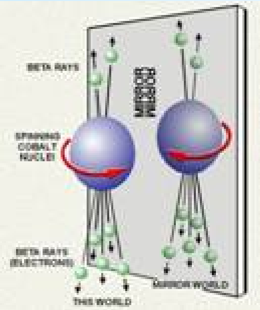
PAUL SCHERRER INSTITUT PSI

Workshop on Precision Measurements at Low Energy

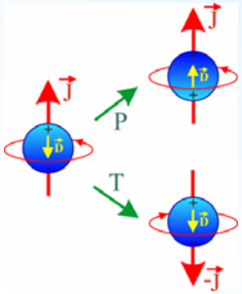
Villigen, 18-19 January 2007

Research on Discrete Symmetries with Stable and Radioactive Isotopes

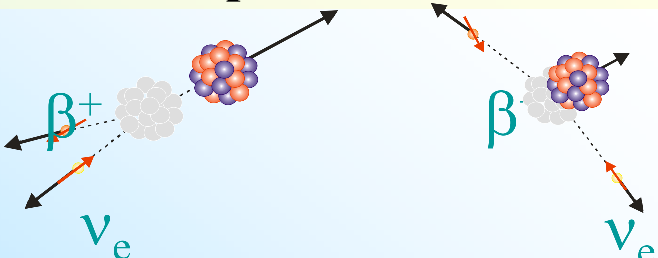


- **Symmetries and Forces**
  - **Properties of Known Forces**
  - **Properties of Fundamental Fermions**
  - **Searches for New Interactions**
  - **Standard Model and Extensions**
- **Discrete Symmetries C, P, T, CP, CPT**
  - **Precision Experiments**
  - **Novel Techniques**
  - **⇒ Some Examples**

CP



emiTTime



Klaus Jungmann, Kernfysisch Versneller Instituut, Rijksuniversiteit Groningen

KVI RIJKSUNIVERSITEIT GRONINGEN

Symmetries and Forces

Forces and Symmetries

Forces and Symmetries

→Lee/Yang 1956

Local Symmetries ⇔ Forces

- fundamental interactions

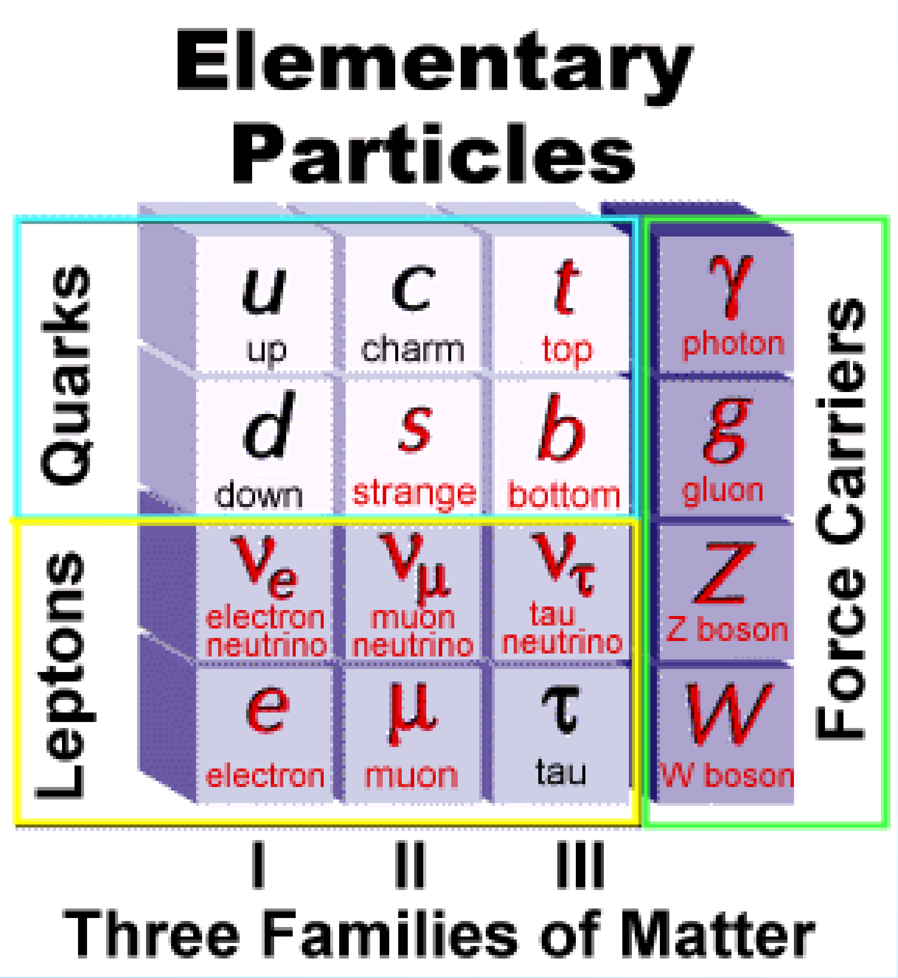
Global Symmetries ⇔ Conservation Laws

- energy
- momentum
- electric charge
- …..

Conservation without known Symmetry

- lepton number
- charged lepton family number
- baryon number
- …..

Properties of Known Forces



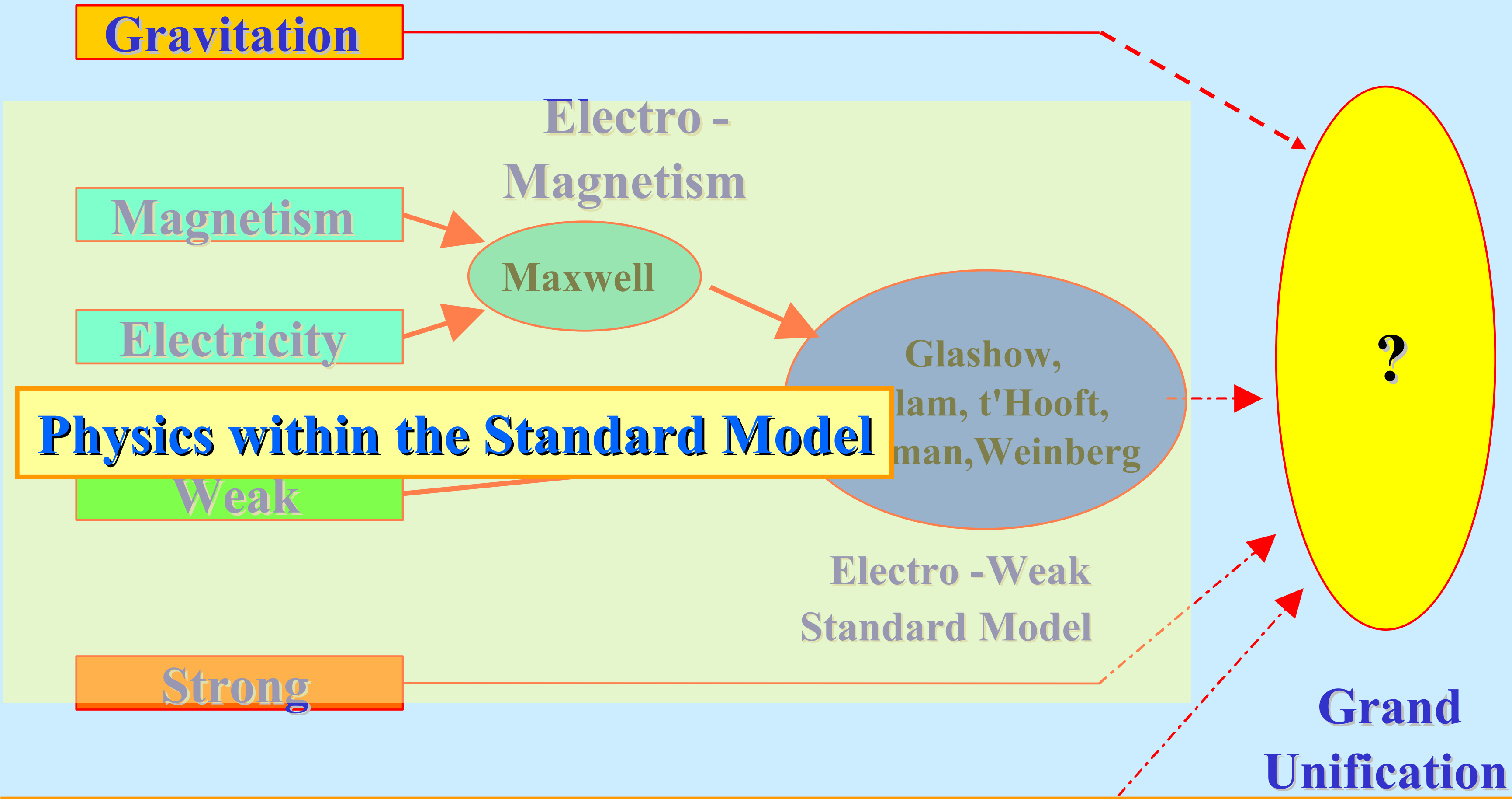
Standard Model

- 3 Fundamental Forces
  - Electromagnetic Weak Strong
- 12 Fundamental Fermions
  - Quarks, Leptons
- 13 (Gauge) Bosons
  - γ, W^+, W^-, Z^0, H, 8 Gluons

However

- many open questions
  - Why 3 generations ?
  - Why some 30 Parameters?
  - Why CP violation ?
  - Why us?
  - …..
- Gravity not included
- No Combind Theory of Gravity and Quantum Mechanics

Fundamental Interactions – Standard Model



Speculative Models:

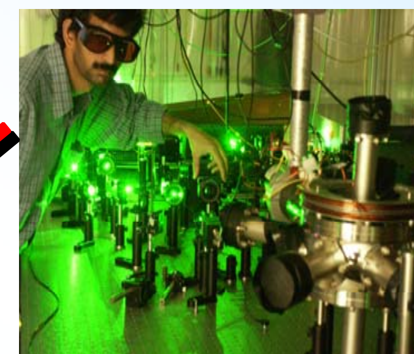
Supersymmetry, Cold dark matter, Tachyons, Radiative muon generation, Technicolor, Leptoquarks, Extra gauge bosons, Extra dimensions, LeftRight Symmetry, Compositeness, Lepton flavour violation, ….

⇒ No Status in Physics , yet: “Not even wrong”

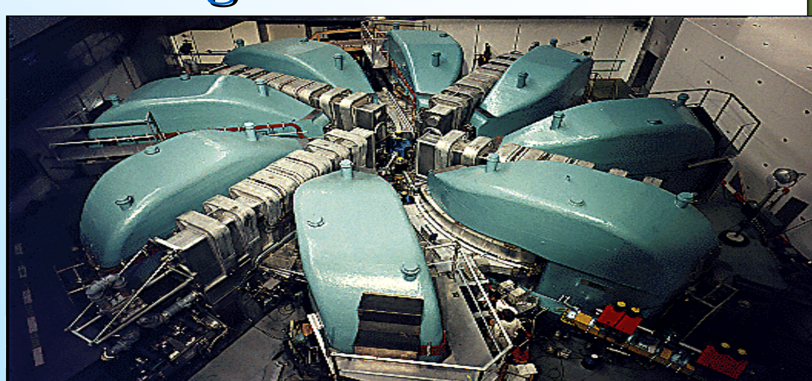
Experiments at the Frontiers of Standard Theory

High Energy Frontier

Precision Frontier



High Power Frontier



Known Interactions - Fundamental Constants and Searches for New Forces

Examples:

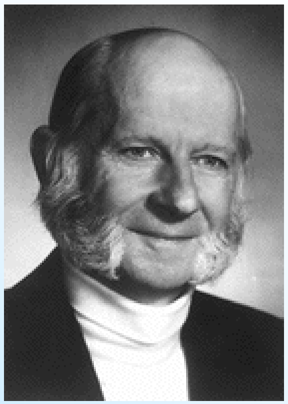
- **Electron g-2**
- **Bound State g-factors**
- **Muon g-2**

High Precision Electron g-2

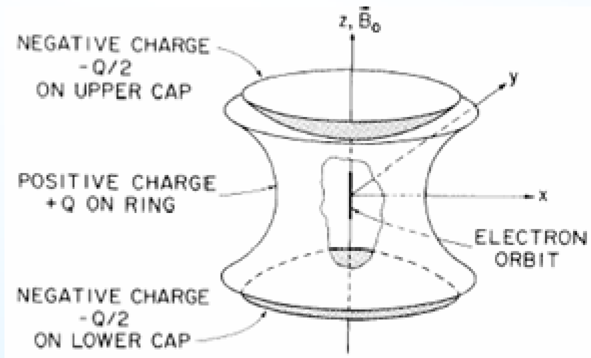
Single electron in a Penning Trap

UNIVERSITY OF WASHINGTON

Harvard University

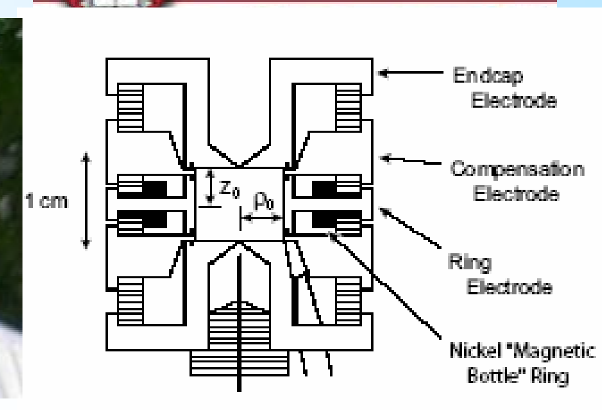


H.G. Dehmelt

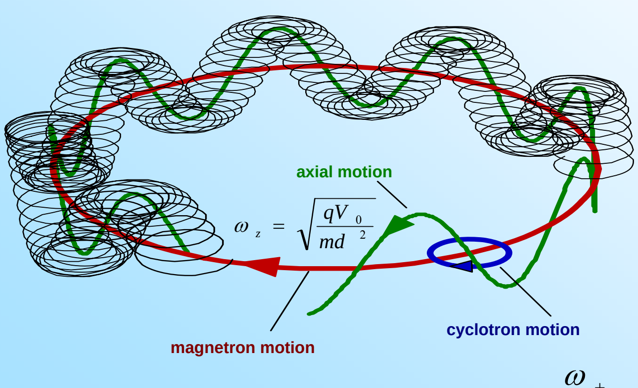


hyperbolic trap

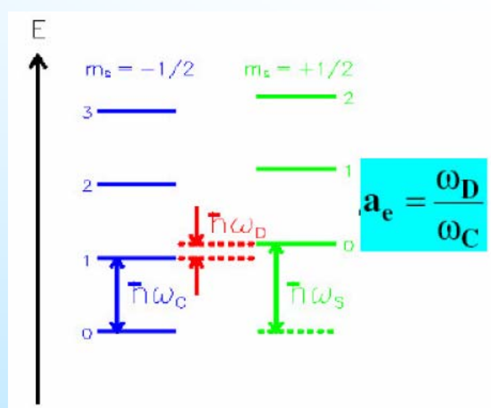
G. Gabrielse

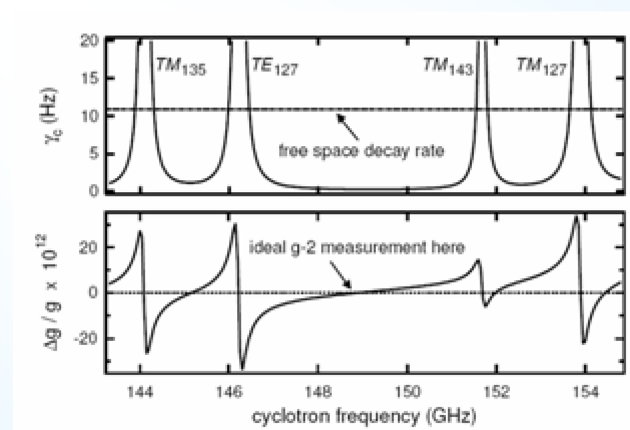


Cylindrical Trap operated at well selected frequencies

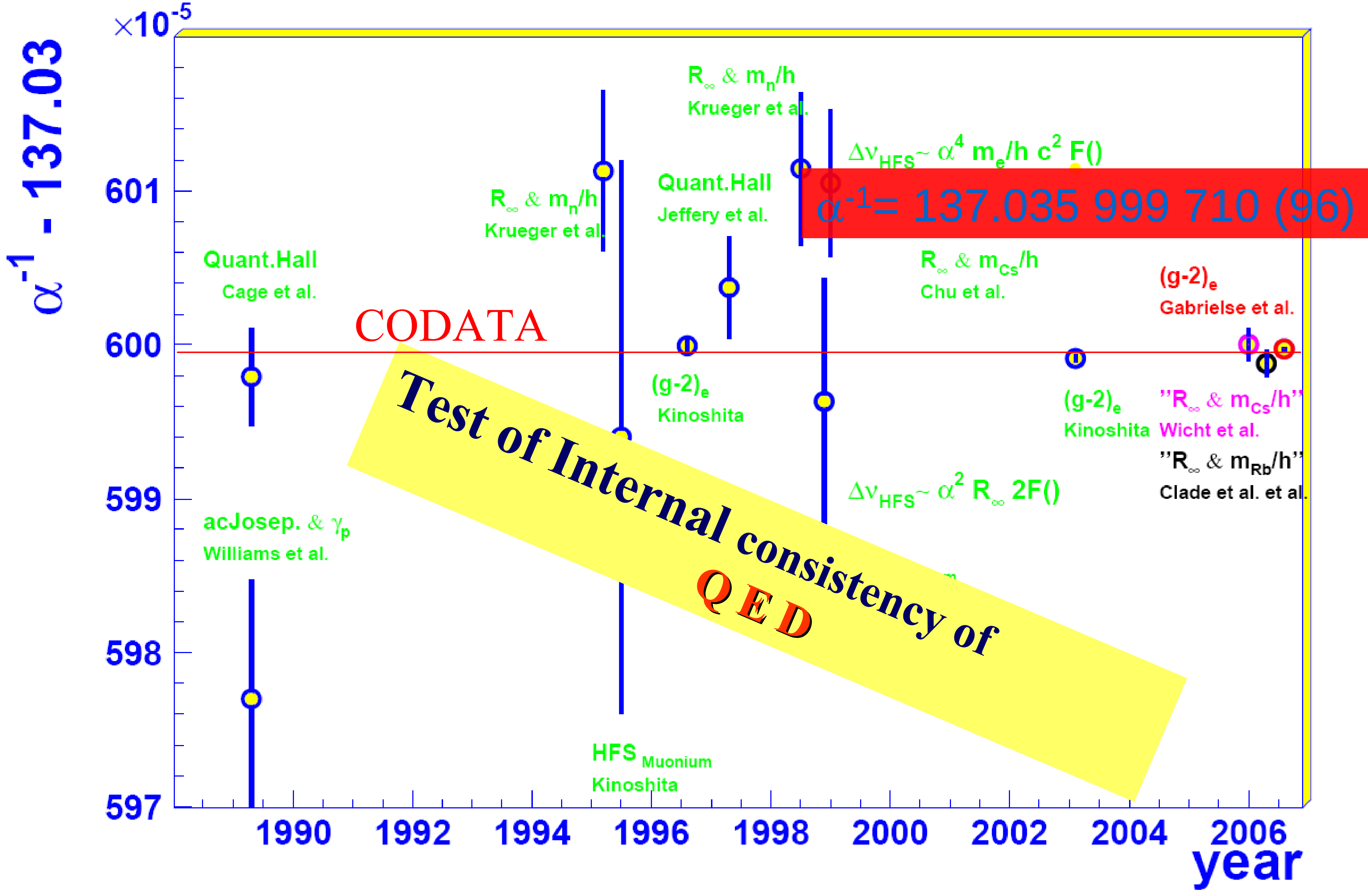


E x B drift



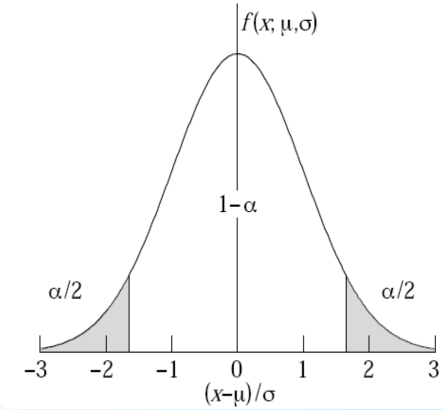


Fine Structure Constant α



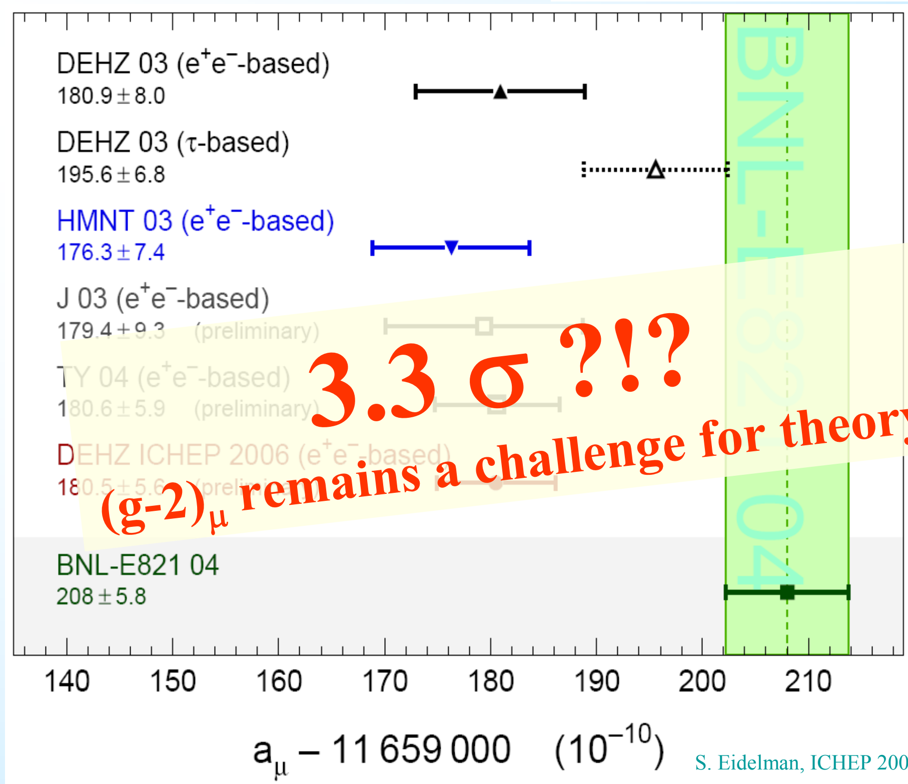
The Muon Magnetic Anomaly

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



Spin precession
in (electro-)
magnetic field

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



3.3 σ ?!?

