KVI

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Physics at the TRImP Facility of KVI

Klaus Jungmann, KVI, University of Groningen

- **KVI and its Research**
- **Fundamental Symmetries and Forces**
  - **Searches for New Interactions**
  - **Standard Model and Extensions**
  - **Precision Experiments**
  - **Novel Techniques**
- **TRIμP Facility @ KVI**

⇒ **Some Examples only**
  - **Discrete Symmetries C, P, T, CP, CPT**
  - **Nuclear β-decays**
  - **EDMs**
  - **Parity Violation**
  - **Applications**

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Kernfysisch Versneller Instituut Groningen

I. Atomic and Sub-Atomic Physics:
Fundamental Forces and Symmetries
II. Applications of developed tools and metods
Radiation – Matter interactions.

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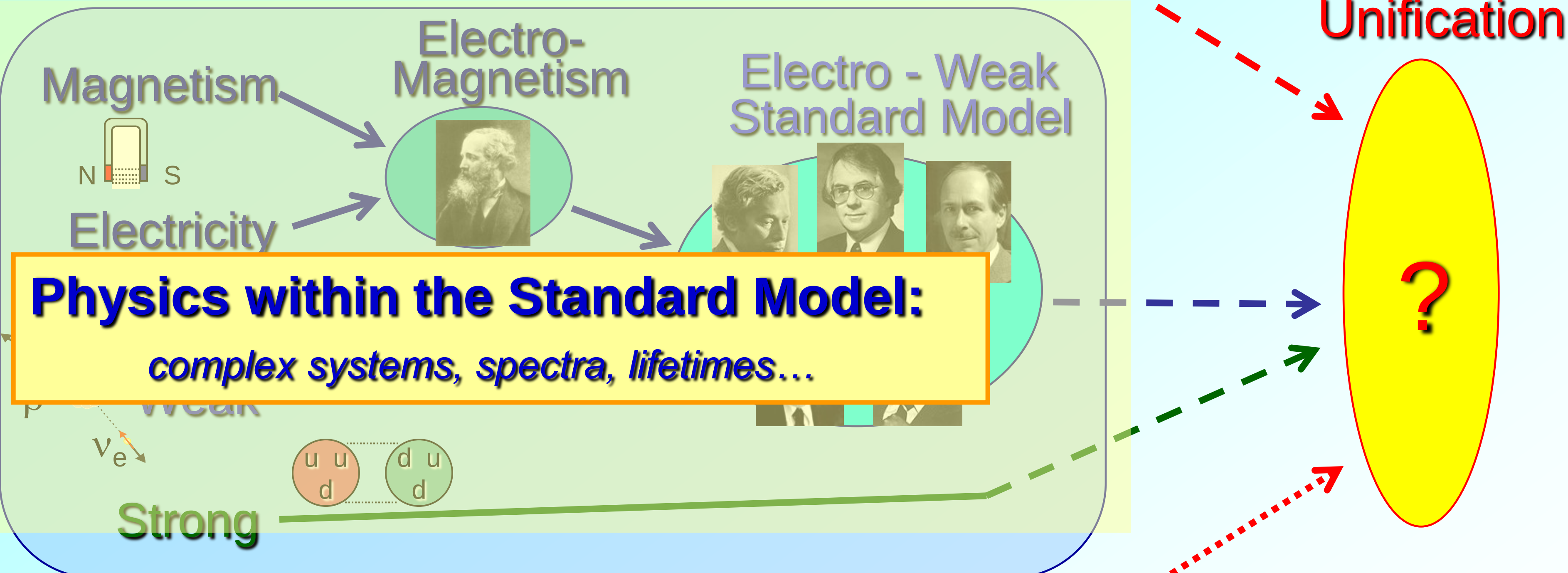
Standard Model in Particle Physics

Gravitation



Physics within the Standard Model:

complex systems, spectra, lifetimes…

Speculative Models:

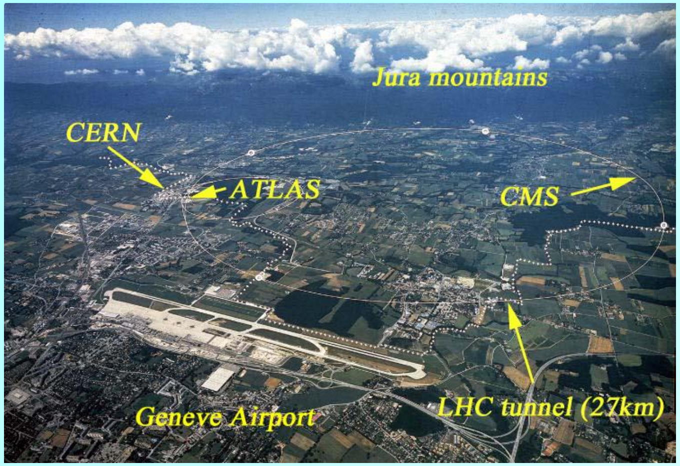
Supersymmetry, Cold dark matter, Tachyons, Radiative muon generation, Technicolor, Leptoquarks, Extra gauge bosons, Extra dimensions, LeftRight Symmetry, Compositeness, Lepton flavour violation, ….

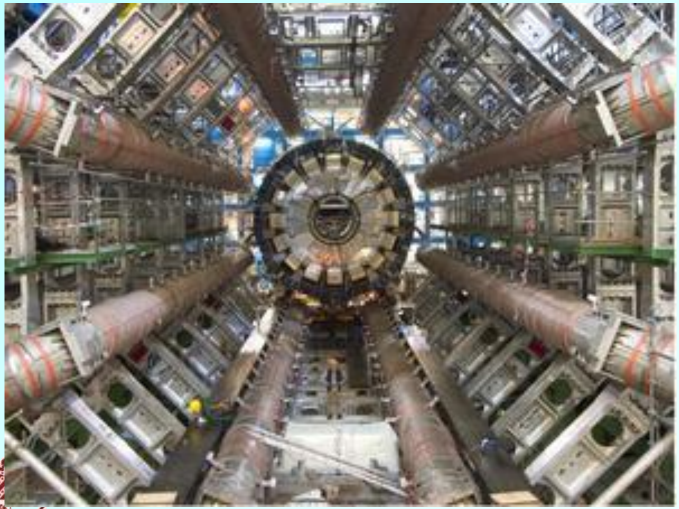
$\Rightarrow$ No Status in Physics , yet: “Not Even Wrong”

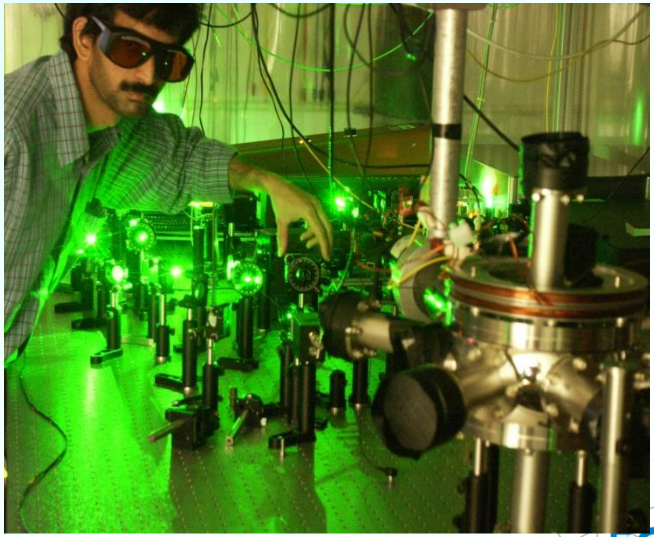
Experiments at the Frontiers of Standard Theory

Direct Search Frontier

Precision Frontier







⇔

complementary approaches

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TRIμP Physics Programme

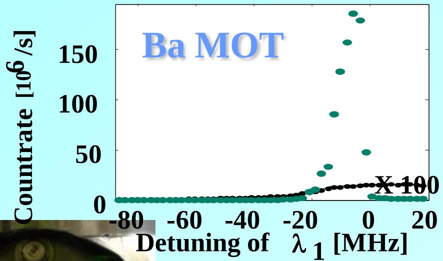
CP – violation:

EDMs

Ba/Ra – atom

deuteron

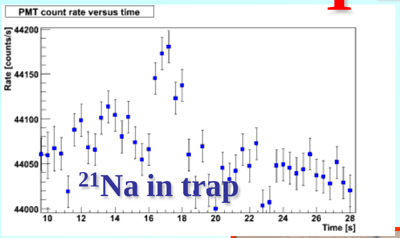
NWO VIDIs: GO, LW

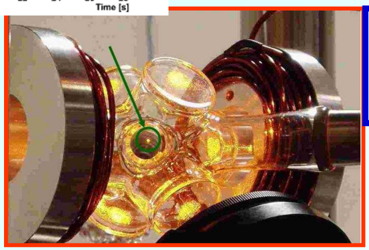


T – violation:

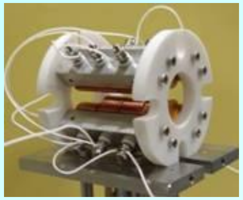
β-decay

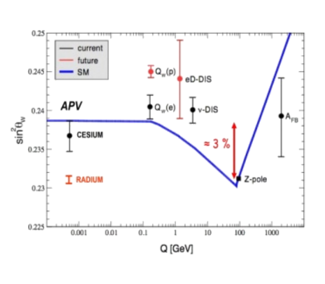
^{21}Na, ‘a’ & ‘D’ coefficients





TRIμP original EU R&D



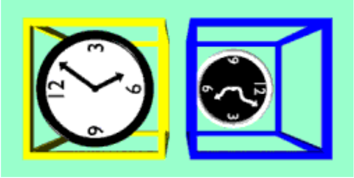


Atomic P – violation

Ra Single Ion

$\sin^2 \theta_W$

Projectruimte: RGET, KJ
NWO VENI: BS
Toptalent: OV



Lorentz/CPT - violation:

- **Weak Interactions**

Projectruimte: GO & RGET

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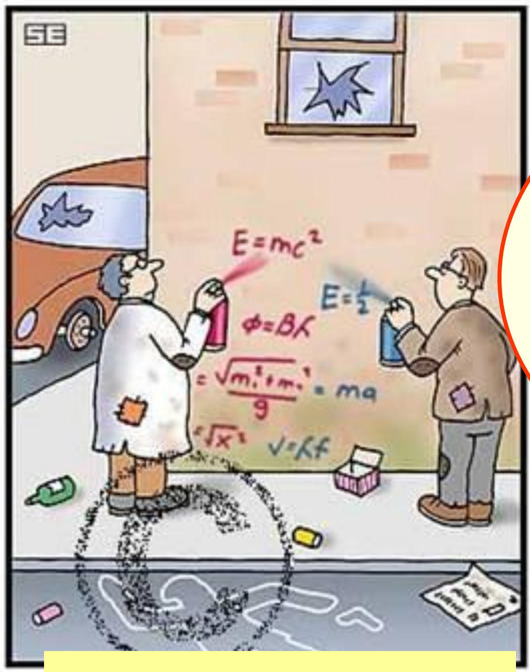
Trapped Radioactive Isotopes – µicrolaboratories for fundamental Physics

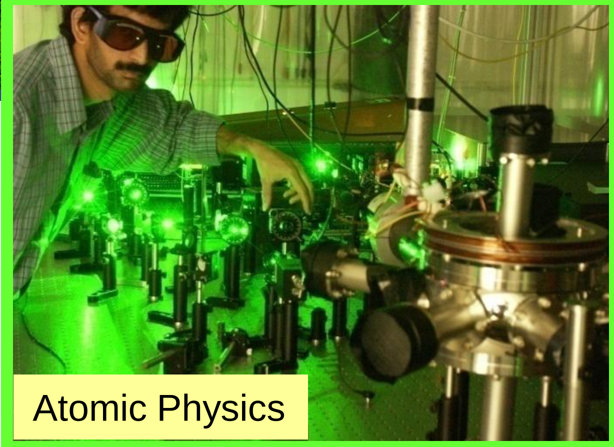


TRIµP

New Dedicated Facility

joins strengths @ KVI

- Fundamental Interactions
- Discrete Symmetries



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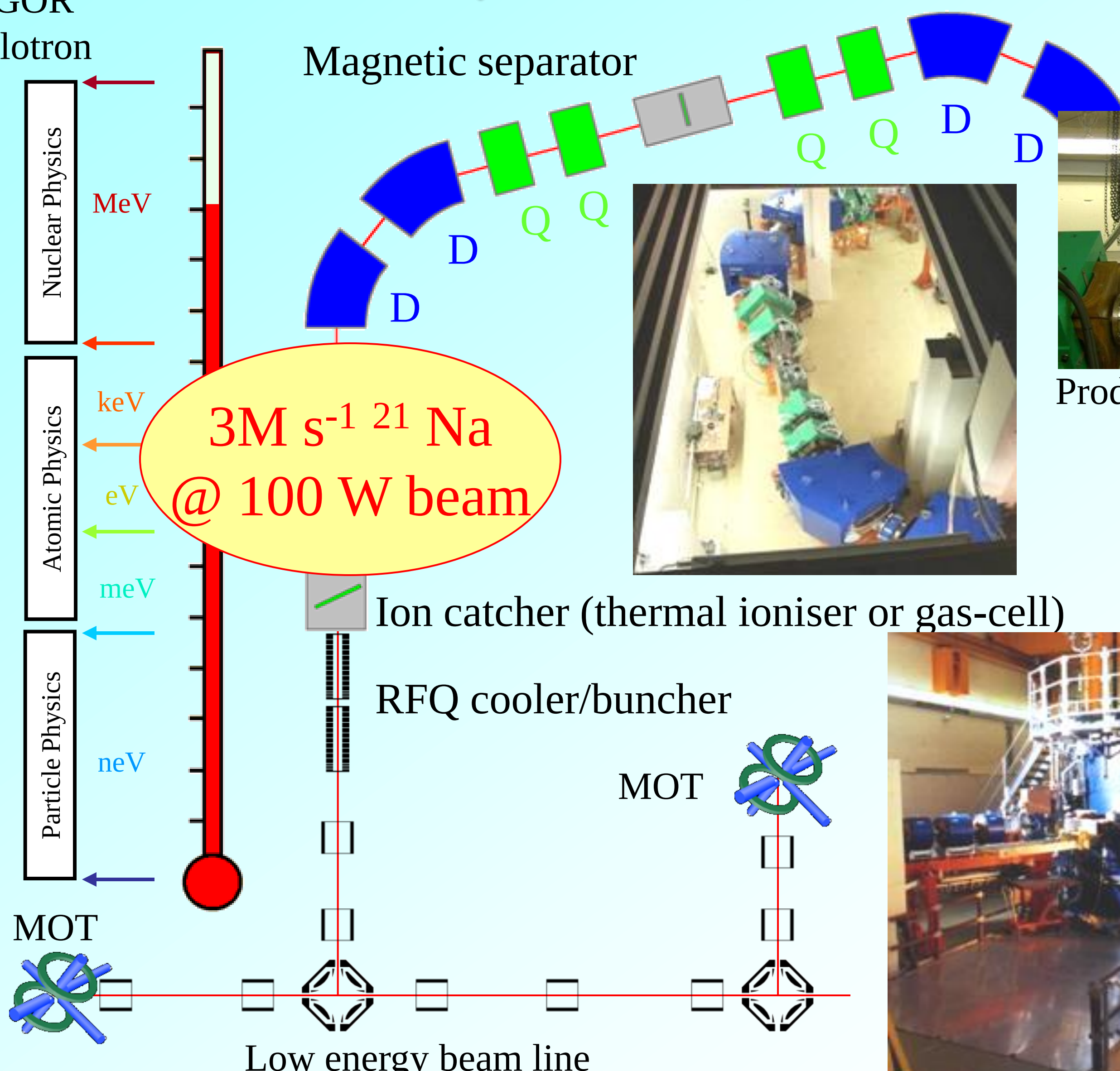
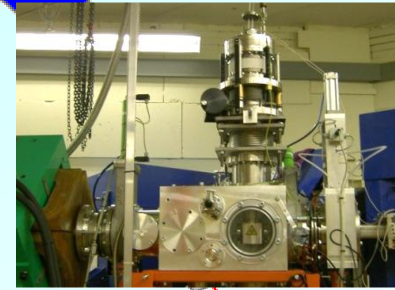
TRIμP Facility

