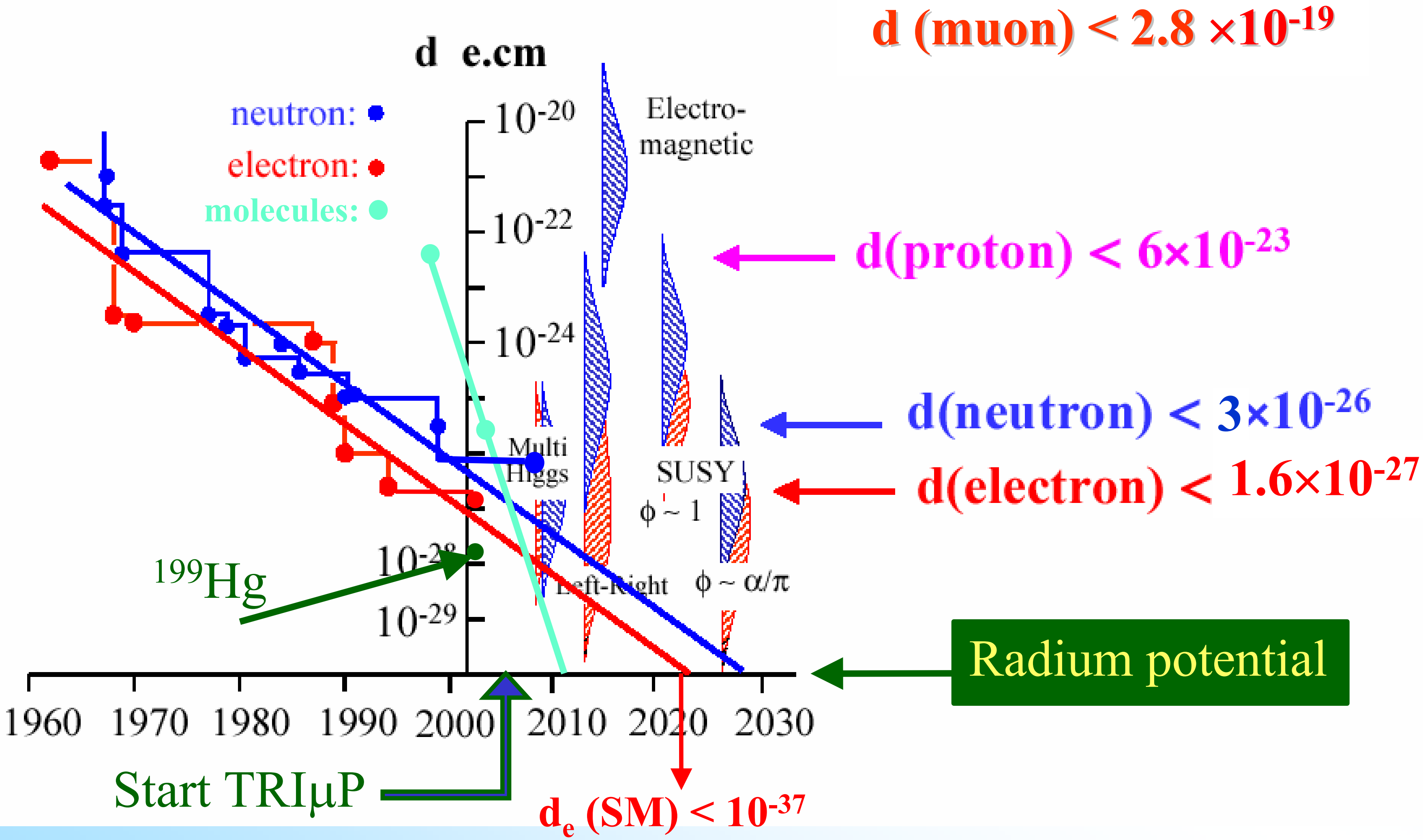
M. J. Ramsey-Musolf

…cale

In the text following Eq. (10), the expression for the integral in Eq. (10) should read $(1/4)[2 + 6g_A/5] \approx 0.88$.

4)$[2 + 6g_A/5] \approx 0.88$.

Some EDM Experiments compared



after E.Hinds

EDM Limits as of summer 2006

Particle	Exp. Limit [10^{-27} *e* cm]	SM [factor to go]	Possible New Physics [factor to go]
e (Tl)	< 1.6	10^{11}	≤ 1
μ	< 1.05 *10^{9}	10^{8}	≤ 200
τ	< 3.1 * 10^{11}	10^{7}	≤ 1700
n	< 29	10^{4}	≤ 30
Tl (odd p)	< 10^{5}	10^{7}	≤ 10^{5}
Hg (odd n)	< 0.21	10^{5}	various

- Why so many ?

- Which is THE BEST candidate to choose ?

None is THE BEST - We need many experiments!

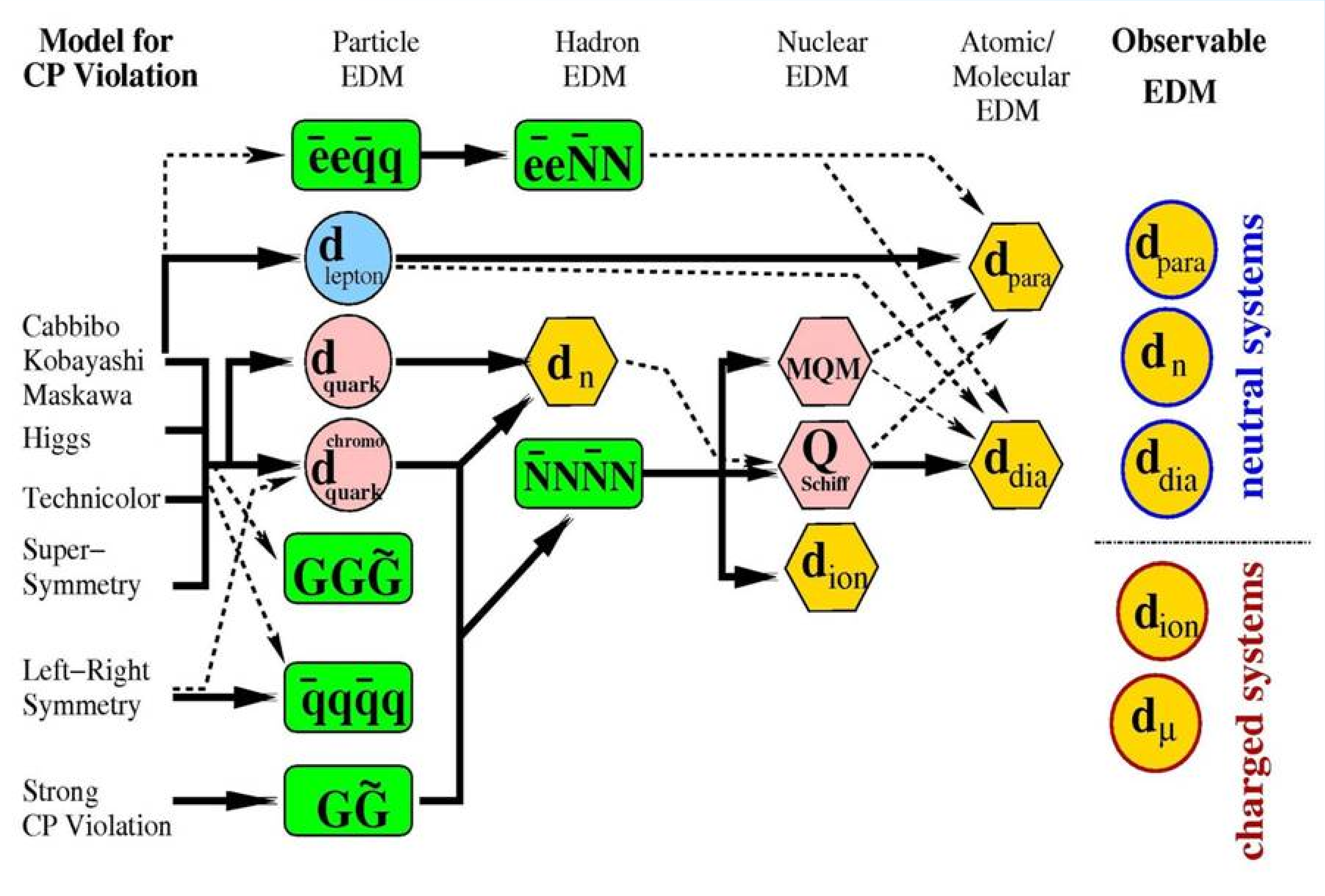
EDMs – Where do they come from ?

(are they just "painted" to particles? Why different experiments?)

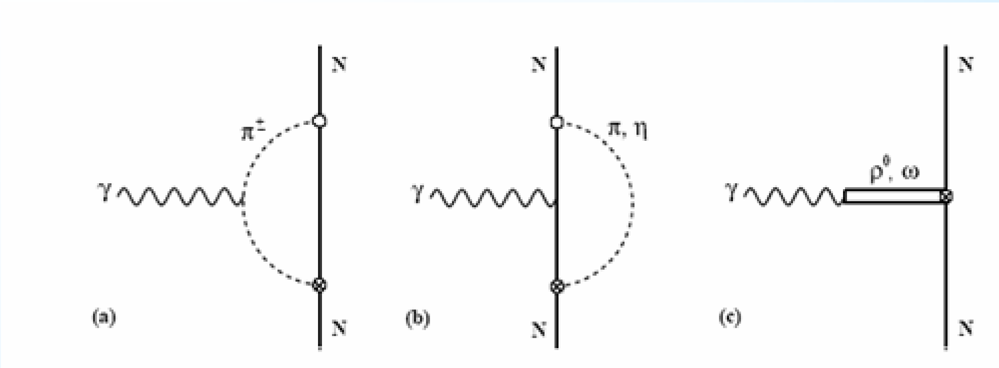
▪ electron	intrinsic ?
▪ quark	intrinsic ?
▪ muon	second generation different ?
▪ neutron/ proton	from quark EDM ? property of strong interactions ? new interactions ?
▪ deuteron	basic nuclear forces CP violating?
	pion exchange ?
▪ ^{6}Li	many body nuclear mechanism ?
▪ heavy nuclei (e.g. Ra, Fr)	enhancement by CP-odd nuclear forces,
	nuclear "shape"
▪ atoms	can have large enhancement, sensitive to electron or nucleus EDMs
▪ molecules	large enhancement factors , sensitive to electron EDM
▪ . . .	

