Eurisol Design Study
Task 10

Pisa-meeting
10-11 April 2006

Fundamental Interactions

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Kath. Univ. Leuven

Physics Topics

Nature of the fermions:

- neutrino's: oscillations/mixing, masses, Dirac/Majorana, …
- quarks: CKM (V_{ud}), …

Nature of the weak force:

- nature of the weak force: V ± A, S, T, P
- parameters: coupling constants, boson masses, …

Symmetries and Conservation laws:

- discrete symmetries: P, T (CP)
- rare and forbidden decays

black = not Eurisol

1. $Ft^{0^+ \rightarrow 0^+}$: mass, $t_{1/2}$, BR
   - unitarity
   - CVC
   - right-handed currents
   - scalar currents

2. Exotic weak interactions: correlations in β-decay
   - scalar
   - tensor

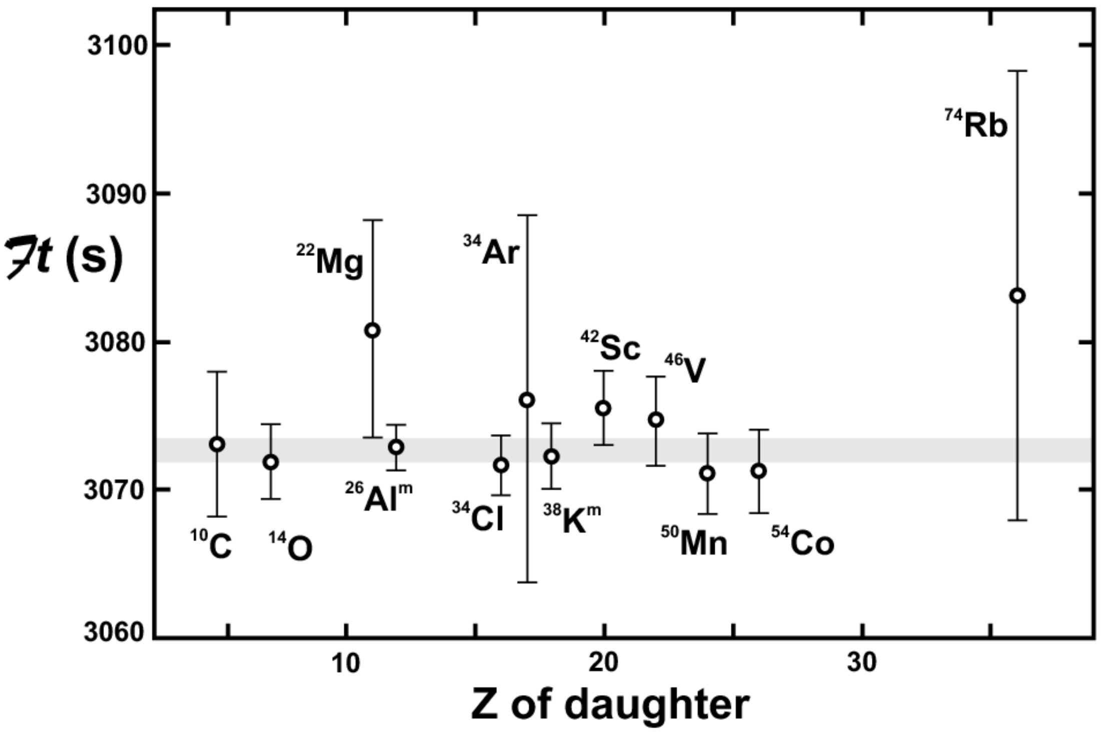
3. Symmetry tests: correlations in β-decay / EDM-searches
   - parity
   - time reversal

→ Need :
- advanced spectroscopy set-ups
- ion and atom traps + means to polarize
- ISOL beams (i.e. 10^3 /s to ≥ 10^8 /s)

1. V_{ud} and the unitarity of the CKM quark-mixing matrix

ℑt-values of $0^+ \rightarrow 0^+$ superallowed Fermi transitions

$$\mathcal{F}t = ft\,(1+\delta_R)\,(1-\delta_C) = \frac{K}{2\,G_F^2\,V_{ud}^2\,(1+\Delta_R^V)}$$ = 3073.5 (12) s (1)



V_{ud}^{0+0+} = 0.9738(4) (1)

V_{us}^{K} = 0.2196(26) (PDG)

0.2254(21) (2)

V_{ub}^{B} = 0.00367(47) (PDG)

$$\sum_i V_{ui}^2 = V_{ud}^2 + V_{us}^2 + V_{ub}^2 = 0.9969(15)$$

0.9991(12)

(~ 2σ shift)

(1) Towner and Hardy (0+->0+), PRL 94 (2003) 092501, PR C71 (2005) 055501

(2) E865, KTeV, NA48, KLOE

Physics information from the $0^+ \rightarrow 0^+$ Fermi transitions

1. V_{ud} matrix element (→ test of unitarity)
2. test of CVC
3. right-handed currents:

$$-0.0006 < \zeta < 0.0018 \quad (90\%\ \text{C.L.})$$

4. scalar currents:

$$-0.005 < \mathrm{Re}\left(\frac{C_S + C_S'}{C_V}\right) < 0.004$$

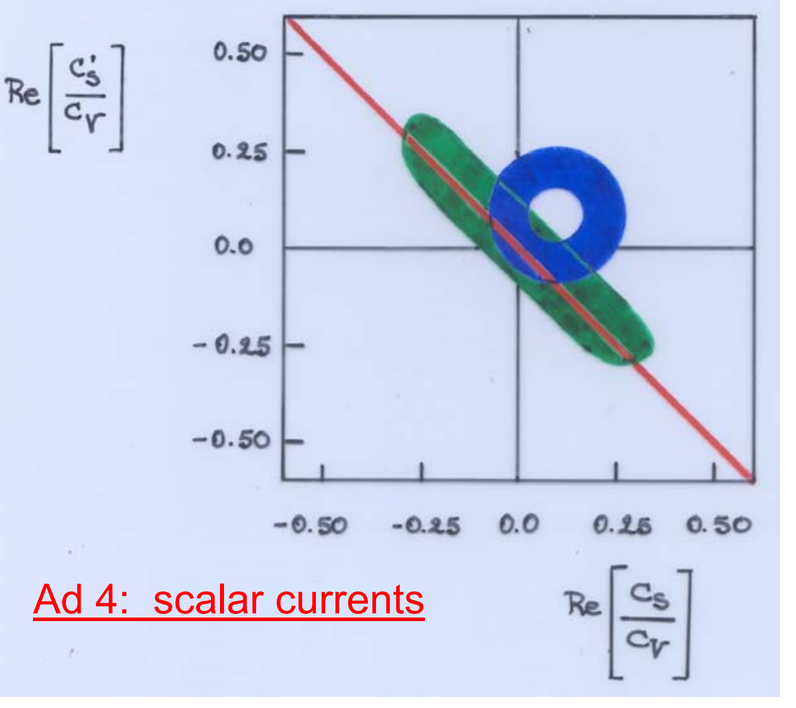
(90% CL)