AGOR cyclotron

- Production Target
- Magnetic Separator
- Ion Catcher
- RFQ Cooler
- MOT

Beyond the Standard Model TeV Physics



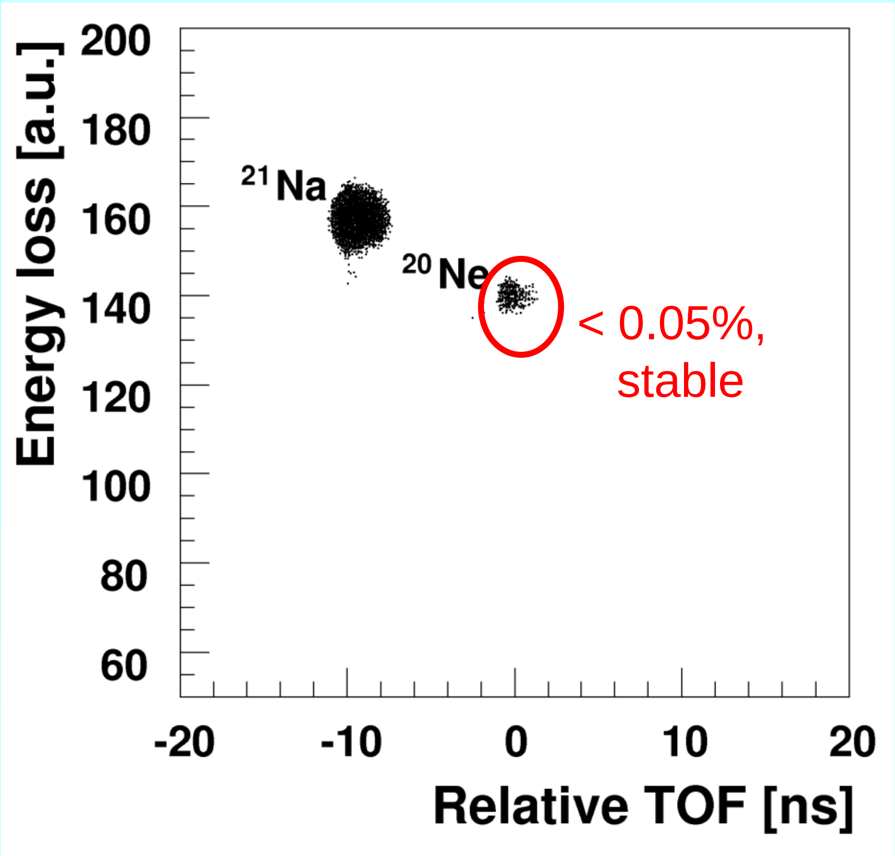


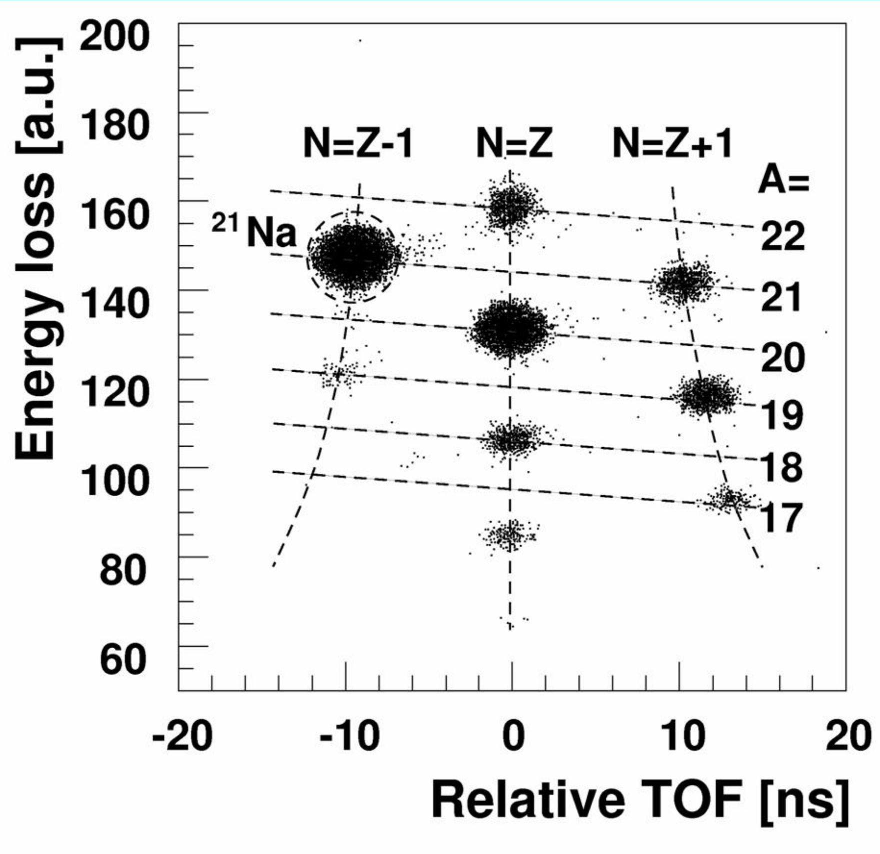
Production target

AGOR

TRIμP

Separator





Yield of ^{21}Na at the focal plane: $3 \cdot 10^6$/100 W {@ 1 atm H_2}

Now achieved: > 99% ^{21}Na

$^{20}Ne + {}^{2}H \rightarrow {}^{21}Na + n$

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Other isotopes produced: ^{8}B, ^{12}N, ^{12}B, ^{19}Ne, ^{20}Na, ^{22}Mg, ^{42}Ti, $^{212-214}$Ra

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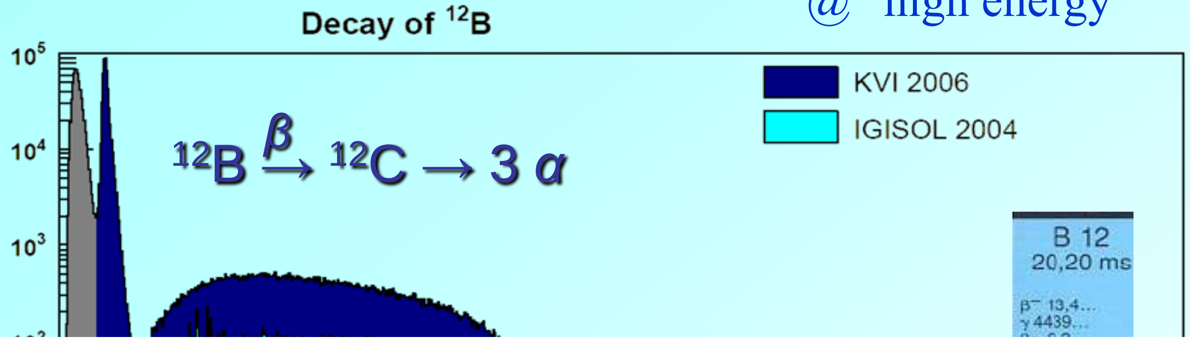
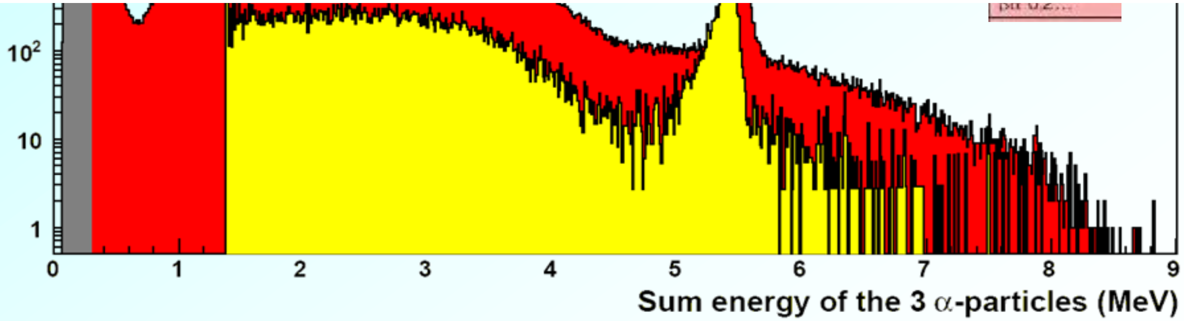
First Completed Experiment

@ "high energy"



	^{12}B decay		^{12}C level			^{12}N decay		
	B.R. (%)	log(ft)	E (MeV)	Γ (keV)	J^π, T	log(ft)	B.R. (%)	
	97.22(30)	4.066(2)	g.s.	-	0^+; 0	4.120(3)	94.55(60)	
98.16(4)	1.201(17)	5.136(6)	4.43891(31)	$10.8(6) \times 10^{-6}$	2^+; 0	5.149(7)	1.898(32)	96.20(10)
0.53(3)	1.3(4) 1.7(5) 1.5(3)	4.13(9)	7.6542(15)	$8.5(10) \times 10^{-3}$	0^+; 0	4.34(6)	2.2(6) 3.0(5) 2.7(4)	*1.26(6)*
0.106(5)	0.13(4) 0.07(2) 0.08(2)	4.2(2)	10.3(3)	3000(700)	$(0^+,2^+)$; 0	4.36(17)	0.85(6) 0.44(16) 0.46(15)	0.52(3)
	?		12.710(6)	$18.1(28) \times 10^{-3}$	1^+; 0	3.52(14)	0.31(12)	
$2.95(15) \times 10^{-4}$	-		15.110(3)	$43.6(13) \times 10^{-3}$	1^+; 1	3.30(13)	$4.4(15) \times 10^{-3}$	*0.119(6)*



H. Fynbo (DK) *et al.*: quantitative implantation in active zone of semiconductor @ KVI

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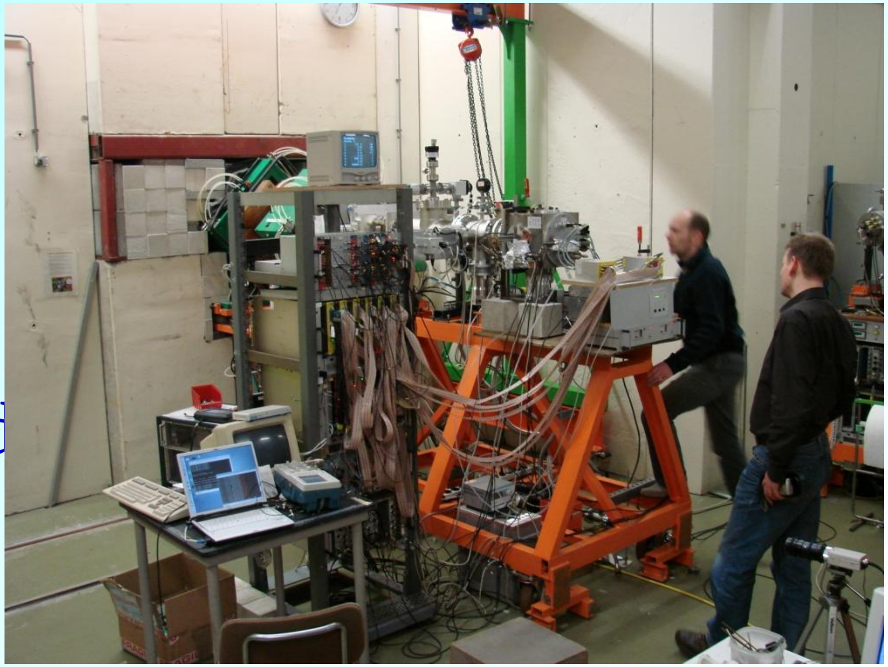
Precise ν spectrum of ^{8}B

R. Raabe (F) *et al.*

Method:

- **Stopping ^{8}B in pixel detector**
- **Measuring of 2 α spectrum from tagged pixel**
- **Best data on tape**



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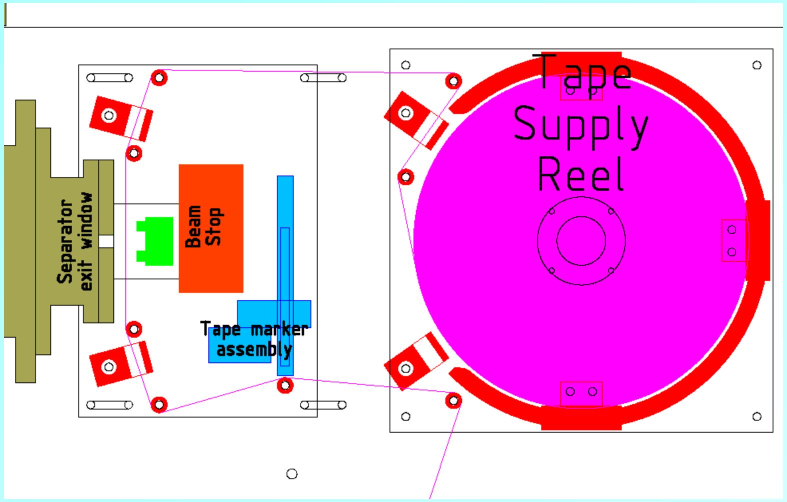
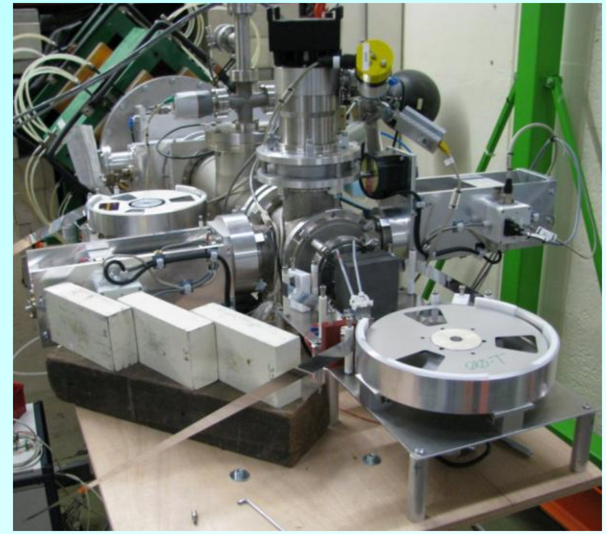
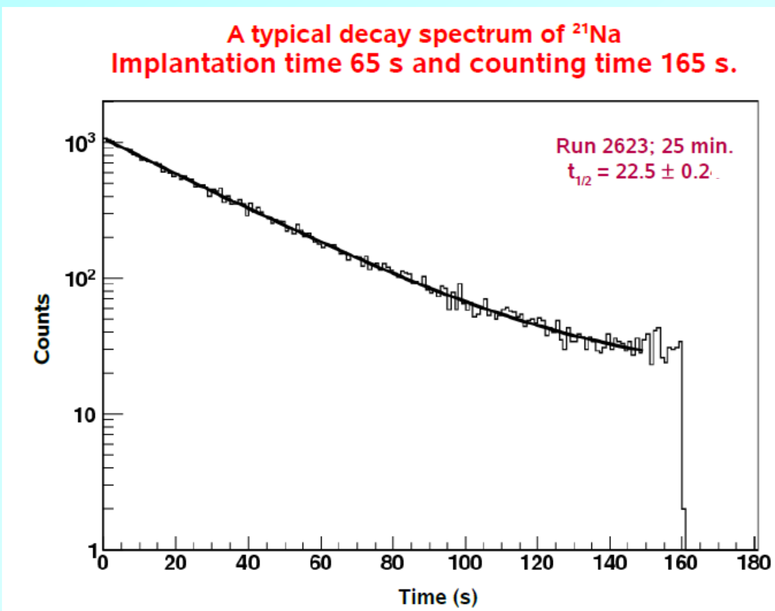
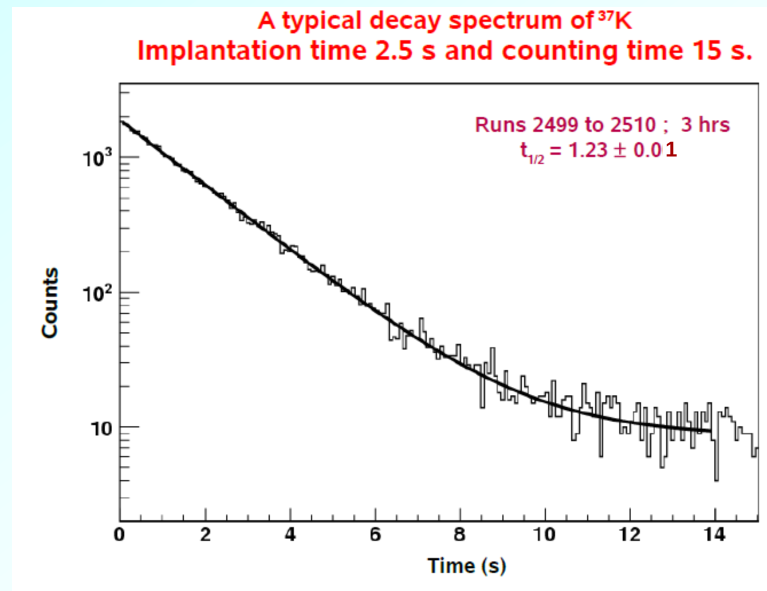
Lifetimes of Relevance for β-decay and CKM Tests









^{19}Ne, ^{21}Na, ^{37}K – work in progress using new Tape device,

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A.Young (USA), H. Wilschut *et al*.(2009)

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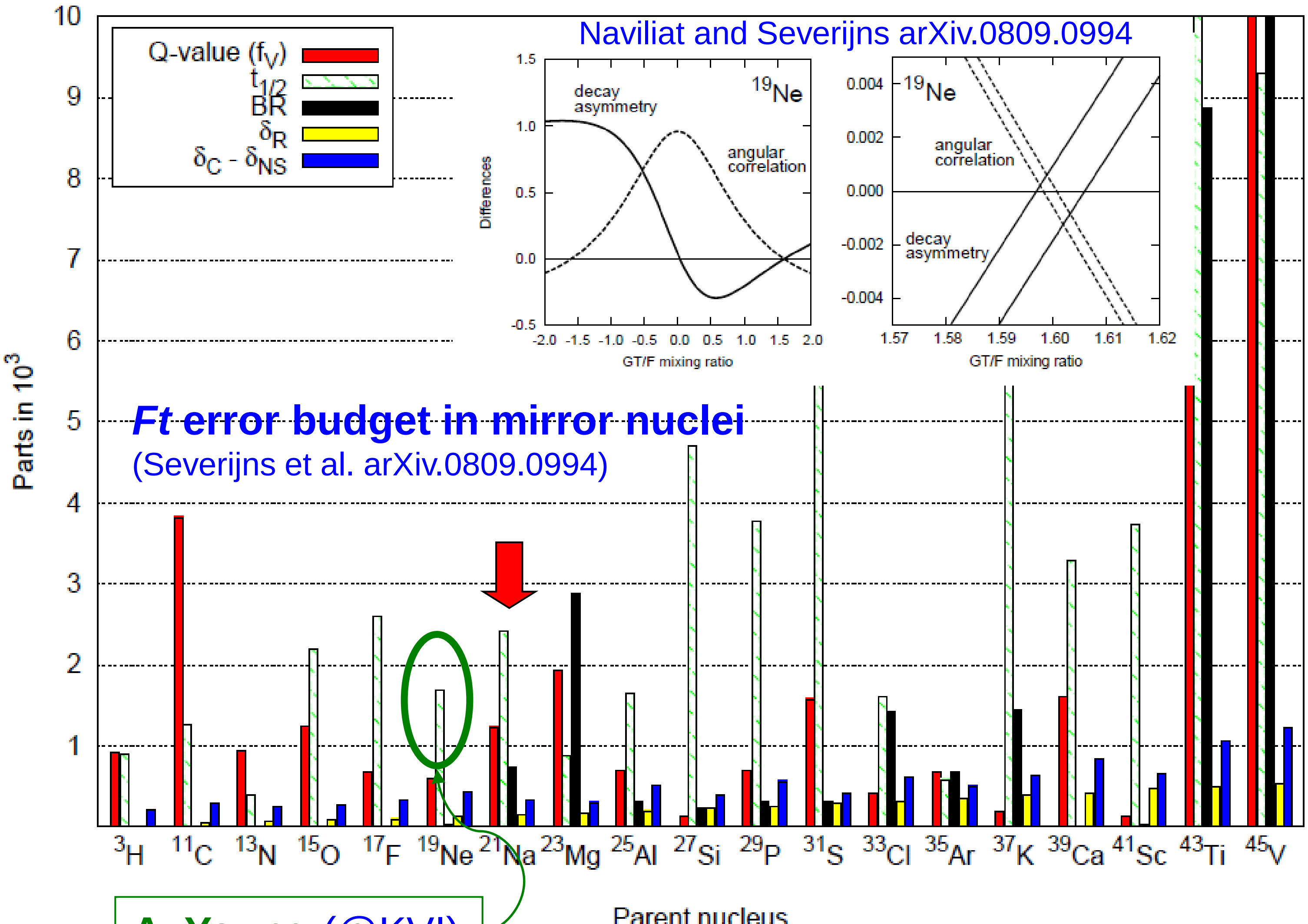
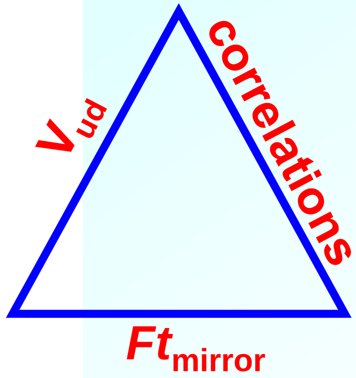
Lifetimes in Mirror Nuclei