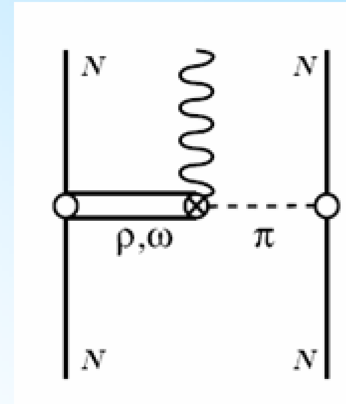
TRIμP

Possible Sources of EDMs



Why a deuteron edm experiment





Deuteron: $$d_{\mathcal{D}} = -4.67\, d_d^c + 5.22\, d_u^c$$

Neutron: $$d_n = -0.01\, d_d^c + 0.49\, d_u^c$$

" Thus, these two EDM measurements probe different linear combinations of d_d^c and d_u^c in this case. Moreover, the deuteron could be significantly more sensitive than the neutron. "

C.P. Liu and R.G.E Timmermans, **Phys.Rev.C 70, 055501 (2004)**

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 : $\vec{\omega}_e = \frac{\vec{d}\bullet\vec{E}}{\hbar}\, \frac{\vec{E}\times\vec{J}}{|\vec{E}\times\vec{J}|}$

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

ω_e = **15.2 mHz**

Generic EDM Experiment Sensitivity

P	*Polarization*	~1
ε	*Efficiency*	~1
N	*Flux of particles [1/s]*	
T	*Measurements Time [s]*	
τ	*Spin Coheren...*	1 s
E	*Ele...*	10^5 V/cm

$$\delta d = \frac{\hbar}{P \varepsilon T \sqrt{N * \tau} \; E}$$

Ω 7*10^{-29} *e cm*

Need to understand systematics

⇒ Work on

- high Polarization , high Field
- high Efficiency
- long Coherence Time

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

Lines of attack towards an EDM

Free Particles

neutron
muon
deuteron
bare nuclei ?
…

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

Atoms

Hg Xe
Tl
Cs Rb
Ra Rn
…

→ nuclear EDM
→ electron EDM
→ enhancements
→ challenging technology

Electric Dipole Moment

goal:
new source of ~~CP~~

Molecules

YbF
PbO
PbF
HfF^+, ThF^+
…

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

Solid State

garnets
($Gd_3Ga_5O_{12}$)
($Gd_3Fe_2Fe_3O_{12}$)
lq. He ?

→ electron EDM
→ strong enhancements
→ systematics ??

New Experimental Approaches

- Molecules
  - strong Enhancement through internal fields
  - YbF, PbO
- Radioactive Atoms
  - fortunate atomic level scheme in Radium
  - nuclear enhancement through deformations
- Charged particles
  - Schiff Theorem circumvented in non-trivial geometry
  - novel idea to exploit motional electric fields in storage rings
  - muon, nuclei, deuteron, molecules (ThF^+)
- Condensed matter
  - alkali atoms in solid He
  - neutrons in superfluid He
  - magnetization in paramagnetic material
  - liquid Xe
- Atoms using novel ideas
  - Xe with "nuclear maser"
  - Rb, Cs in optical lattices

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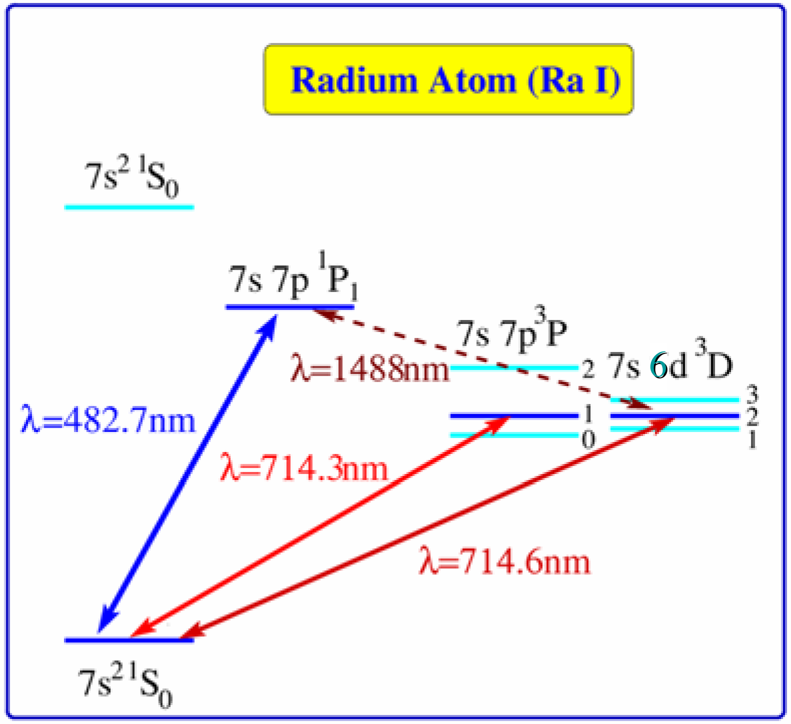
Discrete Symmetries

Permanent
Electric Dipole Moments

Radium Atom

Radium Permanent Electric Dipole Moment



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

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

For ^{225}Ra, we get

$$\langle S_z \rangle_{\mathrm{Ra}} = -1.90\ g\bar{g}_0\ + 6.31\ g\bar{g}_1\ - 3.80\ g\bar{g}_2\ \ (\mathrm{e\ fm}^3)$$

The best calculation in ^{199}Hg (RPA polarization of a spherical even-even core) by Dmitriev and Sen'kov gives

$$\langle S_z \rangle_{\mathrm{Hg}} = 0.0004\ g\bar{g}_0\ + 0.055\ g\bar{g}_1\ + 0.009\ g\bar{g}_2\ \ (\mathrm{e\ fm}^3)$$

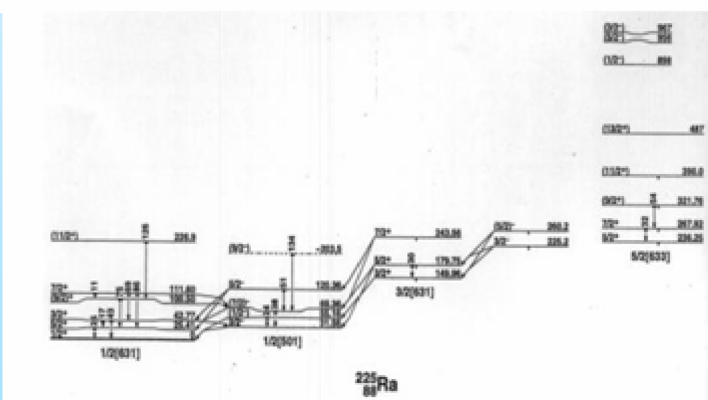
If the three $\bar{g}$'s are comparable, the Schiff moment in Ra is larger by over 100, on average.

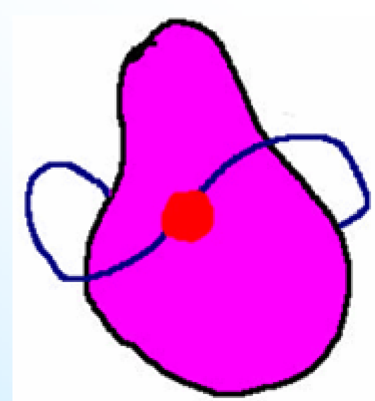
Dzuba et al. [PRA66, 012111 (2002)] find further enhancement of the Ra EDM by a factor of 3 in the atomic physics.

Looks good for the Ra experiment!