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

S. Eidelman, ICHEP 2006

Discrete Symmetries

H.W. Wilschut

The World according to Escher

P

C

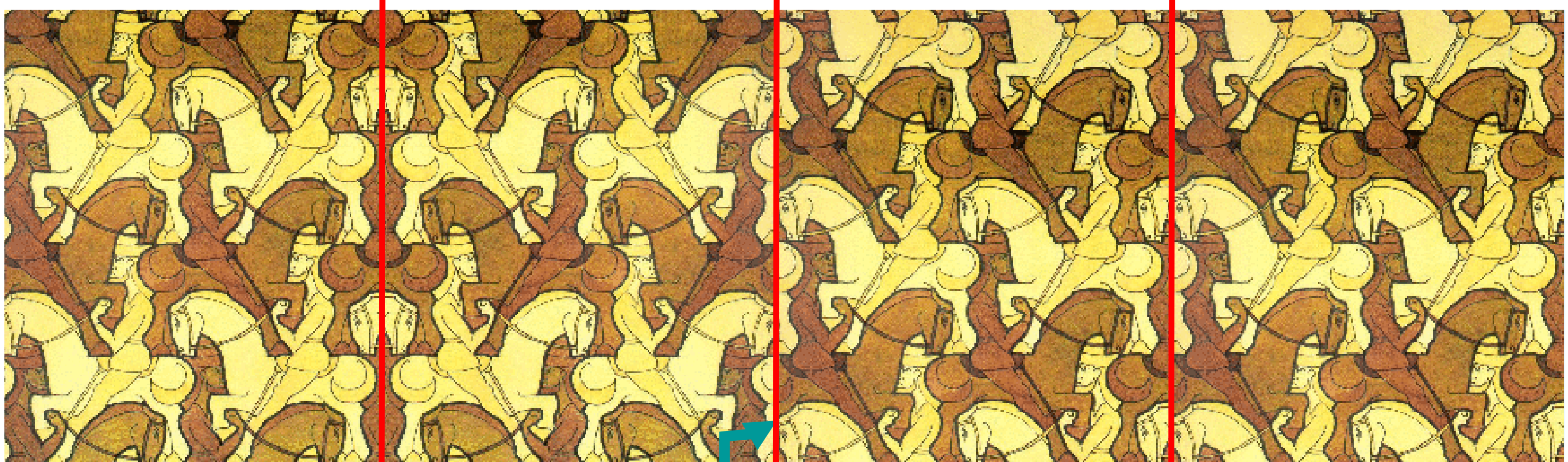
T

start

matter

anti-matter

identical to start



mirror image

time →

← time

Time reversal violation can be measured at low energies

anti-particle

e^+

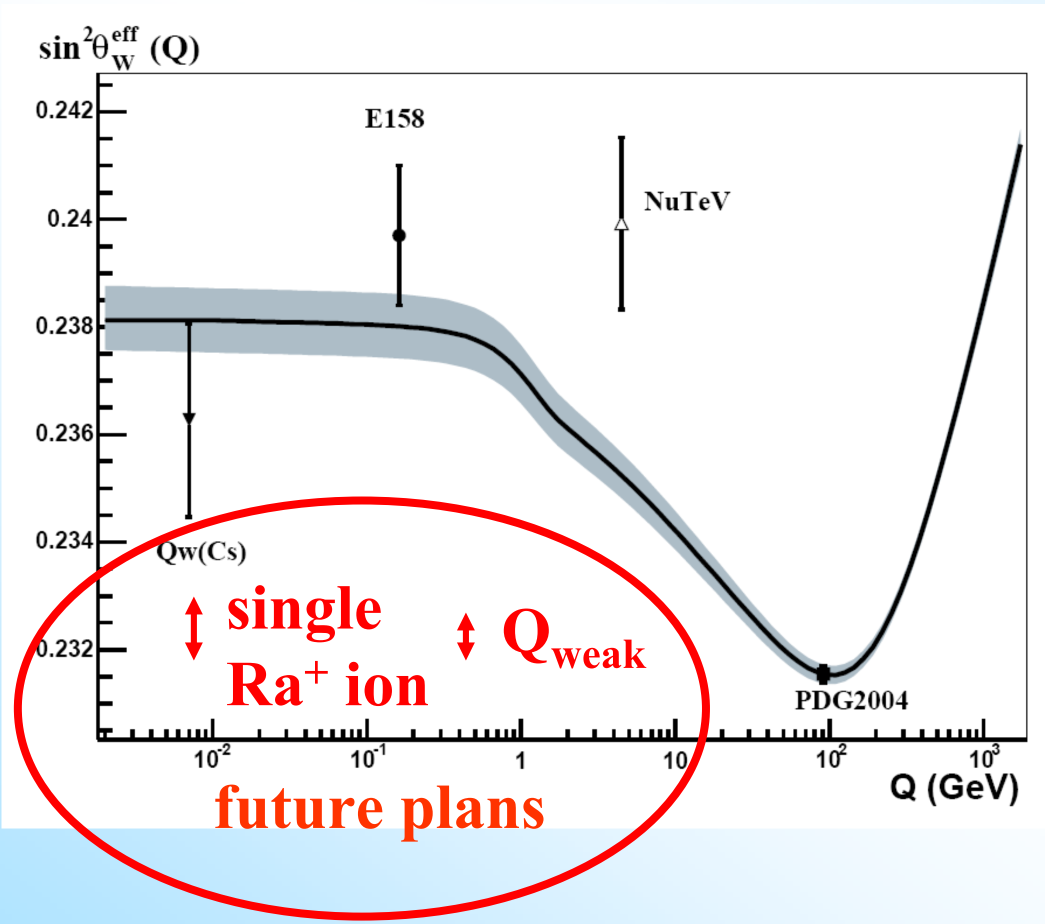
particle

e^-

Discrete Symmetries

Parity

Possible Gains from Parity Violation Experiments



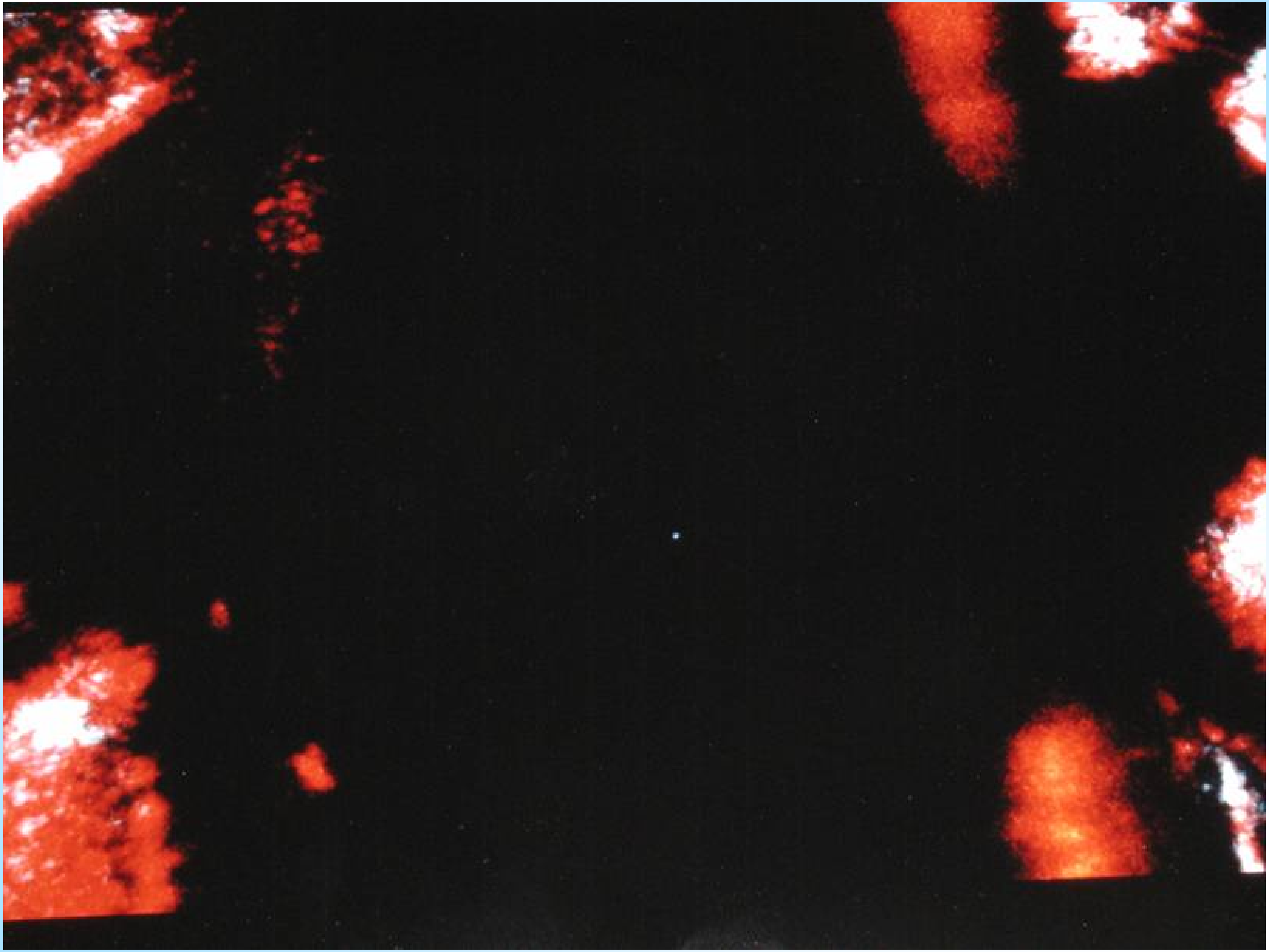
In past:

- excellent test of Standard Model

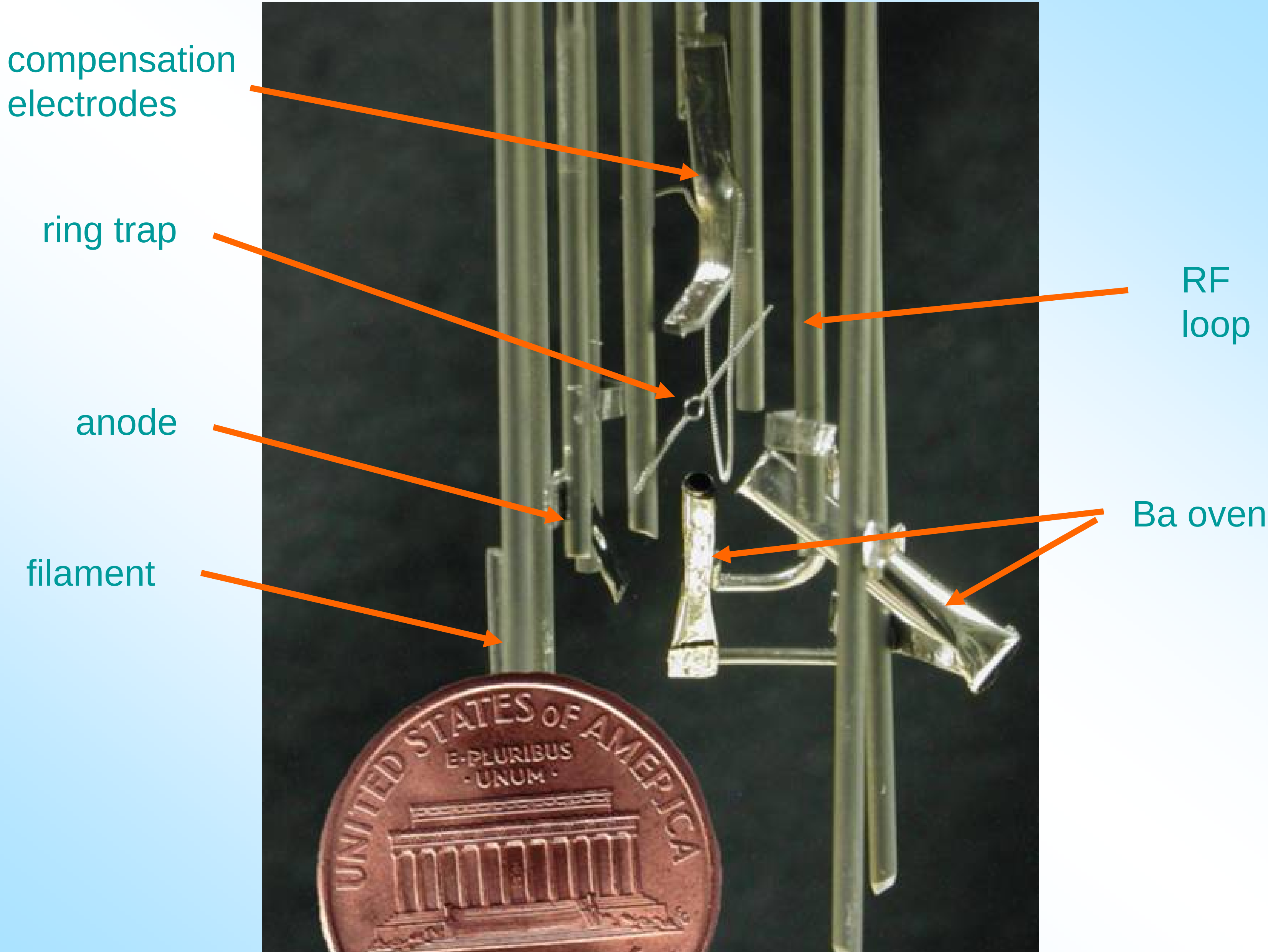
Now:

- 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

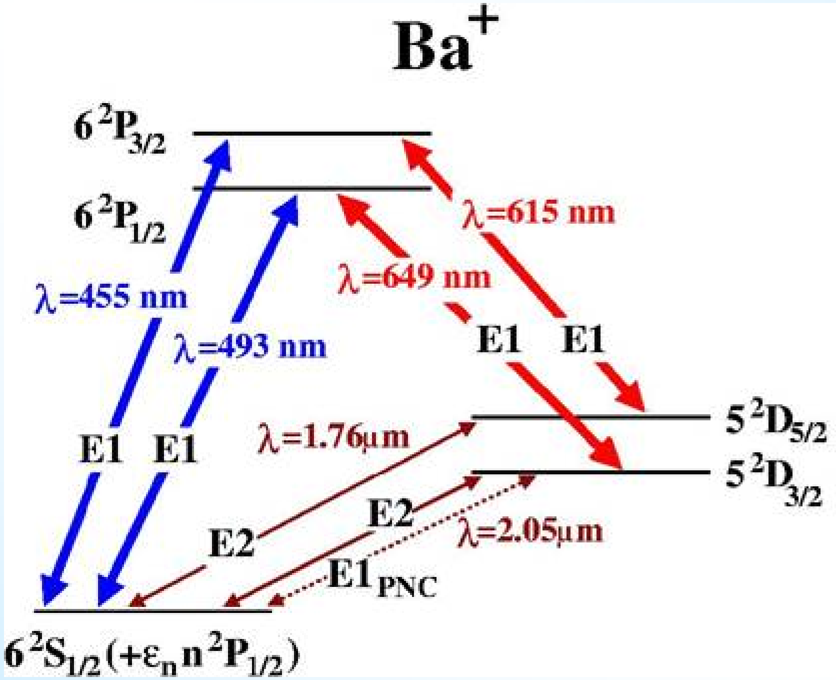
Single Trapped Ba Ion

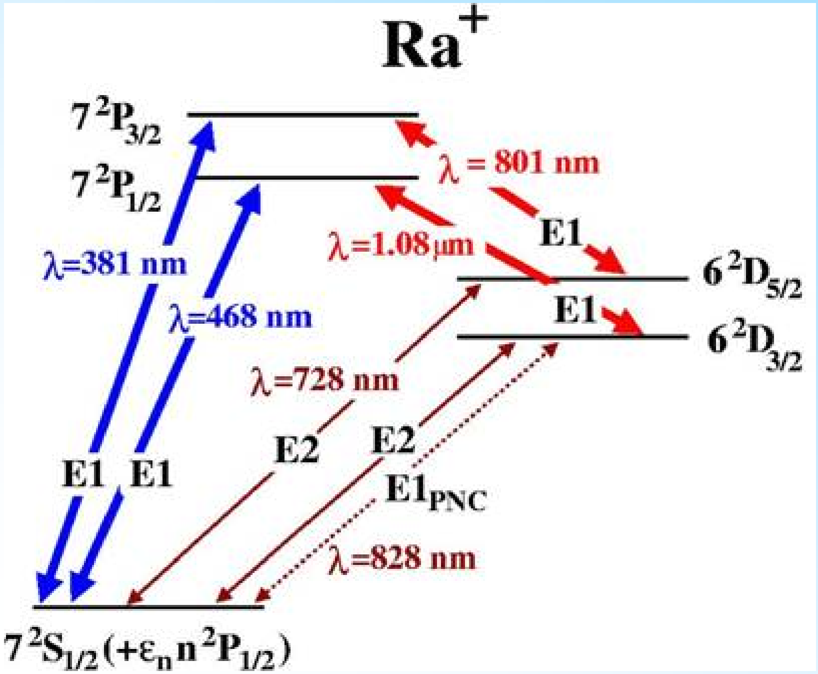


From H.G. Dehmelt

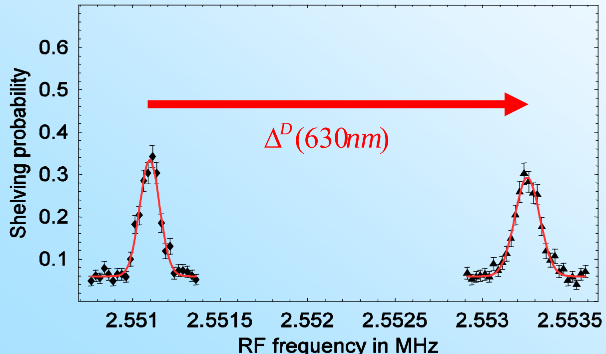


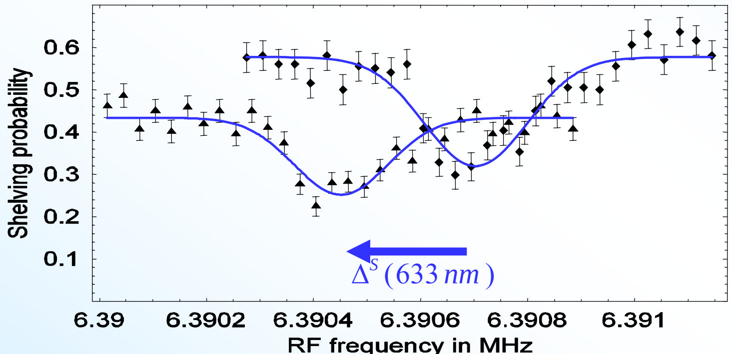
from N. Fortson





- **Parity admixture measured through light shift**
- **Ra^+ some 20 times bigger effects than Ba^+**
- **Ground breaking work at Seattle**