***Ft* error budget in mirror nuclei**

(Severijns et al. arXiv.0809.0994)

A. Young (@KVI)



Combine to search for New Physics

Statistical uncertainty 2009@KVI: 0.07% for ^{21}Na 0.15% for ^{37}K

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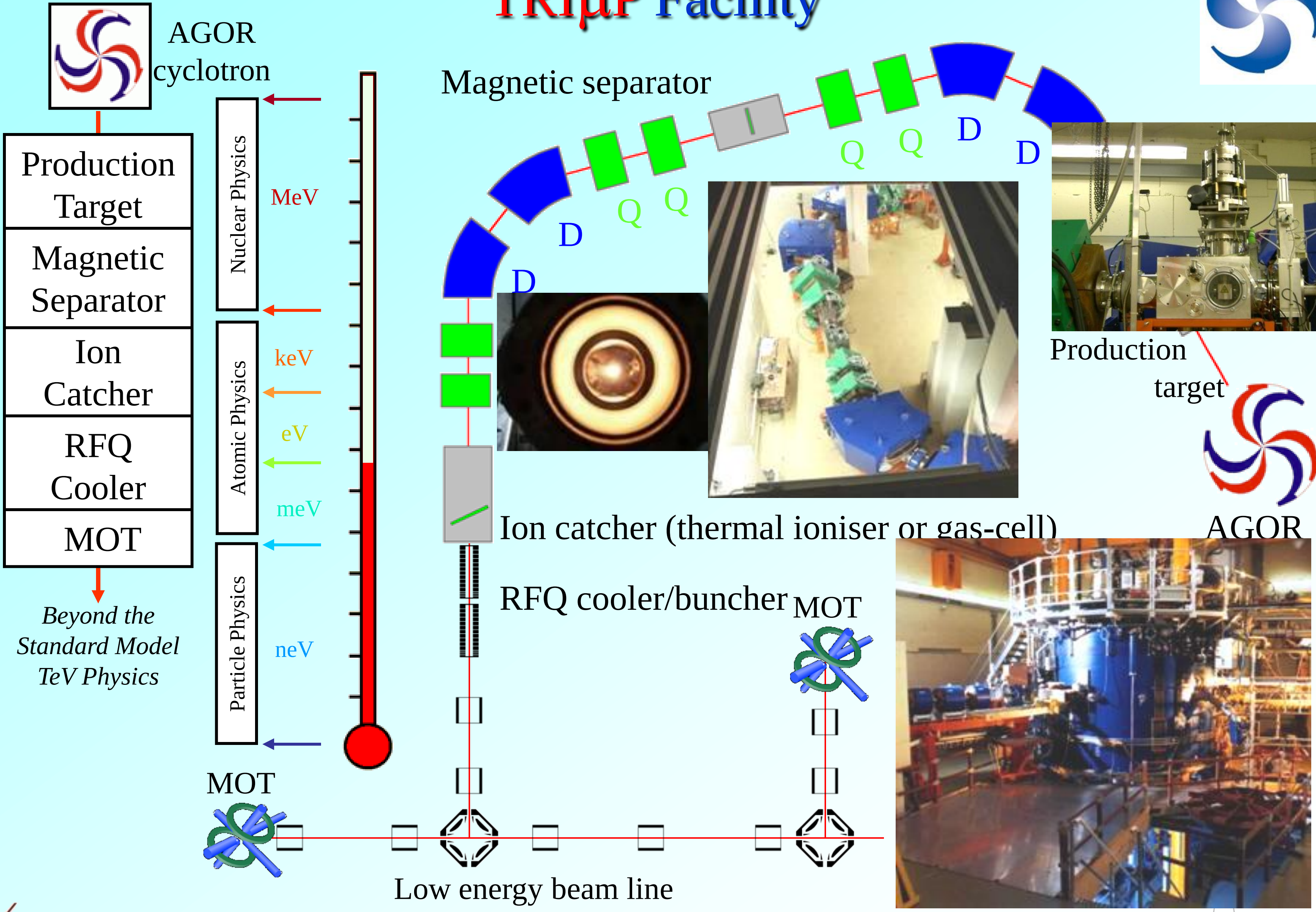
TRIμP Facility



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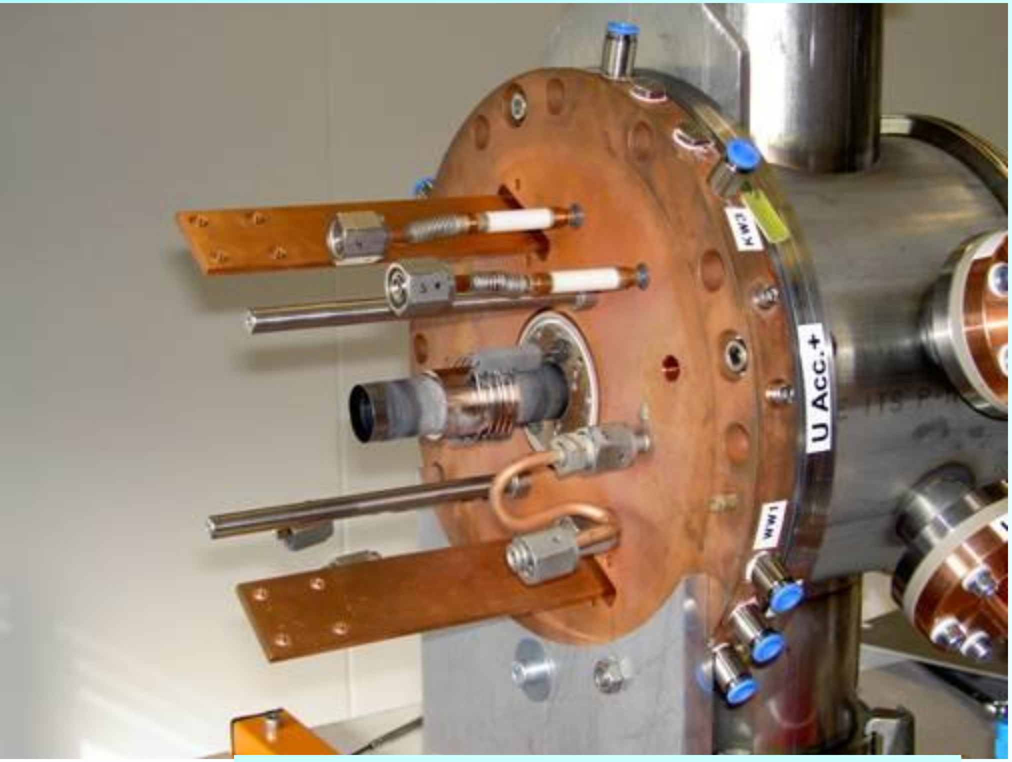
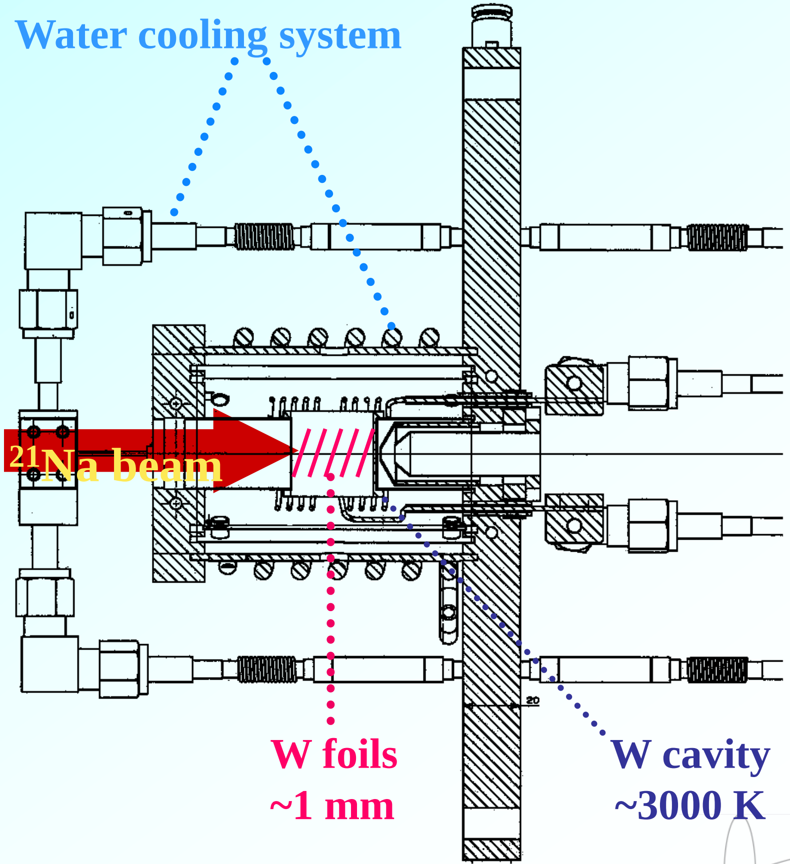
TRIμP Ion Catcher

Gas stopper – a generic solution not appropriate

KVI novel development:
High efficiency for alkali and alkali earth isotopes
→ Thermal Ionizer





O. Dermois, L. Huisman

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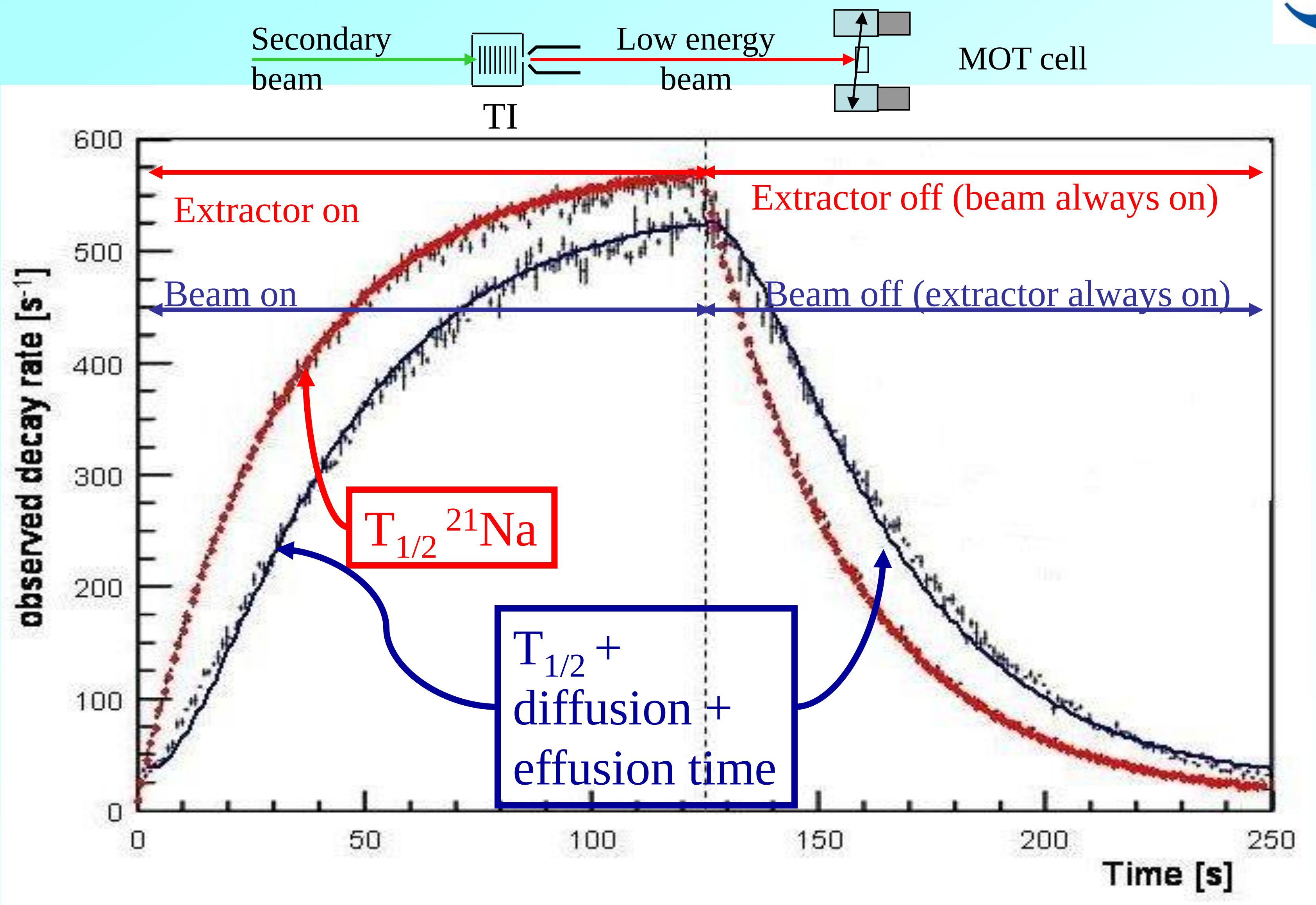
Decay, Diffusion, Effusion Thermal Ionizer



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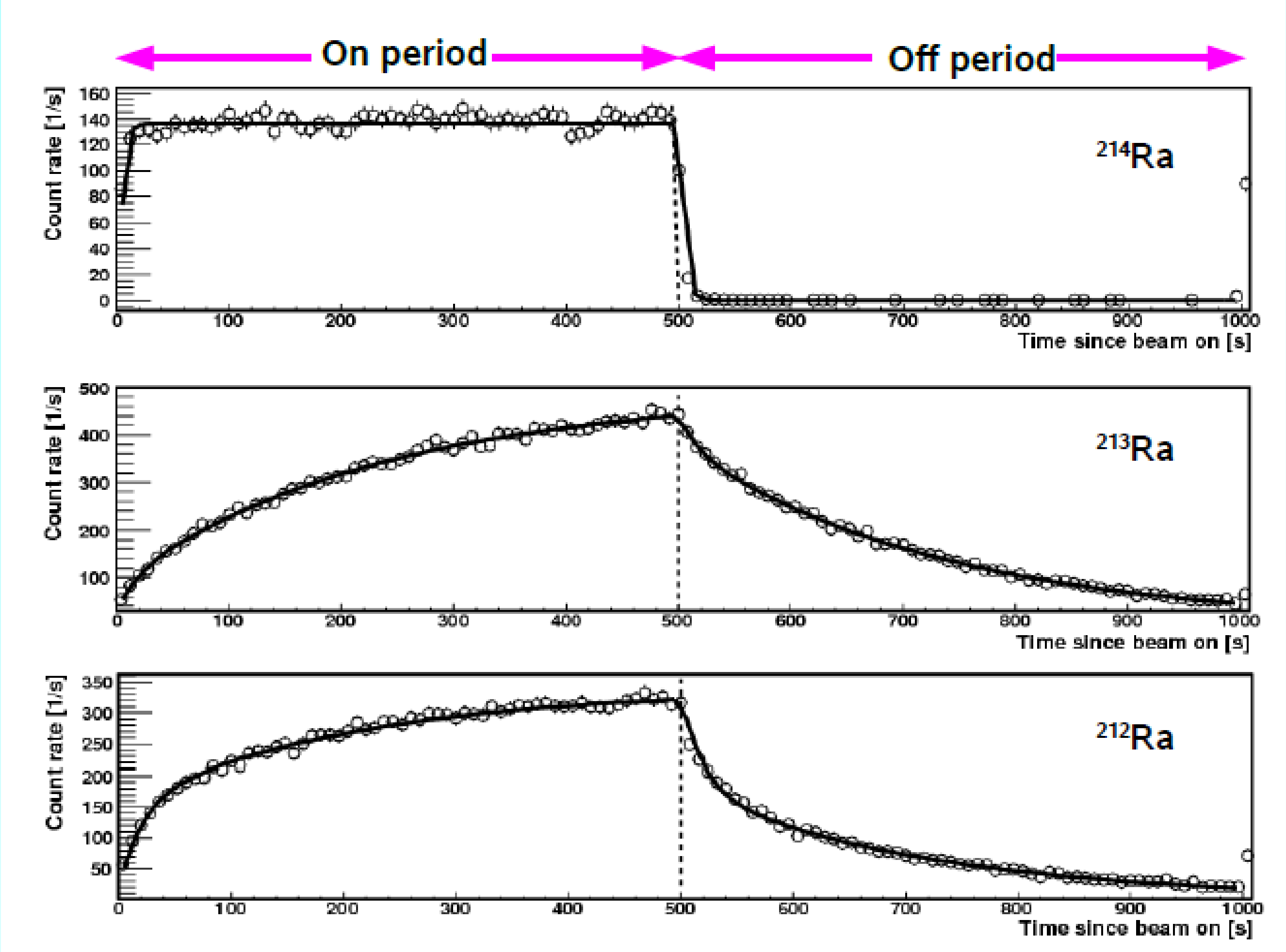
Thermal Ionizer Extraction ‘on’ – ‘off’ Switching: Ra isotopes Lifetimes