Skip to end

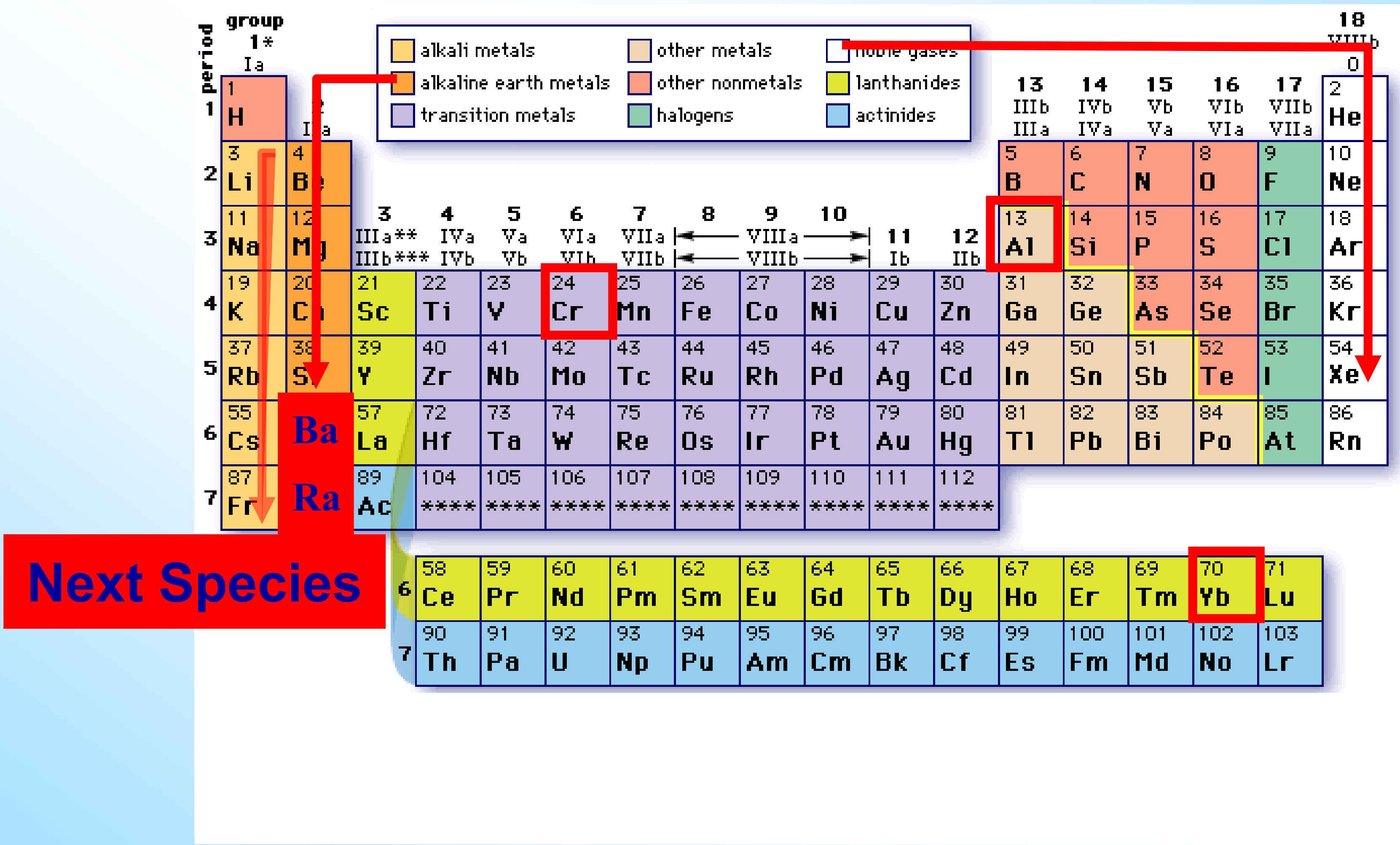
ENAM'04



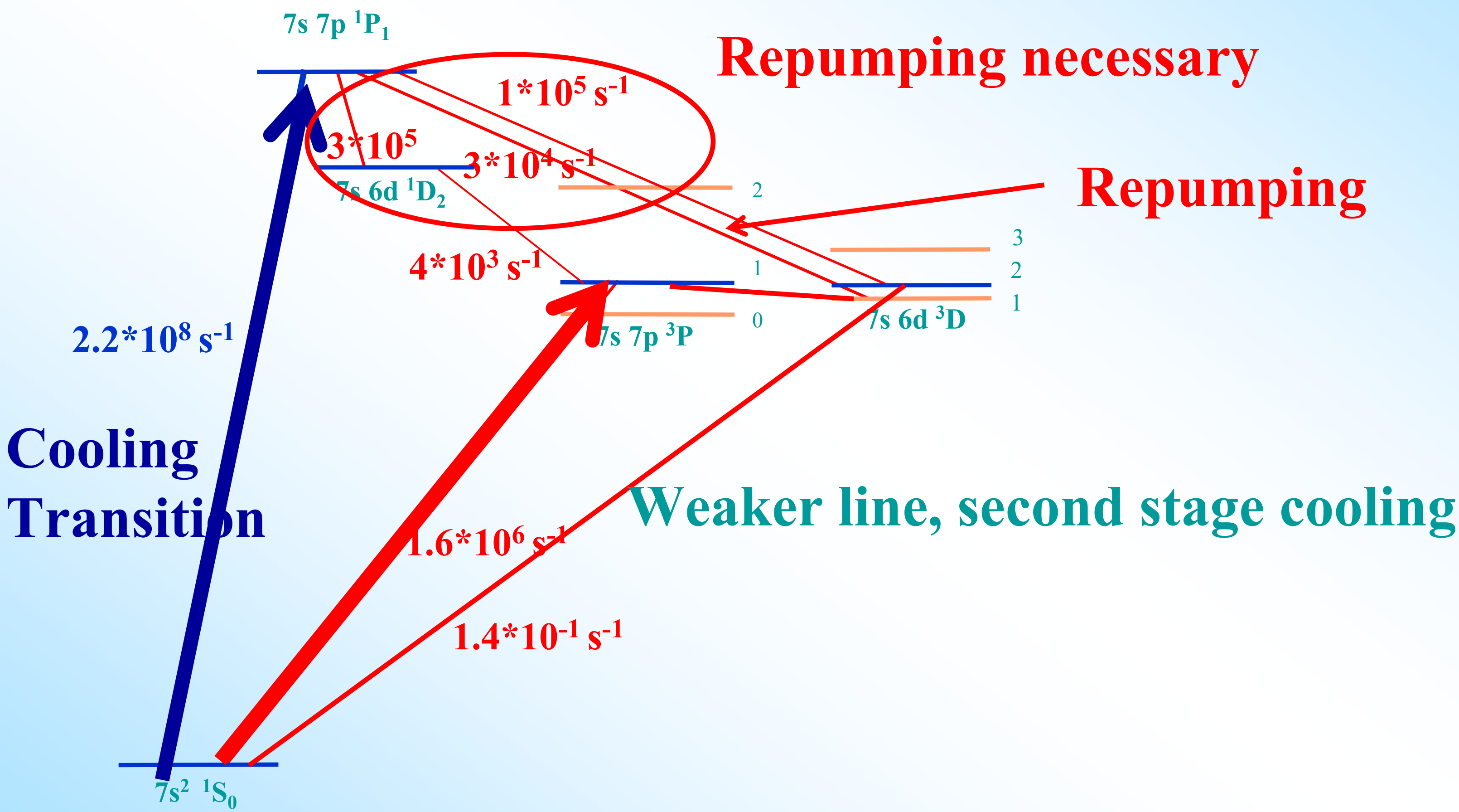


from: J. Engel

Laser Cooling Chart



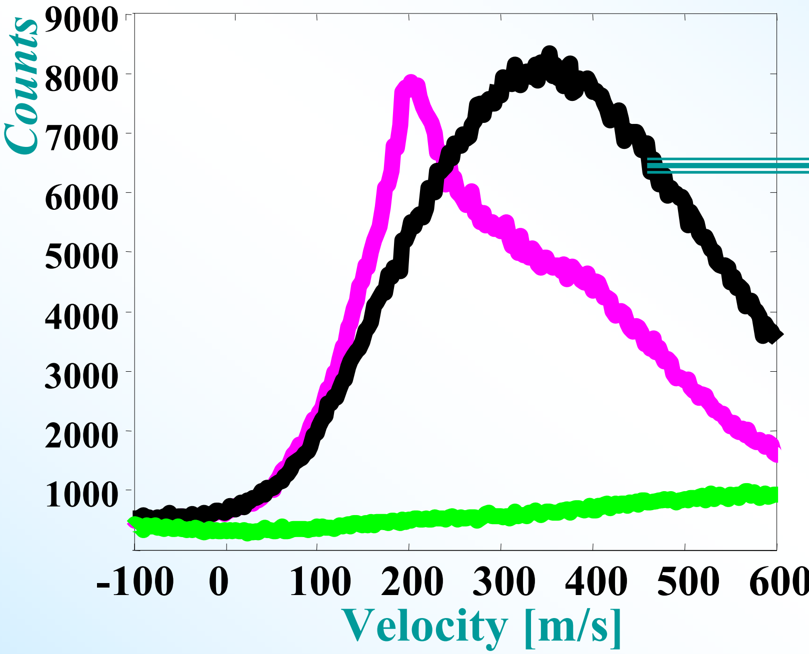
Colloing & Trapping of Heavy Alkali Earth: Ra



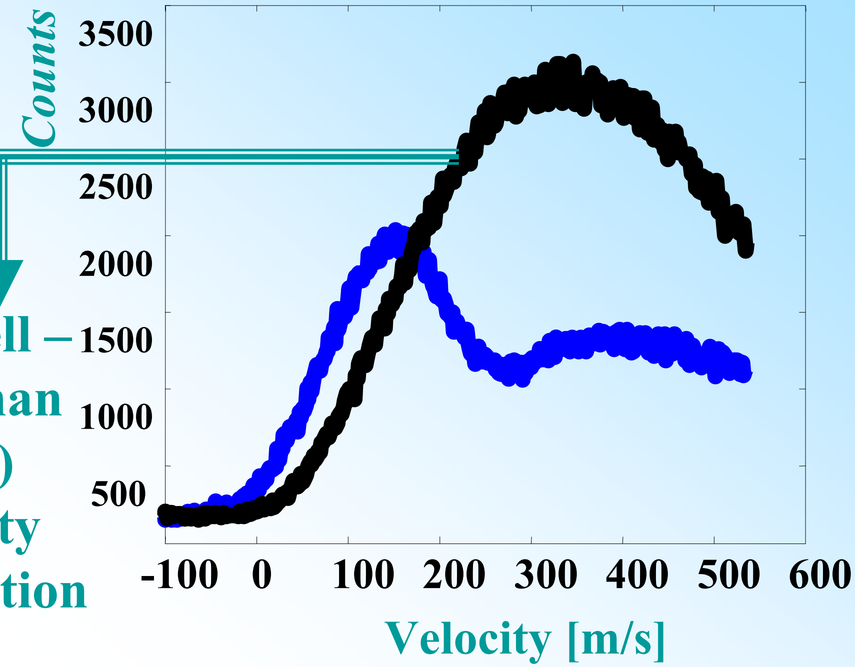
Preliminary Transition Rates as calculated by K. Pachucky (also by V. Dzuba et al.)