Discrete Symmetries

Zoom in on Time -Reversal-violation

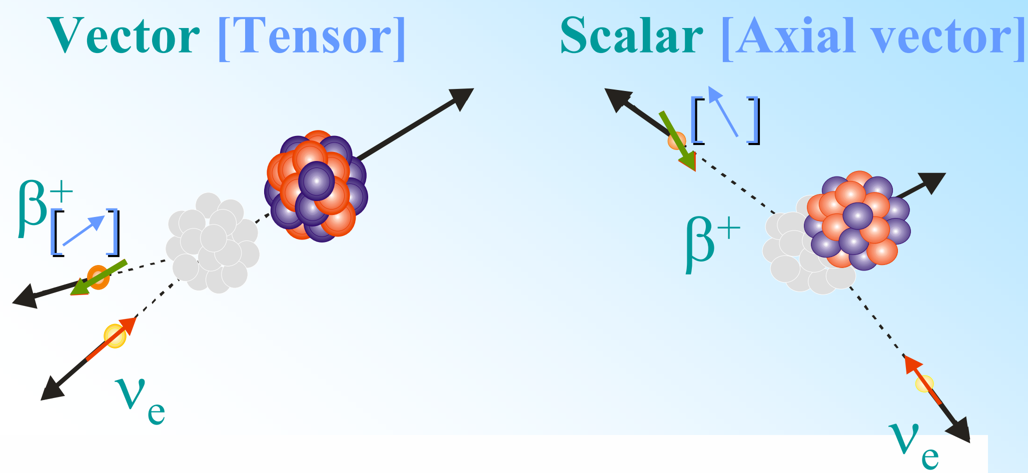
Correlations in nuclear
β-decays

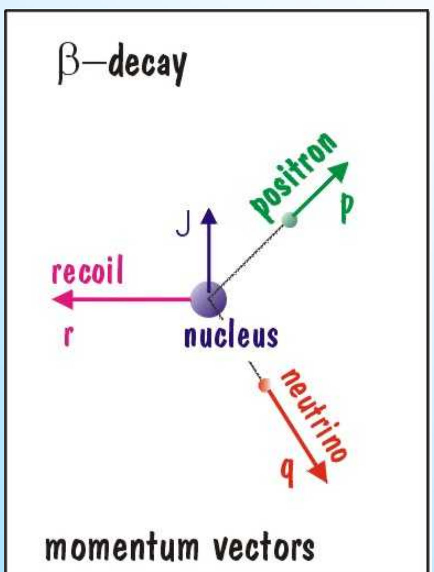
TRIμP

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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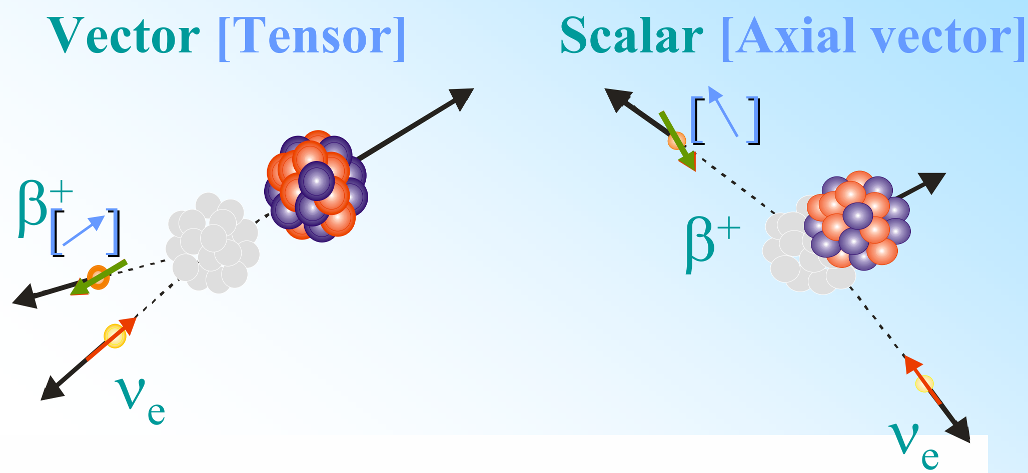

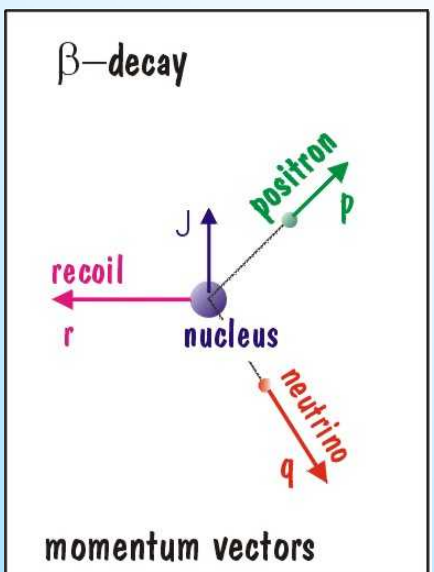

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$$\langle\vec{J}\cdot\vec{p}\times\vec{q}\rangle \neq 0 \quad ?$$

TRIμP

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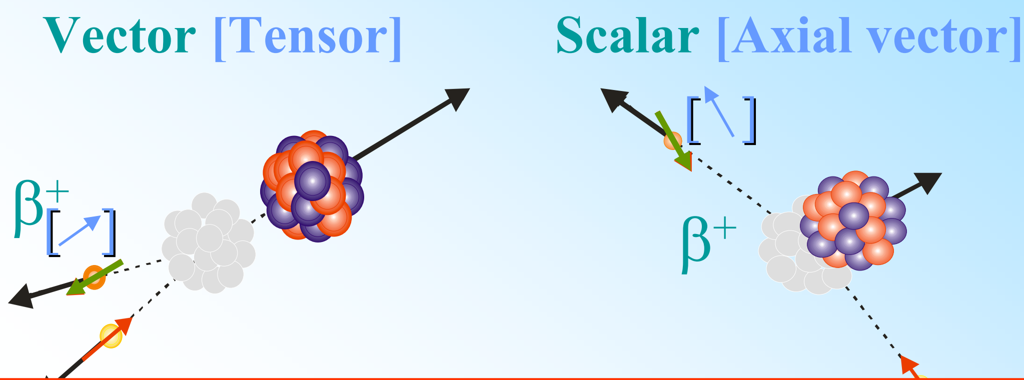
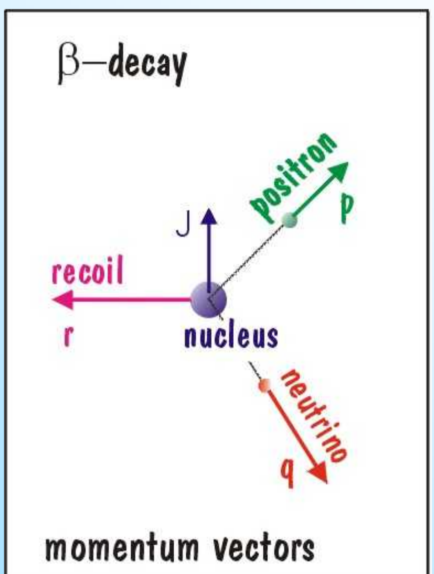
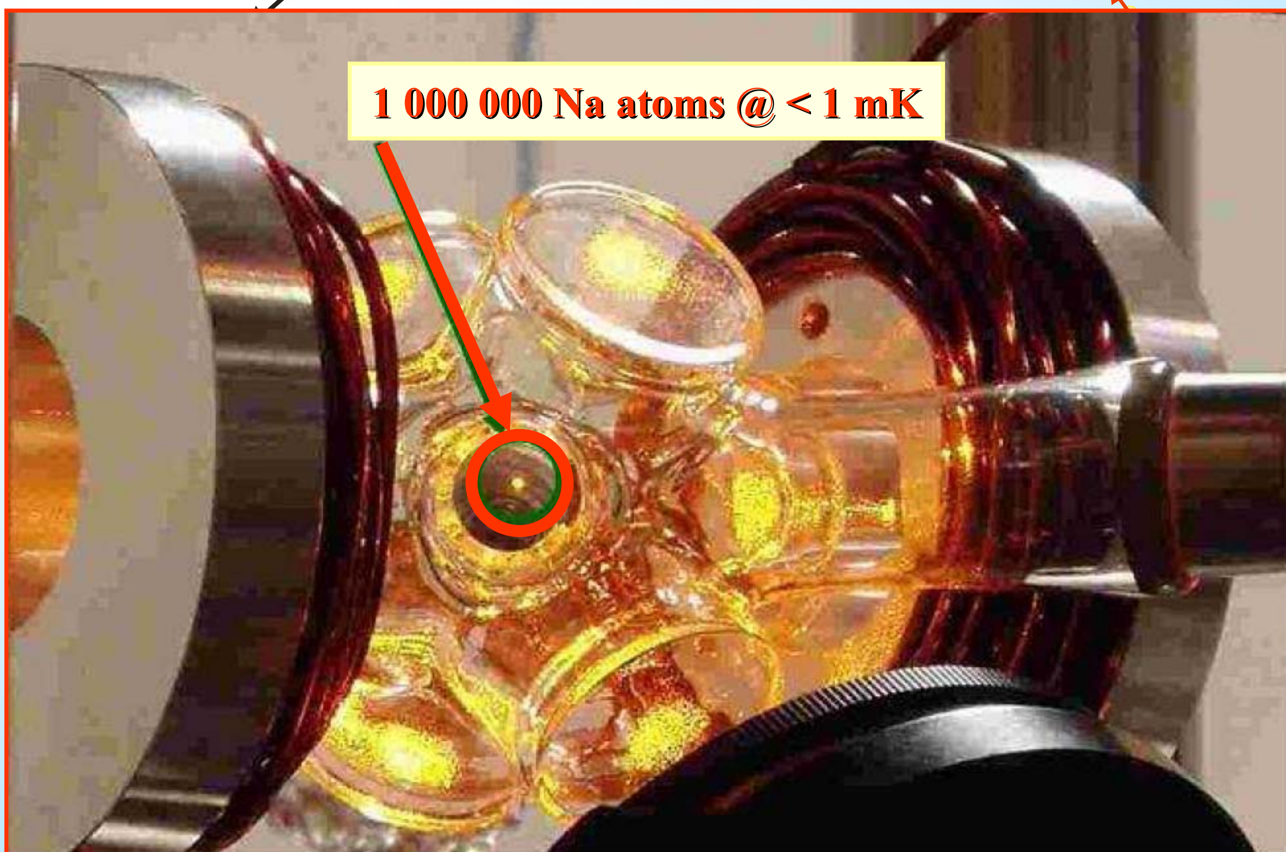






Traps for weak interaction physics

1. Atom traps :

- **TRIUMF-ISAC, ^{38m}K, βν-correlation (J. Behr et al.)**
  A. Gorelov et al., Hyperfine Interactions 127 (2000) 373
- **LBNL & UC Berkeley, ^{21}Na, βν-correlation (S.J. Freedman et al.)**
  N. Scielzo, Ph. D. Thesis (2003)
- **LANL Los Alamos, ^{82}Rb, β-asymmetry (D. Vieira et al.)**
  S.G. Crane et al., Phys. Rev. Lett. 86 (2001) 2967
- **KVI-Groningen, Na, Ne, Mg, D-coefficient (K. Jungmann et al.)**
  Ra, EDM experiment
  G.P. Berg et al., NIM B204 (2003) 526

2. Ion traps :

- **LPC-Caen, ^{6}He, βν-correlation (O. Naviliat-Cuncic et al.)**
  G. Ban et al., NIM A518 (2004) 712
- **WITCH, Leuven-ISOLDE, ^{35}Ar, βν-correlation (N. Severijns et al.)**
  D. Beck et al., Nucl. Inst. Methods Phys. Res., A 503 (2003) 567
- **CPT-trap Argonne, ^{14}O, βν-correlation (G. Savard et al.)**
  G. Savard et al., Nucl. Phys. A654 (1999) 961c
- **ISOLTRAP-CERN, mass for 0+ → 0+ decays (K. Blaum et al.)**