Isotope value	Characteristic half-lifes [s] (KVI work)
^{214}Ra	2.42 ± 0.14
^{213}Ra	162 ± 1.7
^{212}Ra	12.5 ± 1.0

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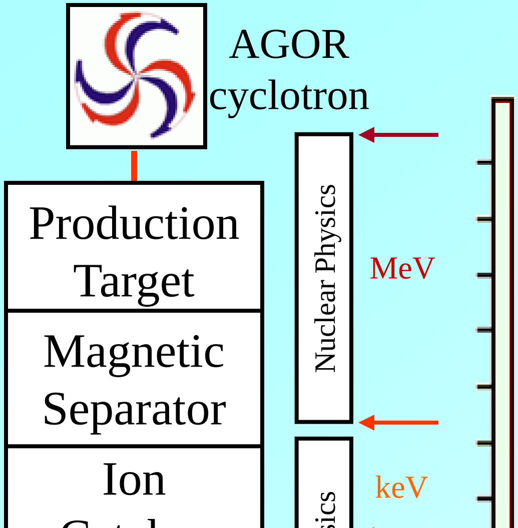
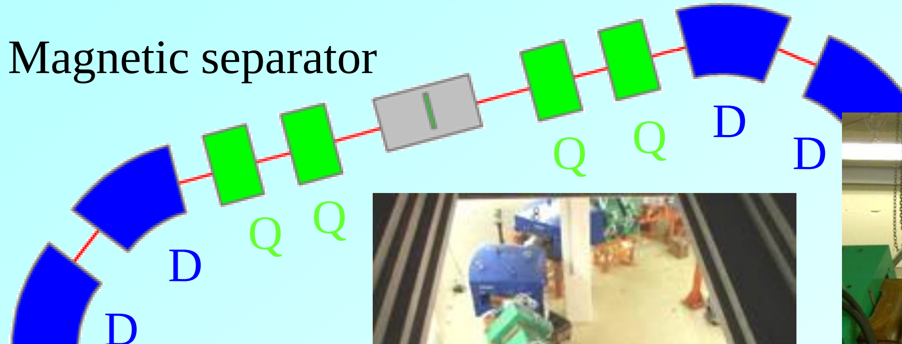
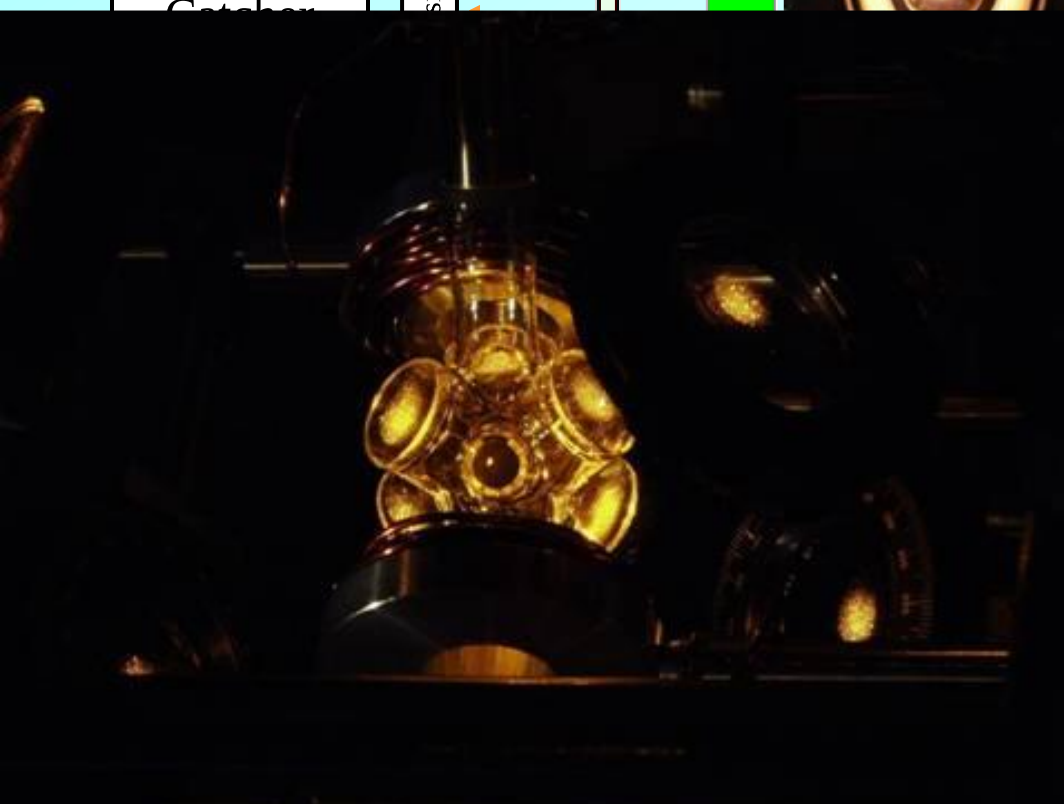
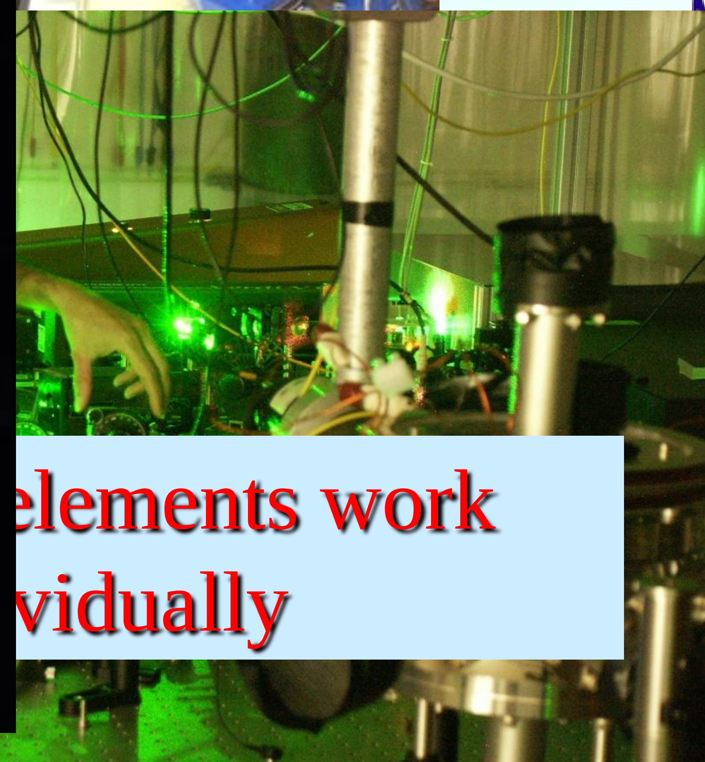




Production
target





elements work
vidually

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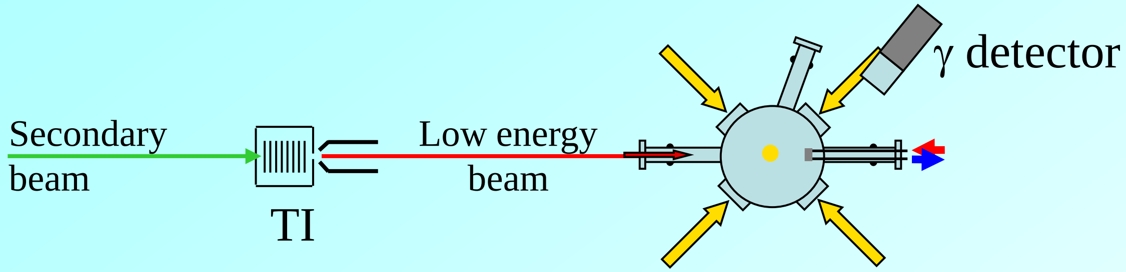
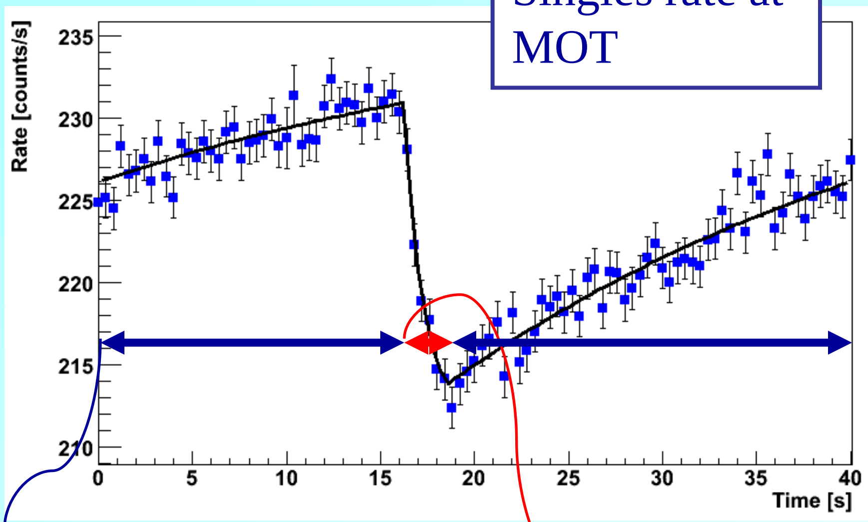
Trapped Radioactive ^{21}Na



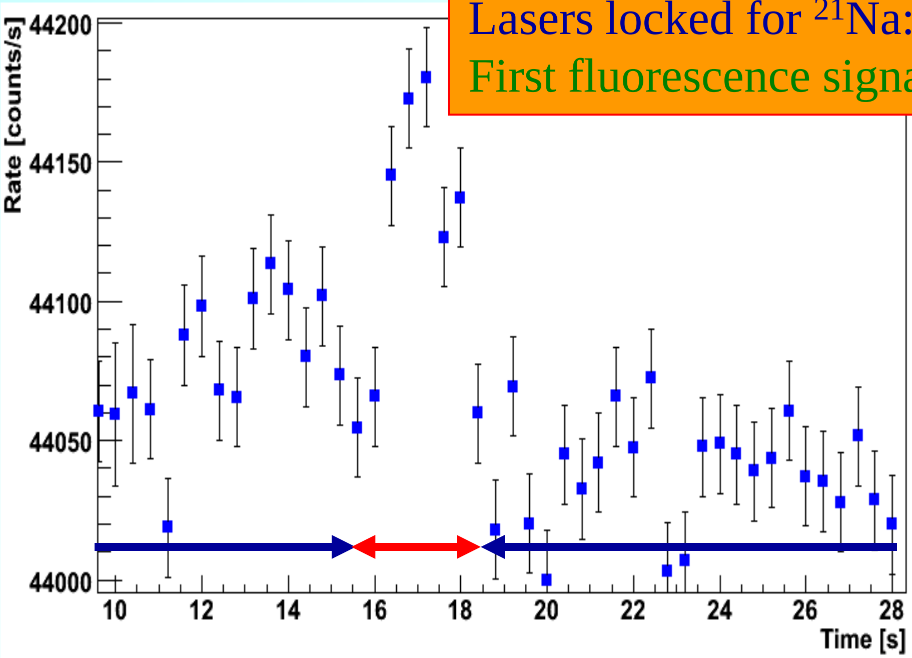
Singles rate at MOT



Neutralizer off (37 s)
^{21}Na accumulation

Neutralizer heated (3 s)

Lasers locked for ^{21}Na:
First fluorescence signal



Maximum reached: >10^5/s in trap cell
Final goal to trap >10^4/s

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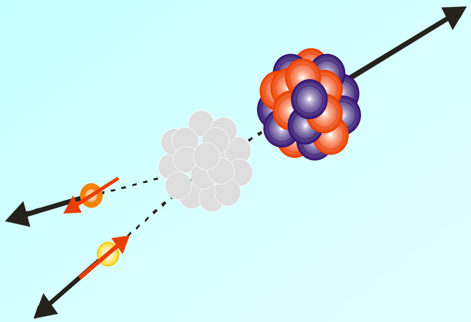
Example: β-Decays



Hans Wilschut et al. → Natrium Isotopes

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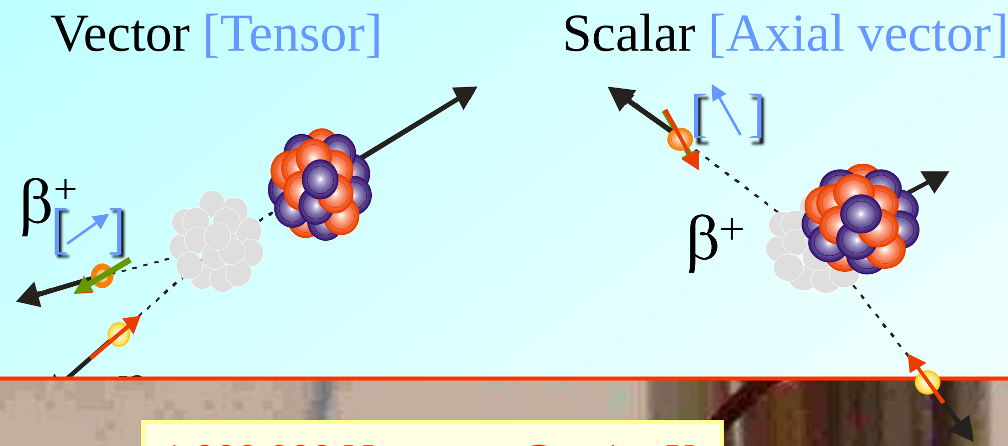
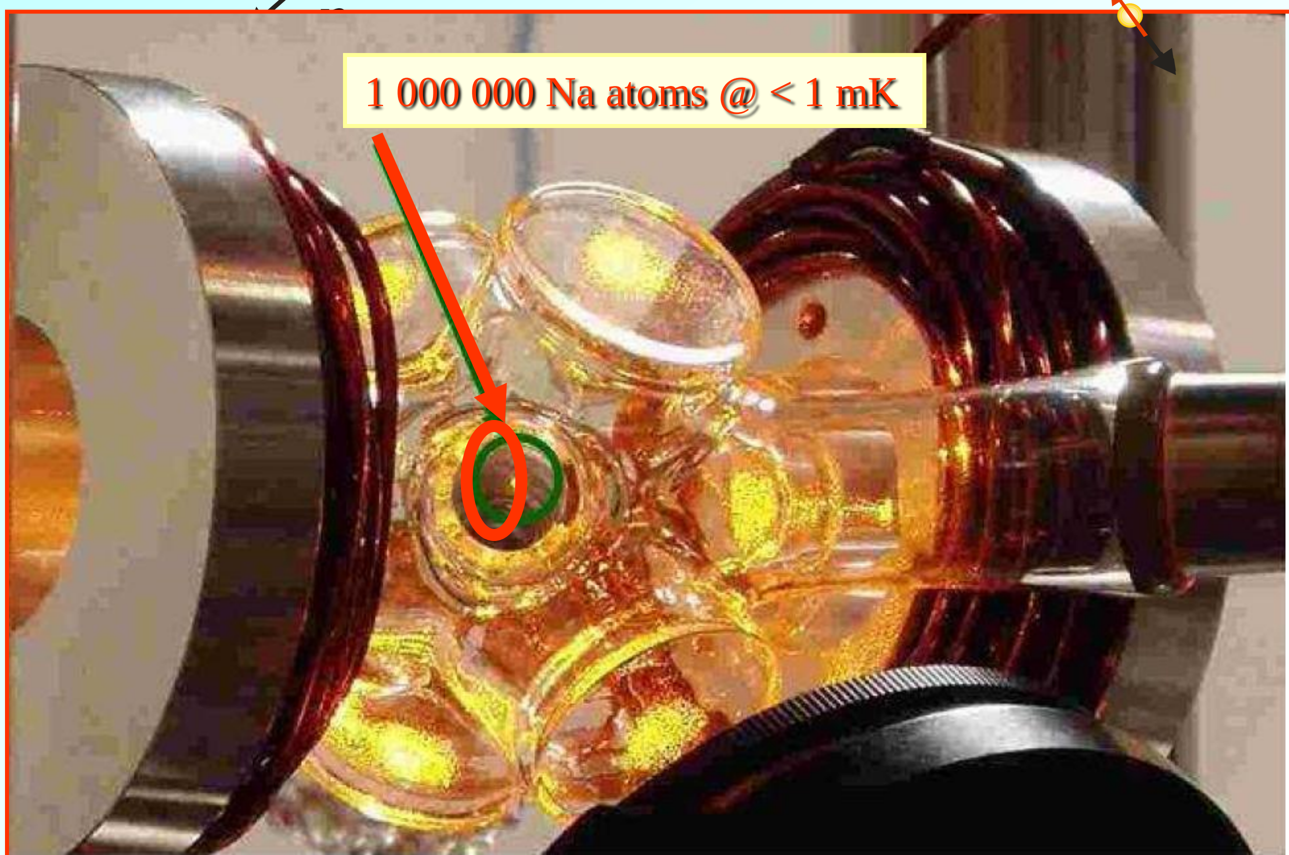
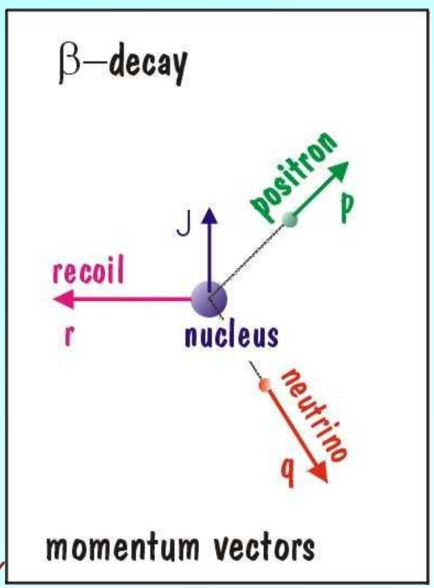
New Interactions in Nuclear β-Decay