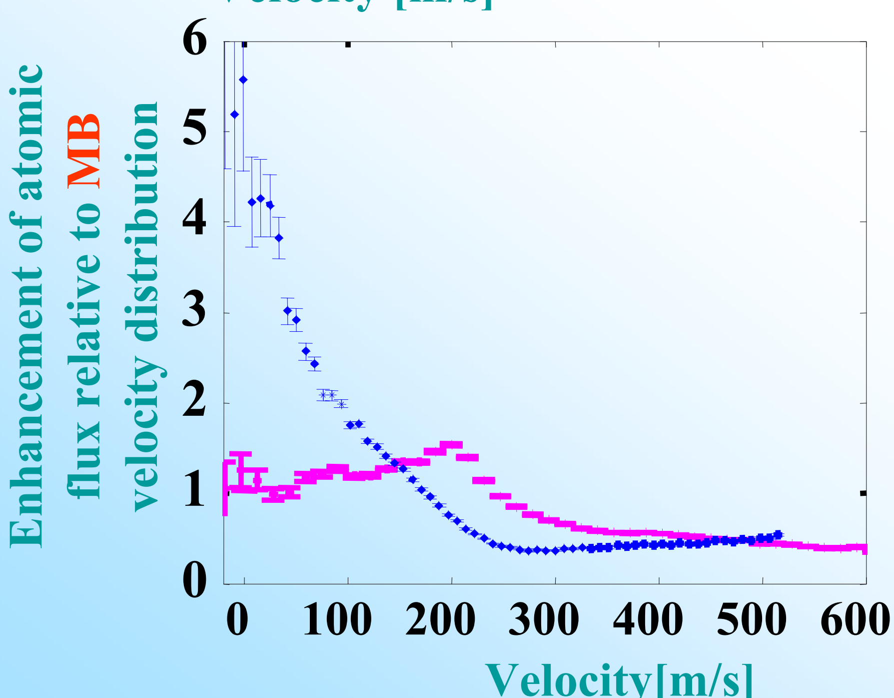
L. Willmann

First time Laser Cooling of Barium



Maxwell – Boltzman (MB) velocity distribution





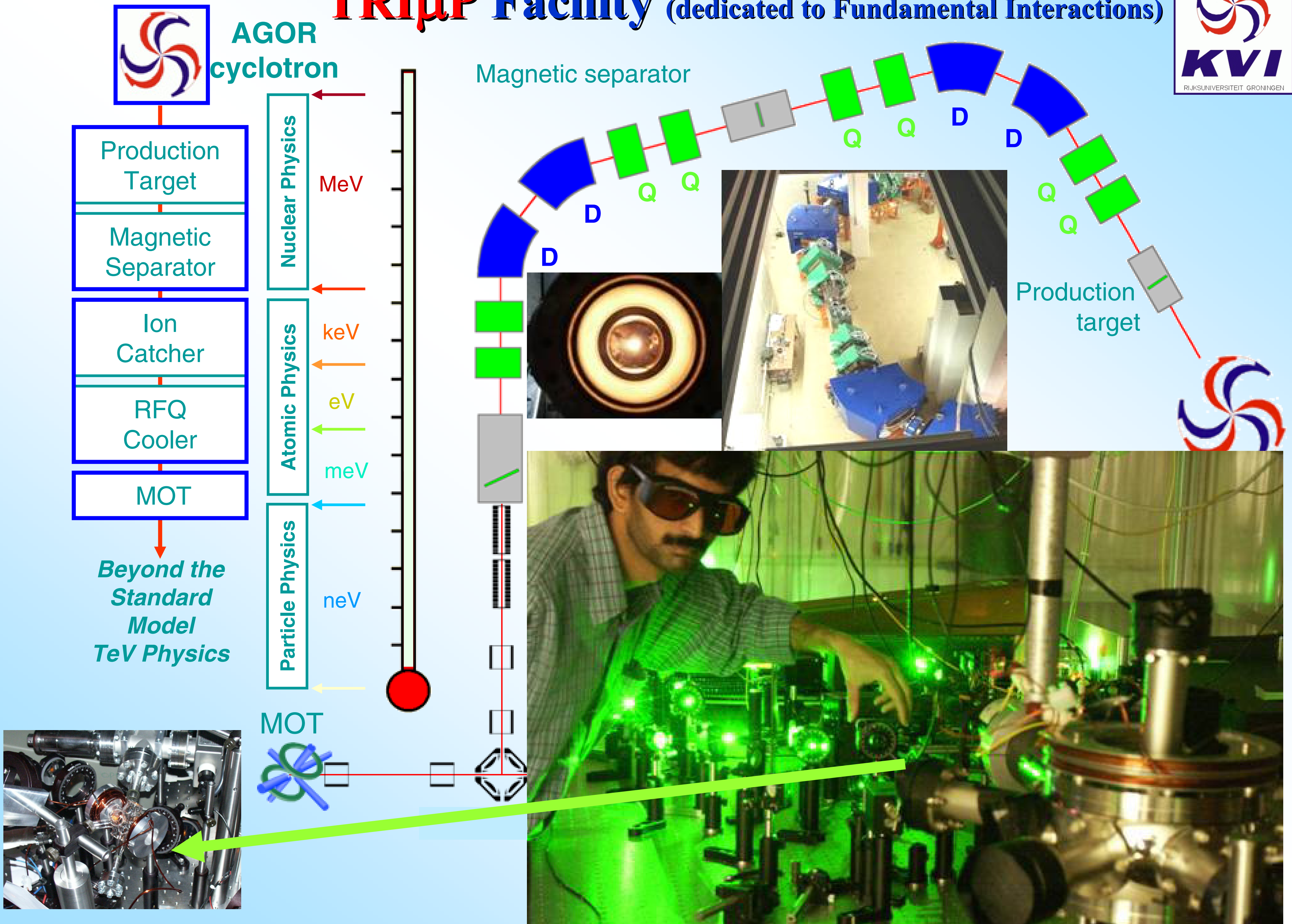
- Fluorescence increase with cooling laser and repumpers

  → IR tuned to 200 m/s velocity class

  → IR tuned to 40 m/s velocity class

L. Willmann et al.

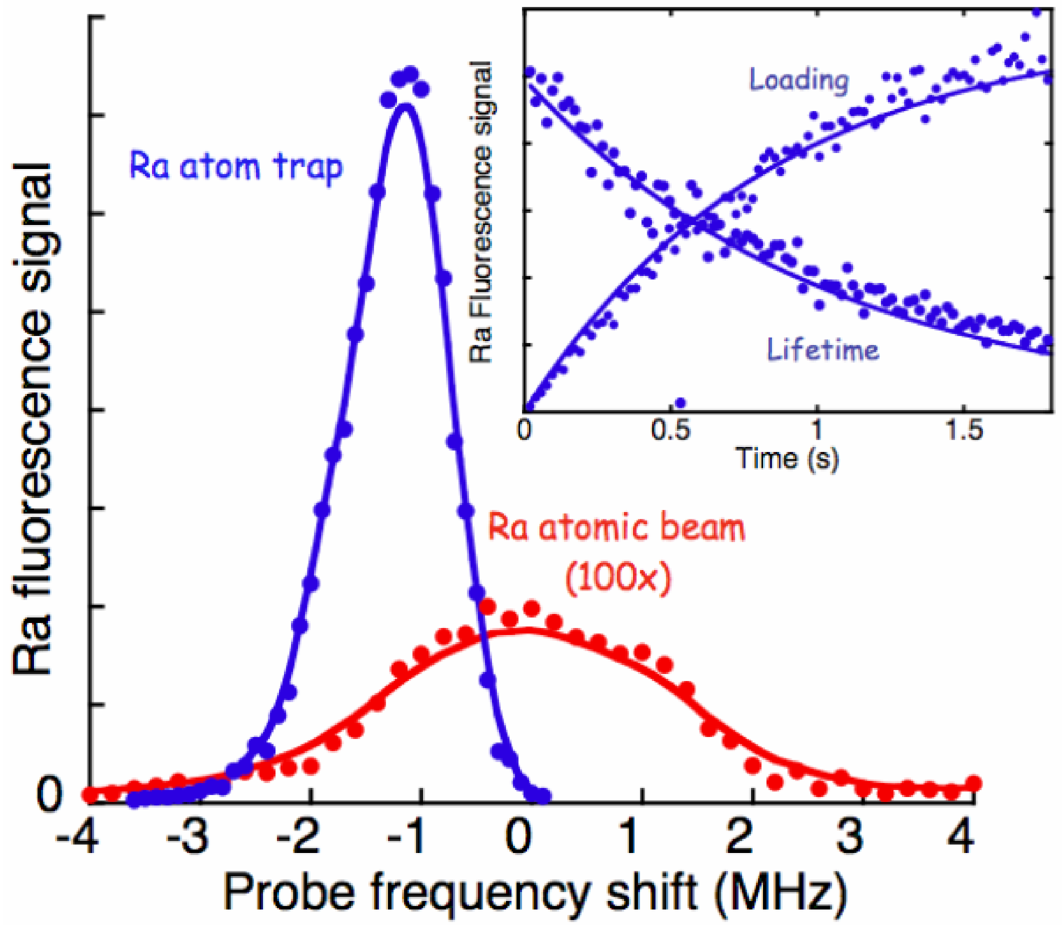
TRIμP Facility (dedicated to Fundamental Interactions)