Ad 3: Left Right Symm.-models

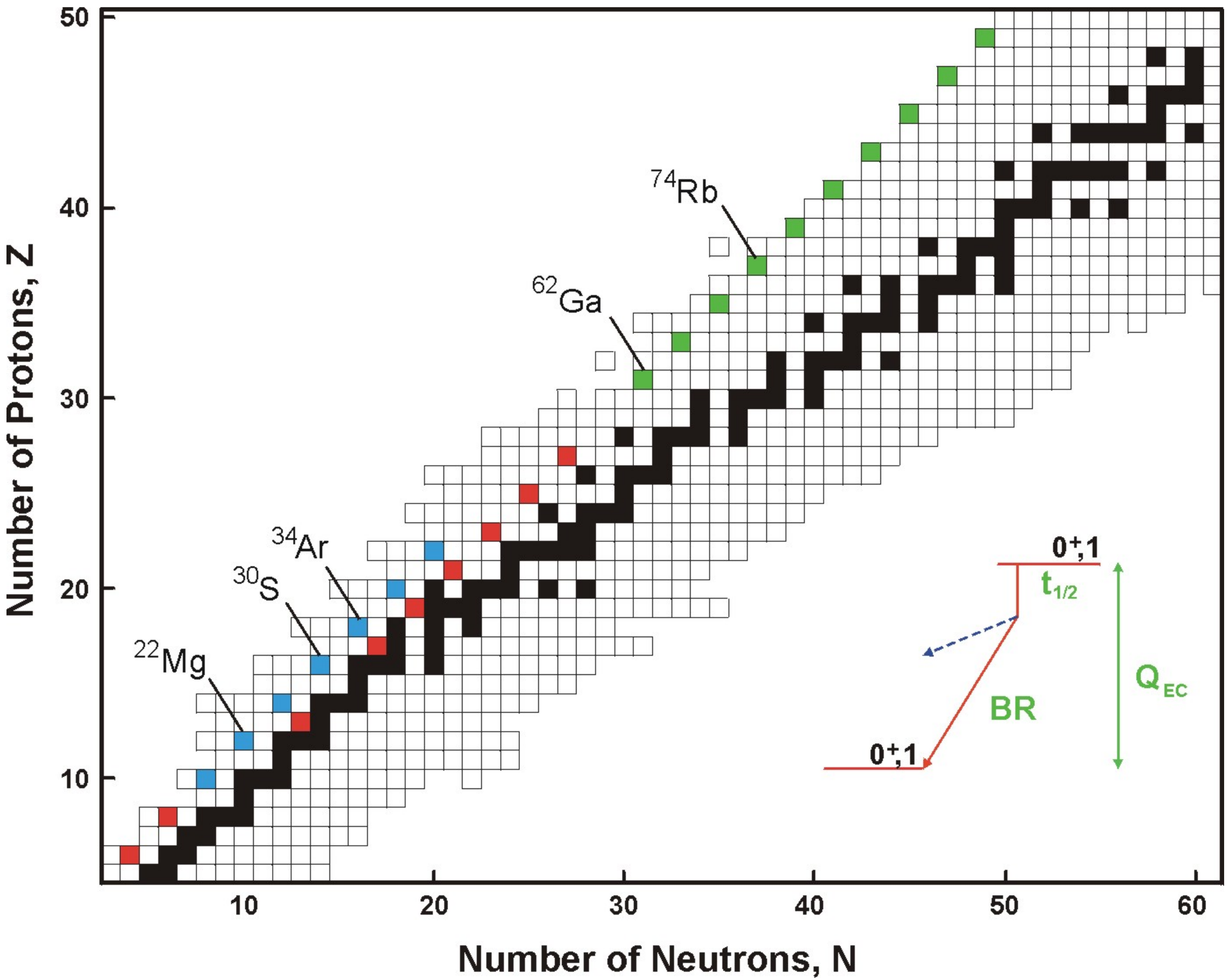
$$W_1 = W_L \cos\zeta - W_R \sin\zeta$$

$$W_2 = W_L \sin\zeta + W_R \cos\zeta$$

$$\delta = m_1^2 / m_2^2$$



Ad 4: scalar currents



Number of Protons, Z
Number of Neutrons, N
10
20
30
40
50
60
^{22}Mg
^{30}S
^{34}Ar
^{62}Ga
^{74}Rb
0+,1
0+,1
t1/2
BR
QEC

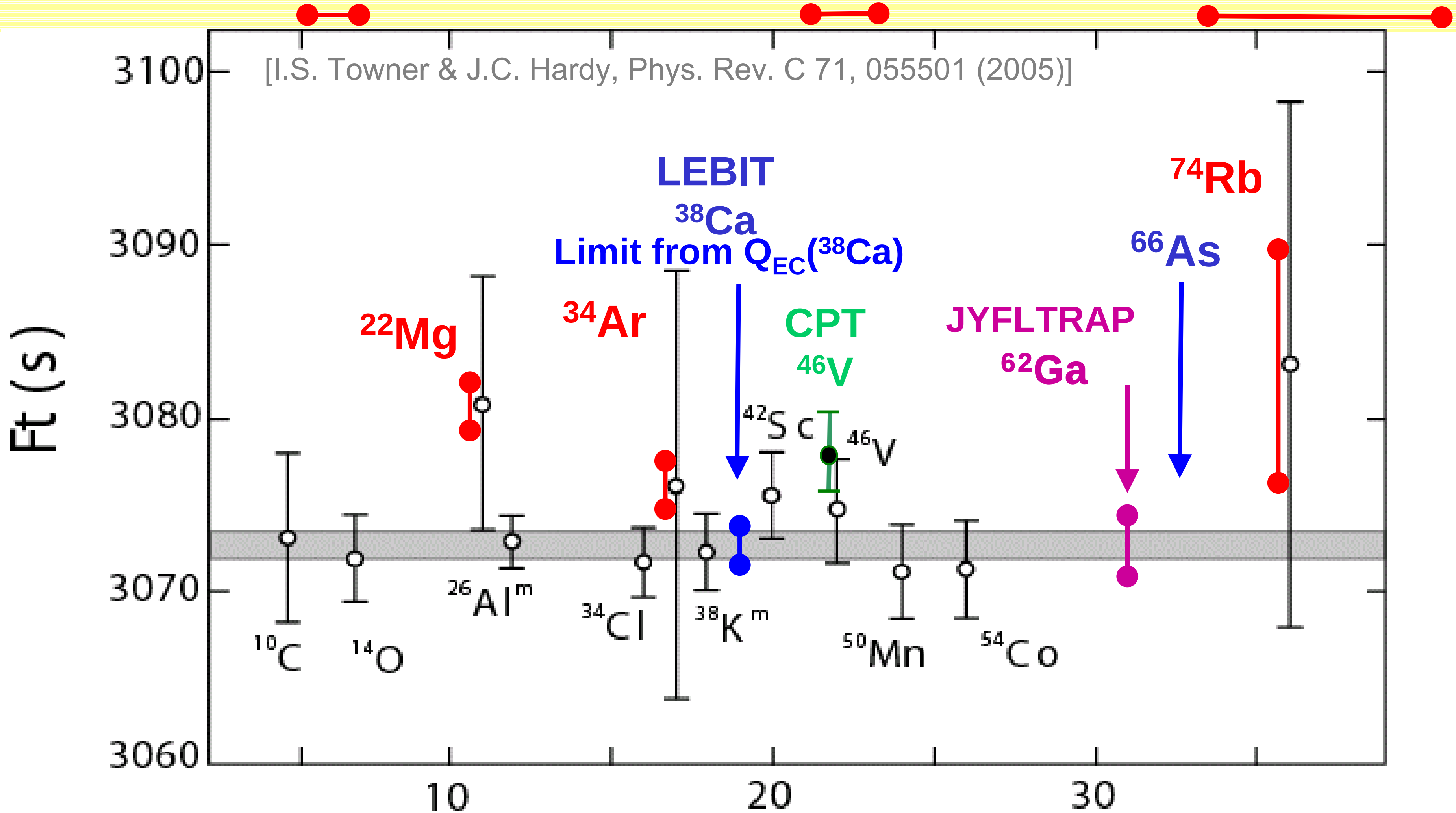
J.C. Hardy

Recent Ft-values results

ISOLTRAP mass measurements

CVC hypothesis confirmed in this mass region

$^{22}Mg \rightarrow {}^{22}Na$: dQ=**0.28 keV**, $^{34}Ar \rightarrow {}^{34}Cl$: dQ=**0.41 keV**, $^{74}Rb \rightarrow {}^{74}Kr$: dQ=**4.5 keV**



F. Herfurth *et al.*, Eur. Phys. J. A 15, 17 (2002)
A. Kellerbauer *et al.*, Phys. Rev. Lett.93, 072502 (2004)
M. Mukherjee *et al.*, Phys. Rev. Lett. 93, 150801 (2004)

T. Eronen *et al.*, to be published (2005)
G. Savard *et al.*, Phys. Rev. Lett. 95, 102501 (2005)

K. Blaum

Conclusion for $0^+ \rightarrow 0^+$ Fermi transitions *Ft*-value determinations

- **further improve results for "classical" isotopes**
- **determine Ft-values for new isotopes of interest :**

$T_z = 1$ isotopes: **^{18}Ne, ^{22}Mg, ^{26}Si, ^{30}S, ^{34}Ar, ^{38}Ca, ^{42}Ti**

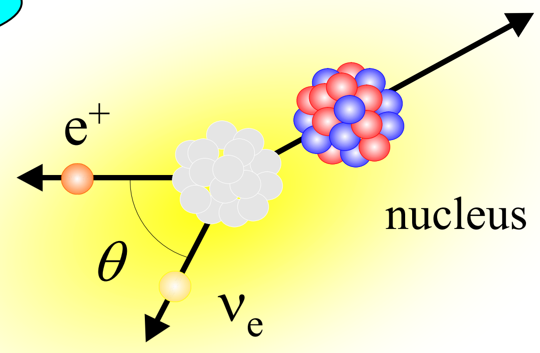
$T_z = 0$ isotopes: **^{62}Ga, ^{66}As, ^{70}Br, ^{74}Rb, ^{78}Y, ^{82}Nb, ^{86}Tc, ^{90}Rh, ^{94}Ag, ^{98}In**