In Standard Model: Weak Interaction is V-A

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







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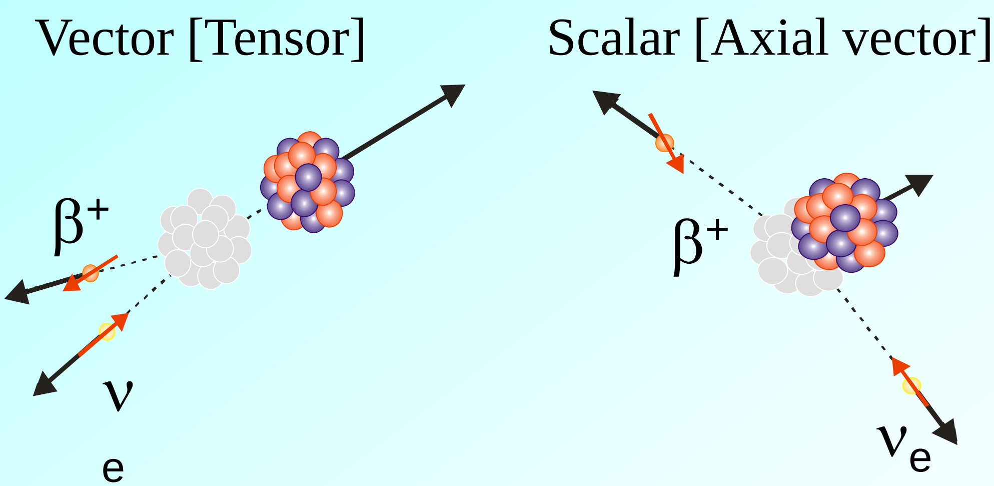

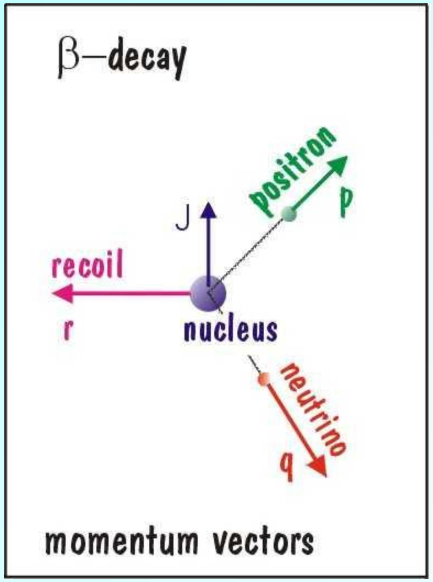

$$\frac{\mathrm{d}^2W}{\mathrm{d}\Omega_e\,\mathrm{d}\Omega_\nu} \sim 1 + a\,\frac{\boldsymbol{p}\cdot\hat{\boldsymbol{q}}}{E} + b\,\Gamma\,\frac{m_e}{E} + \langle \boldsymbol{J}\rangle\cdot\left[A\,\frac{\boldsymbol{p}}{E} + B\,\hat{\boldsymbol{q}} + D\,\frac{\boldsymbol{p}\times\hat{\boldsymbol{q}}}{E}\right]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

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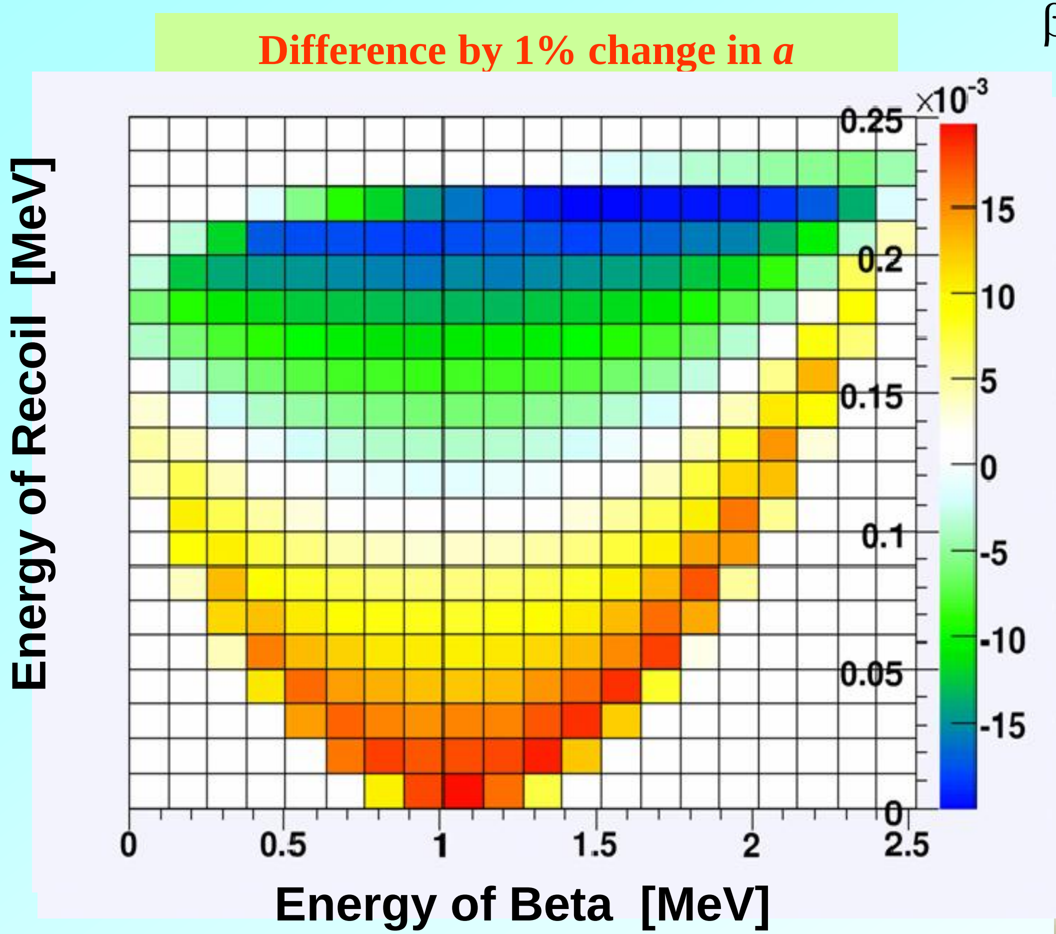
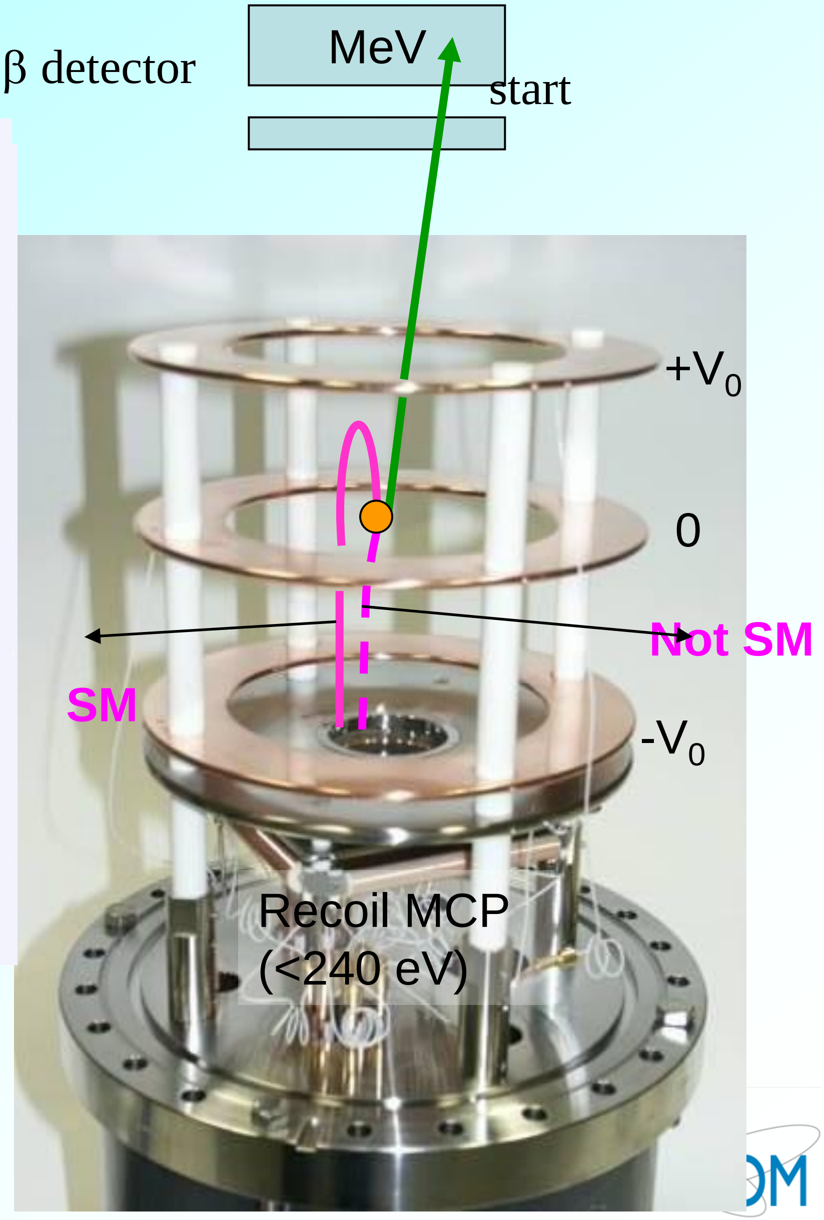
Detection: MOT + RIMS + β detector





1% change in "a" requires ≥ 10^6 events
(LBL: 0.85% for 4×10^6)

TOF→ $E_{//}$

X,Y → $E_{\perp}$

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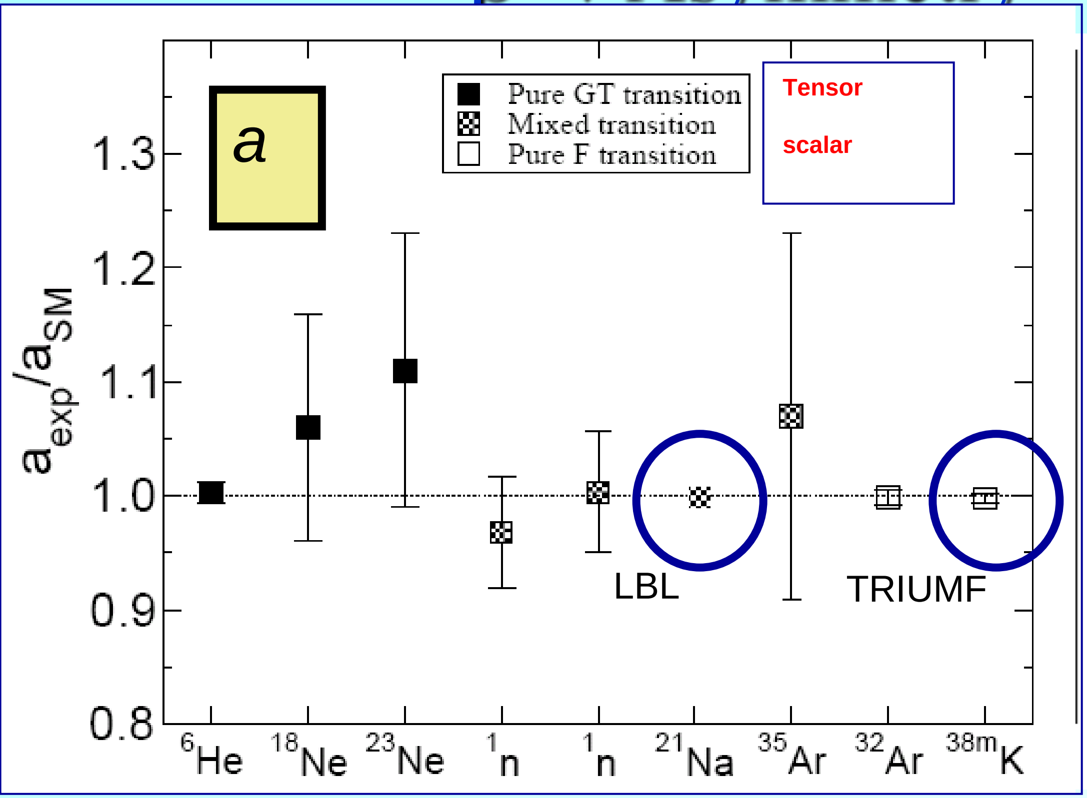
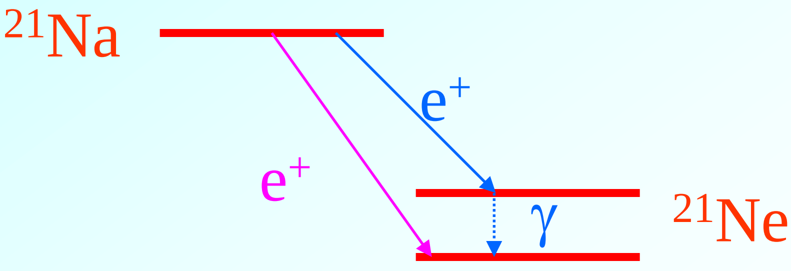
β–ν Asymmetry “a” in ^{21}Na decay



Adapted from Severijns,Beck,Naviliat RMP 78(2006)991

Before any serious conclusions:
$e^+/(e^++\gamma)$ branching ratio
was measured with
5 disagreeing values existed



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

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

No change to SM
‘discrepancy’

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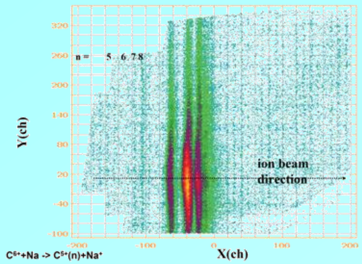
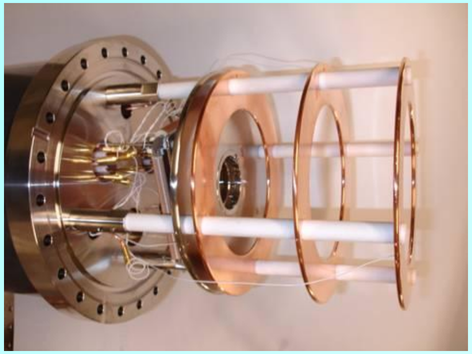
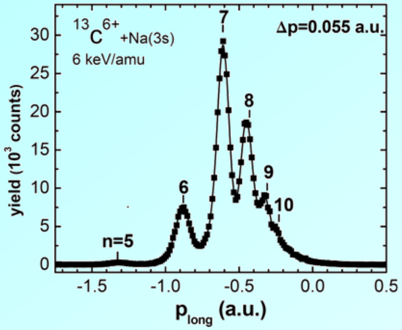
β−ν Asymmetry “a” Measurements @ KVI







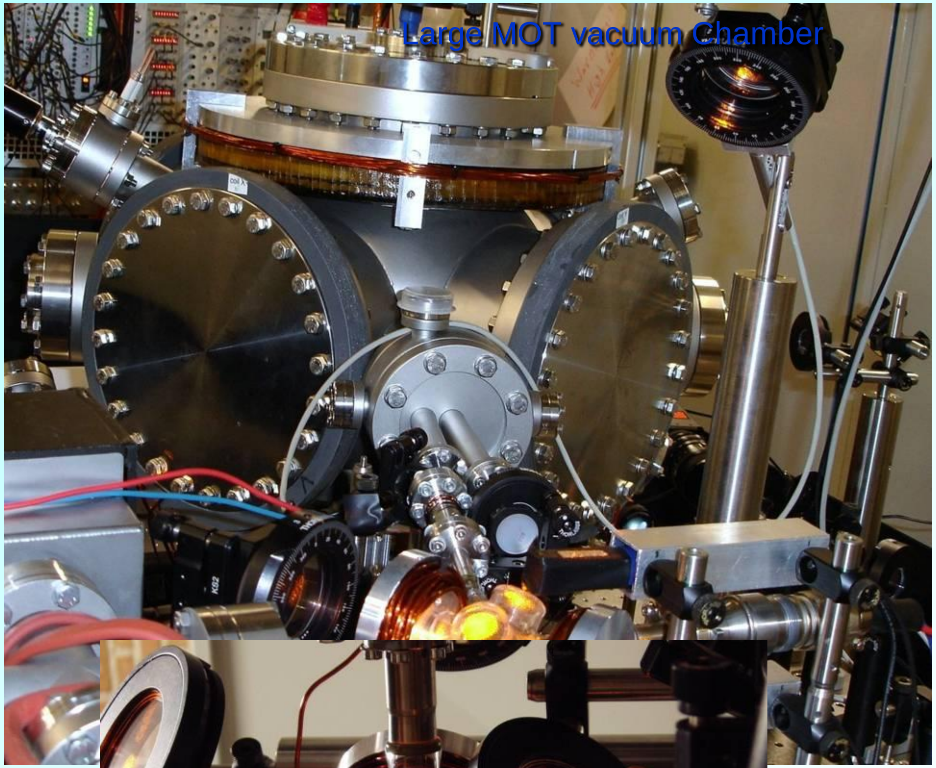
Reaction Microscope

Resolution

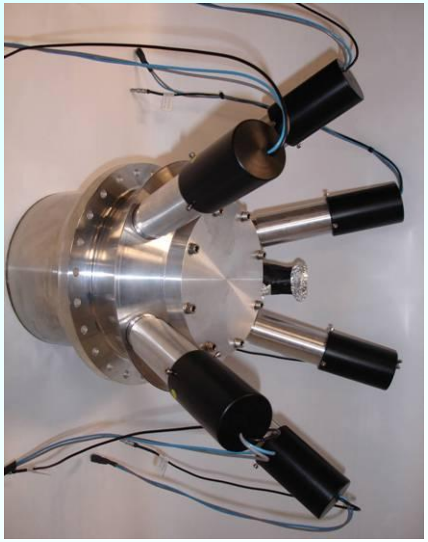
in Ion-Na charge transfer reactions

Δv = 3 m/s

ΔE = 1 meV



Collector MOT



Position Sensitive Scintillation b-counter

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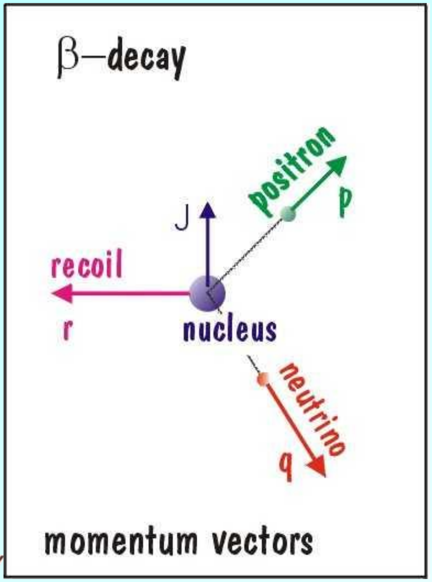
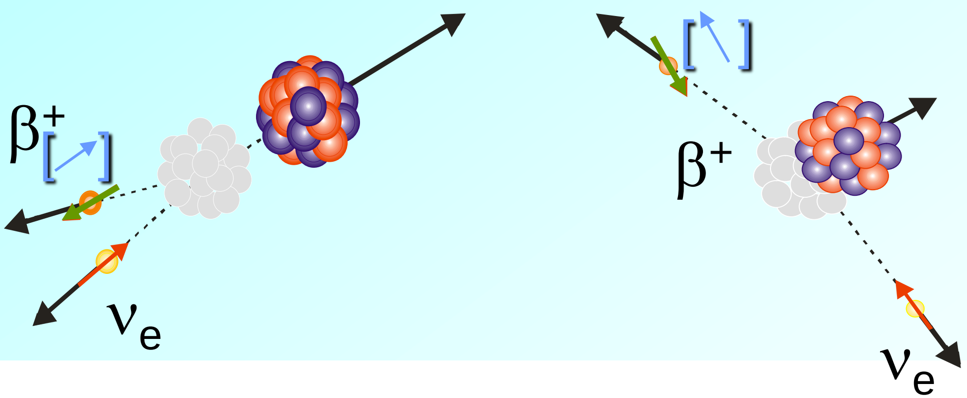
New Interactions in Nuclear β-Decay