Radium slower and trap

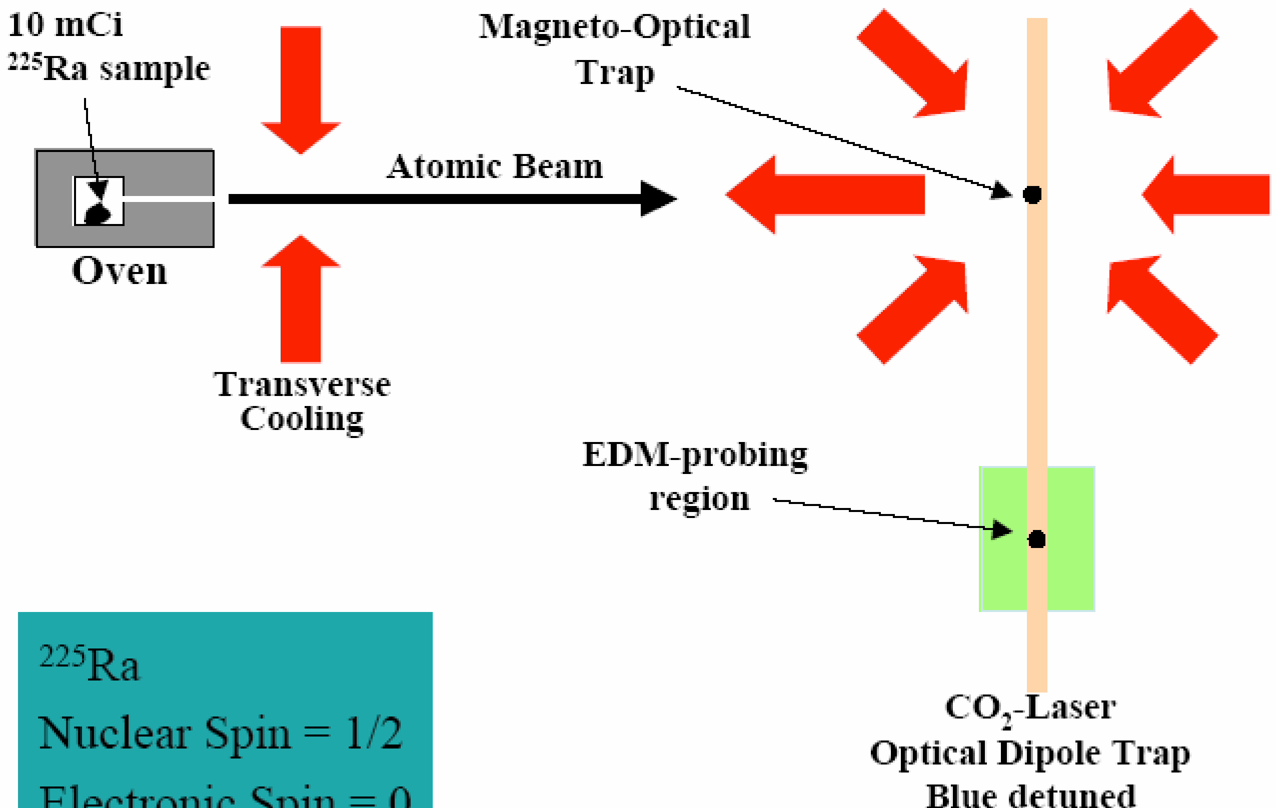
Laser-Trapping of Radium Atoms

- World's first laser trap of radium atoms: both ^{225}Ra and ^{226}Ra atoms are cooled and trapped!
- Key ^{225}Ra frequencies, lifetimes measured.



Search for a Nuclear EDM with Trapped Radium Atoms

Irshad Ahmad, Roy J. Holt, Zheng-Tian Lu, Elaine C. Schulte
Physics Division, Argonne National Laboratory



^{225}Ra

Nuclear Spin = 1/2

Electronic Spin = 0

$t_{1/2}$ = 15 days

from R. Holt, Argonne

New Experimental Approaches

- Molecules
  - strong Enhancement through internal fields
  - YbF, PbO
- Radioactive Atoms
  - fortunate atomic level scheme in Radium
  - nuclear enhancement through deformations
- **Charged particles**
  - **Schiff Theorem circumvented in non-trivial geometry**
  - **novel idea to exploit motional electric fields in storage rings**
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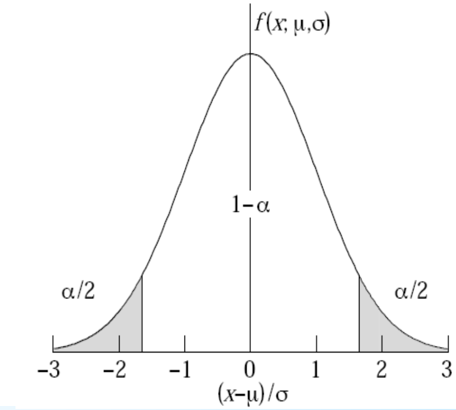
  - Xe with "nuclear maser"
  - Rb, Cs in optical lattices

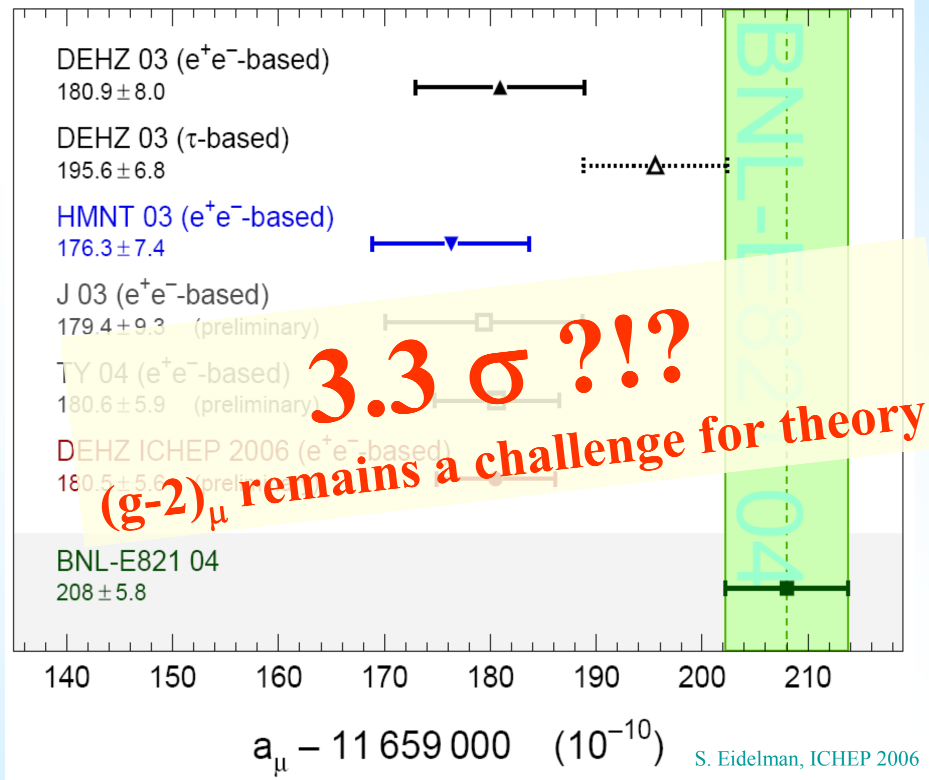
The Muon Magnetic Anomaly

Spin precession in (electro-) magnetic field

$$\vec{\omega} = \frac{e}{m}\left[a_\mu \vec{B}\right]$$

α	δ
0.3173	1σ
4.55×10^{-2}	2σ
2.7×10^{-3}	3σ
6.3×10^{-5}	4σ
5.7×10^{-7}	5σ
2.0×10^{-9}	6σ





S. Eidelman, ICHEP 2006

3.3 σ ?!?