→ needs:

- **beams ($\geq 10^3$ /s) of 'classical' and new $0^+ \rightarrow 0^+$ isotopes**
- **advanced spectroscopic techniques (for $t_{1/2}$ and BR)**
- **Penning traps (mainly for Q_{EC}/mass)**

2a. Search for exotic SCALAR and TENSOR type Weak Interactions

e.g. **βν-correlation**



$$\Rightarrow \quad W(\theta) = 1 + \frac{\bar{p}\cdot\bar{q}}{E_e E_\nu}\tilde{a}$$

with $\tilde{a} \equiv \dfrac{a}{1+\dfrac{\Gamma m}{E_e} b}$ and $\Gamma = \sqrt{1-(\alpha Z)^2}$

$$a_F \cong 1 - \frac{|C_S|^2 + |C'_S|^2}{|C_V|^2}$$

$$a_{GT} \cong -\frac{1}{3}\left[1 - \frac{|C_T|^2 + |C'_T|^2}{|C_A|^2}\right]$$

$$b_F \cong \mathrm{Re}\,\frac{C_S + C'_S}{C_V}$$

$$b_{GT} \cong \mathrm{Re}\,\frac{C_T + C'_T}{C_A}$$

(assuming maximal P-violation and T-invariance for V and A interactions)

recoil corr. (induced form factors) ≈ 10^{-3} ; radiative corrections ≈ 10^{-4}

constraints from nuclear beta decay

- **within the SM**

$$C_A/C_V \approx -1.27$$

$$C_S = C'_S = C_T = C'_T = 0$$

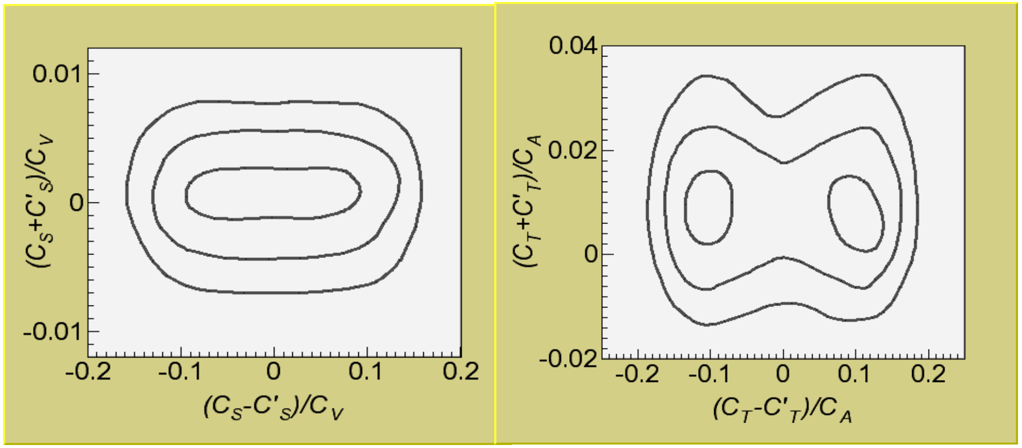
no time reversal violation (other than phase in the CKM quark-mixing matrix)

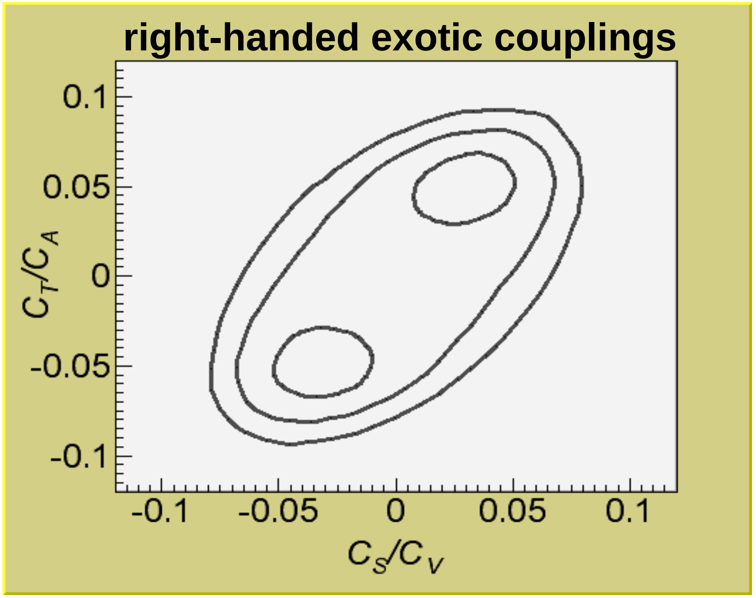
- **beyond the SM**

N. Severijns, M. Beck, O. Naviliat-Cuncic, in press in Rev.Mod.Phys.

(excluding neutron lifetime measurement by A. Serebrov *et al.* 2005)