from N. Severijns

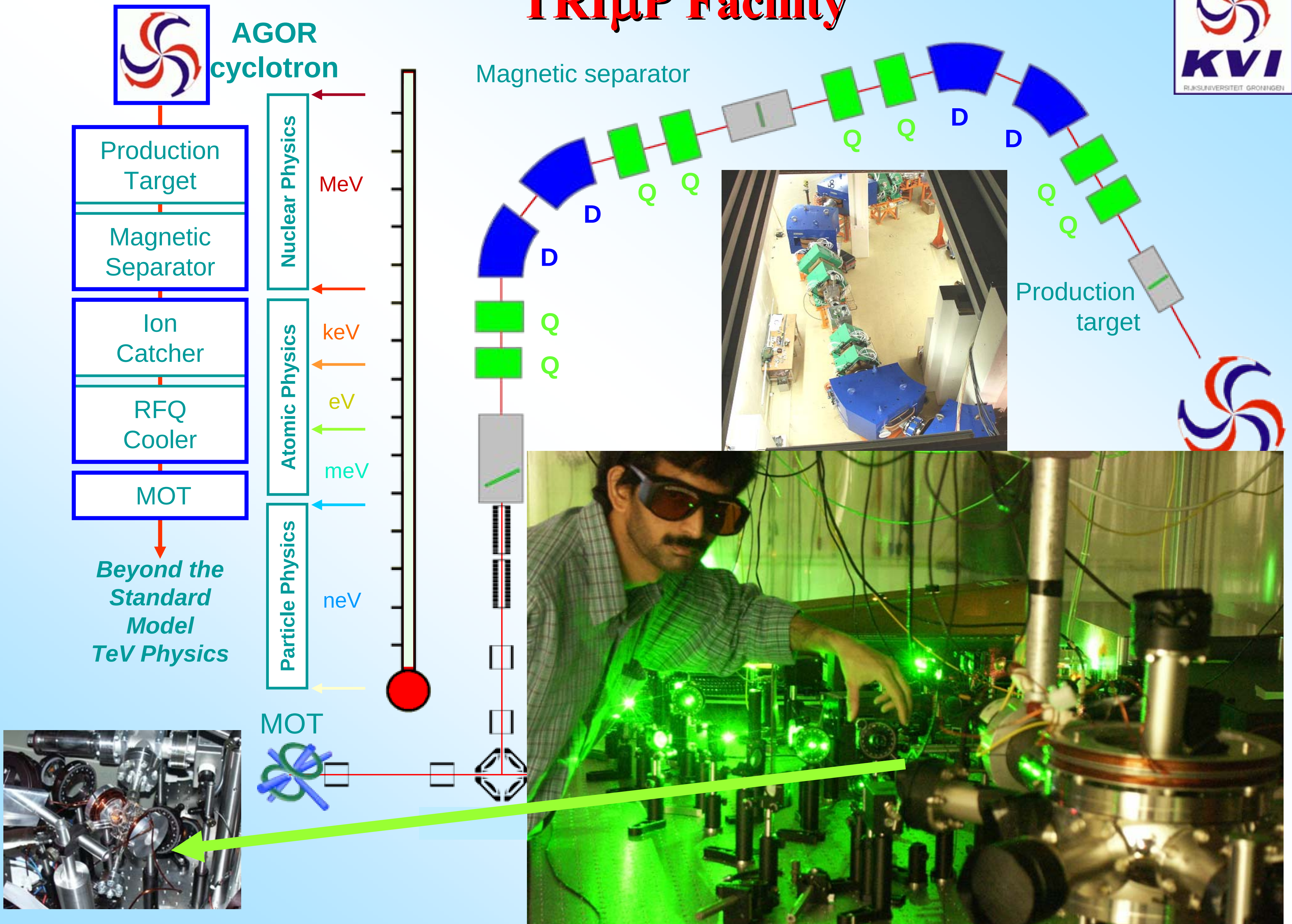
The TRImP Facility

@ KVI Groningen

Dedicated to Fundamental Interactions and Symmetries

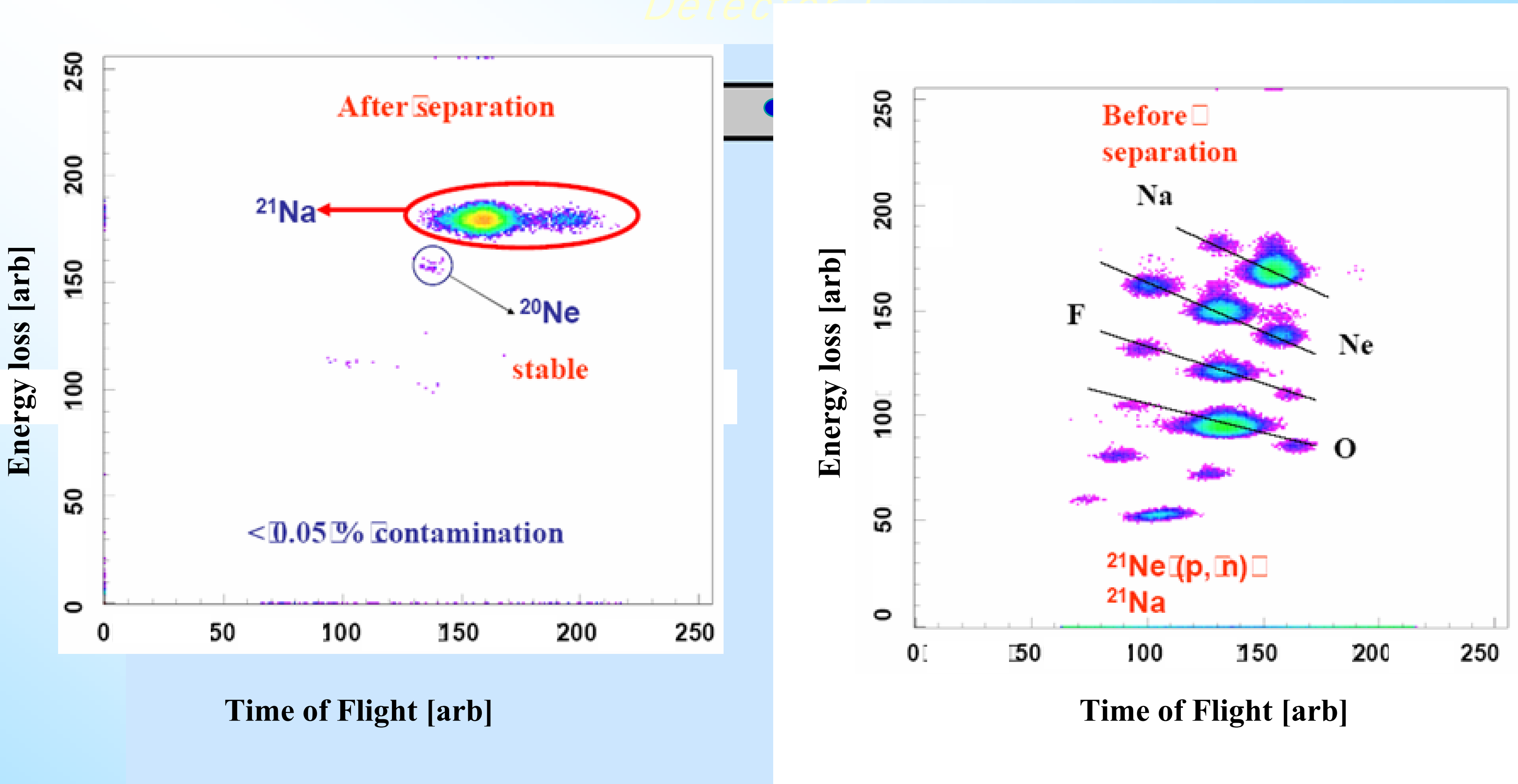
β-decays
EDMs

TRIμP Facility



TRIμP

Separator commissioning

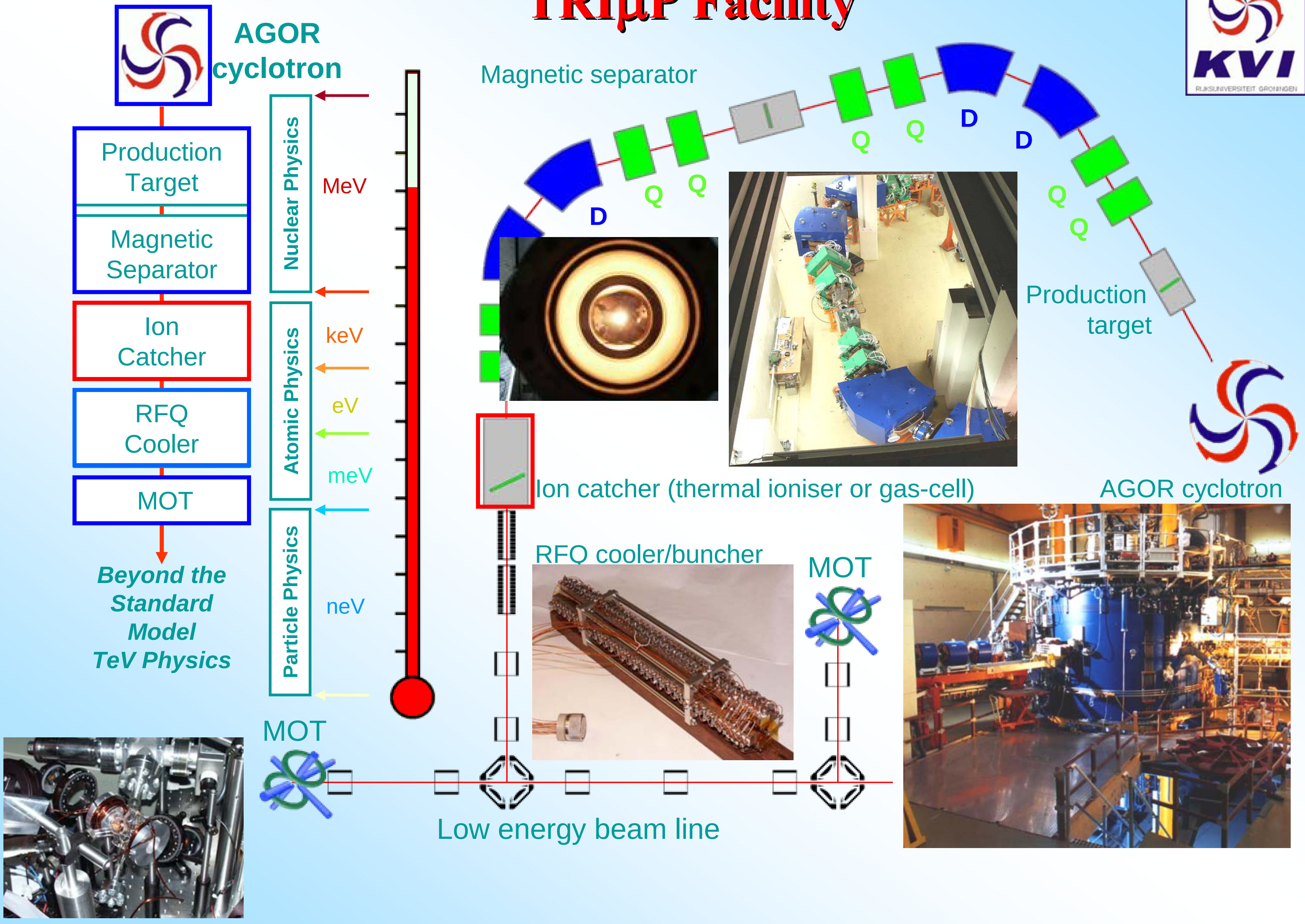


Yield of ^{21}Na at the focal plane: 5.3 MHz/kW {@ 1 atm H_2}

Now achieved: > 99% ^{21}Na

Other isotopes produced: ^{12}N, ^{12}B, ^{19}Ne, ^{20}Na, ^{22}Mg, ^{213}Ra

TRIμP Facility

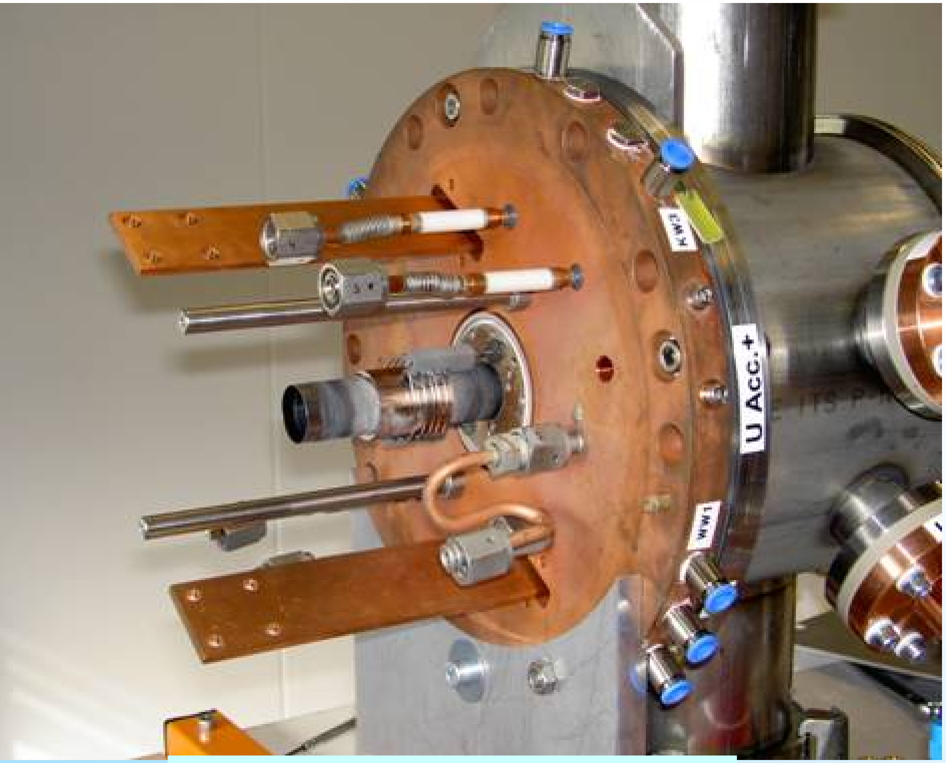


TRIμP Ion Catcher

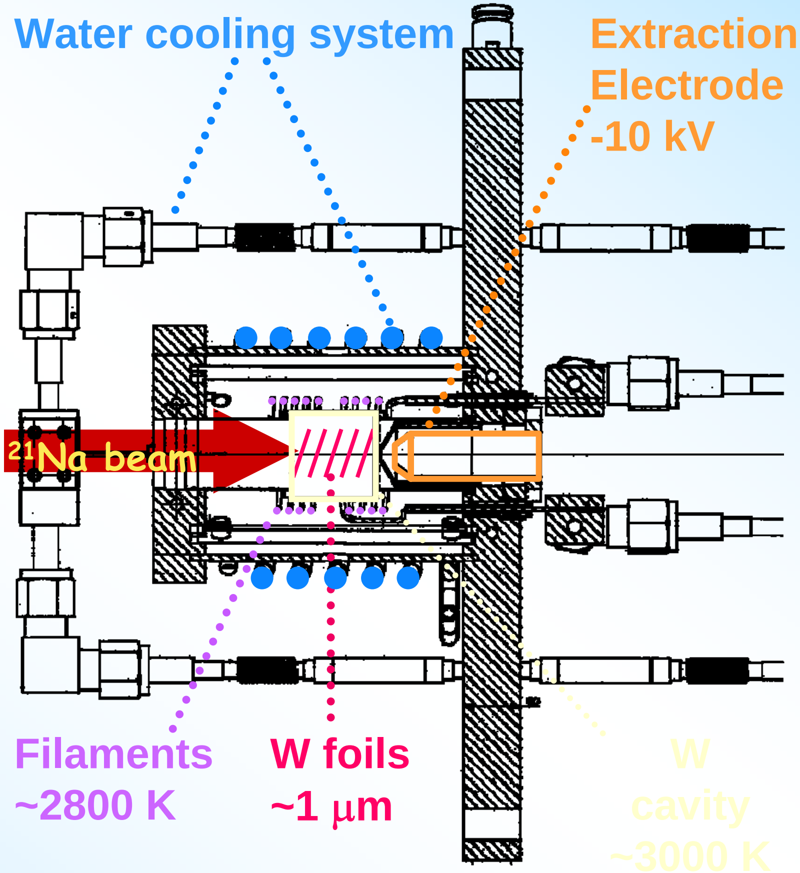
High efficiency for Na isotopes: Thermal Ioniser

Gas stopper – a generic solution

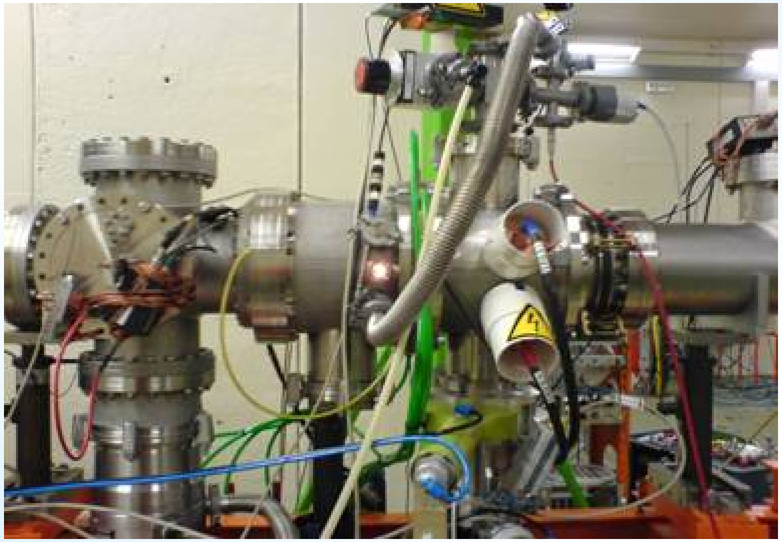
Recent results on stopping in cooled Helium gas
(RIASH, P.Dendooven → FOM projectruimte)

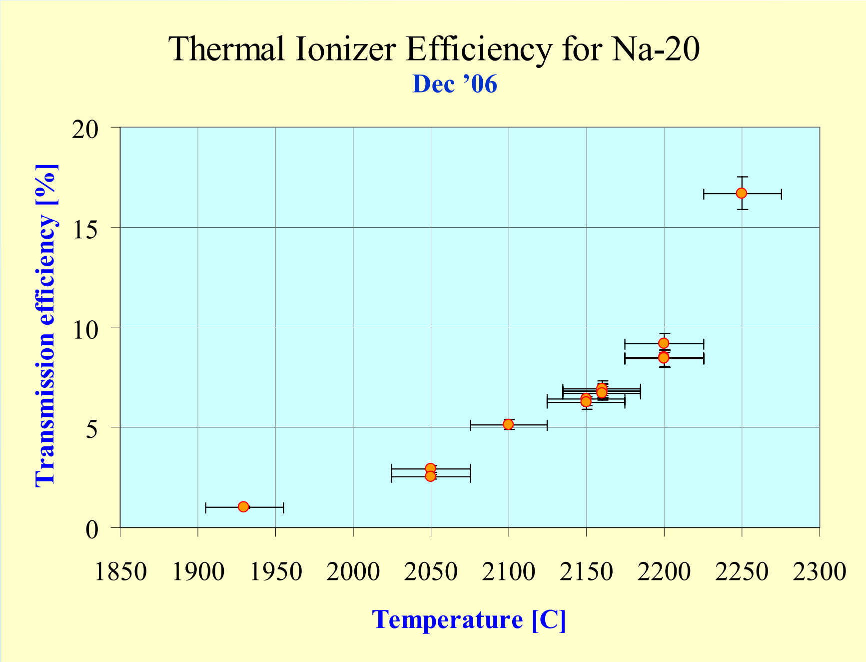


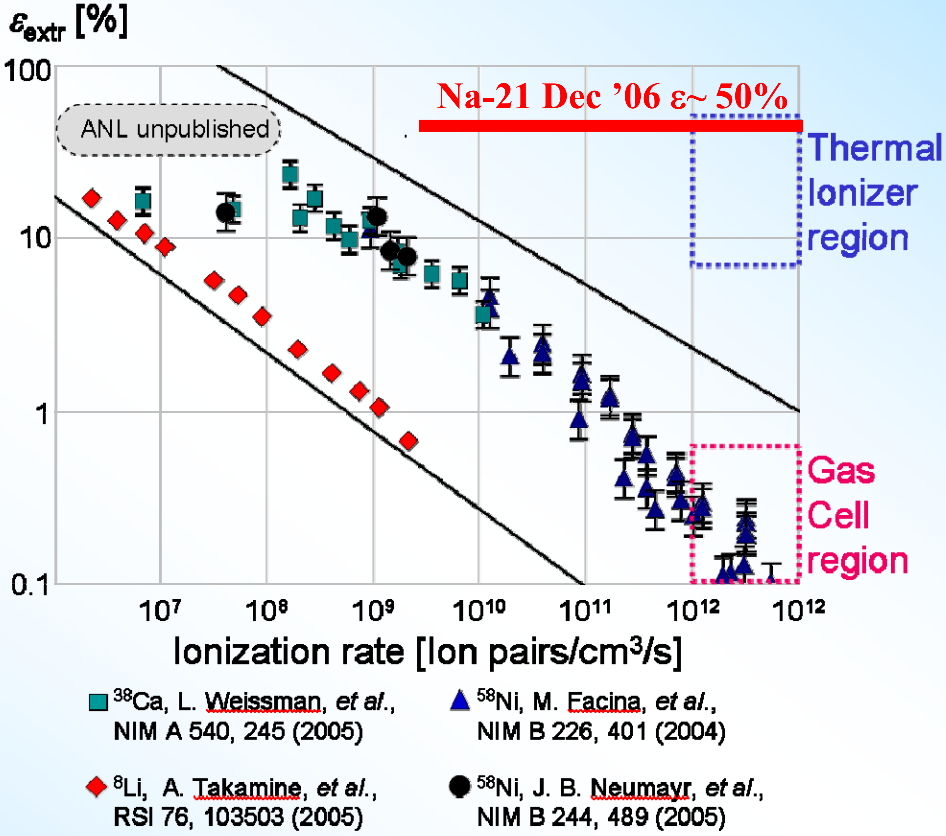
O. Dermois, L. Huisman



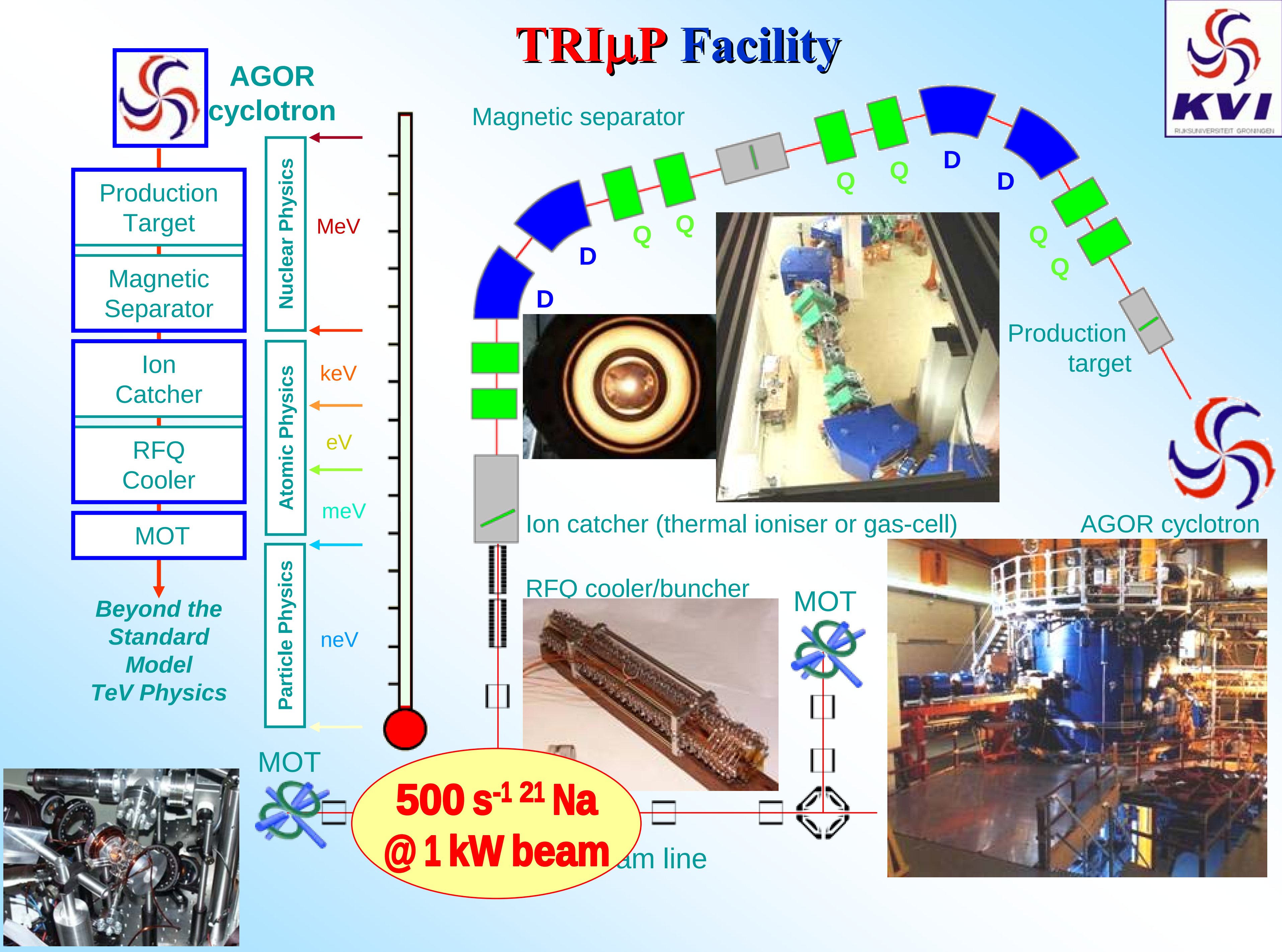
First Thermal Ionizer Results







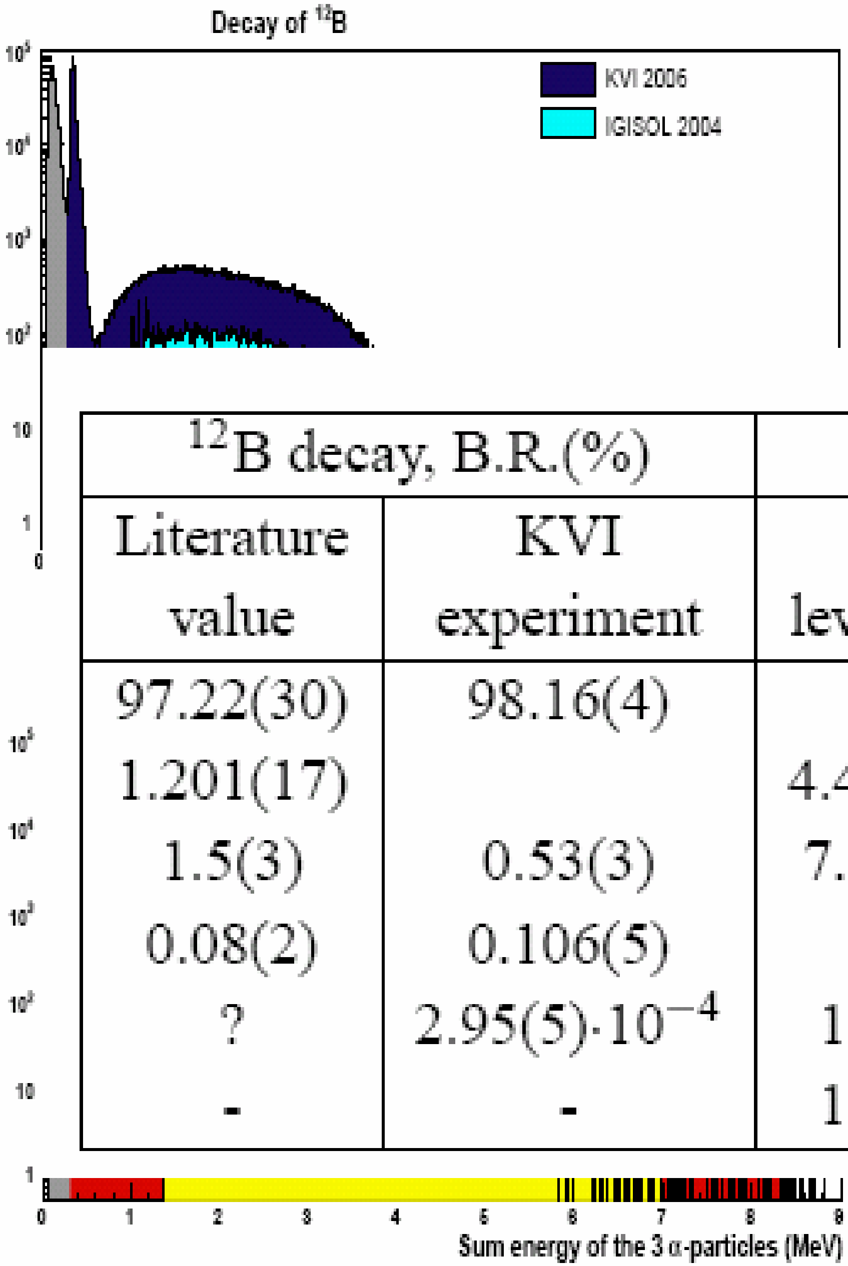
TRIμP Facility



Since the production works - Just an intermezzo

$$^{12}X \rightarrow \beta + 3\alpha$$

β-decay studies of states in ^{12}C
Fynbo et al.



^{12}B decay, B.R.(%)		^{12}C	^{12}N decay, B.R.(%[illegible]	
Literature value	KVI experiment	Energy level (MeV)	Literature value	[illegible]nt
97.22(30)	98.16(4)	g.s.	94.55[illegible]	[illegible]0(10)
1.201(17)		4.43891(31)	1[illegible]	[illegible]
1.5(3)	0.53(3)	7.6542(15)	[illegible]	1.26(6)
0.08(2)	0.106(5)	10.3[illegible]	[illegible](15)	0.52(3)
?	$2.95(5)\cdot10^{-4}$	12.[illegible]	0.31(12)	0.199(6)
-	-	15.11[illegible]	4.4(15)x10-3	?