In Standard Model:
Weak Interaction is
V-A

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



Vector [Tensor] **Scalar [Axial vector]**



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

- *R* and *D* test both Time Reversal Violation
  - ***D*** → most potential
  - ***R*** → scalar and tensor (EDM, *a*)
  - technique *D* measurements yield *a*, *A*, *b*, *B*

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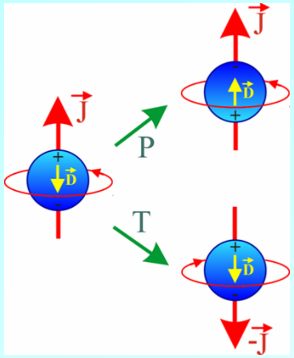
Example: Permanent Electric Dipole Moments



Lorenz Willmann et al. → Radium Atom
Gerco Onderwater et al. → Deuteron

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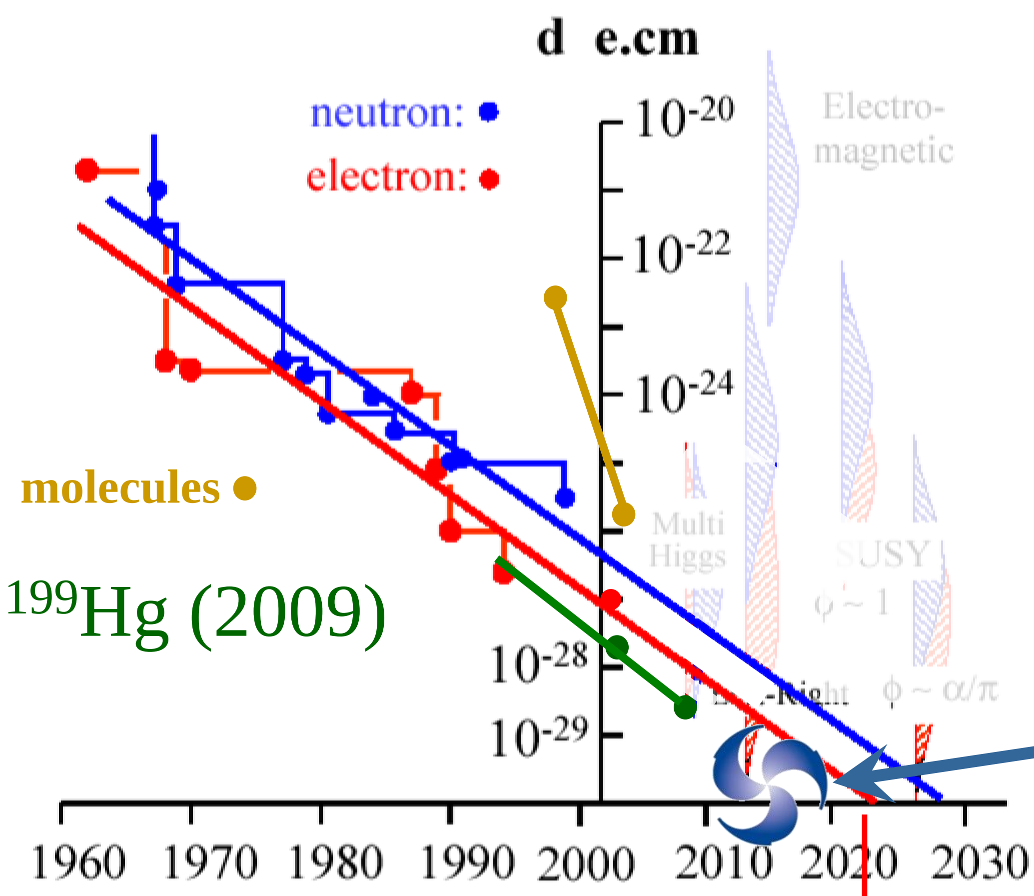
Limit on EDM in Time



Radium has biggest enhancement factors:

KVI well positioned in international field

TRIμP/KVI Radium EDM

d_e (SM) < 10^{-37}

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EDM Limits as of summer 2007

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}	$\leq 10^{5}$
Hg (odd n)	< 0.031	10^{4}	various

- Why so many ?

- Which is THE BEST candidate to choose ?

None is THE BEST - We need many experiments!

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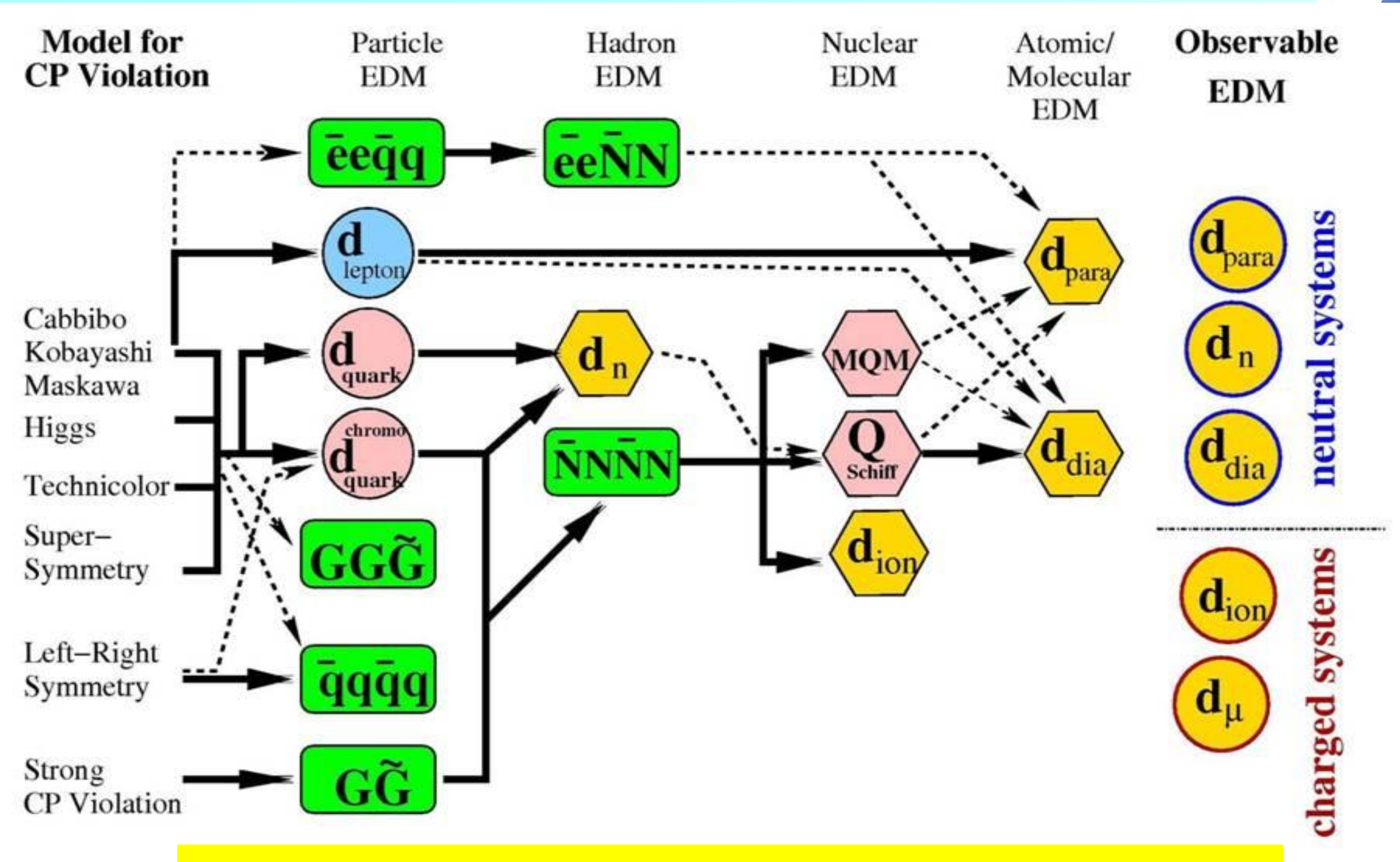
Possible Sources of EDMs



The best experiment until now- ^{199}Hg @Seattle – leaves SUSY very little room …

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

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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 T…*	1 s
E	*Elect…*	10^5 V/cm

Need to understand systematics

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

≤ $7*10^{-29}$ *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**

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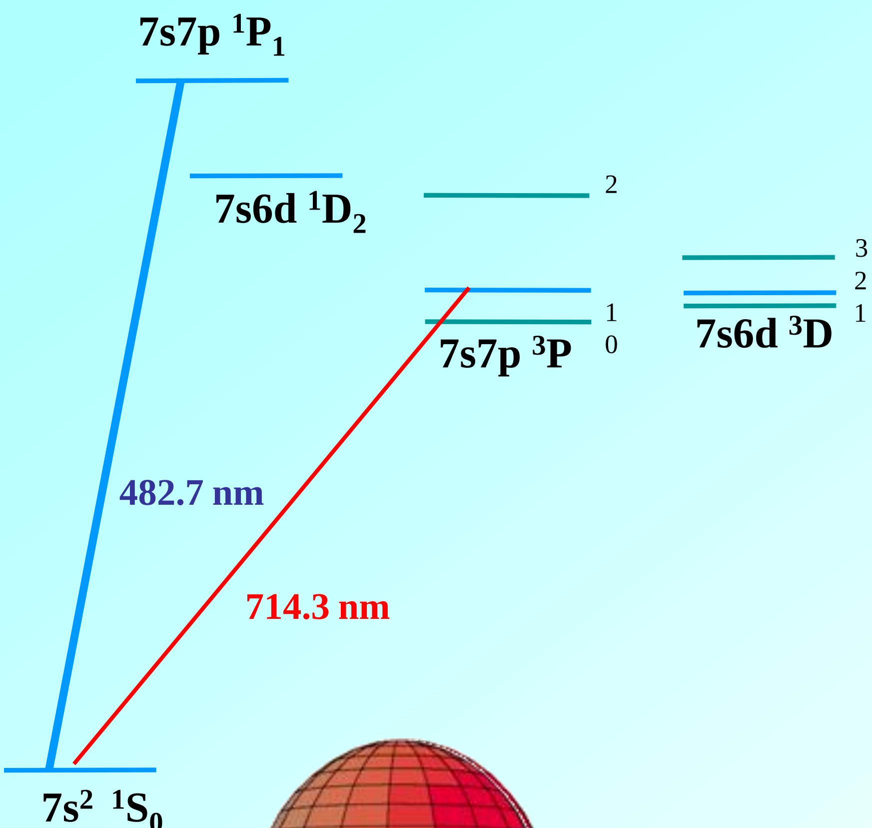
Why Radium?

Atomic energy level diagram of Ra

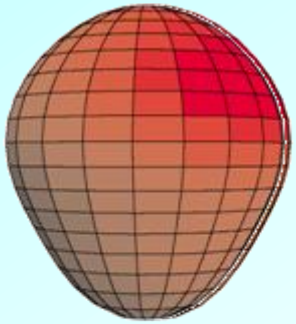


➤ **Nearly degenerate opposite parity $^3P_1$ and $^3D_1$** ***enhancement > 5000 e EDM***

$$d = \frac{<{}^3D_1 \,|\, -er \,|\, {}^3P_1 >< {}^3P_1 \,|\, H_{EDM} \,|\, {}^3D_1 >}{E({}^3D_1) - E({}^3P_1)}$$

V. A. Dzuba et al. Phys. Rev. A, 61, 062509 (2000)

Density distribution of nuclear charge has mixed octupole and quadrupole deformation



➤ **Deformed charge distribution in some isotopes (^{225}Ra). Nucleon EDM enhances ≈ 10^2**

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J. Engel et al. Phys. Rev. C, 68, 025501 (2003)

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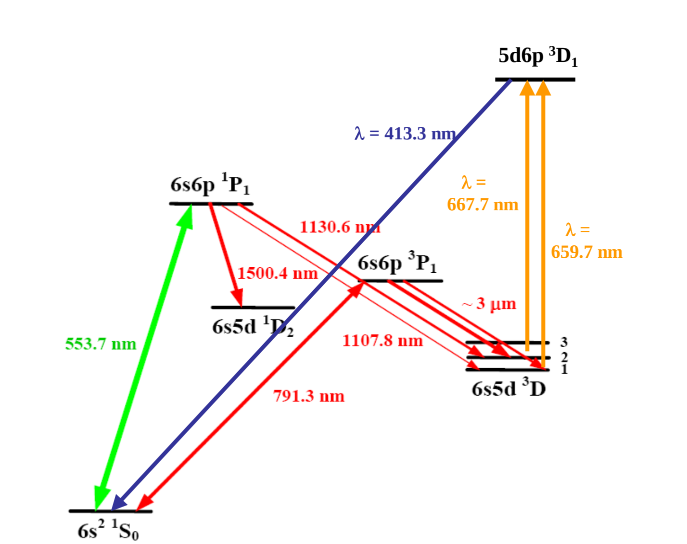
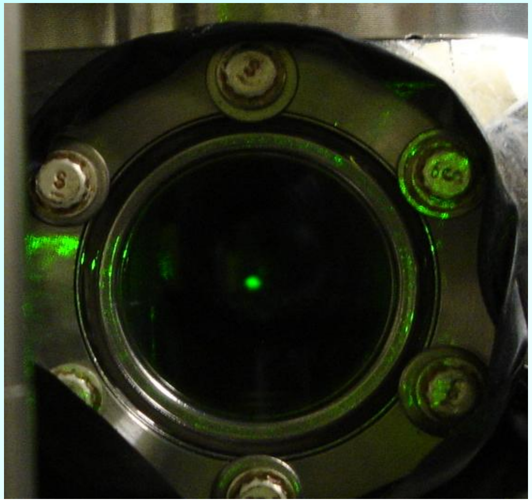
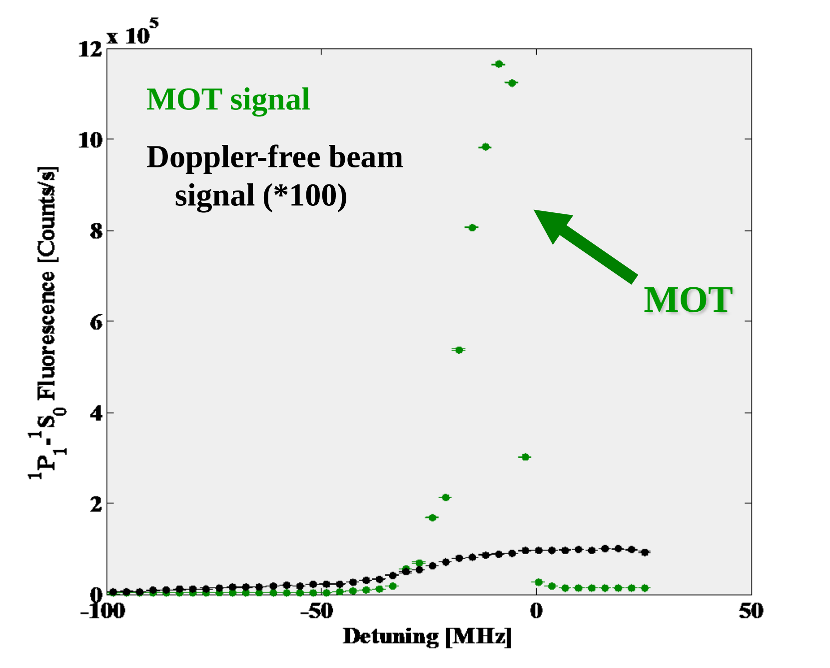
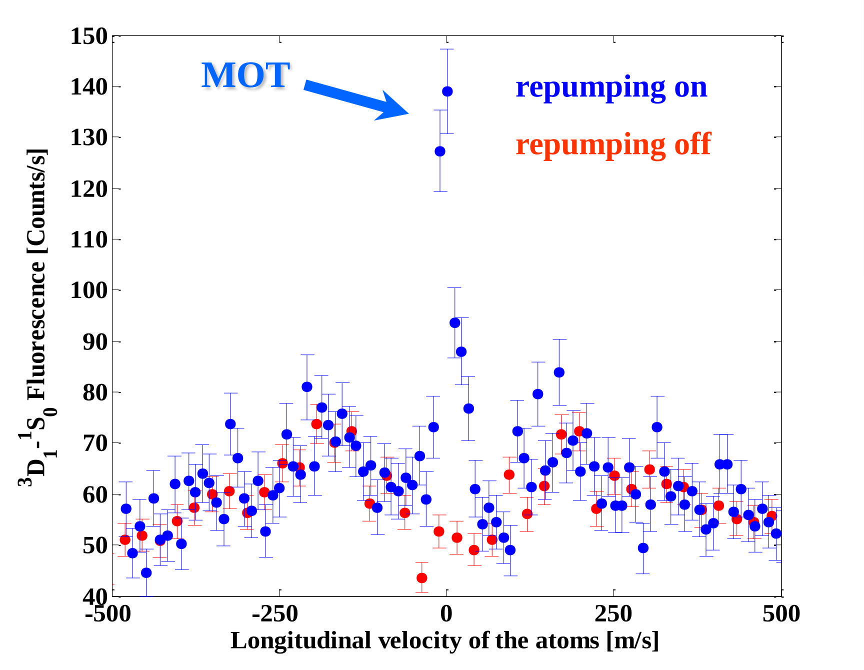
Big Step: Efficient Trapping of Barium Atoms