sums and differences of couplings



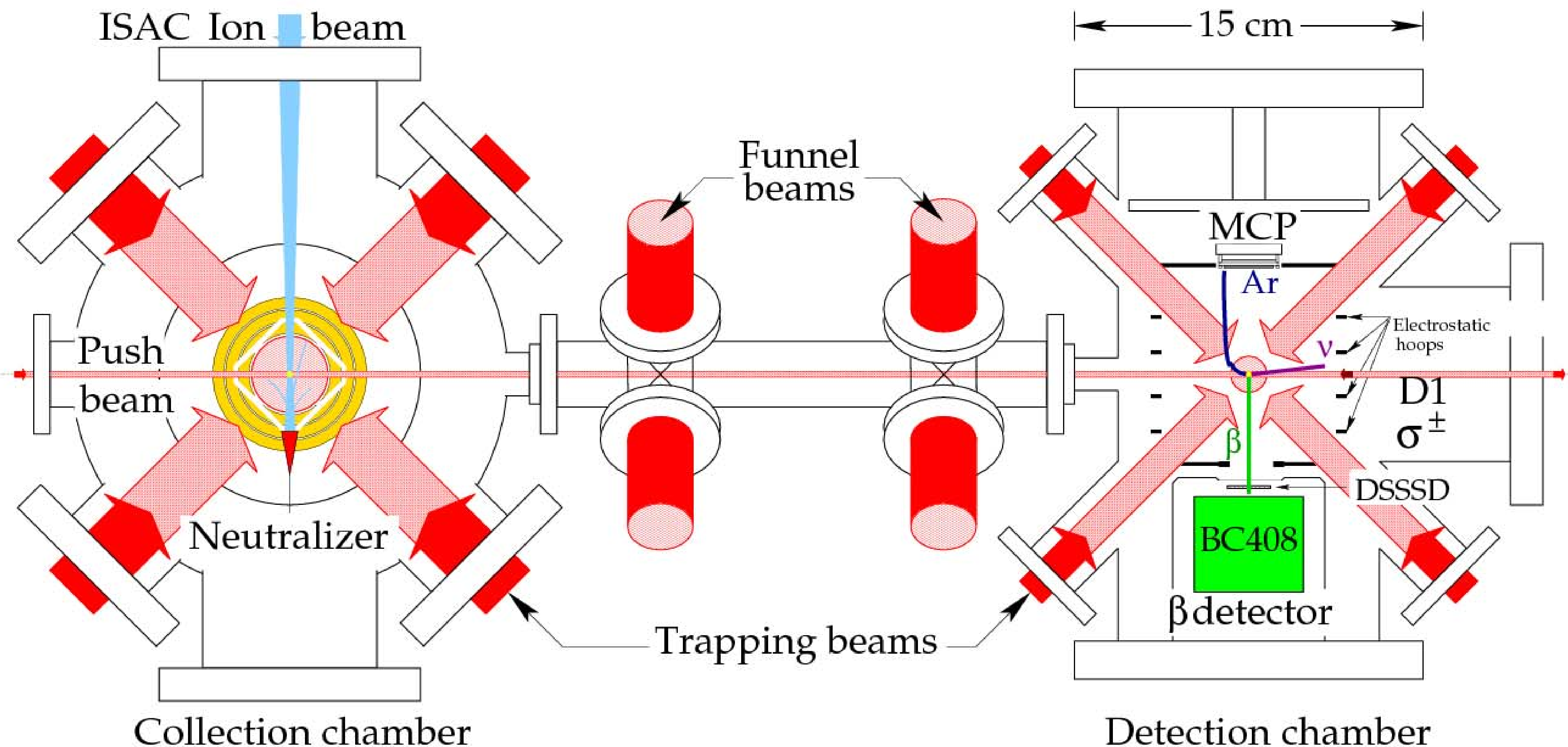


sizable room to accommodate exotic interactions without affecting SM conclusions

contours show 1σ, 2 σ and 3 σ confidence levels

O. Naviliat-Cuncic

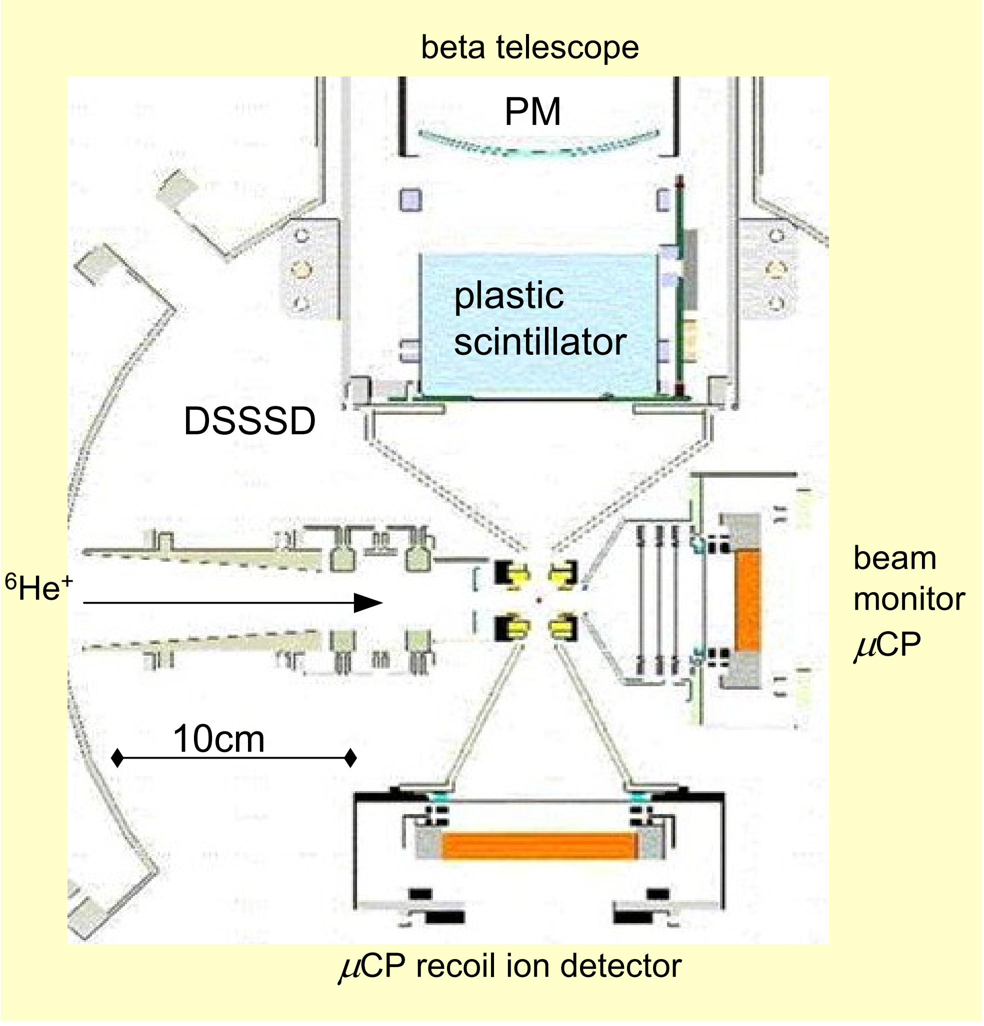
TRIUMF Neutral Atom Trap: *β-ν* correl. to search for scalar couplings



$\tilde{a}=0.9981\pm0.0030^{+0.0032}_{-0.0037}$ **(A. Gorelov, J. Behr et al., Phys. Rev. Lett. 94 (2005) 142501)**

LPC **Paul trap** : *β-ν* correl. to search for tensor couplings

$$^{6}\text{He} \rightarrow {}^{6}\text{Li} + e^{-} + \bar{\nu}_e$$

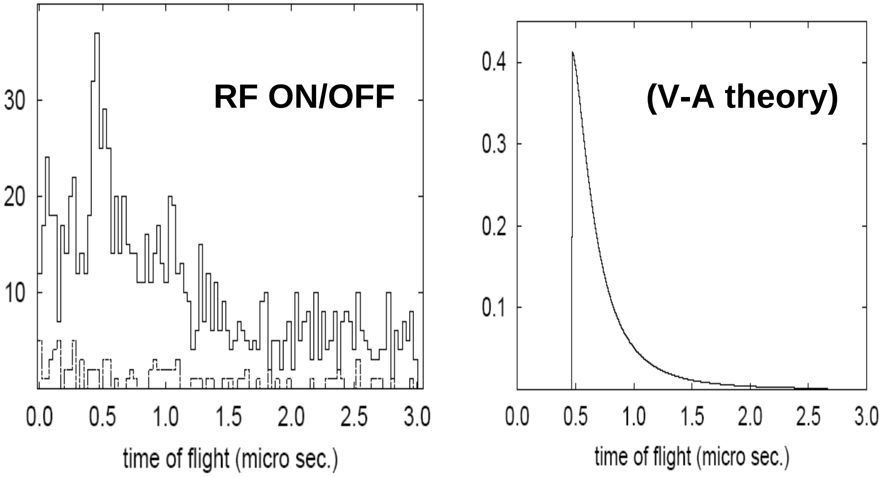


- LPC trap (Caen)

- ^{6}He decay (pure GT)
- RFQ cooler and decay Paul traps
- measure all TOF of ions in coincidence

- difficulties: cloud phase space, response fctn.

- First direct *β*-decay from an ion trap

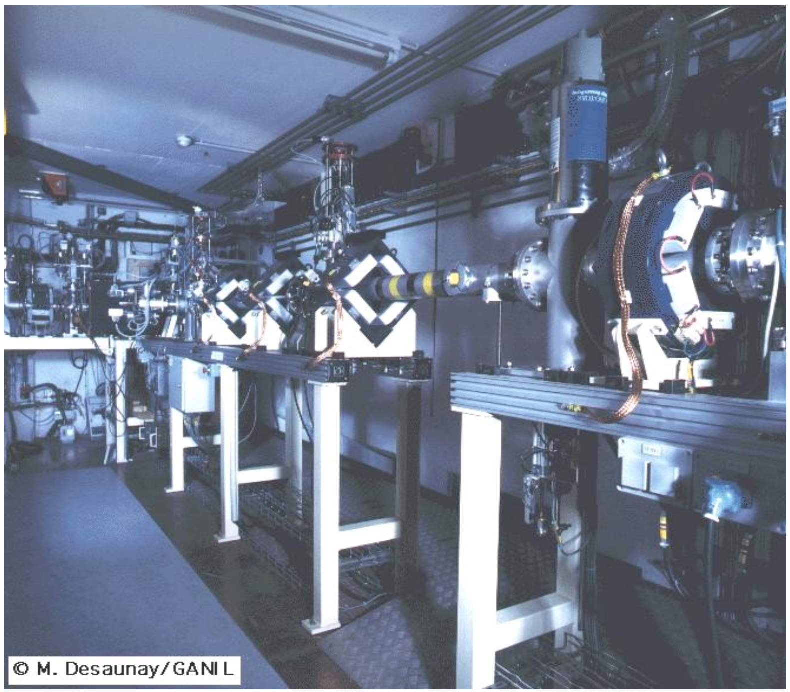


G. Ban, O. Naviliat-Cuncic et al., Nucl. Phys. A 752 (2005) 67

O. Naviliat-Cuncic

LPCTrap at SPIRAL-GANIL

production of ^{6}He (SPIRAL TSS)