PRELIMINARY

$^{12}X \rightarrow \beta + {}^{12}C$

$\hookrightarrow 3\alpha$

Discrete Symmetries

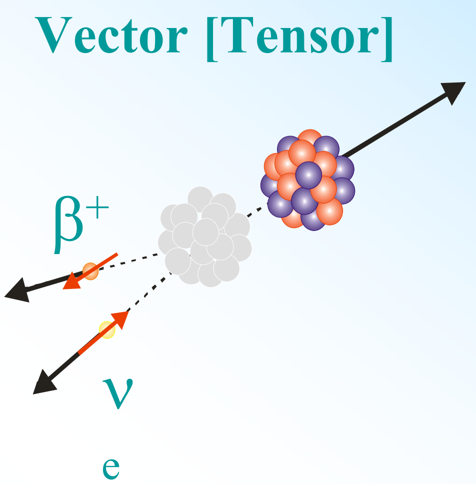
back to

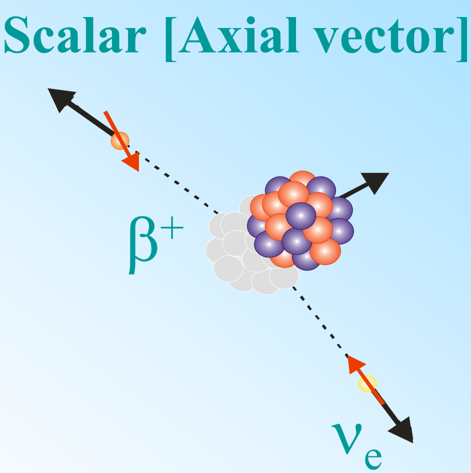
β-decays

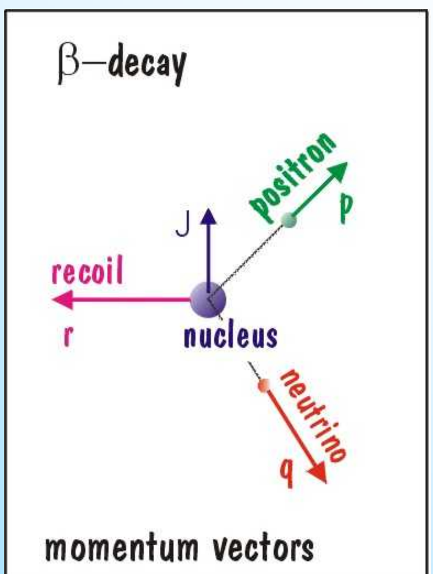
New Interactions in Nuclear β-Decay

In Standard Model:
Weak Interaction is
V-A

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

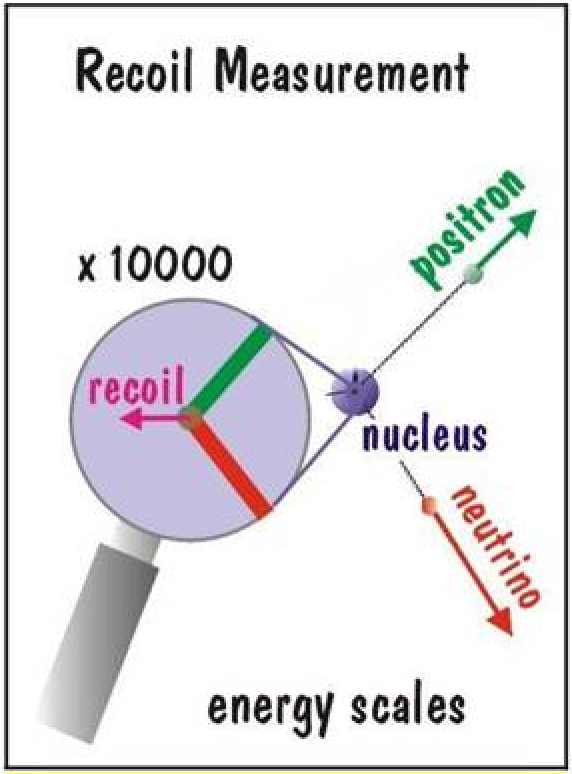




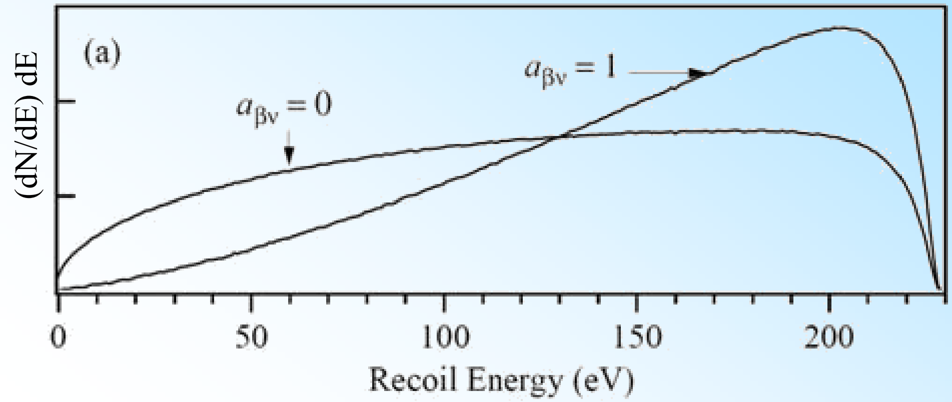


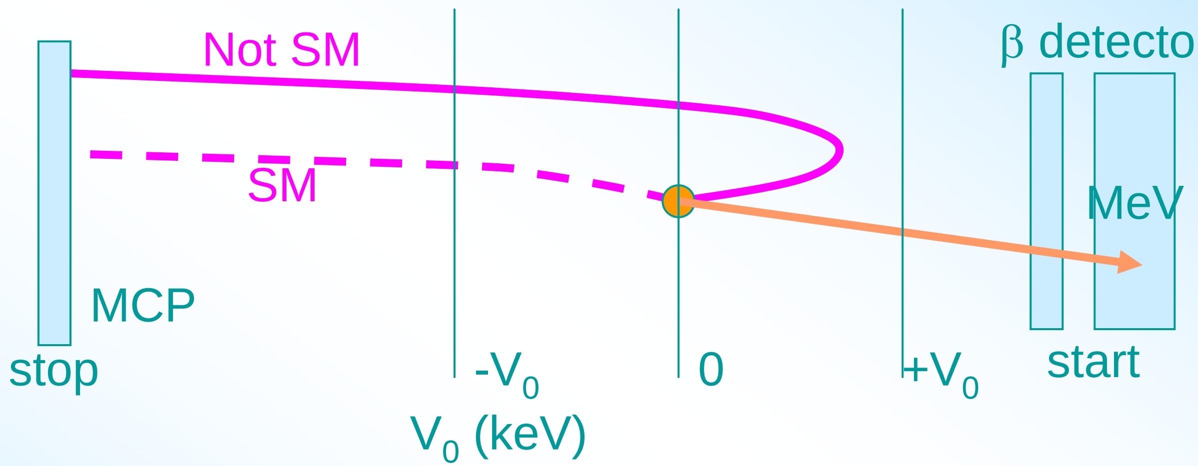
$$\frac{d^2W}{d\Omega_e d\Omega_\nu} \sim 1 + a\,\frac{\boldsymbol{p}\cdot\hat{\boldsymbol{q}}}{E} + b\,\Gamma\,\frac{m_e}{E} + \langle \boldsymbol{J}\rangle \cdot \left[A\,\frac{\boldsymbol{p}}{E} + B\,\hat{\boldsymbol{q}} + D\,\frac{\boldsymbol{p}\times\hat{\boldsymbol{q}}}{E}\right] + \langle \boldsymbol{\sigma}\rangle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

Principle : MOT + RIMS



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





TOF→ $E_{//}$

X,Y → $E_{\perp}$

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

New Interactions in Nuclear β-Decay

In Standard Model: Weak Interaction is V-A

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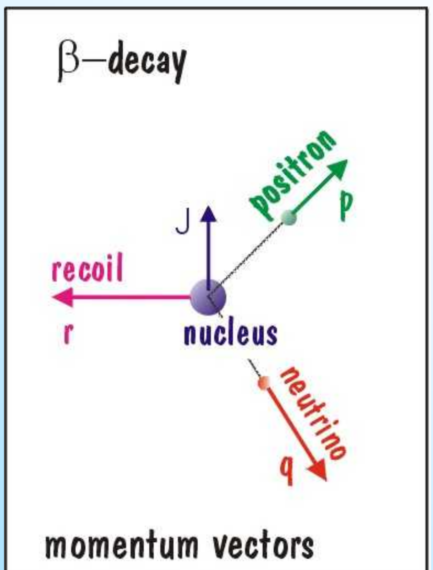


Vector [Tensor]   Scalar [Axial vector]

^{21}Na Berkeley:
Scielzo,Freedman, Fujikawa, Vetter
PRL 93, 102501-1 (2004)

$a_{exp} = 0.5243(91)$
$a_{theor} = 0.558(6)$

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

??

^{38m}K TRIUMF
A. Gorelov et al.
PRL 94, 142501 (2005)

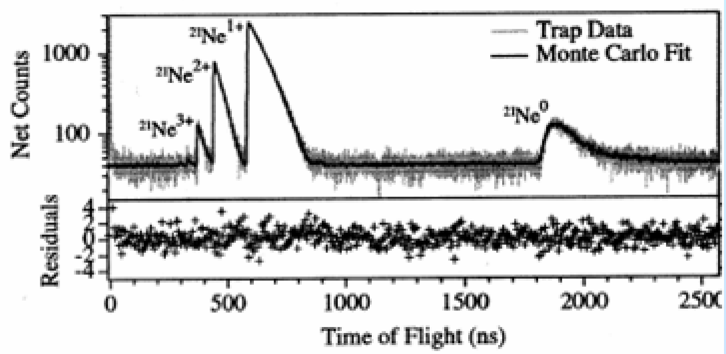
$a_{exp} = 0.9978(30)(37)$
$a_{theor} = 1$

Asymmetry "a" in ^{21}Na decay

^{21}Na $\beta-\nu$ L.B.L. Scielzo et al. PRL 93 102501 (2004)

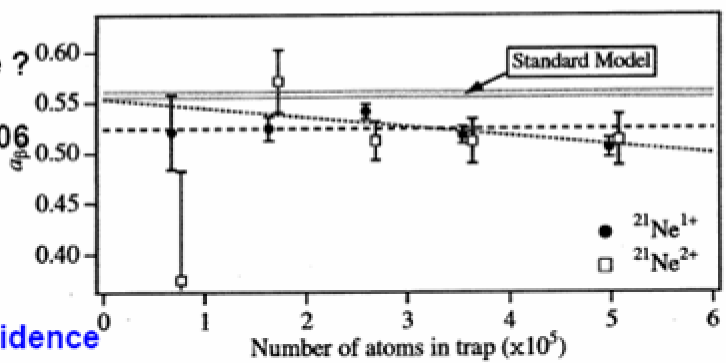
a=0.5243 ± 0.0091

S.M. a=0.558 (?)



Density dependence ?

a=0.551 ± 0.013 ± 0.006



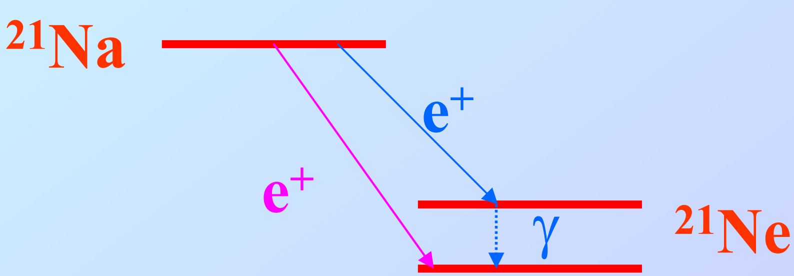
Also demonstrated:
electron-recoil coincidence

Before any serious conclusions:
$e^+/(e^+ + \gamma)$ branching ratio needed to be re-measured
5 disagreeing values existed

⇒ New measurement
(Caen,Bordeaux,KVI)
First user experiment
@ TRIμP facility at KVI
L. Achouri et al.
preliminary: 4.85(12) %

⇒ New publication
(Texas A&M)
V.E. Iacob et al.,
Phys.Rev.C74, 015501 (2006)
final value: 4.74(4) %

⇒ **No change to SM discrepancy**



Discrete Symmetries

Zoom in on T-violation

Permanent
Electric Dipole Moments

In many Models related to EDMs: Properties of Fundamental Fermions

In SO(10) the (electron) electric dipole moment
is approximately related to rare muon decays, e.g. $\mu \rightarrow e\,\gamma$

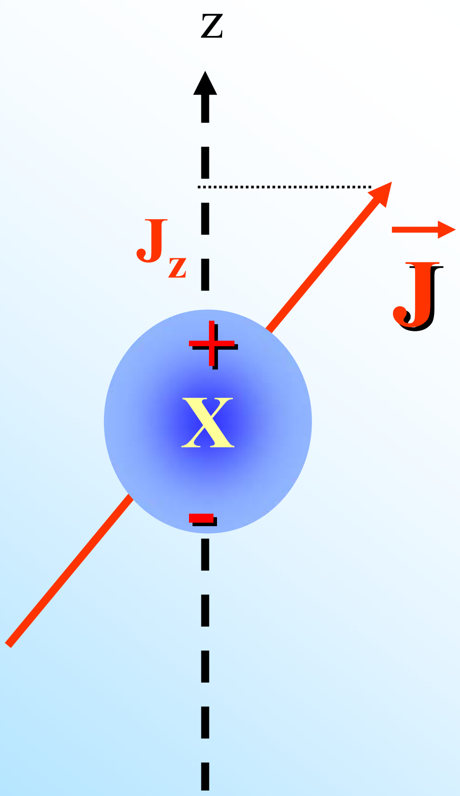
$$\frac{|d_e|}{10^{-27}\ e\ \mathrm{cm}} = 1.3 \sin\phi \sqrt{\frac{\mathrm{B.R.}\ (\mu \rightarrow e\,\gamma)}{10^{-12}}}$$

Violations of lepton flavour and CP in supersymmetric unified theories[1]

Riccardo Barbieri[†], Lawrence Hall[‡] and Alessandro Strumia[†]

IFUP – TH 72/94
UCB-PTH-94/29
hep-ph/9501334
LBL 36381
January 1995

Fundamental Particles



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

magnetic moment:

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

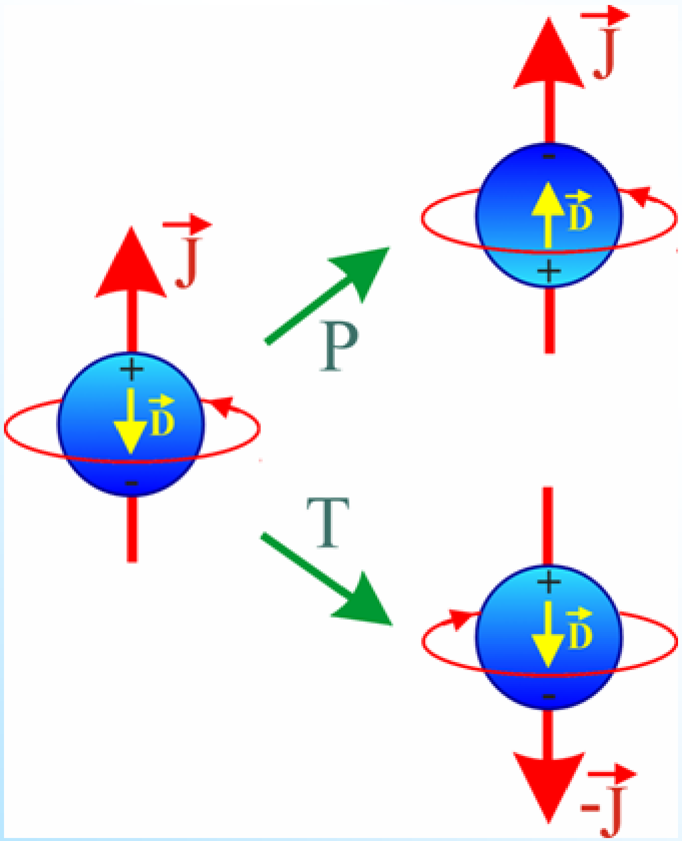
electric dipole moment:

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

magneton:

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

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



Permanent Electric Dipole Moment

violates:

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

if CPT conservation assumed

Standard Model value orders of magnitude below experimental limit:

$\Rightarrow$ **Window for New Physics beyond Standard Theory**

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 explained by (Kostelecky et al.):

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

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	*Number of particles [1/s]*	10^6/s
T	*Measurements Time [s]*	5
τ	*Spin Coherence Ti*	1 s
E	*Elect*	10^5 V/cm

Need to understand systematics

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

Ω $7*10^{-29}$ *e cm*

⇒ 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
…

→ electron EDM
→ nuclear 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

Solid State

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

→ electron EDM
→ strong enhancements
→ systematics ??

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	< 30	10^{4}	≤ 30
Tl (odd p)	< 10^{5}	10^{7}	≤ 10^{5}
Hg (odd n)	< 0.21	10^{5}	various

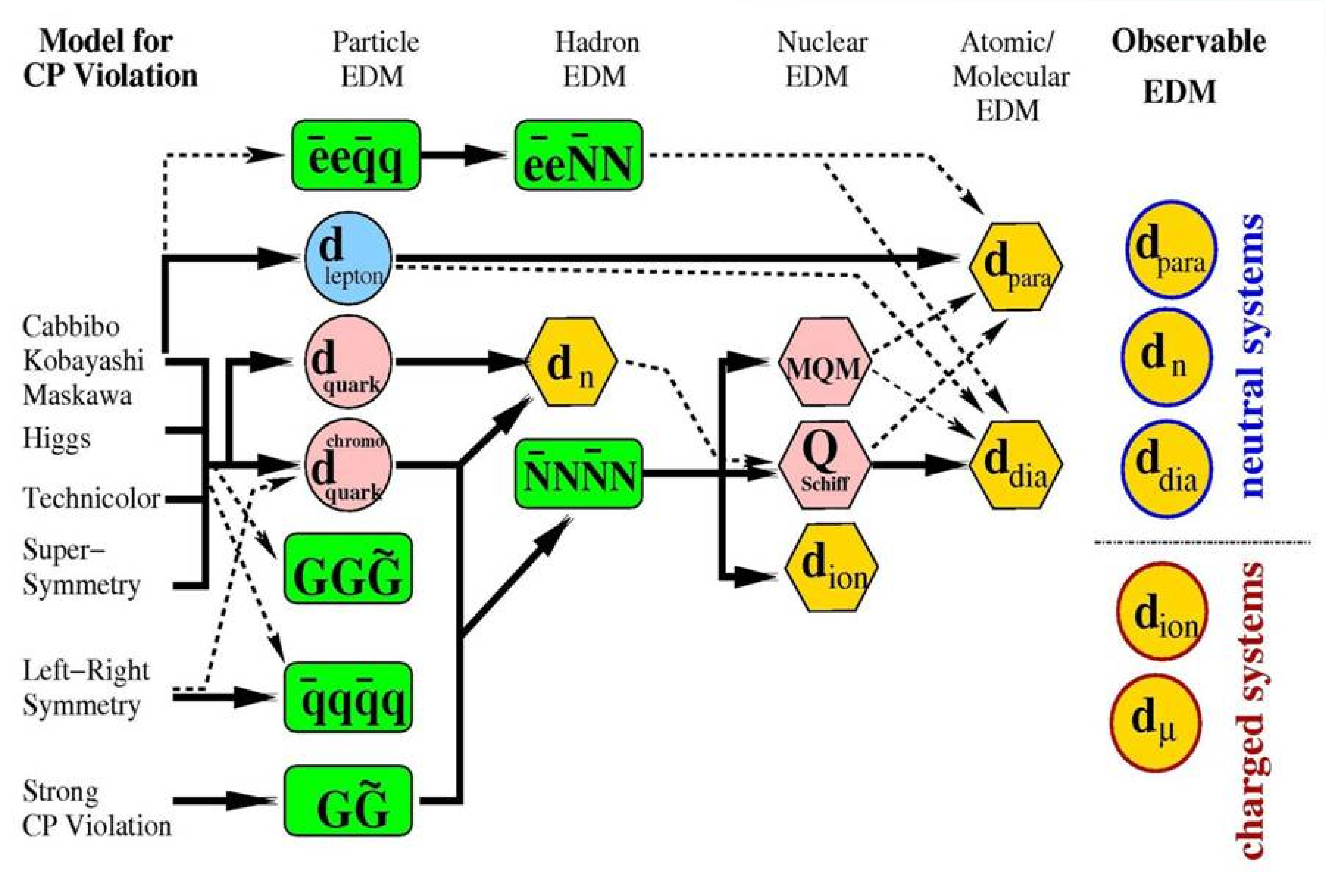
- Why so many ?

- Which is THE BEST candidate to choose ?

None is THE BEST - We need many experiments!