- 7 lasers at one time
- high trapping efficiency ~ 1%
- improvements possible









S. De et al., Phys. Rev. A 79 , 041402(R) (2009)

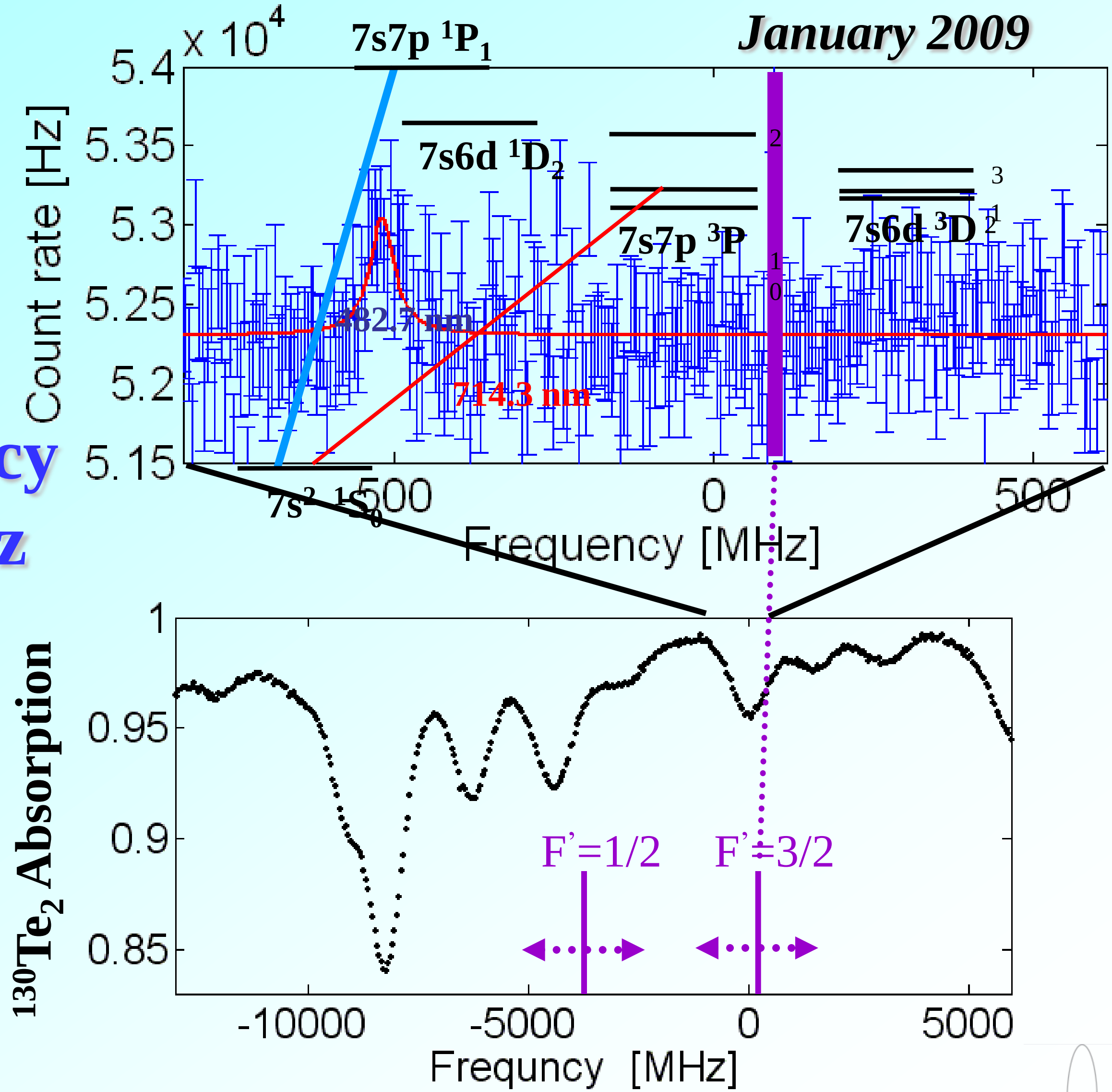
Laser Fluorescence from Radium

Laser cooling transition
$^1S_0\,(F=1/2)$ - $^1P_1\,(F'=3/2)$
10^4 Ra atoms/s
in atomic beam
from reference source

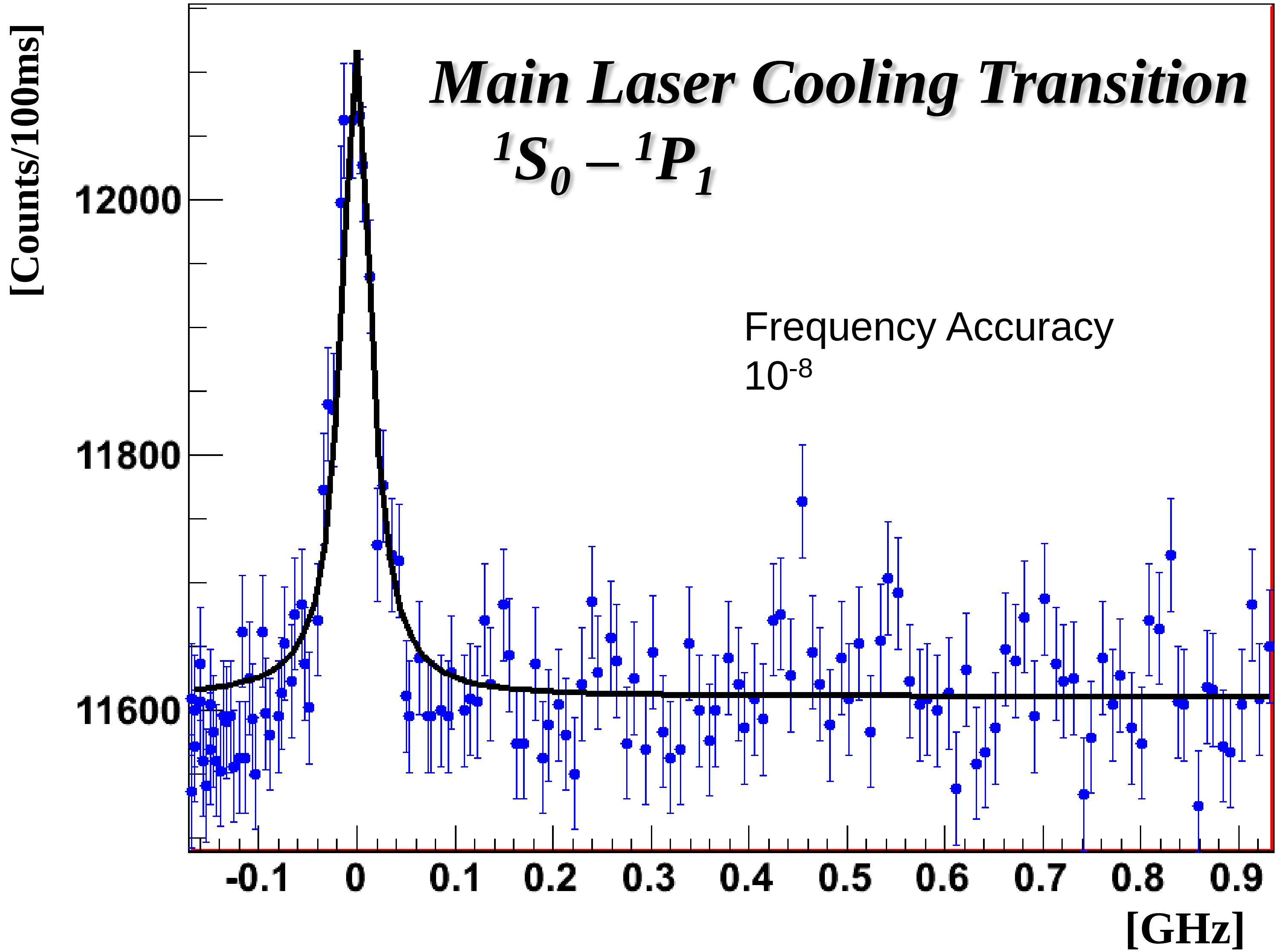
Absolute Frequency
621042.14(3) GHz

Frequency reference $^{130}Te_2$ molecular absorption

482.7nm light from
Frequency doubled
Ti:Sapphire laser



Radium cooling transition



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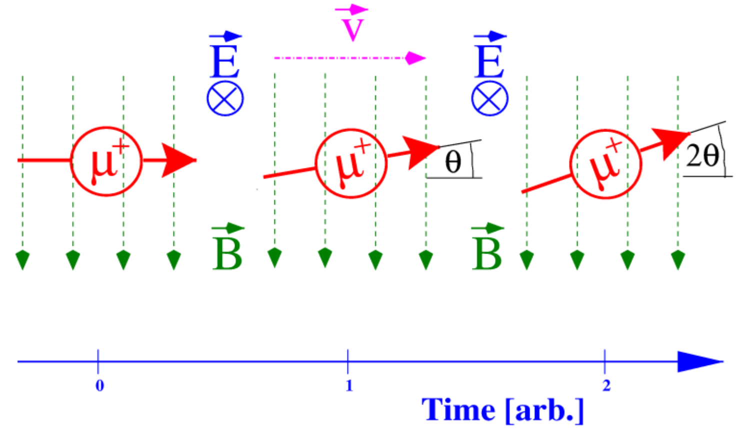
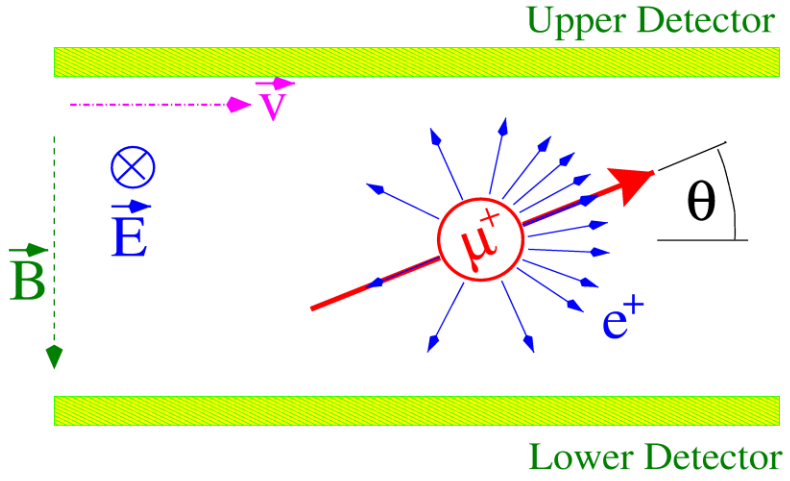
Permanent Electric Dipole Moment in a Ring



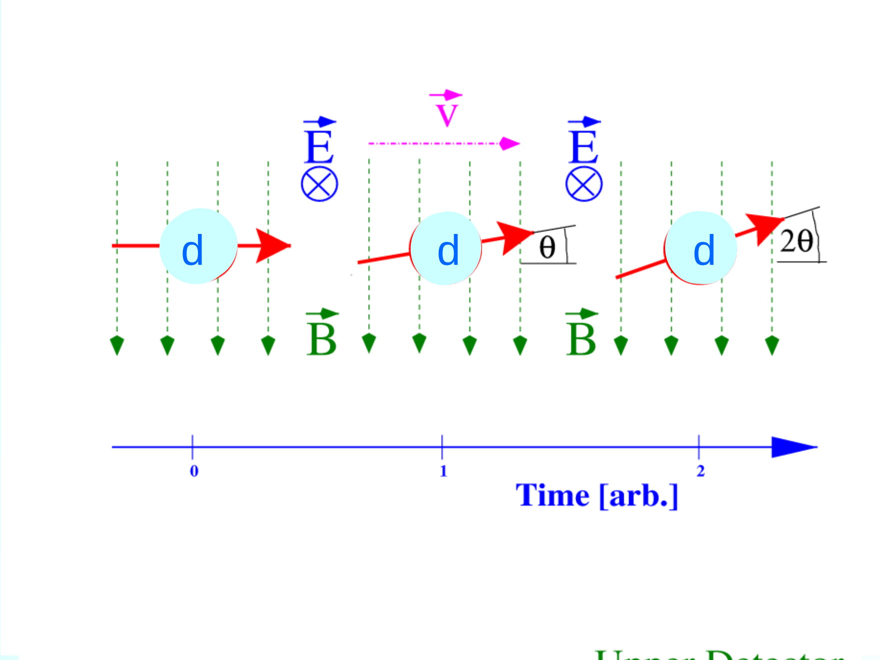
Spin precession
in (electro-)
magnetic field

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



TRIμP

Permanent Electric Dipole Moment in a Ring



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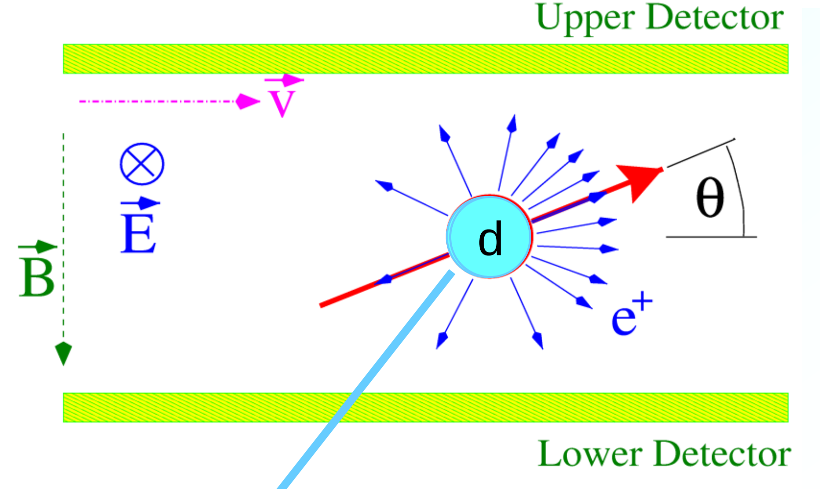
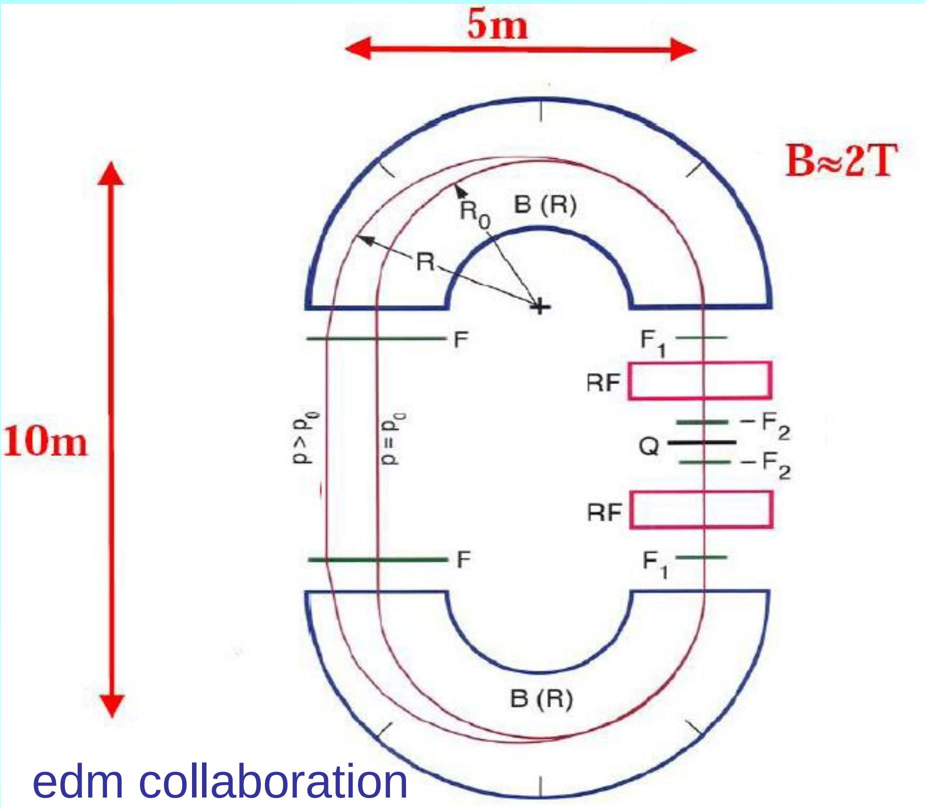
$$\vec{\omega} = \frac{e}{m}\left[\mathbf{a}_\mu \vec{\mathbf{B}} - \left(\mathbf{a}_\mu - \frac{\mathbf{1}}{\gamma^2 - \mathbf{1}}\right)\frac{\vec{\beta} \times \vec{\mathbf{E}}}{\mathbf{c}}\right] + \frac{\mathbf{e}}{\mathbf{m}}\left[\frac{\eta}{\mathbf{2}}\left(\frac{\vec{\mathbf{E}}}{\mathbf{c}}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



Deuteron is stable:
Different polarimeter needed

TRIμP

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



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}, …

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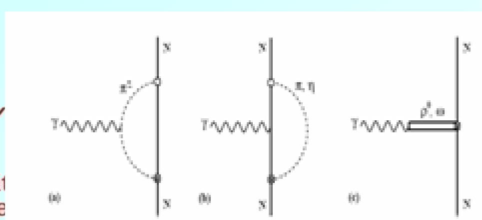
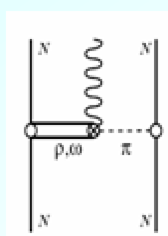




$$d_D = -4.67 d_d^c + 5.22 d_u^c,$$

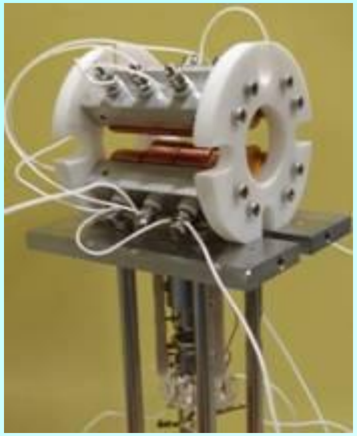
$$d_n = -0.01 d_d^c + 0.49 d_u^c$$

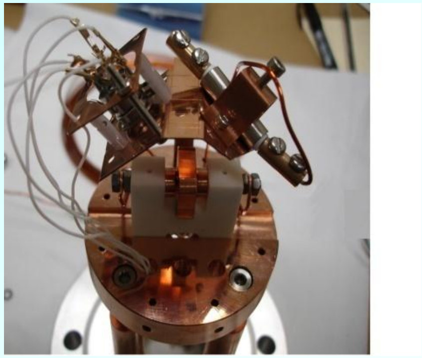
C.P. Liu,
R.G.E. Timmermans

Phys.Rev.C 70, 055501 (2004

Parity Violation

in Single Ions





Klaus Jungmann
Rob Timmermans
et al.