LIRAT low energy line

cooling (H_2)/ bunching

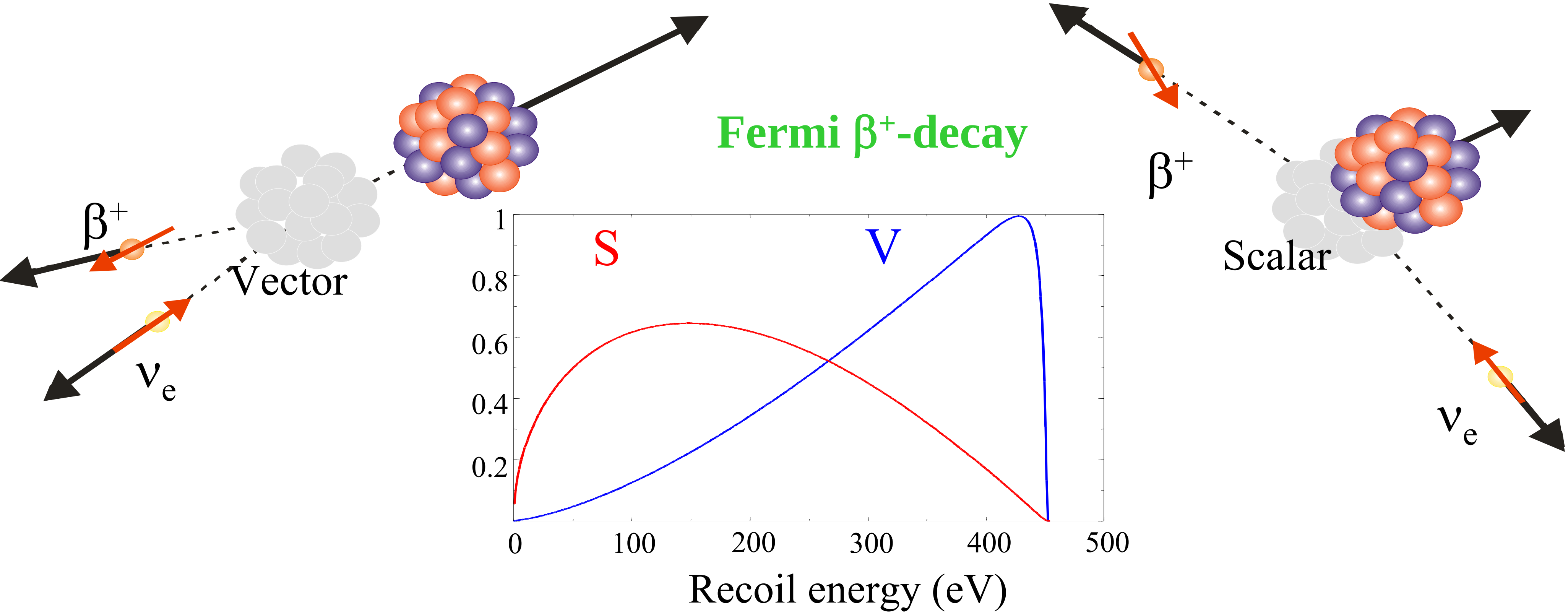
table top experiment

O. Naviliat-Cuncic

WITCH – Weak Interaction Trap for CHarged particles

ISOLDE-CERN (K.U.Leuven, Univ. Munchen, CERN)

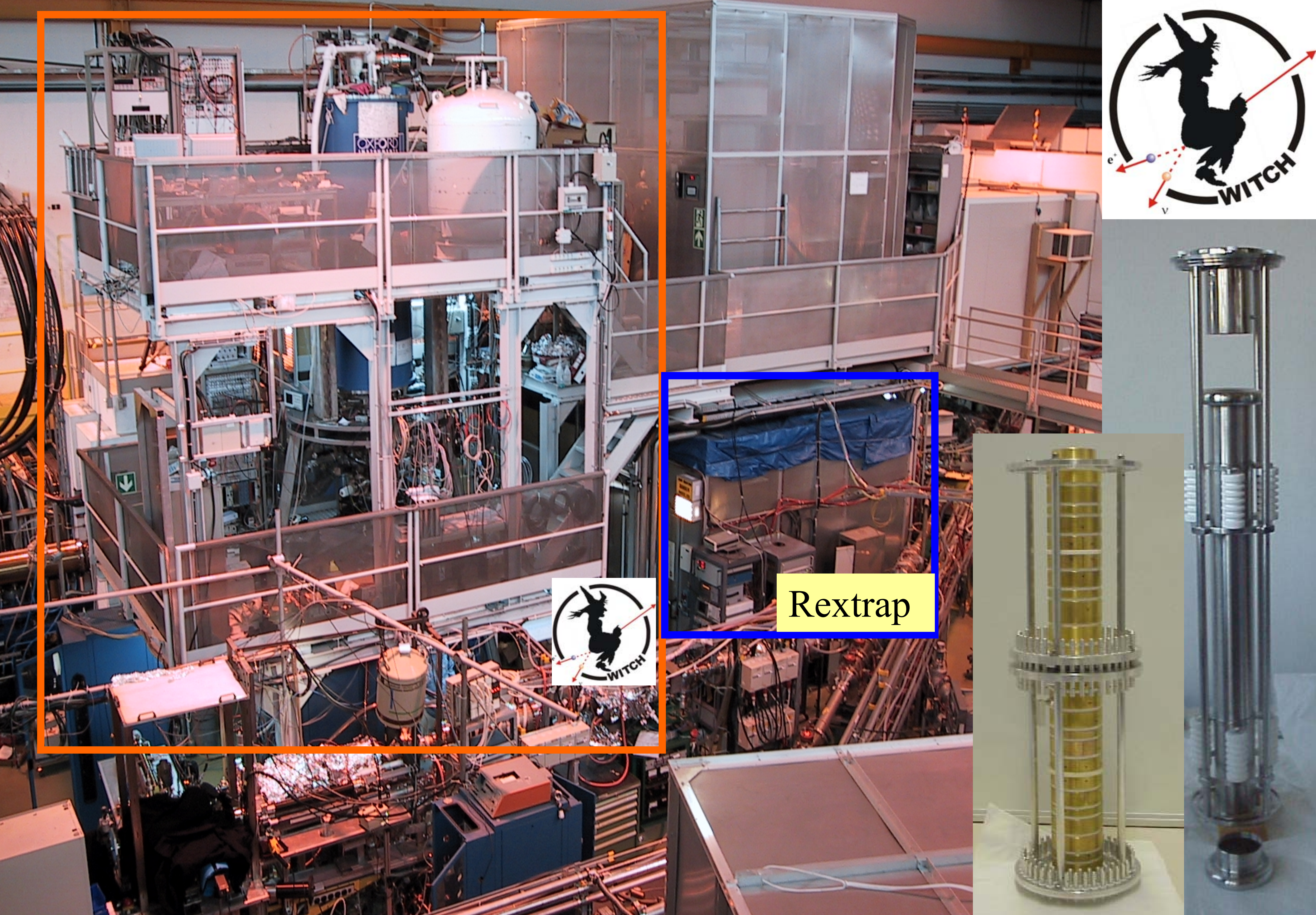
cooler & decay Penning trap + retardation spectrometer



<u>First goal :</u>

search for scalar weak interaction by measuring shape of recoil ion energy spectrum after β-decay

M. Beck et al., Nucl. Instr. Meth. A503 (2003) 567



WITCH
Rextrap
WITCH

Present status

<u>Ions used for tuning and trapping:</u>

^{39}K, ^{130}Xe,... , ^{35}Ar, ^{122}In (radioactive)