TRIμP

Possible Sources of EDMs

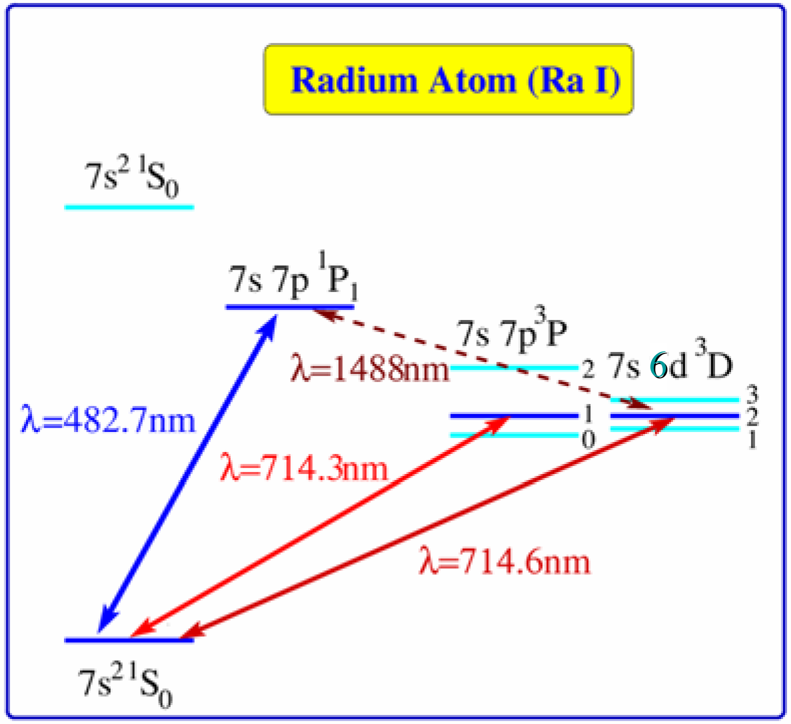


Discrete Symmetries

Permanent
Electric Dipole Moments

Radium Atom

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

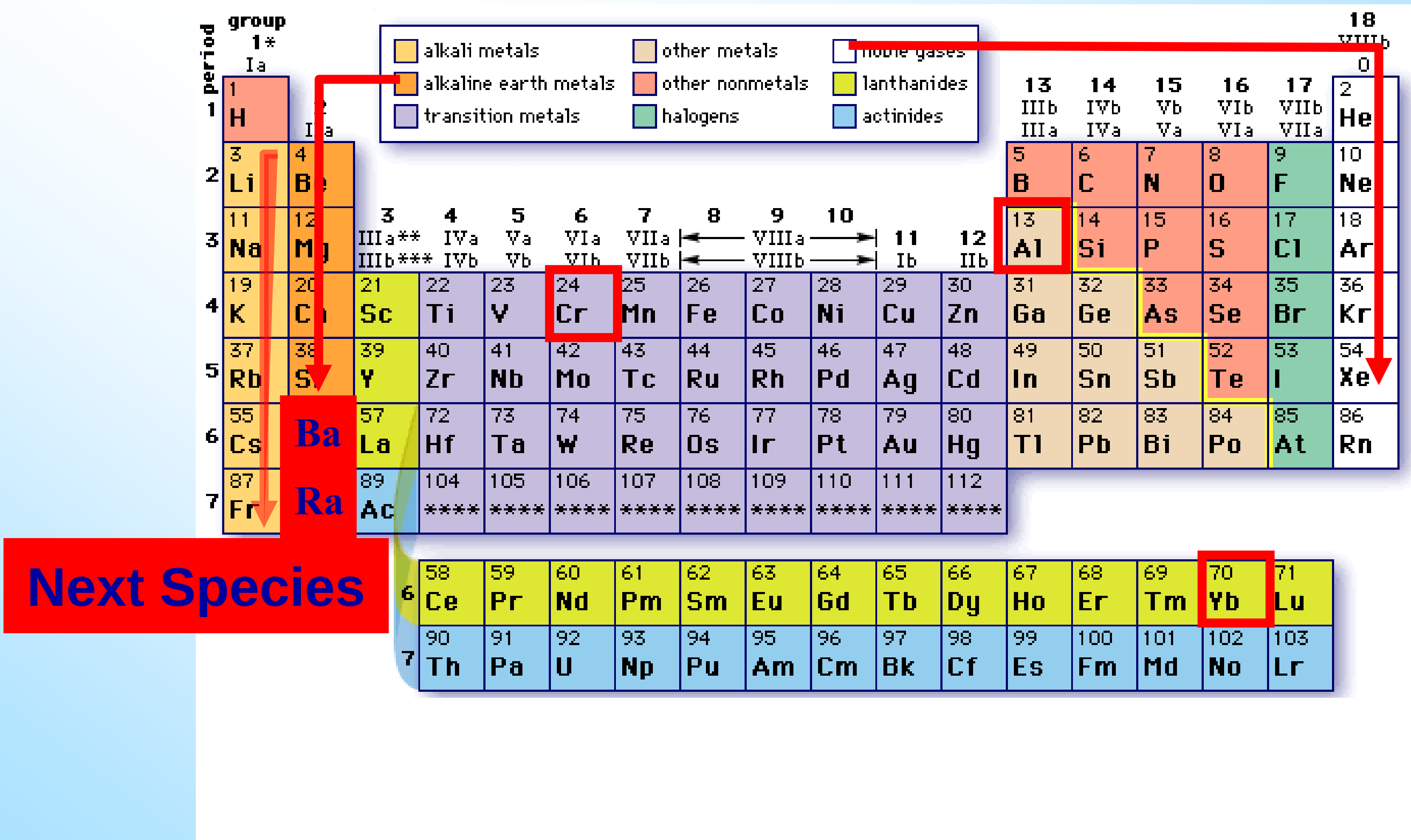
⇒ electron EDM

^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)

Laser Cooling Chart

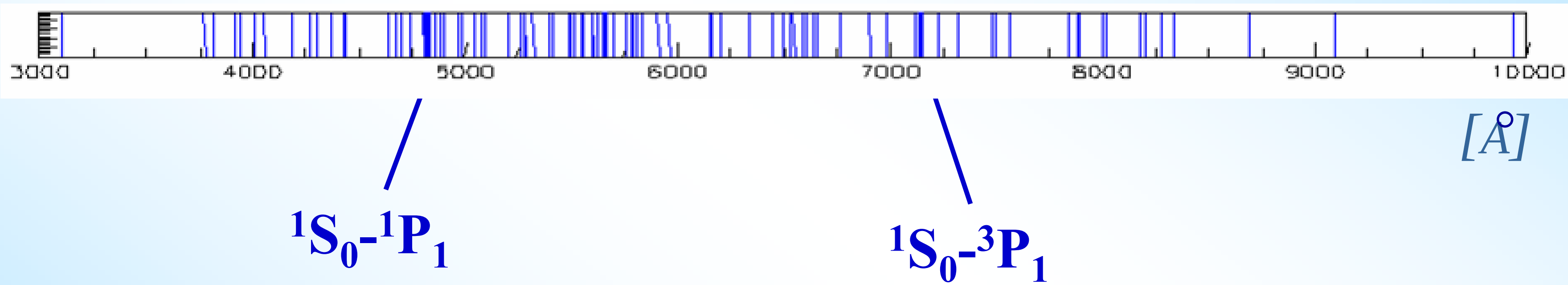


Radium Spectroscopy Data

Radium Discharge analyzed with grating spectrometer

Ebbe Rasmussen, Z. Phys, 87, 607 , 1934; Z. Phys, 86, 24, 1933.

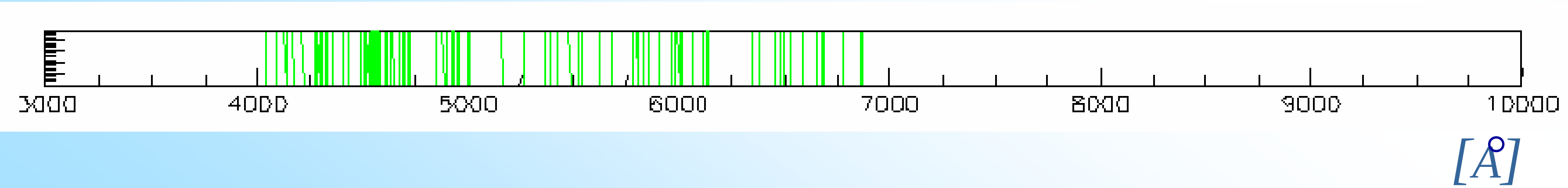
Resolution ~ 0.05 Å, *99 lines, absolute accuracy*



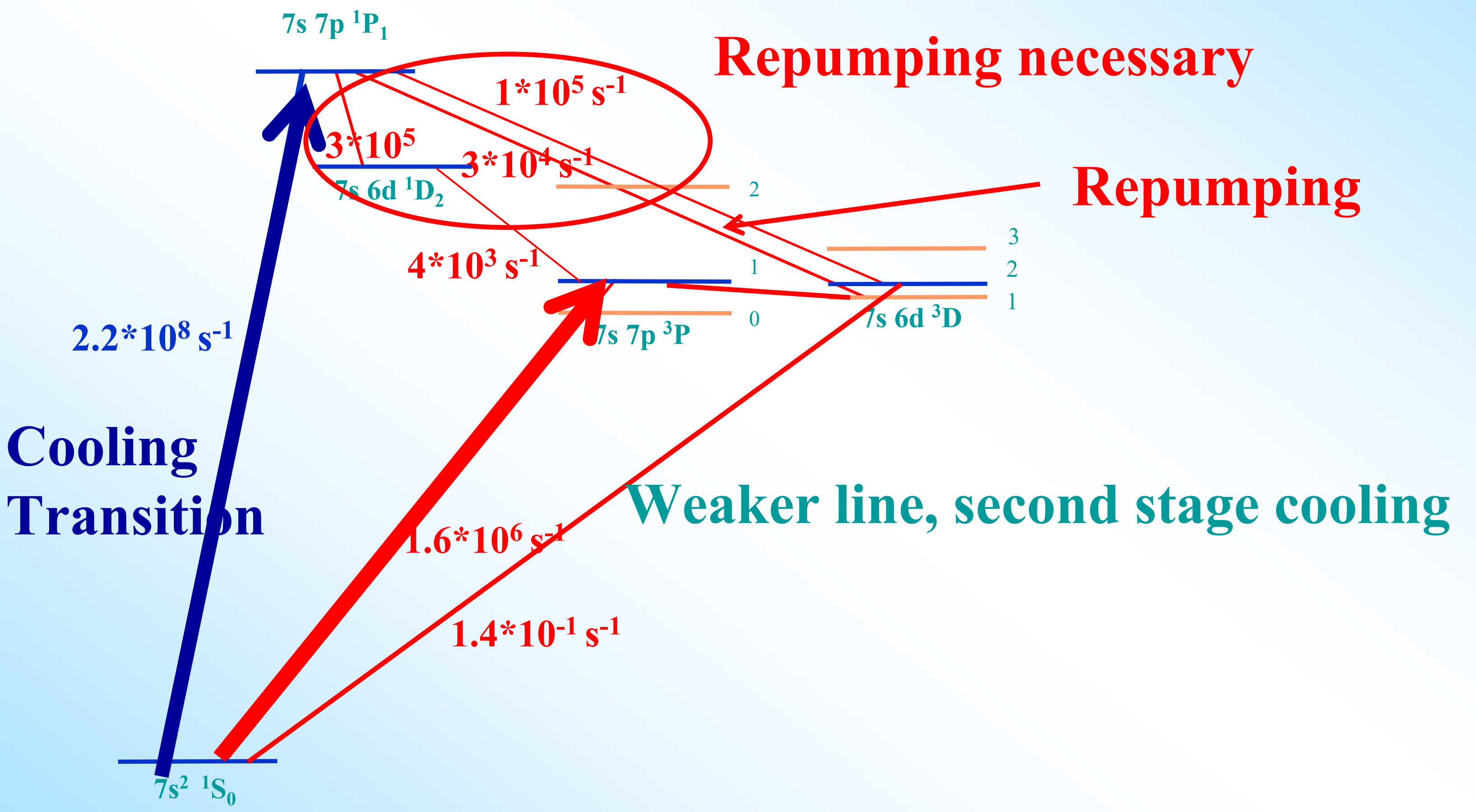
Corrections in deduced energy levels

H.N. Russel, Phys. Rev. 46, 989 (1934)

Similar to Barium ⇒ identification as alkaline earth element



Colloing & Trapping of Heavy Alkali Earth: Ra

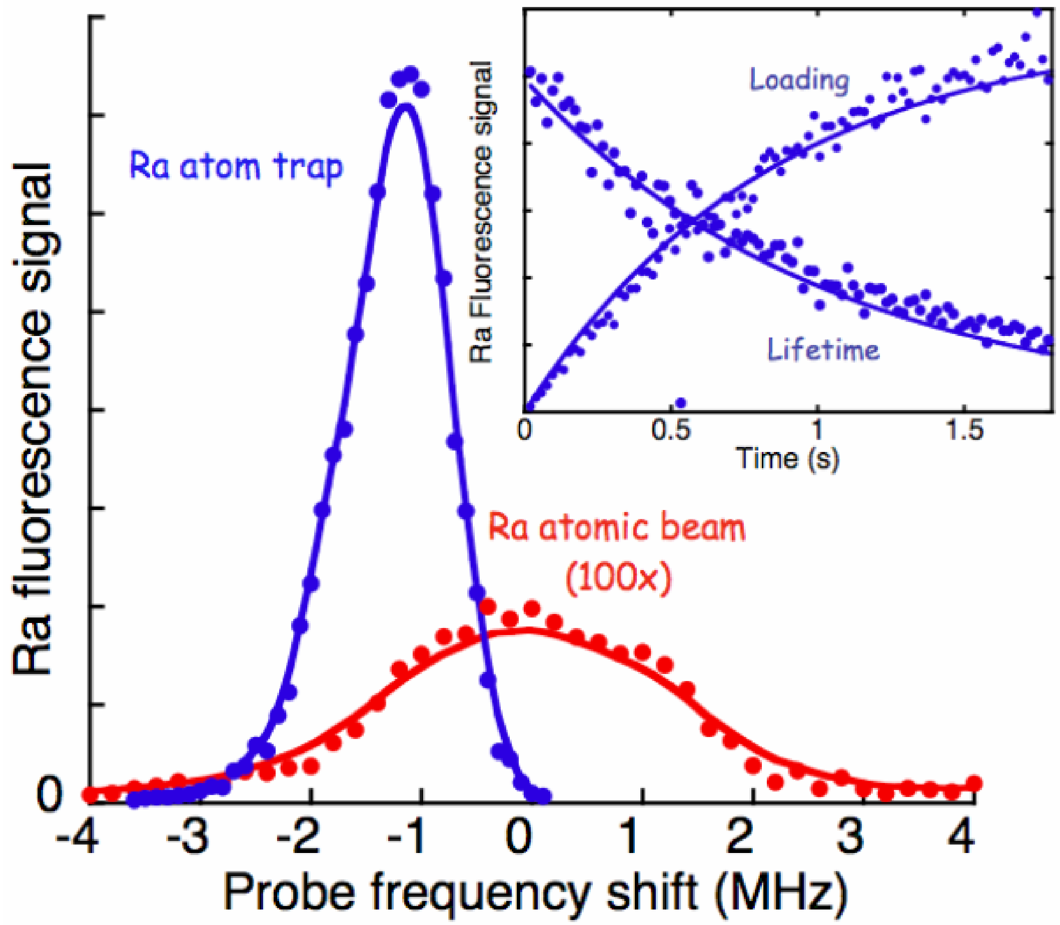


Preliminary Transition Rates as calculated
by K. Pachucky (also by V. Dzuba et al.)

L. Willmann

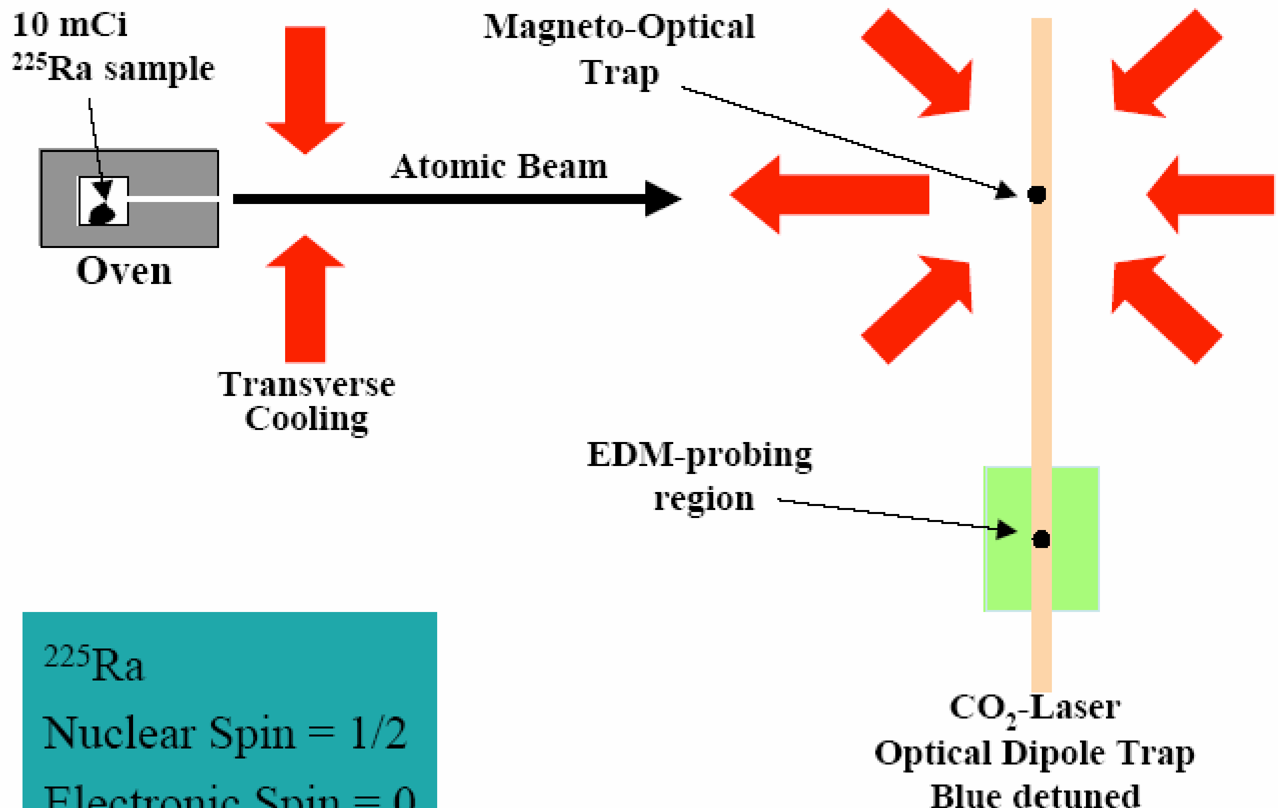
Laser-Trapping of Radium Atoms

- 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

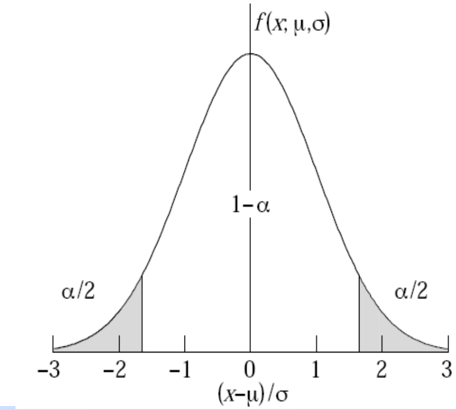
Discrete Symmetries

Permanent
Electric Dipole Moments

Charged Particles
muon
deuteron
nuclei

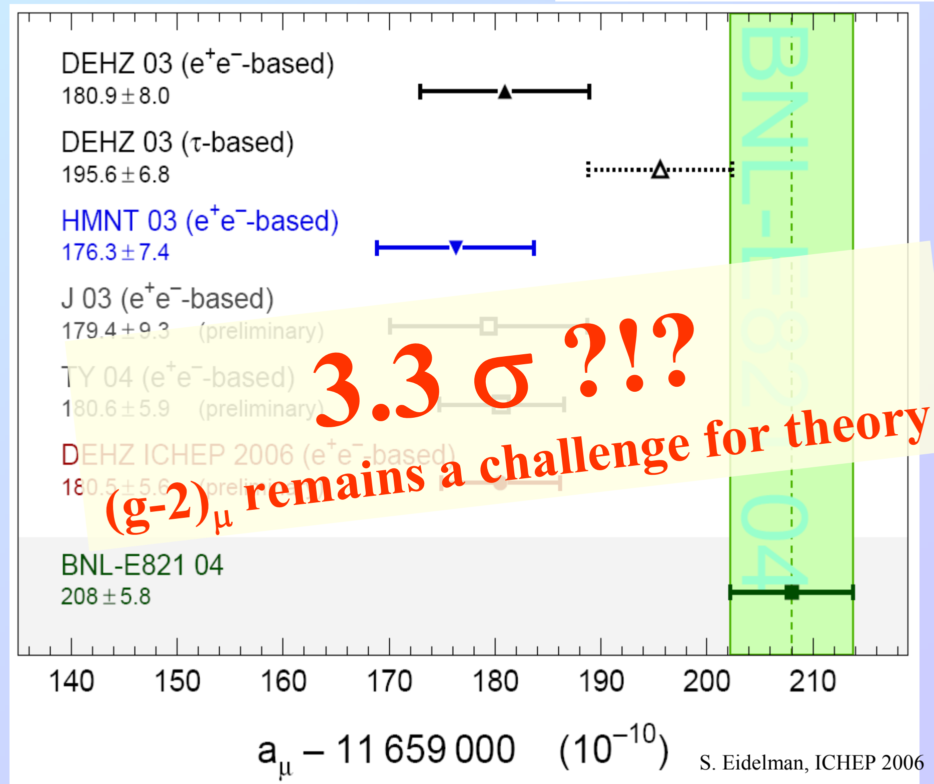
The Muon Magnetic Anomaly

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



Spin precession
in (electro-)
magnetic field

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



S. Eidelman, ICHEP 2006

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

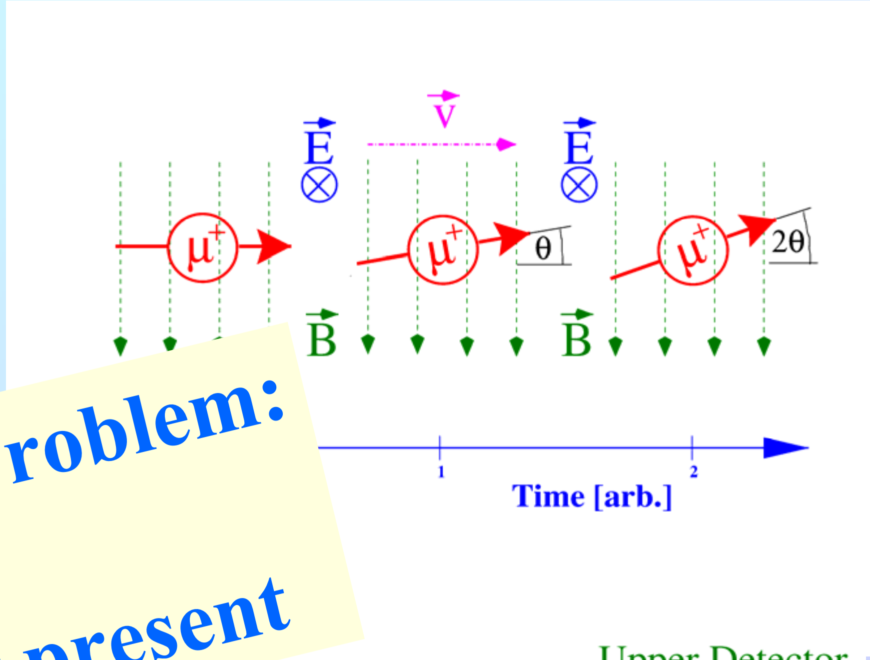
$$\mathcal{L}_{\rm DM} = \frac{1}{2}\left[D\bar{\mu}\sigma^{\alpha\beta}\frac{1+\gamma_5}{2} + D^*\bar{\mu}\sigma^{\alpha\beta}\frac{1-\gamma_5}{2}\right]\mu F_{\alpha\beta}$$

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

$$a_\mu \frac{e}{2m_\mu} = \Re D$$
$$d_\mu = \Im D$$

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

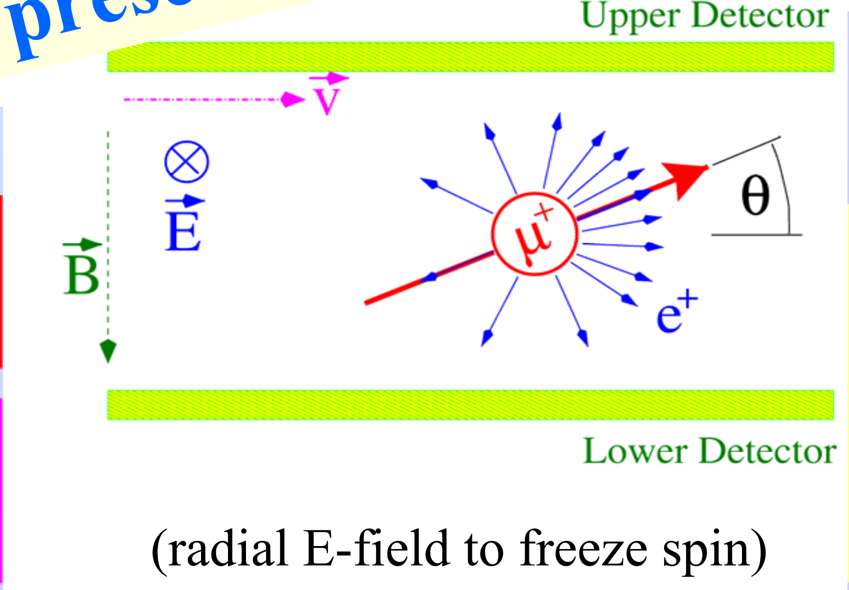
The Muon Electric Dipole Moment



One Serious Problem:
N_μ
available at present

Spin precession in (electro-) magnetic field

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



(radial E-field to freeze spin)

Muon EDM – A Parasitic Measurement

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

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.