$(g\text{-}2)_\mu$ remains a challenge for theory

Magnetic and Electric Dipole Moment are Real and Imaginary part of a more general Dipole Moment

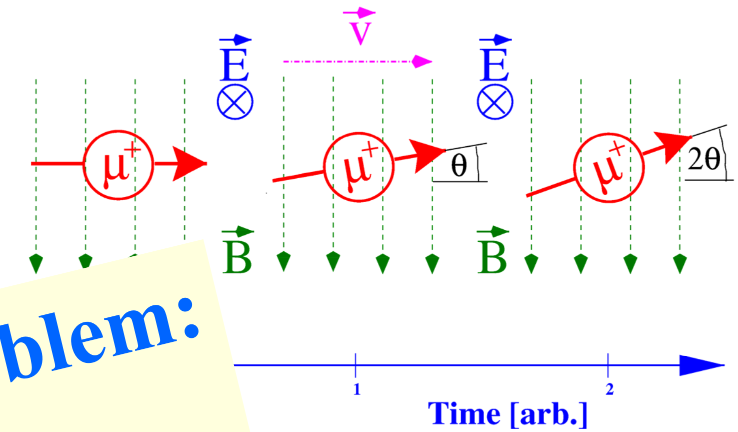
$$\mathcal{L}_{\rm DM} = \frac{1}{2}\left[D\bar{\mu}\sigma^{\alpha\beta}\frac{1+\gamma_5}{2} + D^*\bar{\mu}\sigma^{\alpha\beta}\frac{1-\gamma_5}{2}\right]\mu\, F_{\alpha\beta}$$

$$\sigma^{\alpha\beta} = \tfrac{1}{2}\left[\gamma^\alpha, \gamma^\beta\right]$$

$$\begin{aligned} a_\mu \frac{e}{2m_\mu} &= \Re D \\ d_\mu &= \Im D \end{aligned}$$

$$d_\mu^{NP} = 3 \cdot 10^{-22} \cdot \left(\frac{a_\mu^{NP}}{3 \cdot 10^{-9}}\right) \cdot \tan\phi_{CP}\ e\ cm$$

The Muon Electric Dipole Moment

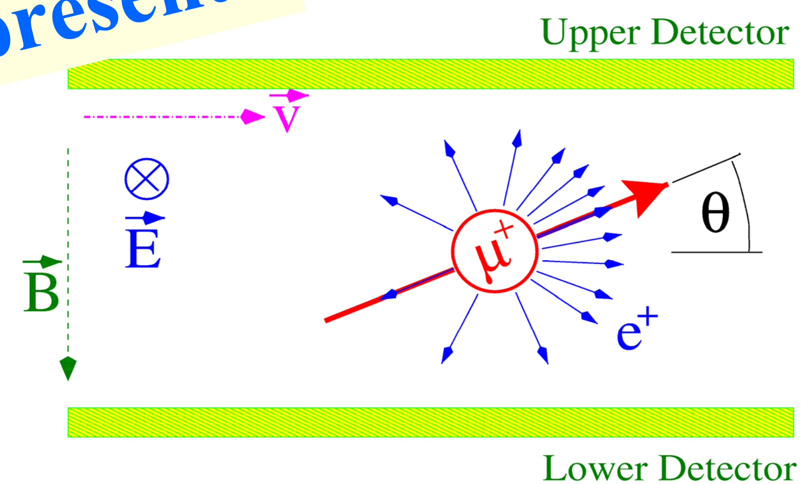


One Serious Problem:
N_μ
available at present

Spin precession in (electro-) magnetic field

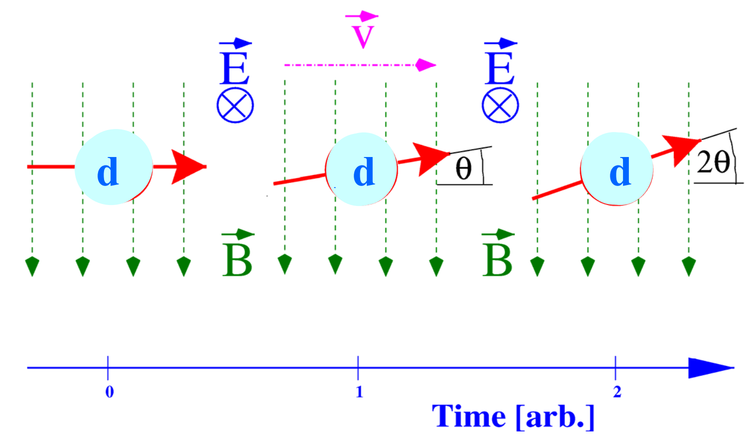
$$\vec{\omega} = \frac{e}{m}\left[\mathbf{a}_\mu \vec{\mathbf{B}} - \left(\mathbf{a}_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta} \times \vec{\mathbf{E}}}{\mathbf{c}}\right]$$

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



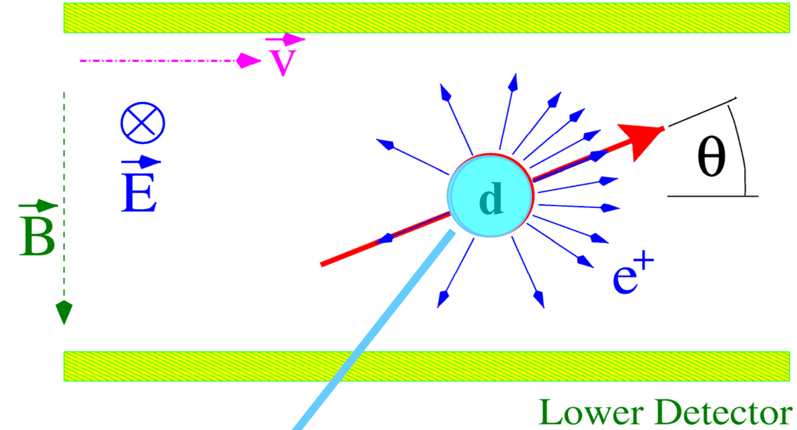
(radial E-field to freeze spin)

The Muon Electric Dipole Moment



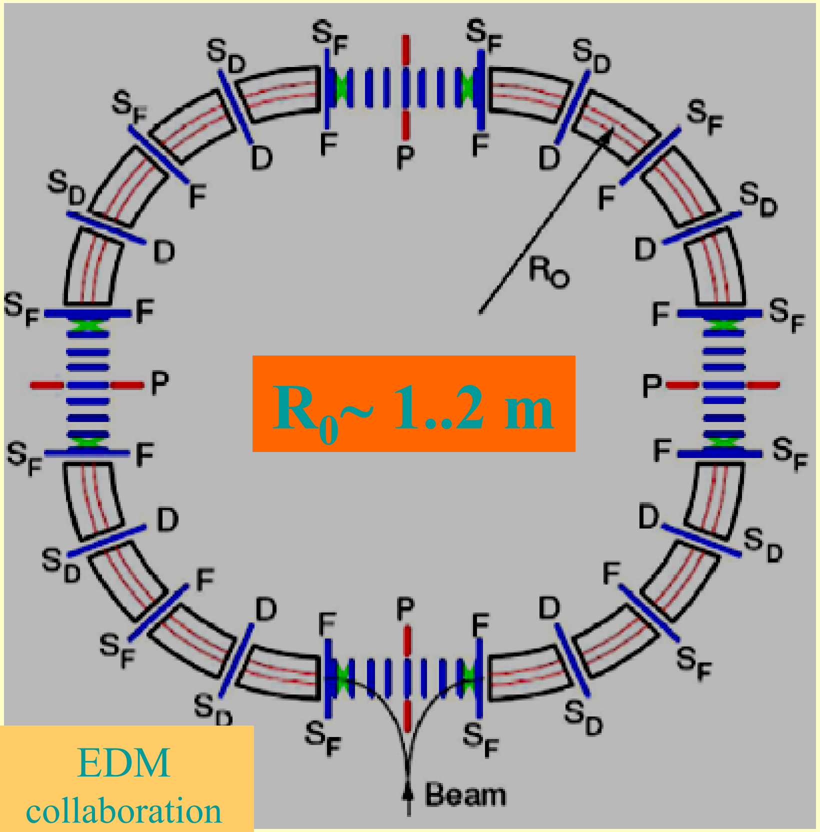
Spin precession
in (electro-)
magnetic field

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



Deuteron is stable:
Different polarimeter needed

Searches for EDMs in charged particles:
Novel Method invented
Motional Electric Fields exploited



EDM collaboration

International Collaboration
(USA, Russia, Japan, Italy, Germany, NL, …)

- **possible sites discussed: BNL, KVI, Frascati, …**
- **Limit $d_D < 10^{-27} \ldots 10^{-29}$ e cm**
- **Can be >10 times more sensitive than neutron d_n, best test for Θ_{QCD}, …**

Various technical realizations being discussed.

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

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

Discrete Symmetries

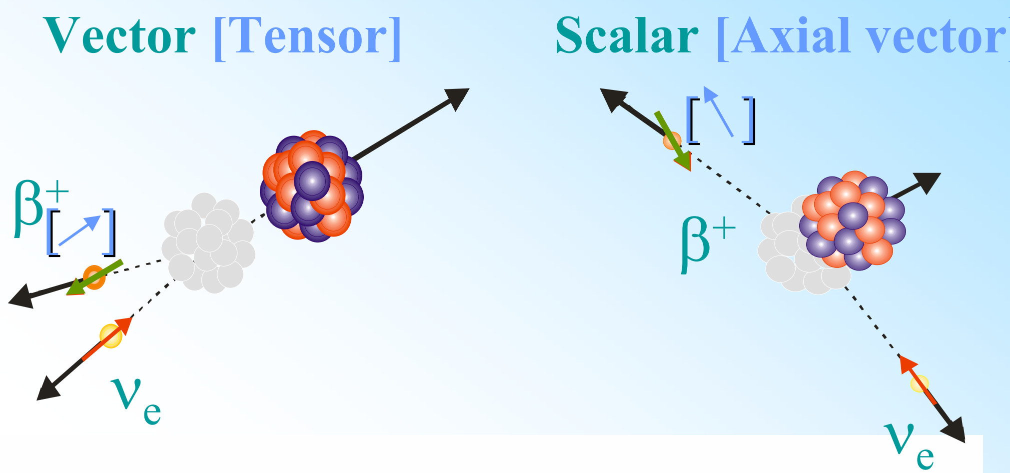
- Parity
  - Parity Nonconservation in Atoms
  - Nuclear Anapole Moments
  - Parity Violation in Electron-Scattering
- Time Reversal and CP-Violation
  - Electric Dipole Moments
  - R and D Coefficients in β-Decay
- CPT Invariance