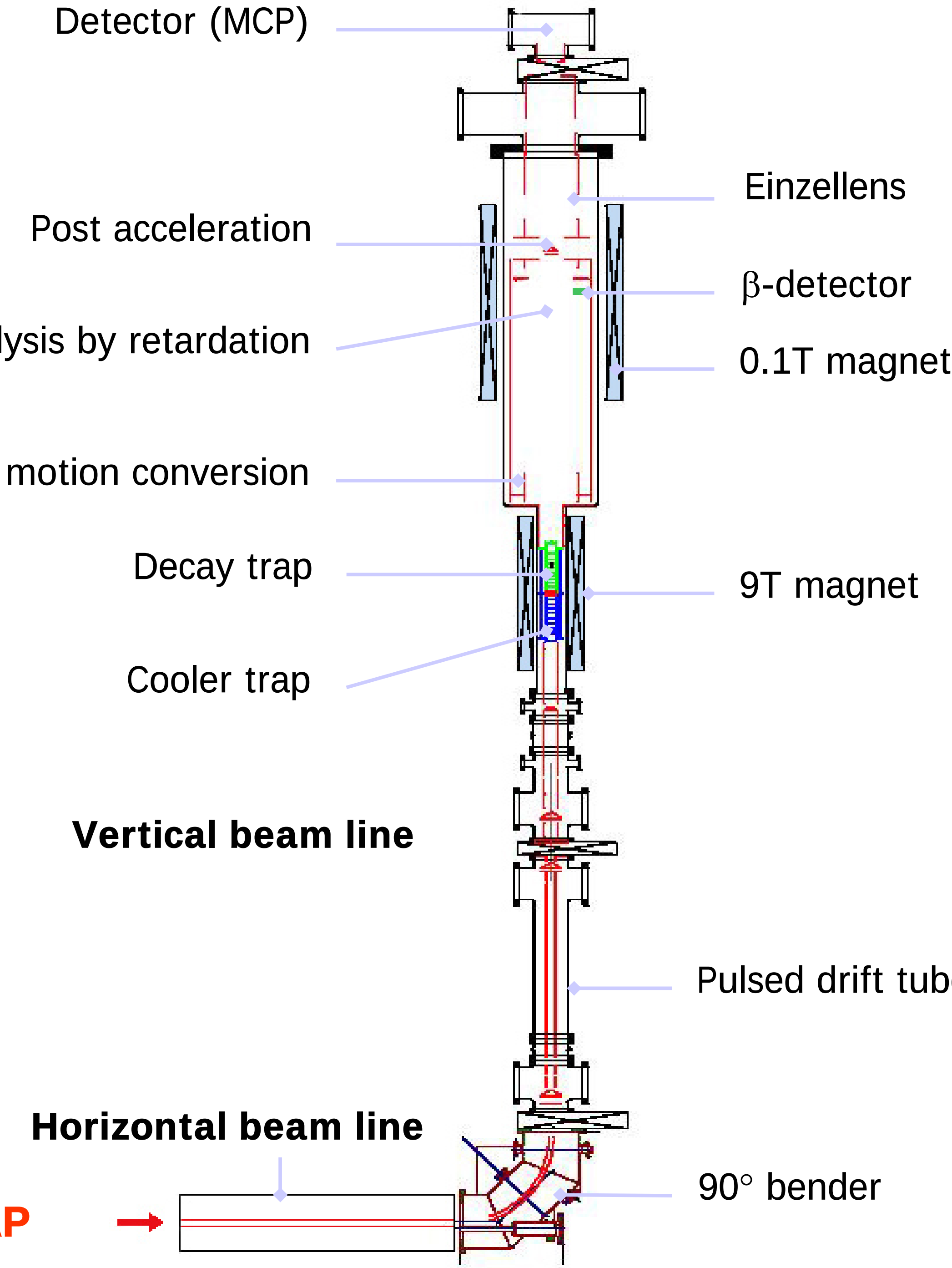
<u>Trapping times</u>: up to **1 s**

<u>Efficiencies</u>:

- horiz. beamline: **~100%**
- Pulsed Drift Tube: **~40%**
- injection in 9T field : **~1%**
- trapping in cooler trap: **~50%**
- transfer to decay trap: **~70%**

<u>Goals for 2006:</u>

- **improve efficiencies**
- **measure recoil spectrum**

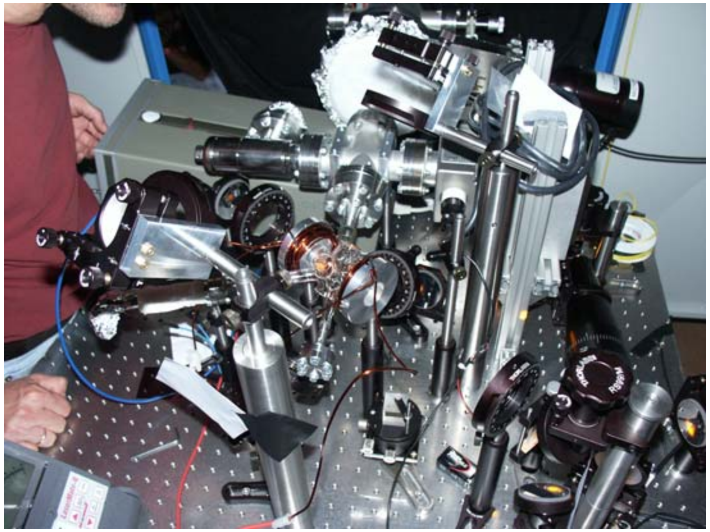


traps for correlations in beta decay

present:

isotope	trap	meas.	lab
^{21}Na	MOT	a_F [1]	LBNL
^{38m}K	MOT	a_F [2]	TRIUMF
^{6}He	Paul	a_{GT}	LPC/GANIL
^{35}Ar	Penning	a_F	KUL/ISOLDE
^{21}Na, ^{19}Ne, ^{23}Mg	MOT	a, D	KVI
^{82}Rb	MOT	A_{GT}	LANL

(1) = 0.5243(91) Scielzo et al. PRL 93(2004) 102501
(2) = 0.9978(30)(37) Gorelov et al. PRL 94 (2005) 142501



KVI-MOT laser set-up

needs: - **more isotopes (e.g. ^{8}He, ^{26m}Al, ^{37}K, ^{46}V, …)**

- **high intensities ($\geq 10^8$ /s)**
- **nuclear polarization (e.g. for A_{GT}-correlation, sensitive to T-interaction)**
  - **MOT: realized already (TRIUMF and LANL, KVI in progress)**
  - **Paul: optical pumping**
  - **Penning: before injection, with collinear laser set-up**
- **need factor 10 better precision (~ 10^{-3}) on *ft*-values ($t_{1/2}$, BR, Q_{EC} (mass)) for T = 1/2 mirror β-transitions, viz. ^{21}Na, ^{23}Mg, ^{35}Ar, ^{37}K, ^{39}Ca, …**

3. Symmetry tests

- **Time Reversal Violation**

Cosmological matter-antimatter asymmetry ↔ δ_{CKM} in Standard Model

Explore by:

(- direct measurements: K, B, D mesons)

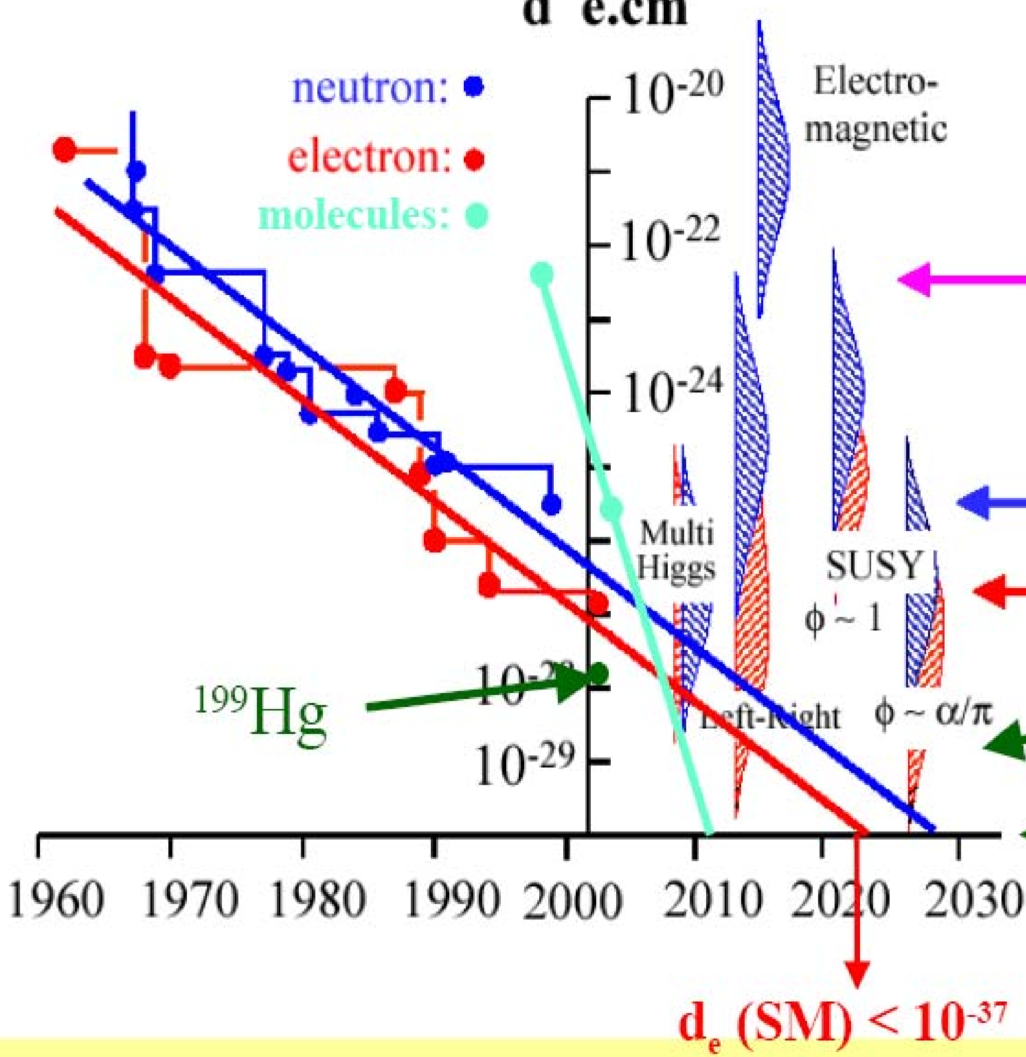
- **indirect measurements:**
  - **permanent electric dipole moments (EDM)**
  - **correlations (D and R) in nuclear β-decay**