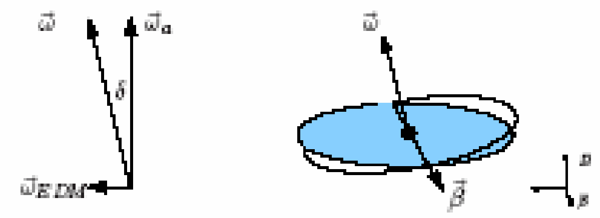


Figure 1: A muon EDM would tilt the spin precession plane.

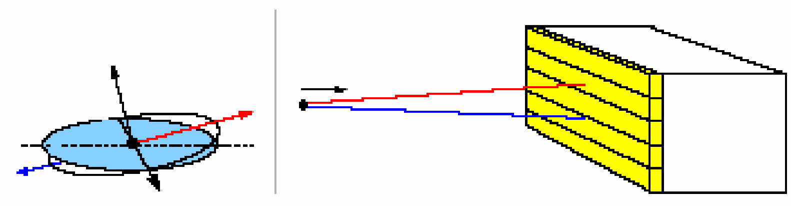
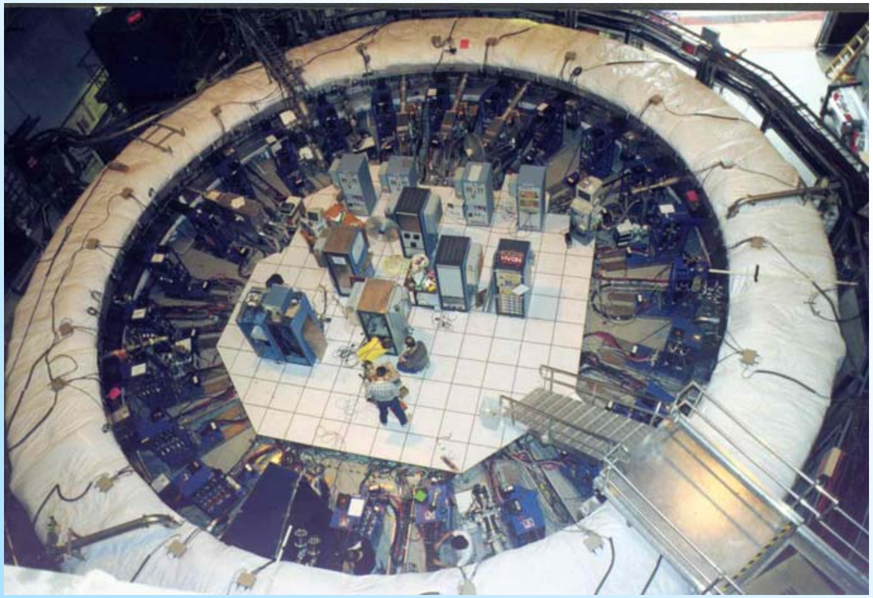


Figure 2: A tilt in the precession plane results in a vertical oscillation of hits on the detector face.

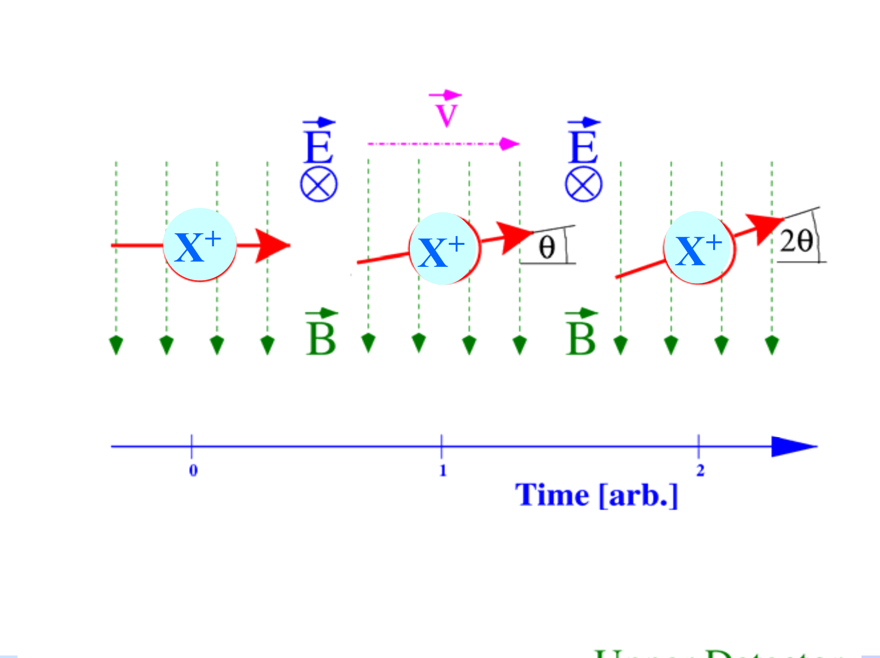


presently:

$d_\mu < 2.8 \cdot 10^{-19}$ ecm (95% C.L.)

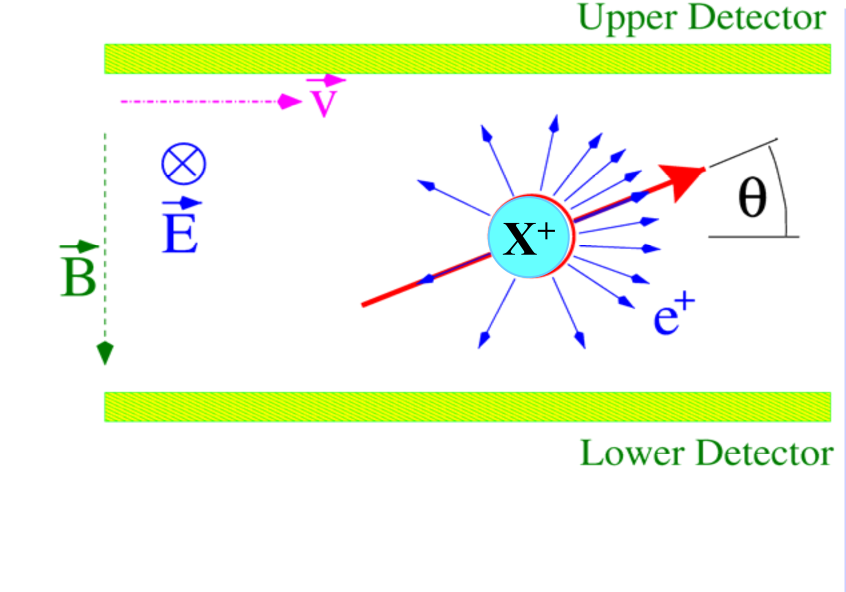
better value expected to come out soon

The Muon Electric Dipole Moment



Spin precession
in (electro-)
magnetic field

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

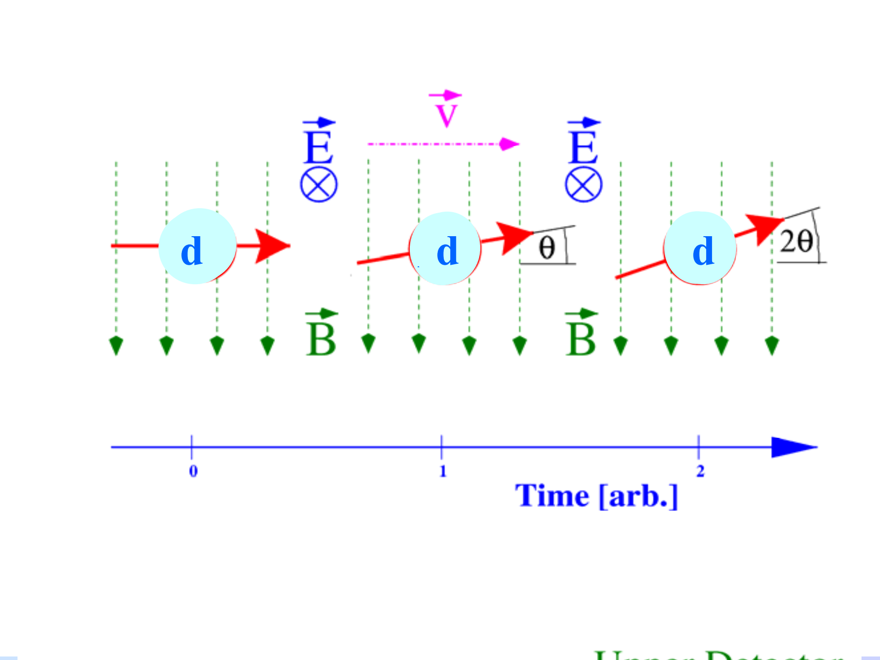


Some Candidate Nuclei for EDM in Ring Searches

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

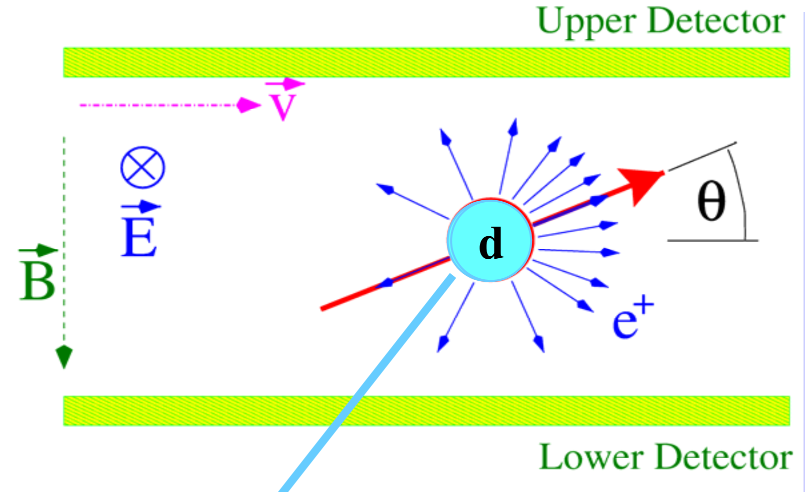
The Muon Electric Dipole Moment



Spin precession
in (electro-)
magnetic field

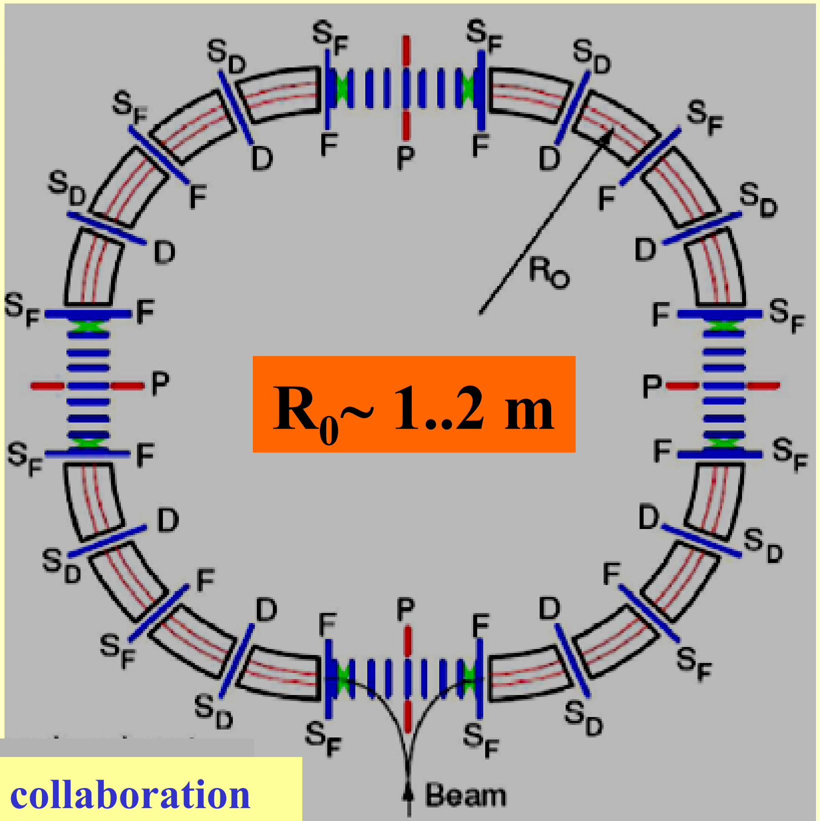
$$\vec{\omega} = \frac{e}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right]$$

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



Deuteron is stable:
Different polarimeter needed

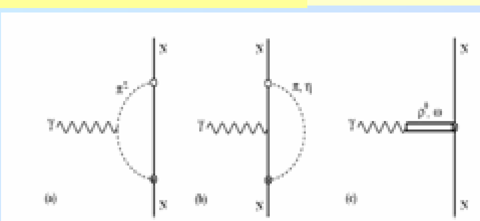
Searches for EDMs in charged particles: Novel Method invented Motional Electric Fields exploited

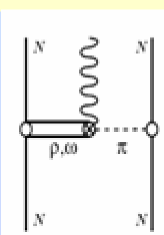


edm collaboration
⇒ C.J.G. Onderwater

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}, …**





$$d_D = -4.67 d_d^c + 5.22 d_u^c,$$

$$d_n = -0.01 d_d^c + 0.49 d_u^c$$

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

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

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

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

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 ?

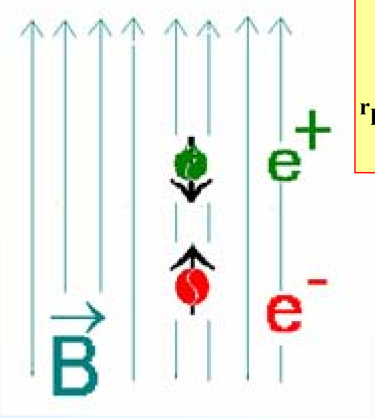
often quoted:

- 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 $\approx 10^{-27}$ GeV

Leptons in External Magnetic Field



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

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

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

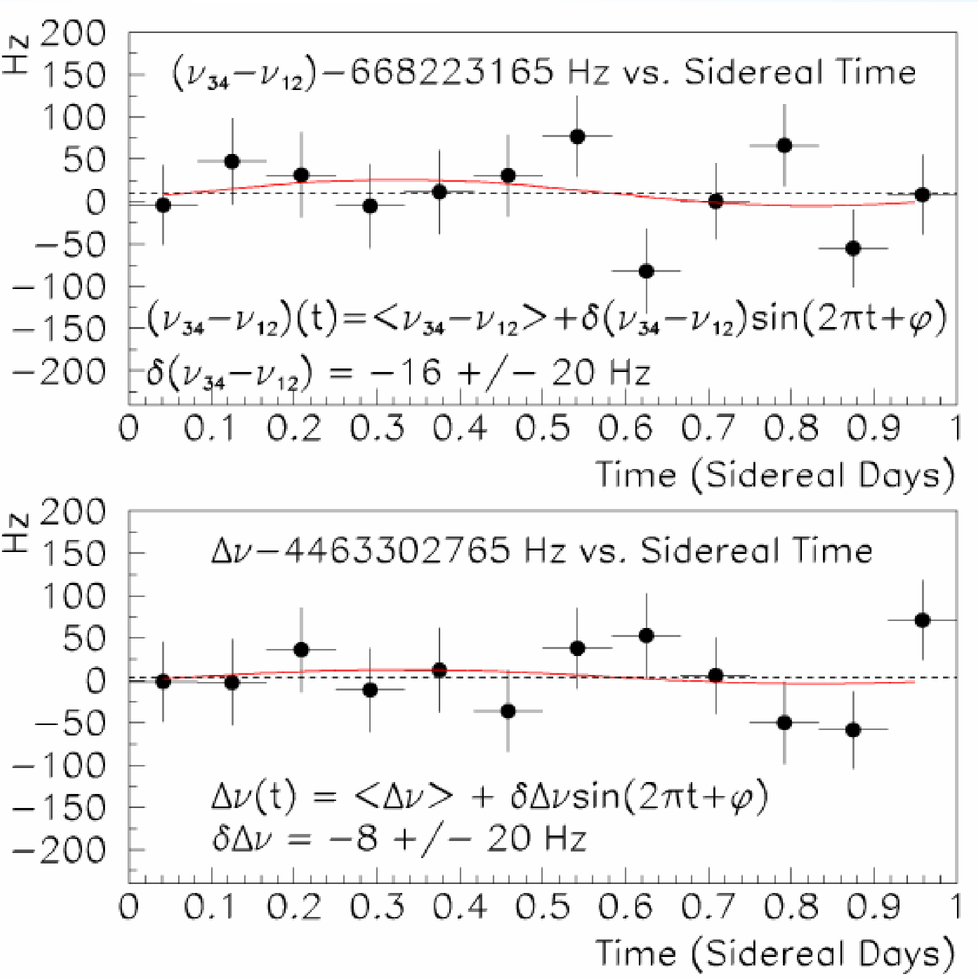
For g-2 Experiments :

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

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

(2007)