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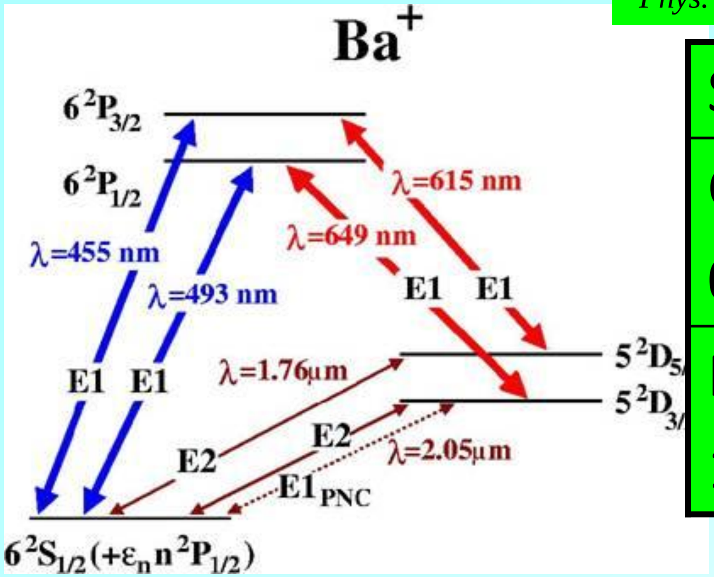
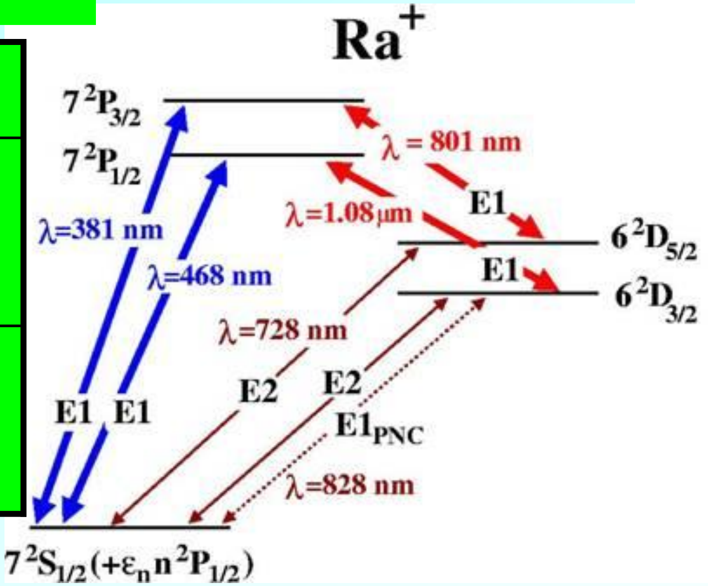
Relative sensitivity

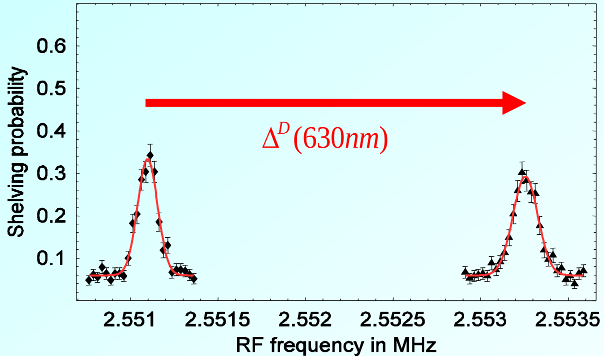
L.W.Wansbeek et al., Phys. Rev. A 78, 050501 (2008)

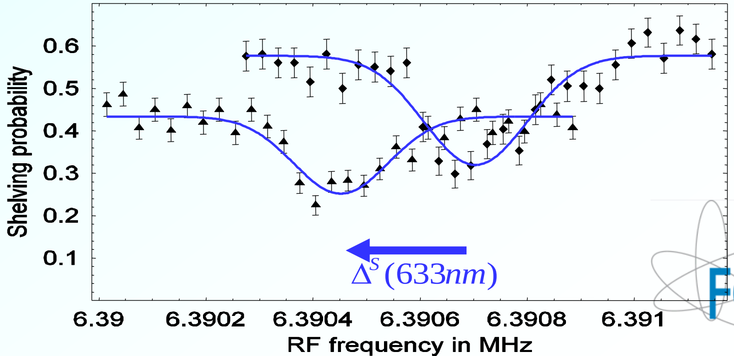


S-S	S-D
Cs 0.9	Ba⁺ 2.2
Fr 14.2	Ra⁺ 46.4



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





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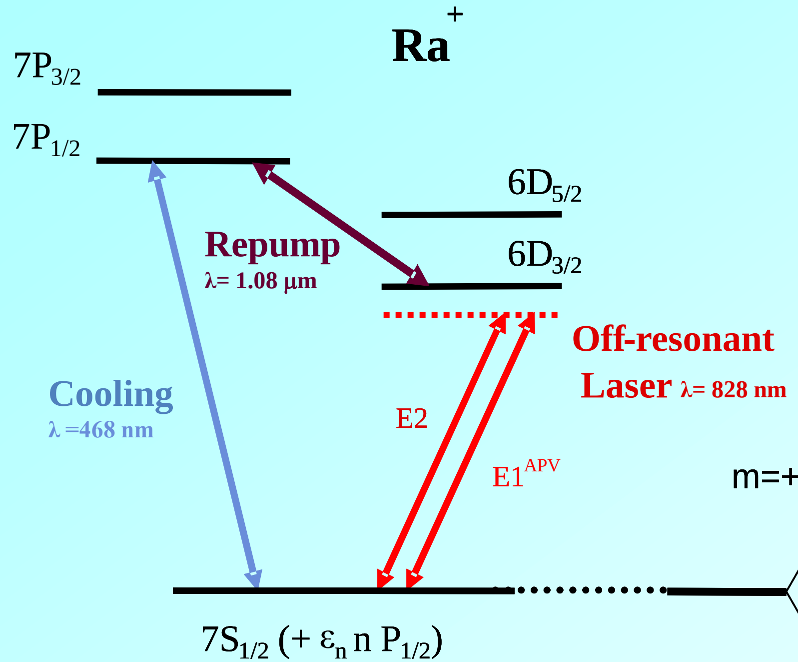
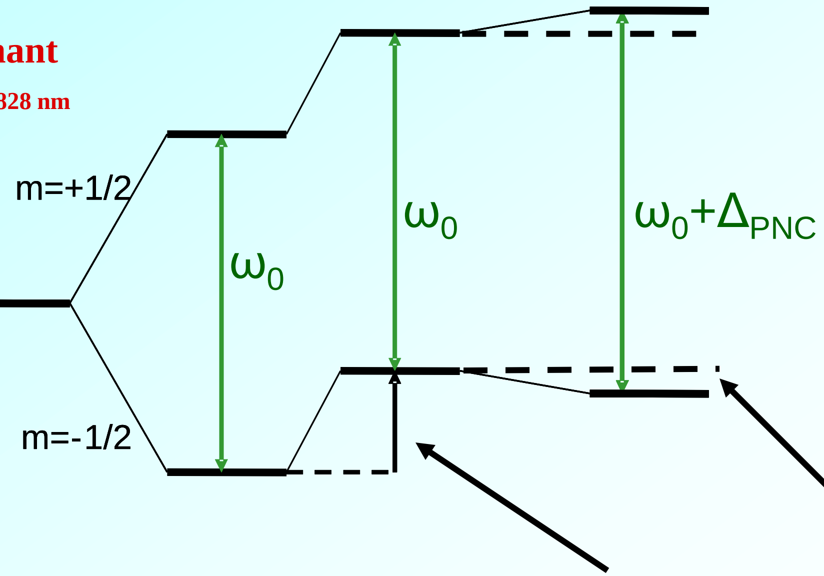
Atomic Parity Violation in Ra^+

Interference of $E2/E1^{APV}$

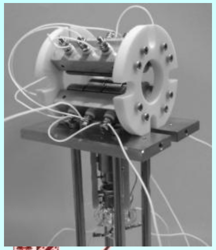


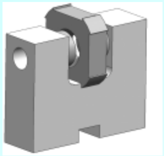
Cooling localizes single ion within one wavelength

Interference produces *differential* light shift of the ground state m-levels:



Measurement with RF spectroscopy + electron shelving method





$$|\Omega_{m'm}|^2 = |\Omega^{E2}_{m'm} + \Omega^{APV}_{m'm}|^2 \approx |\Omega^{E2}_{m'm}|^2 + 2\,\mathrm{Re}(\Omega^{APV*}_{m'm}\Omega^{E2}_{m'm})$$

shift≈1MHz $\Delta_{PNC} \approx 0.5$ Hz

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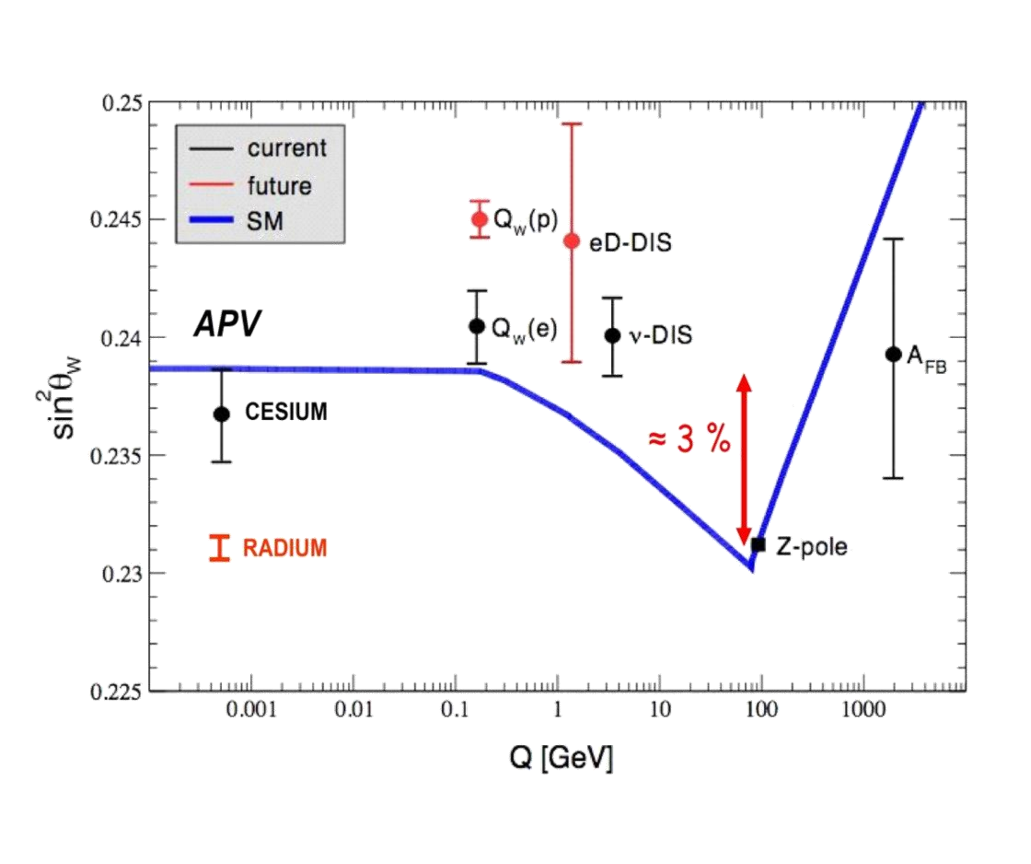
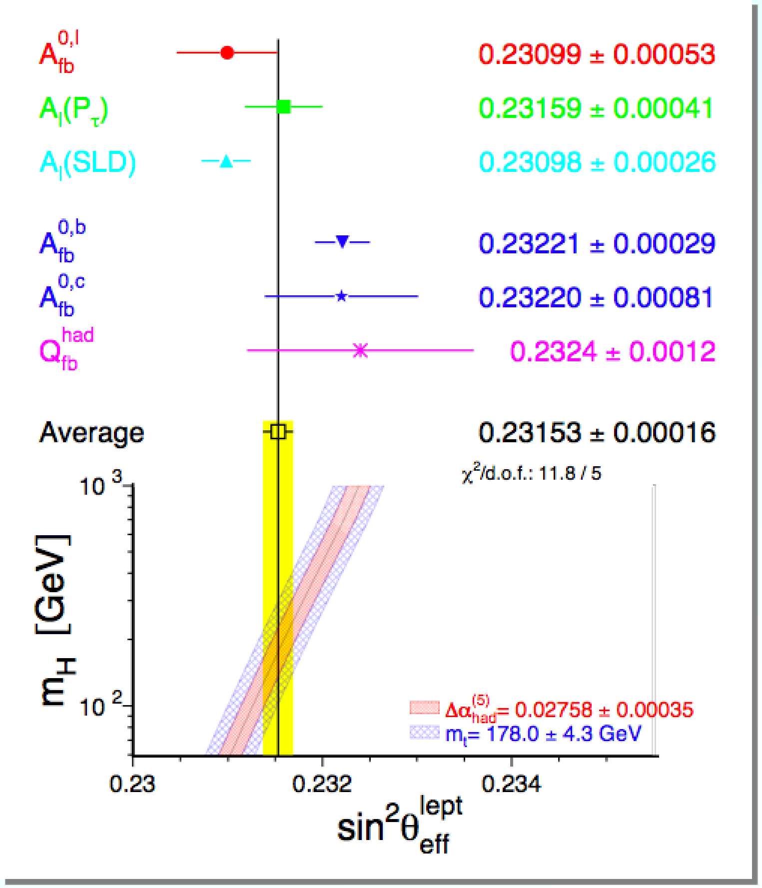
Determination of Weak Mixing Angle





Average: $\sin^2\theta_W = 0.23122(17)$

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Summary

- **KVI Research** addresses
  - Fundamental Interactions and Symmetries and
  - Applications
  - At Home and with Strategic Partners

- The **TRIμP Facility**
  - Stands Ready and
  - Open for Users now to
  - Study Fundamental Symmetries and Forces in Nature

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Thank YOU !

Production results

Product	For	/s/pnA	Beam	[MeV/u]	Reaction / type		Target
^{21}Na	commiss.		^{21}Ne	20	(p,n)		CH_2
^{21}Na	commiss.		^{24}Mg	30	(p,α)		CH_2
^{21}Na	commiss.		^{24}Mg	30		fragment	C
^{12}B	Fynbo		^{11}B	22.3	(d,p)	direct	D_2
^{12}N	Fynbo		^{12}C	22.3	(p,n)	resonant	H_2
^{19}Ne	TUNL	1.1×10^3	^{19}F	10	(p,n)	resonant	H_2
^{20}Na	TRIμP	1.0×10^4	^{20}Ne	22.3	(p,n)	resonant	H_2
^{21}Na	LPC	3×10^3	^{21}Ne	43	(p,n)	direct	H_2
^{21}Na	TRIμP	1.3×10^4	^{20}Ne	22.3	(d,n)	direct	D_2
^{21}Na	TRIμP	8×10^3	^{20}Ne	40.0	(d,n)	direct	D_2
^{22}Mg	LPC		^{23}Na	31.5	(p,2n)	evap.	H_2
^{42}Ti	Blank	20	^{40}Ca	45.0	(^{3}He,n)	direct	^{3}He
^{8}B	Raabe	5	^{12}C	30.0		fragment	^{12}C
^{213}Ra	TRIμP	600	^{206}Pb	8.0	(^{12}C,5n)	Fus-evap.	^{12}C
^{214}Ra	TRIμP	300	^{206}Pb	8.0	(^{12}C,4n)	Fus-evap.	^{12}C
^{212}Ra	TRIμP	200	^{206}Pb	8.0	(^{12}C,6n)	Fus-evap.	^{12}C

Gas target: 10 cm, 1 atm, LN_2 temperature

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TRIμP: Trapped Radioactive