Note: Standard Model values for parameters observed are beyond experimental reach → sensitive probes for new physics

needs:
- **high intensity Ra beams (for EDM searches)**
- **high intensity ^{19}Ne, ^{21}Na, … beams (for D- and R-correlations)**
- **means to polarize ^{19}Ne, ^{21}Na, …**

EDM Experiments Compared

New 2004 from muon g-2:
d (muon) < 2.8 ×10^{-19}



d(proton) < 6×10^{-23}

d(neutron) < 6×10^{-26}

d(electron) < 1.6×10^{-27}

Deuteron potential

Radium potential

G. Onderwater

Summary of requirements

- **beams** with intensity ranging from 10^8 /s to $\geq 10^8$ /s (mostly at and close to N = Z line)
  - 'classical' and new $0^+ \rightarrow 0^+$ isotopes (Ft-values)
  - ^{8}He, ^{26m}Al, ^{32}Ar, ^{46}V, … (GT and $0^+ \rightarrow 0^+$ → exotic weak interactions)
  - ^{21}Na, ^{23}Mg, ^{35}Ar, ^{37}K, ^{39}Ca, … (T = 1/2 mirror transitions → exotic weak interactions)
  - polarized ^{19}Ne, ^{21}Na, … beams (D- and R-correlations → time reversal violation)
  - Ra beams (EDM → time reversal violation)

- improved **Ft-values** for $0^+ \rightarrow 0^+$ and for T = 1/2 **mirror** β-transitions
  - advanced spectroscopic techniques (for $t_{1/2}$ and BR)
  - Penning trap (precision trap for Q_{EC}/mass; cylindrical trap + spectroscopy set-up for $t_{1/2}$ and BR)

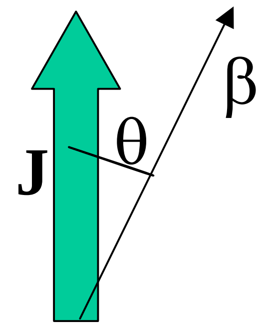
- **traps** for **correlations** in **β-decay :**
  - Paul trap (rather easy operation, easy combination with detectors)
  - cylindrical Penning trap (slightly more difficult operation, isobar purification)
  - MOT (easy combination with detectors, alkalines and earth alkalines)

- **nuclear polarization** in traps (A_{GT} (T-interaction), D- and R-correlations (time reversal violation))
  - **MOT:** realized already (TRIUMF and LANL, KVI in progress)
  - **Paul trap:** optical pumping
  - **Penning trap:** before injection, with collinear laser set-up

2b. Search for TENSOR type WEAK INTERACTIONS

β asymmetry

$$W(\theta) = 1 + \bar{J} \cdot \frac{\bar{p}}{E_e} A$$



$$\lambda_{J'J} = \begin{cases} 1 & \text{for } J \rightarrow J-1 \\ -\dfrac{J}{J+1} & \text{for } J \rightarrow J+1 \end{cases}$$

$$\gamma = \sqrt{1-(\alpha Z)^2}$$

for a pure Gamow-Teller transition :

$$A_{GT}^{\beta^m} \cong \lambda_{J'J}\left[m1 + \frac{\alpha Z m}{p} \mathrm{Im}\left(\frac{C_T + C_T'}{C_A}\right) + \frac{\gamma m}{E_e} \mathrm{Re}\left(\frac{C_T + C_T'}{C_A}\right) \right]$$

(assuming maximal P-violation and T-invariance for V and A interactions)

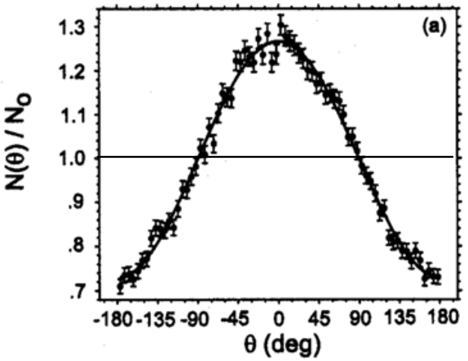
$-0.008 < \mathrm{Im}\,(C_T+C'_T)/C_A < 0.014$ (90% CL) from ^{8}Li @ PSI, R. Huber et al., PRL 90 (2003) 202301

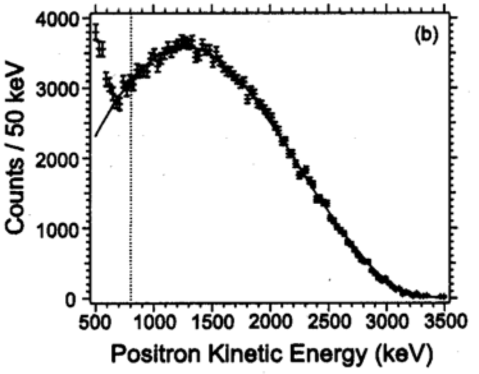
$\Delta A/A = 0.01 \rightarrow$ (for $\gamma m/E_e \cong 0.5$) $\mathrm{Re}\,[(C_T+C_T')/C_A] < 0.040$ (95% CL)

recoil corr. (induced form factors) ≈ 10^{-3} ; radiative corrections ≈ 10^{-4}

A_{GT} independent of nuclear matrix elements

present β-asymmetry parameter experiments :





1. Atom trap :

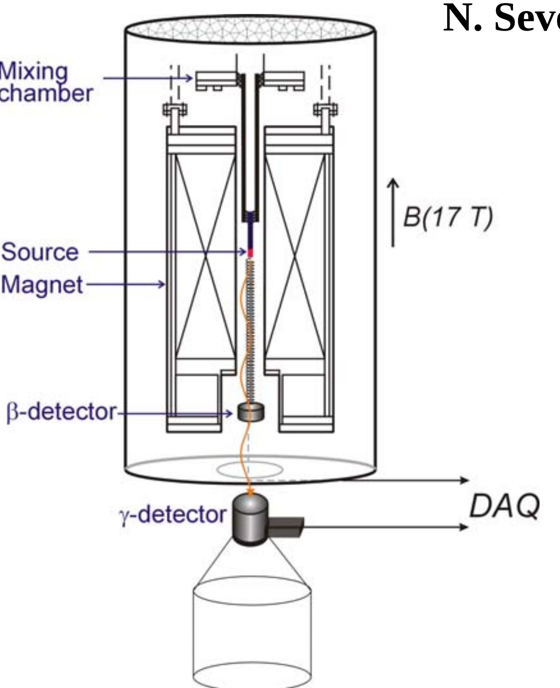
- LANL Los Alamos, ^{82}Rb -tensor (D. Vieira et al.)

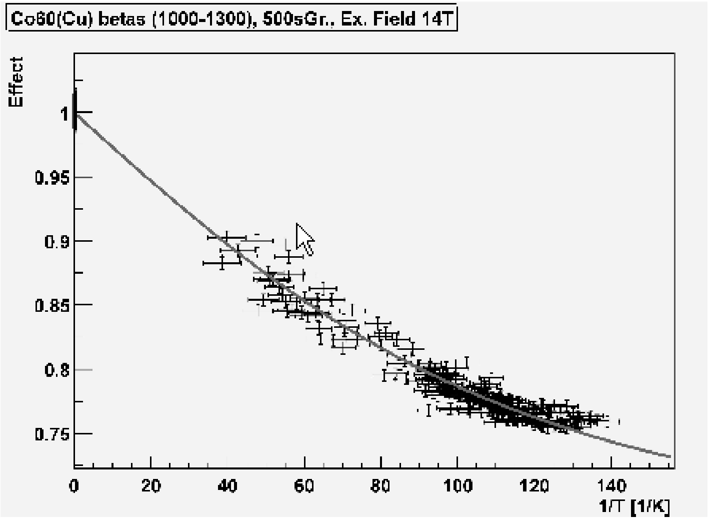
S.G. Crane et al., Phys. Rev. Lett. 86 (2001) 2967

2. Low Temp. Nucl. Orient. :

- ISOLDE + Leuven, ^{114}In, ^{60}Co, ^{133}Xe - tensor (I. Kraev et al.)