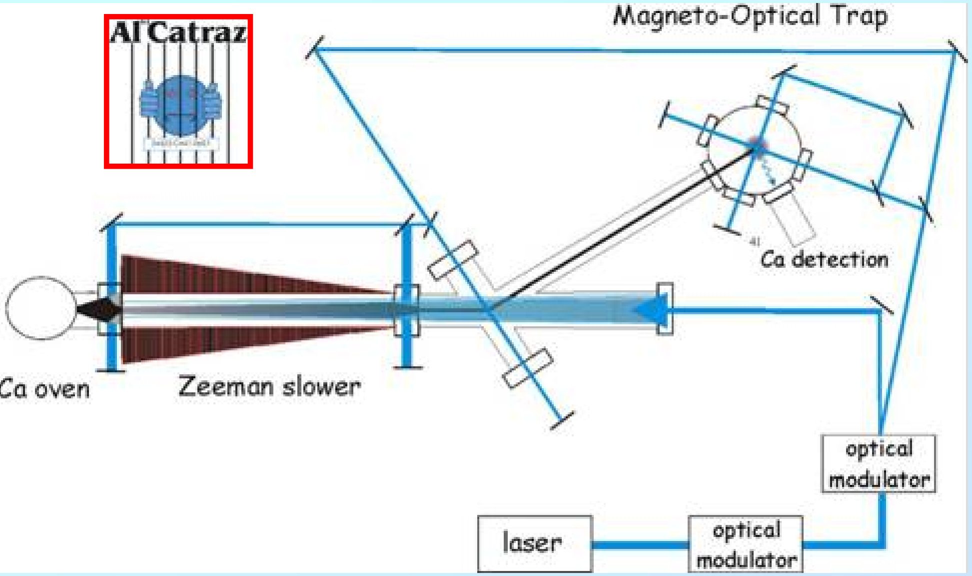
Applications of Developped Techniques

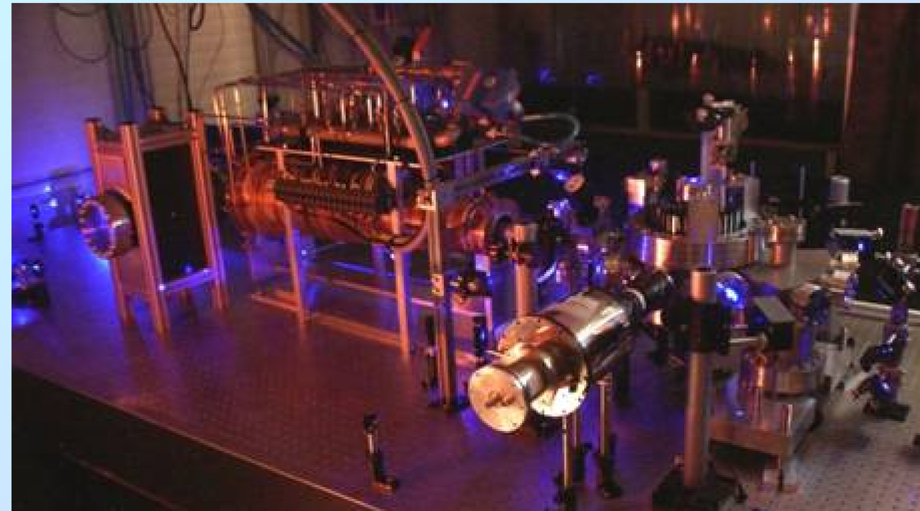
ALCATRAZ

TRIμP

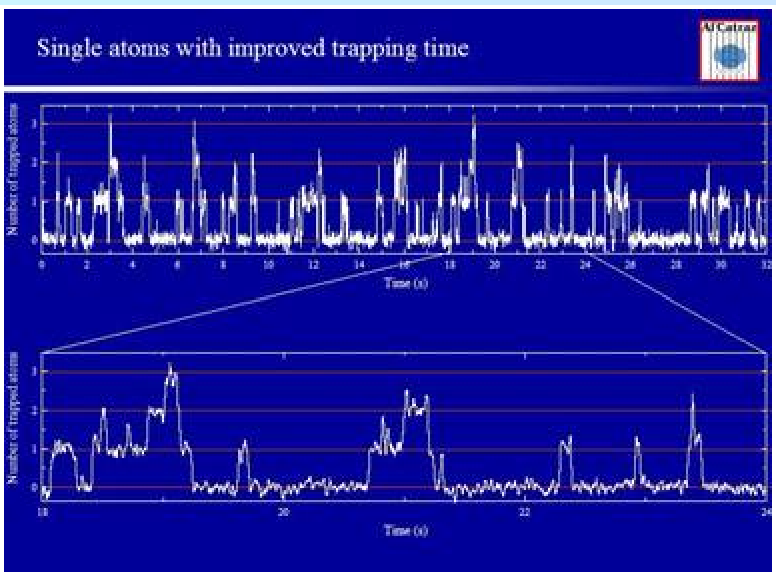
The ALCATRAZ Experiment

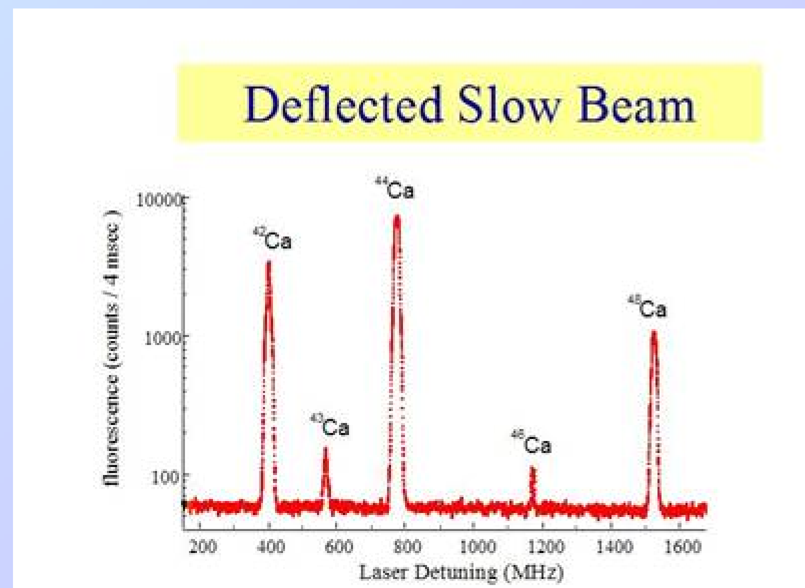
a precursor for TRIμP (R. Hoekstra, R. Morgenstern et al.) → Early Spin Off





10^{-12} sensititivity reached → working towards 10^{-14}





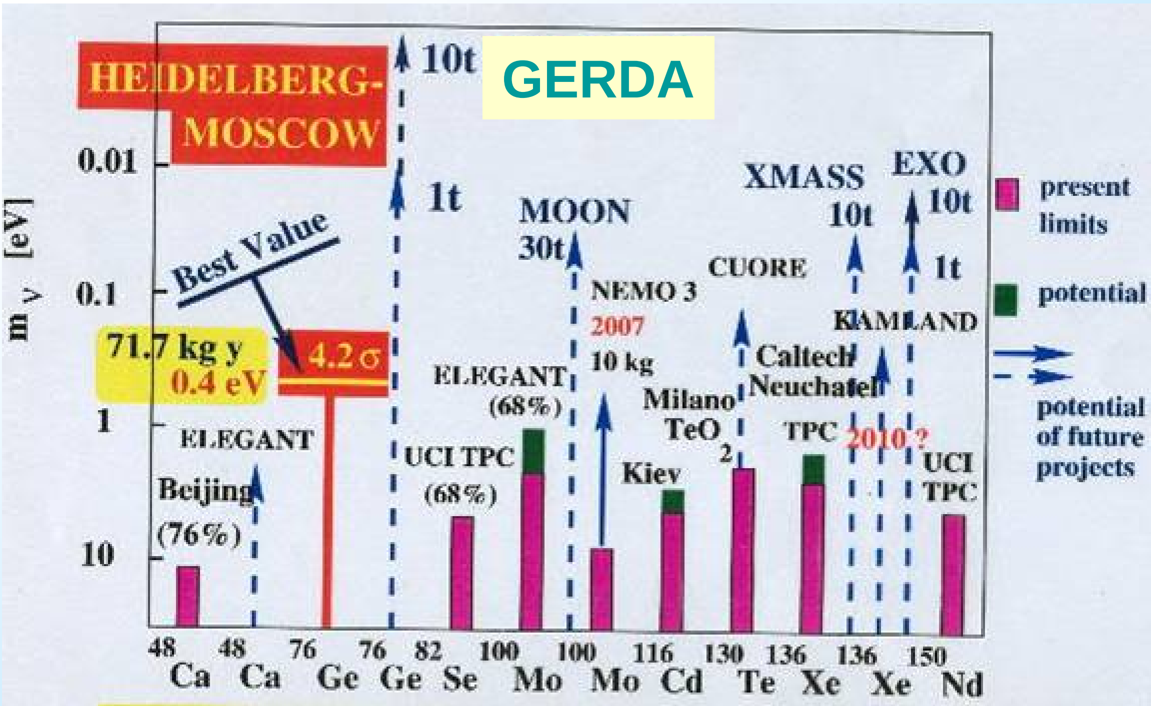
Lepton Number

0ν2β decay

Neutrinoless Double β-Decay

$$(A,Z) \rightarrow (A,Z+2) + 2e^-$$

$$1/T_{1/2} = G_{0\nu}(E_0,Z)\,|M_{GT} + (g_V/g_A)^2 \cdot M_F|^2 \langle m_\nu \rangle^2$$

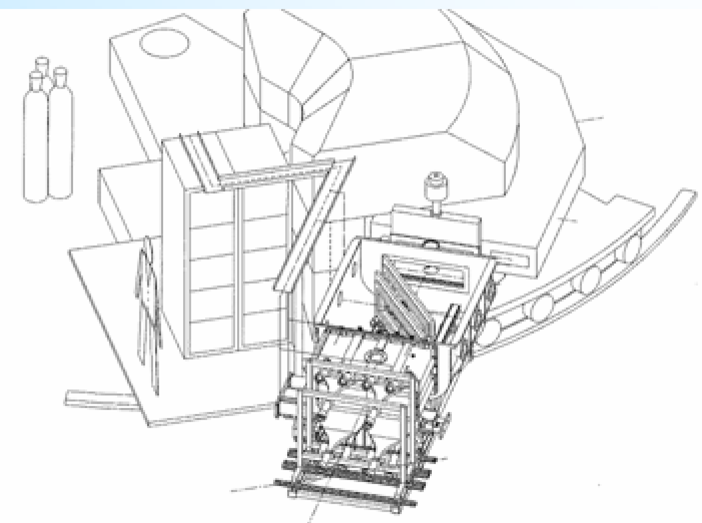


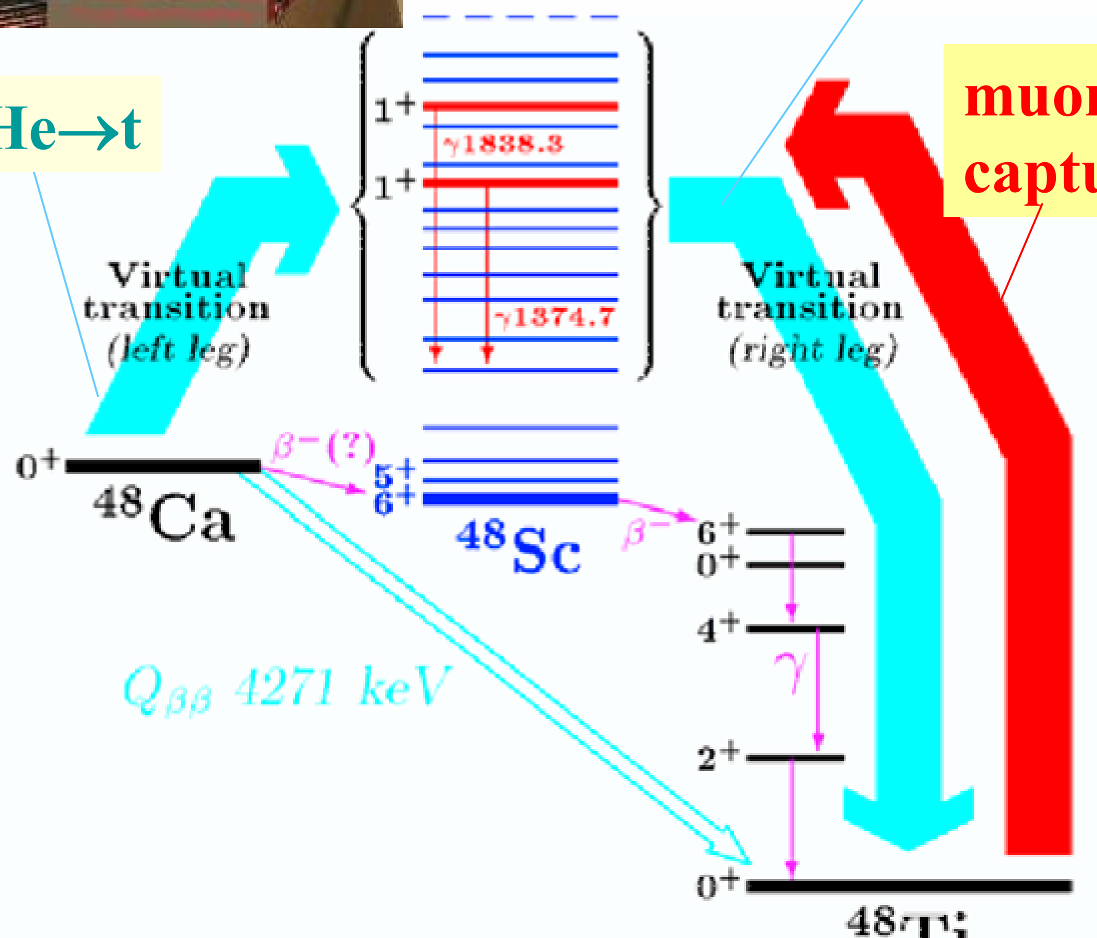
- confirmation of Heidelberg-Moscow needed
- independent experiment(s) with different technologies required
- need nuclear matrix elements

CUORICINO

KVI Contribution to 2β0ν Matrixelements

Big
Bite
Spectrometer





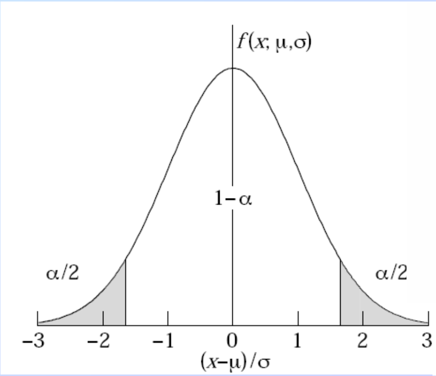
Summary

- There are **plenty of opportunities** to investigate Fundamental Interactions using **trapped and stored particles** .

- Precision Experiments are indispensable .

- Experiment and Theory both needed.

- Systematics and Statistics crucial.

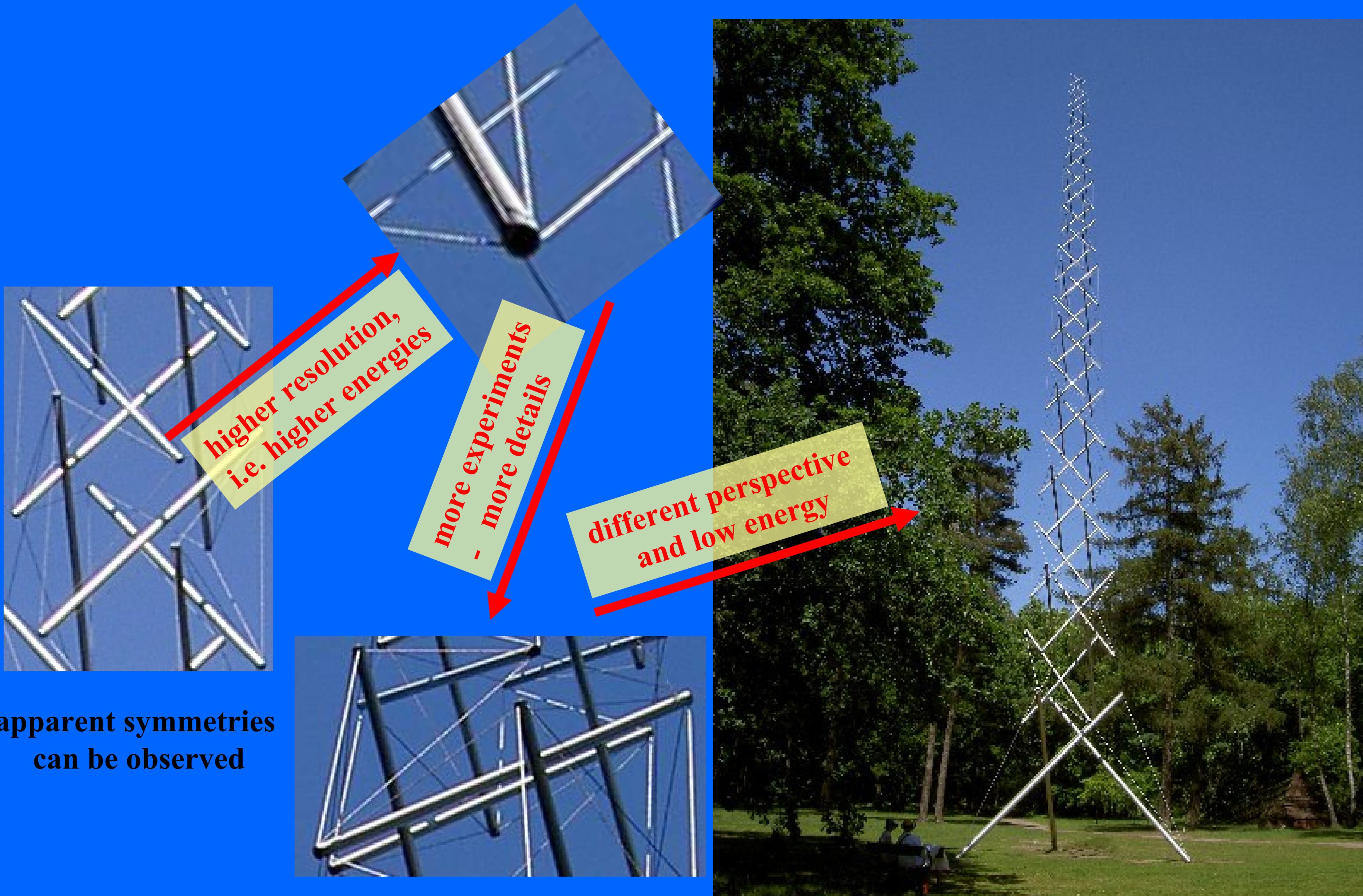


α	δ
0.3173	1σ
4.55×10^{-2}	2σ
2.7×10^{-3}	3σ
6.3×10^{-5}	4σ
5.7×10^{-7}	5σ
2.0×10^{-9}	6σ

- New facilities promise progress.

- Experiments require **LONG TERM COMMITMENTS** and **RIGOROUS SUPPORT** after **CAREFUL SELECTION.**

Thank YOU !



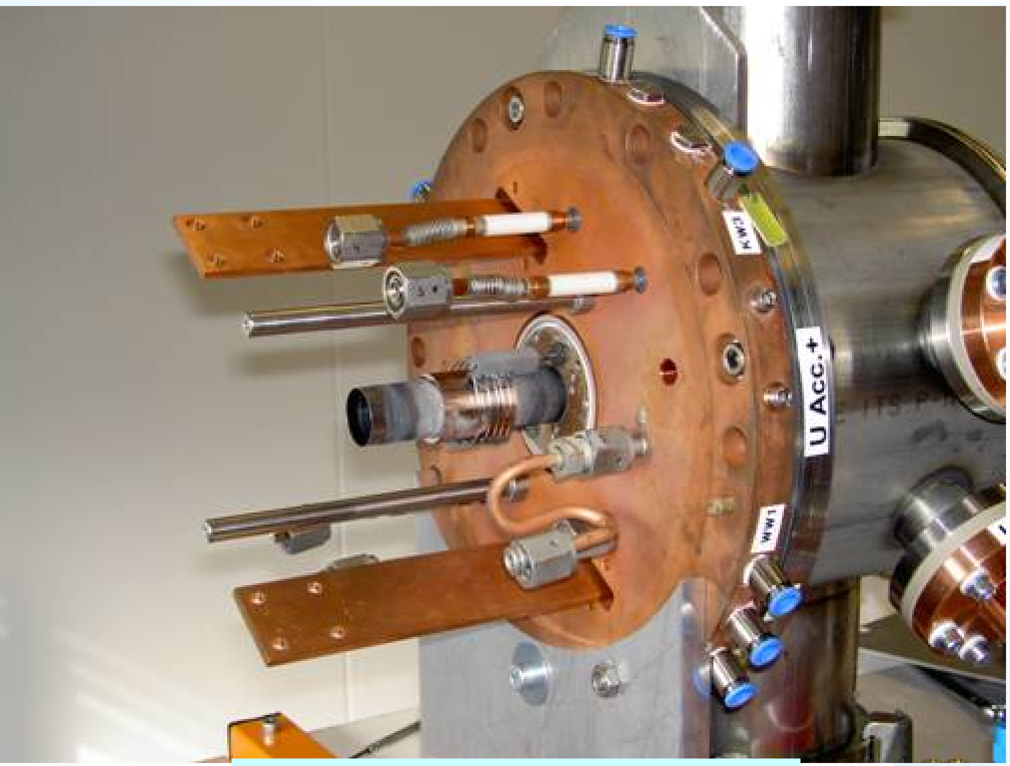
apparent symmetries can be observed

TRIμP Ion Catcher

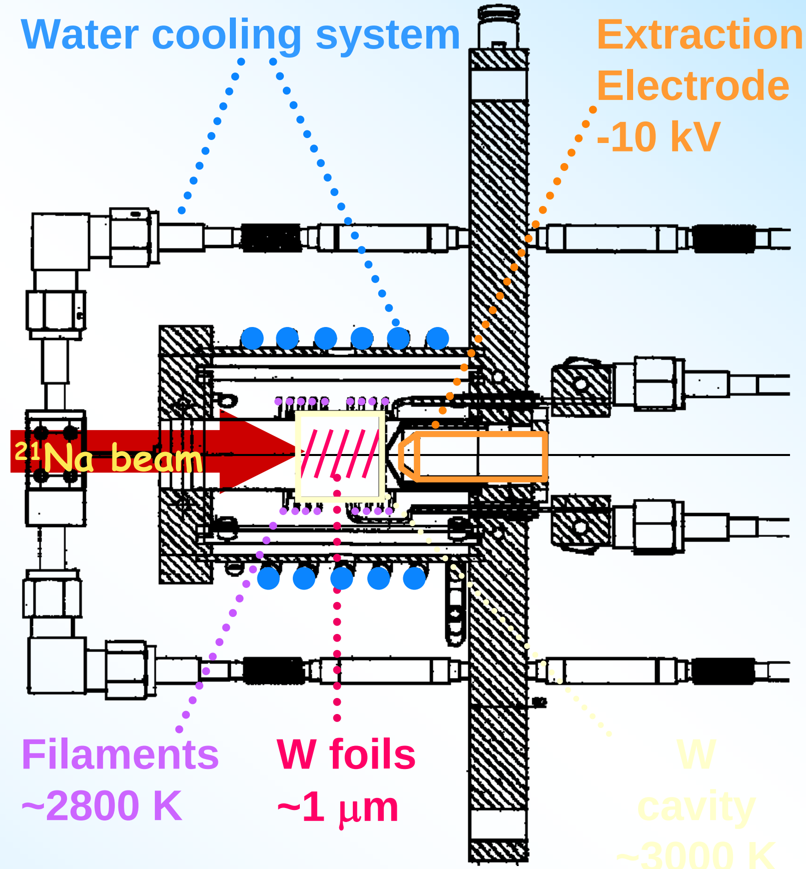
High efficiency for Na isotopes: Thermal Ioniser

Gas stopper – a generic solution

Recent results on stopping in cooled Helium gas (RIASH, P.Dendooven → FOM projectruimte)



O. Dermois, L. Huisman



First Thermal Ionizer Results