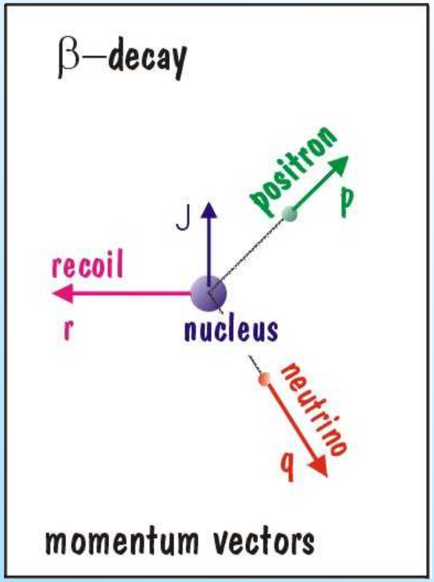
TRIμP

New Interactions in Nuclear β-Decay

In Standard Model: Weak Interaction is V-A

In general β-decay could be also S , P, T





$$\frac{d^2W}{d\Omega_e d\Omega_\nu} \sim 1 + a\frac{\boldsymbol{p}\cdot\hat{\boldsymbol{q}}}{E} + b\Gamma\frac{m_e}{E} + \langle\boldsymbol{J}\rangle\cdot\left[A\frac{\boldsymbol{p}}{E} + B\,\hat{\boldsymbol{q}} + D\frac{\boldsymbol{p}\times\hat{\boldsymbol{q}}}{E}\right] + \langle\boldsymbol{\sigma}\rangle\cdot\left[G\frac{\boldsymbol{p}}{E} + Q\,\langle\boldsymbol{J}\rangle + R\,\langle\boldsymbol{J}\rangle\times\frac{\boldsymbol{p}}{E}\right]$$

- ***R*** and ***D*** test both **T**ime **R**eversal **V**iolation
  - ***D*** → most potential
  - ***R*** → scalar and tensor (EDM, *a*)
  - technique *D* measurements yield *a, A, b, B*

TRIμP

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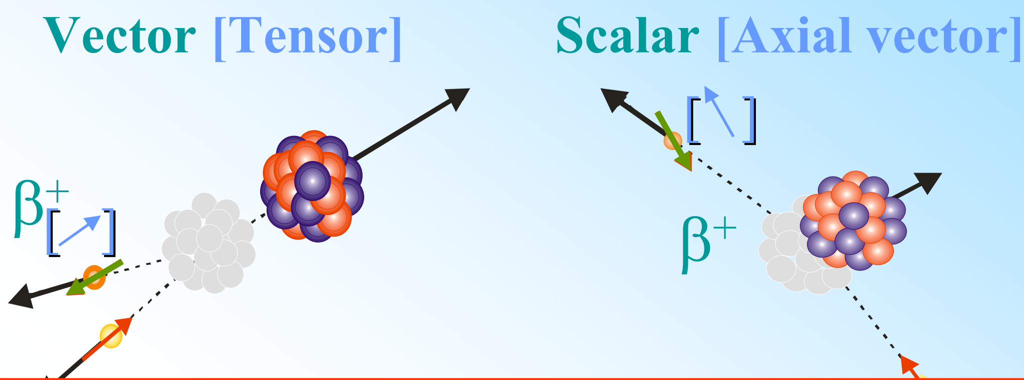
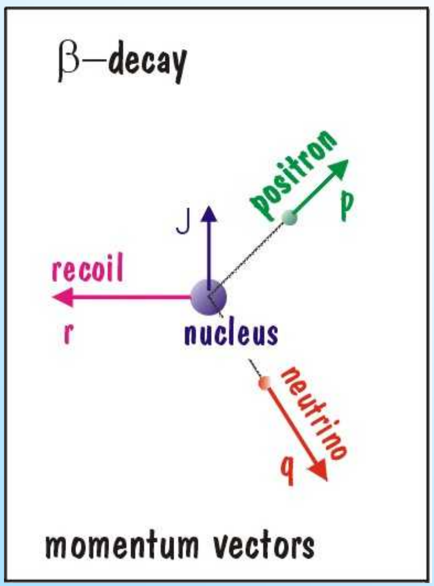
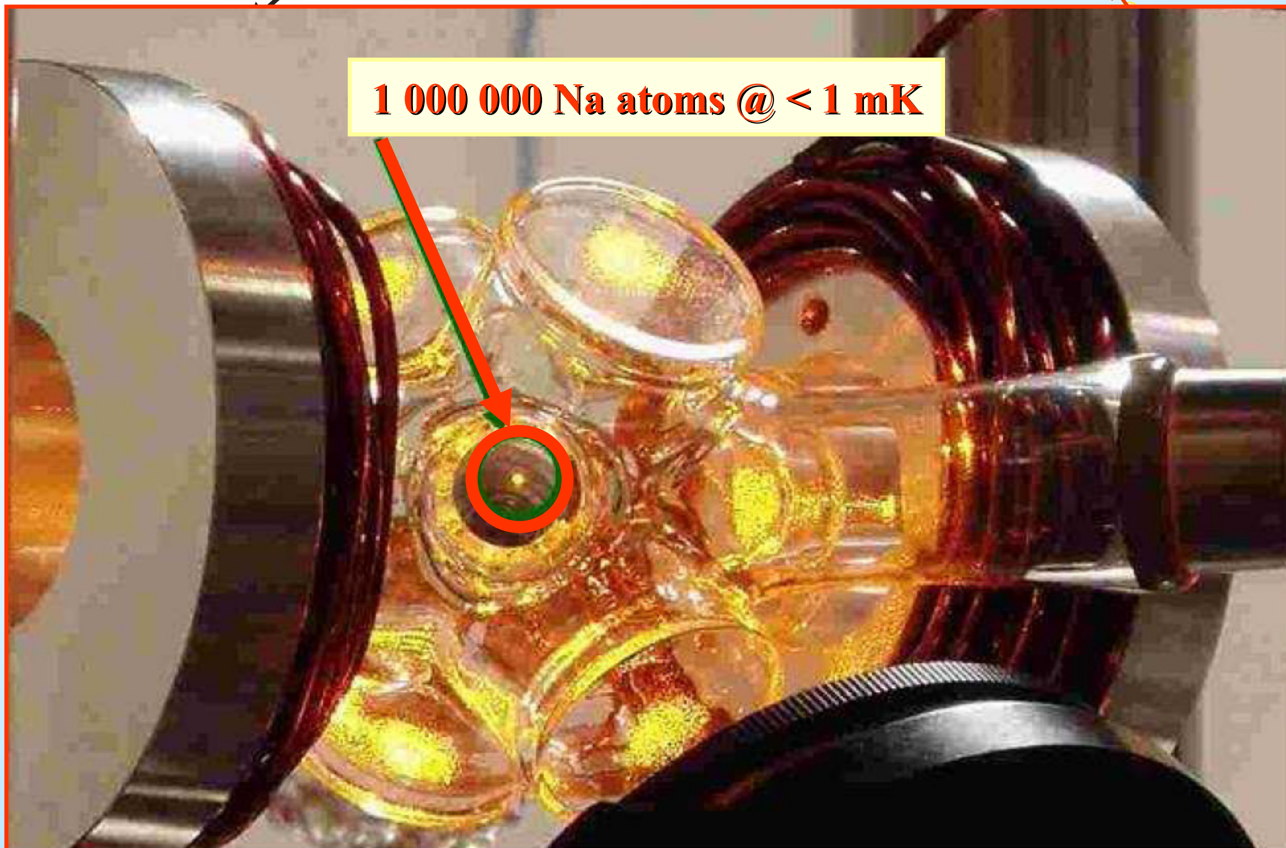
In Standard Model:
Weak Interaction is
V-A

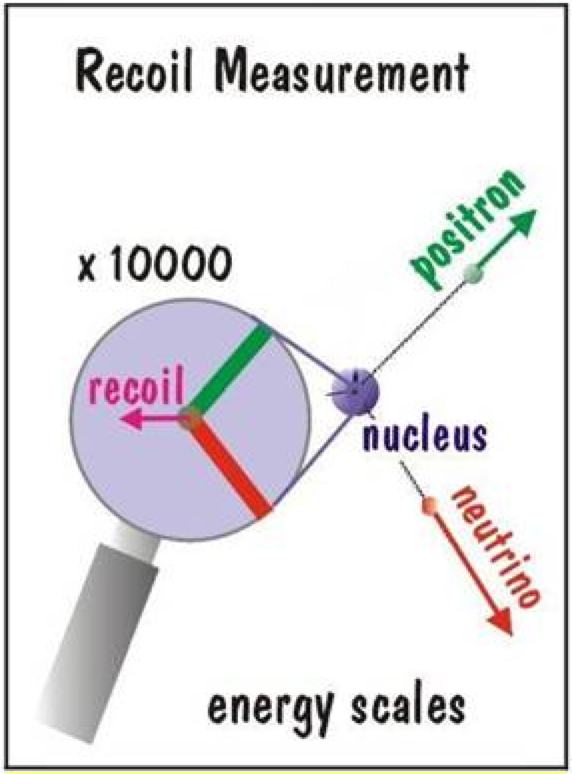
In general β-decay
could be also
S , P, T



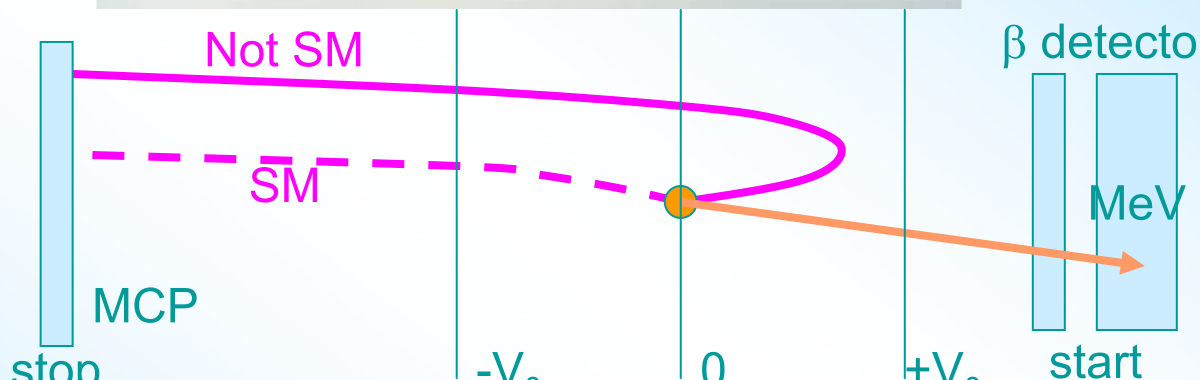




Princip



$$E_{recoil} = \frac{(\vec{p} + \vec{q})^2}{2M_{recoil}} < 230 \text{ eV}$$



$$\frac{d^2W}{d\Omega_e d\Omega_\nu} \sim 1 + a\frac{p \cdot \hat{q}}{E} + b\Gamma\frac{m_e}{E}$$

TOF → $E_{//}$

X,Y → $E_{\perp}$

Discrete Symmetries

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  - Parity Nonconservation in Atoms
  - Nuclear Anapole Moments
  - Parity Violation in Electron-Scattering
- Time Reversal and CP-Violation
  - Electric Dipole Moments
  - R and D Coefficients in β-Decay
- **CPT Invariance**

Discrete Symmetries

CPT

- Lorentz Invariance, preferred reference frame
- Particle – Antiparticle properties
- Spin
- Fermions and Bosons only
- ….

CPT – Violation
Lorentz Invariance Violation

CPT tests

$$r_K = \frac{|m_{K^0} - m_{\overline{K}^0}|}{m_{K^0}} \le 10^{-18}$$

$$r_e = \frac{|g_{e^-} - g_{e^+}|}{g_{avg}} = 1.2 \cdot 10^{-3} \cdot \frac{|a_{e^-} - a_{e^+}|}{a_{avg}} \le 2 \cdot 10^{-12}$$

? Are they comparable - Which one is appropriate ?

$\Rightarrow$ Use common ground, e.g. energies

generic CPT and Lorentz violating DIRAC equation

$$(i\gamma^\mu D_\mu - m - a_\mu \gamma^\mu - b_\mu \gamma_5 \gamma^\mu - \frac{1}{2} H_{\mu\nu} \sigma^{\mu\nu} + i c_{\mu\nu} \gamma^\mu D^\nu + i d_{\mu\nu} \gamma_5 \gamma^\mu D^\nu)\psi = 0$$

$$iD_\mu \equiv i\partial_\mu - qA_\mu$$

a_μ, b_μ break CPT

$a_\mu, b_\mu, c_{\mu\nu}, d_{\mu\nu}, H_{\mu\nu}$ break Lorentz Invar.

What is best CPT test ?

often quoted:

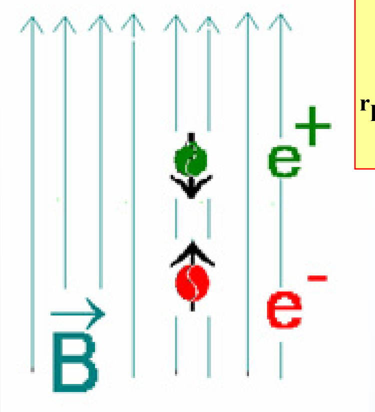
- K^0- $\overline{K^0}$ mass difference (10^{-18})
- e^- - e^+ g- factors $(2 * 10^{-12})$

- **We need an interaction with a finite strength !**

New Ansatz (Kostelecky)

- K $\approx 10^{-21}$ GeV
- n $\approx 10^{-30}$ GeV
- p $\approx 10^{-24}$ GeV
- e $\approx 10^{-27}$ GeV
- μ $\approx 10^{-23}$ GeV
- Future: Anti hydrogen $\approx 10^{-??}$ GeV

Leptons in External Magnetic Field



$$\Delta\omega_a = \omega_a^{l^-} - \omega_a^{l^+} \approx -4b_3^l$$

$$r_l = \frac{|E^{l^-}_{spin\ up} - E^{l^+}_{spin\ down}|}{E^{l^-}_{spin\ up}} \approx \frac{\eta\Delta\omega_a}{m_l c^2}$$

Bluhm , Kostelecky, Russell, Phys. Rev. D **57**,3932 (1998)

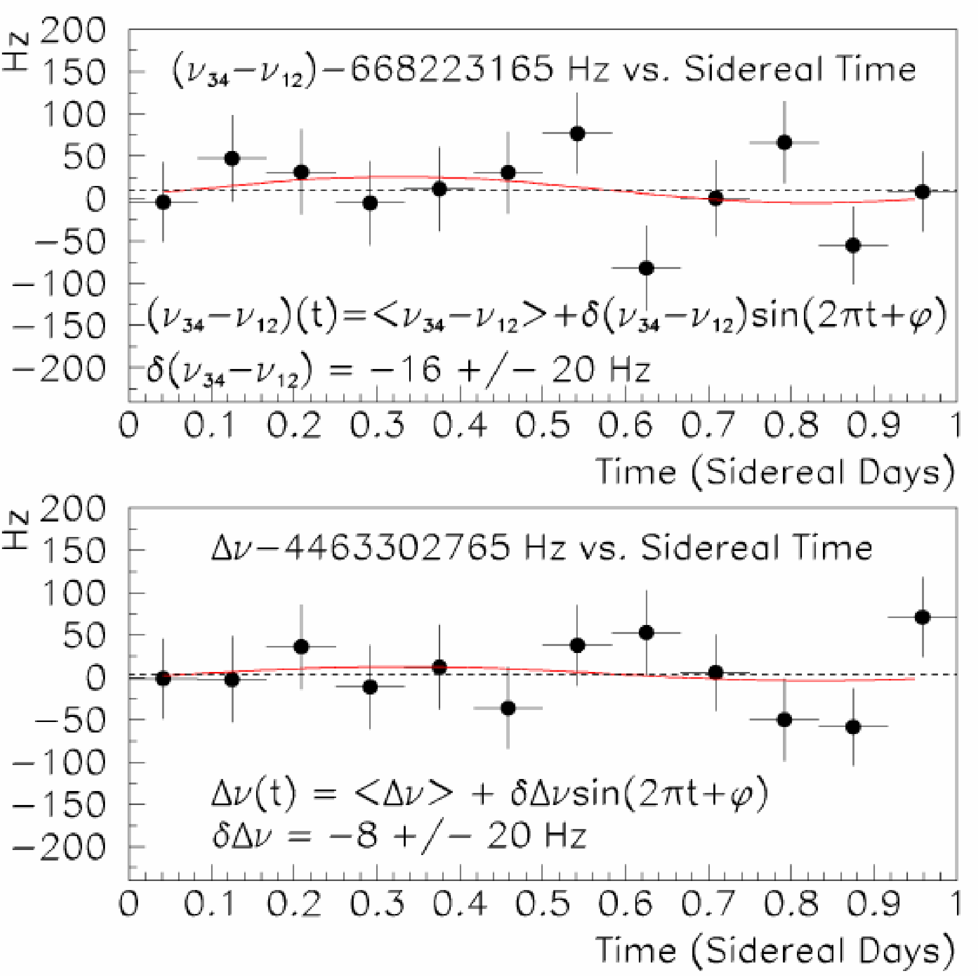
For g-2 Experiments :

$$r_l = \frac{\eta\omega_c}{m_l c^2} \cdot \frac{|a_{l^-} - a_{l^+}|}{a_{avg}}$$

Dehmelt, Mittleman, Van Dyck, Schwinberg, Phys.Rev.Lett. **83**, 4694 (1999)

$\Rightarrow$ *electron:* $r_e \le 1.2 \cdot 10^{-21}$ *muon:* $r_\mu \le 3.5 \cdot 10^{-24}$

CPT and Lorentz Invariance from Muon Experiments



V.W. Hughes et al., Phys.Rev. Lett. 87, 111804 (2001)

Muonium:

new interaction below

$2 * 10^{-23}$ GeV

Muon g-2:

new interaction below

$3 * 10^{-22}$ GeV (CERN&BNL combined)

order of magnitude better expected from BNL when analysis will be completed

(2006)

Discrete Symmetries

Summing up

EDM Searches

Many objects need to be tested

→ need "e∗cm free" guidance by theory

- Systems under observation:
  - ''point" particles — e, μ, τ
  - nucleons — n, p
  - Nuclei — ^{2}H, ^{223}Fr, …
  - Atoms — Xe, Tl, Cs, Hg, Rn, Ra, …
  - Molecules — PbO, YbF, TlF, ThF^{+}, …
- Methods
  - Classical (Cells, Atomic & Molecular Beams)
  - Modern (Traps, Fountains, Interferences)
  - Innovative (Radioactive Species, Storage Rings, {Particles} in Condensed Matter, "masers", …)

There are many promising approaches to the questions:

- **Is there any EDM?**
- **And what is the Source for an EDM?**

Conclusions

- Large number of Possibilities
  - Find Physics beyond Standard Theory
  - EDM searches offer a particular nice way at low energies
  - HE CP-violation searches and LE T-violation searches complementary
- Urgent issues to be solved in Theory and Experiment
  - Spectroscopic Groundwork
  - Schiff Moments
  - Relation to other approaches towards T-violation
- We need NOT one EDM experiment – BUT MANY
- Novel Approaches promise Significant Progress towards
  - finding New Physics
  - limiting Parameters in Speculative Models

Let's just do it √

Thank YOU !