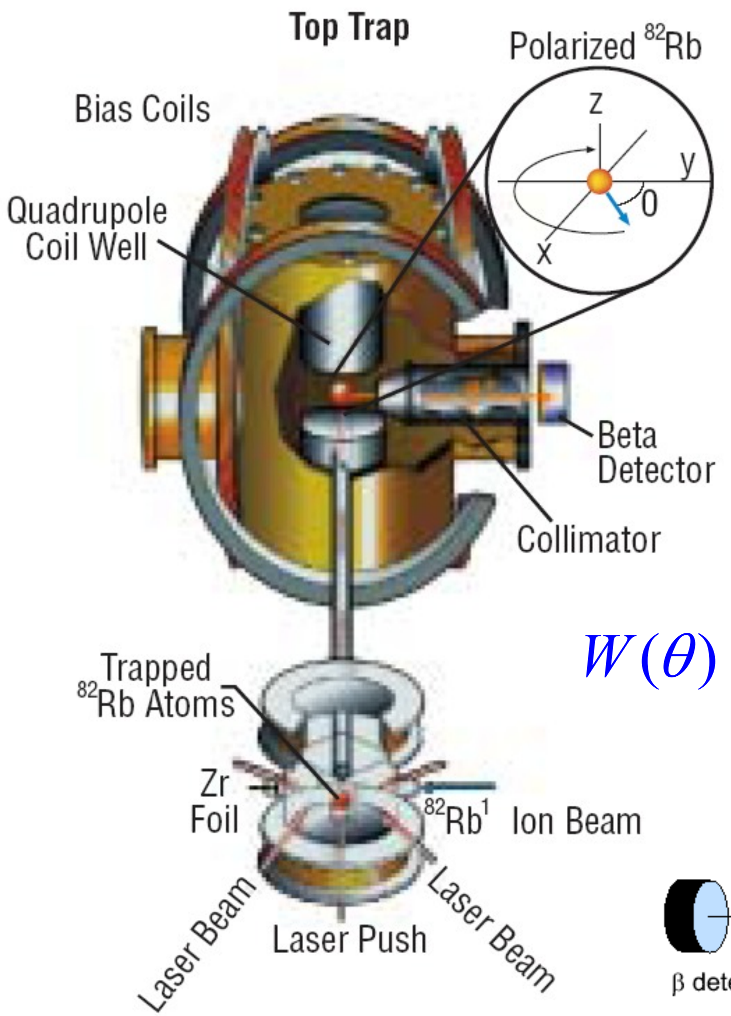
N. Severijns, submitted to PRL; I. Kraev et al., in preparation

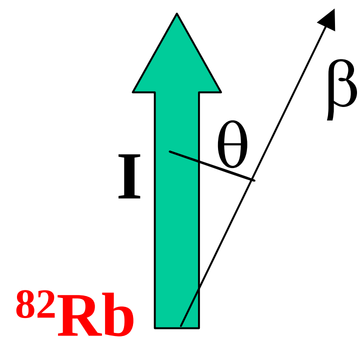


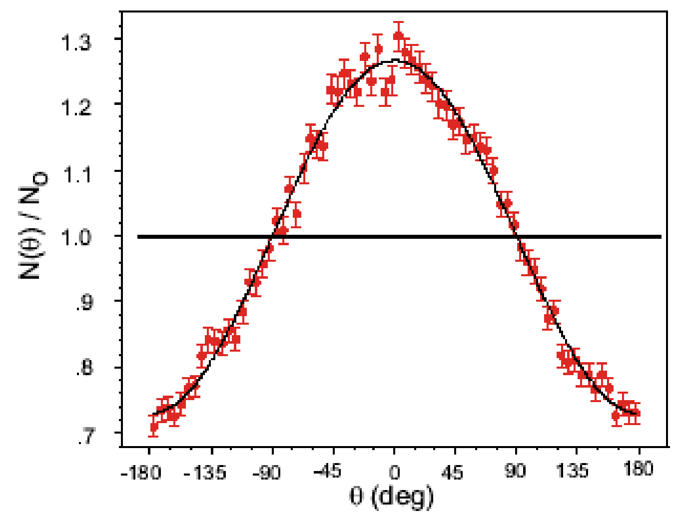


The neutral atom trap at Los Alamos - LANL

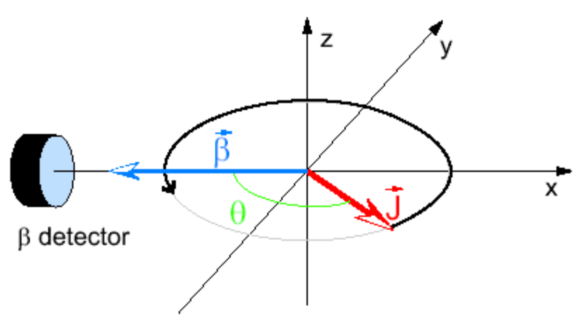
angular distribution ↓

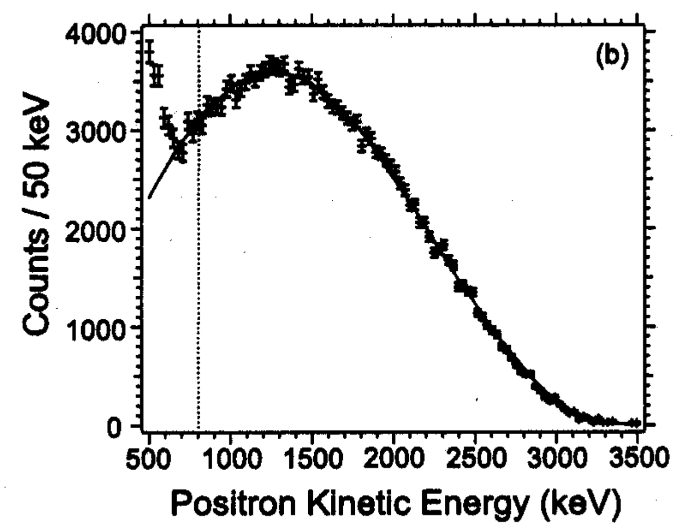






$$W(\theta) = 1 + \bar{J} \cdot \frac{\bar{p}}{E_e} A_{exp}$$

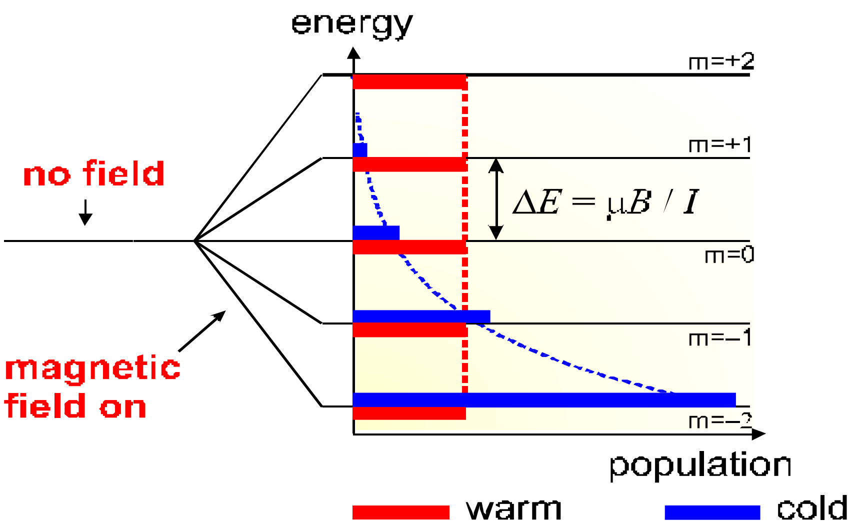




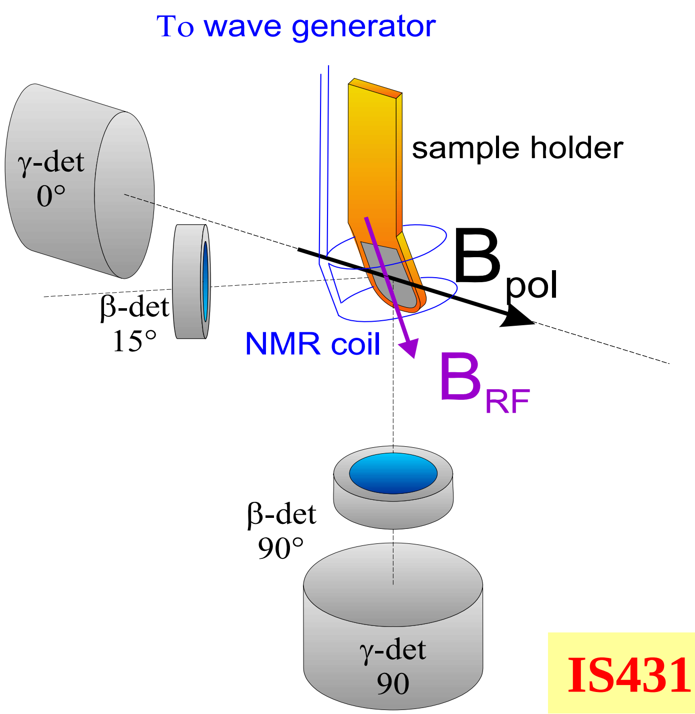
S.G. Crane et al., Phys. Rev. Lett. 86 (2001) 2967
D.J. Vieira et al., Hyp.Int. 127 (2000) 387

positron energy spectrum ↑

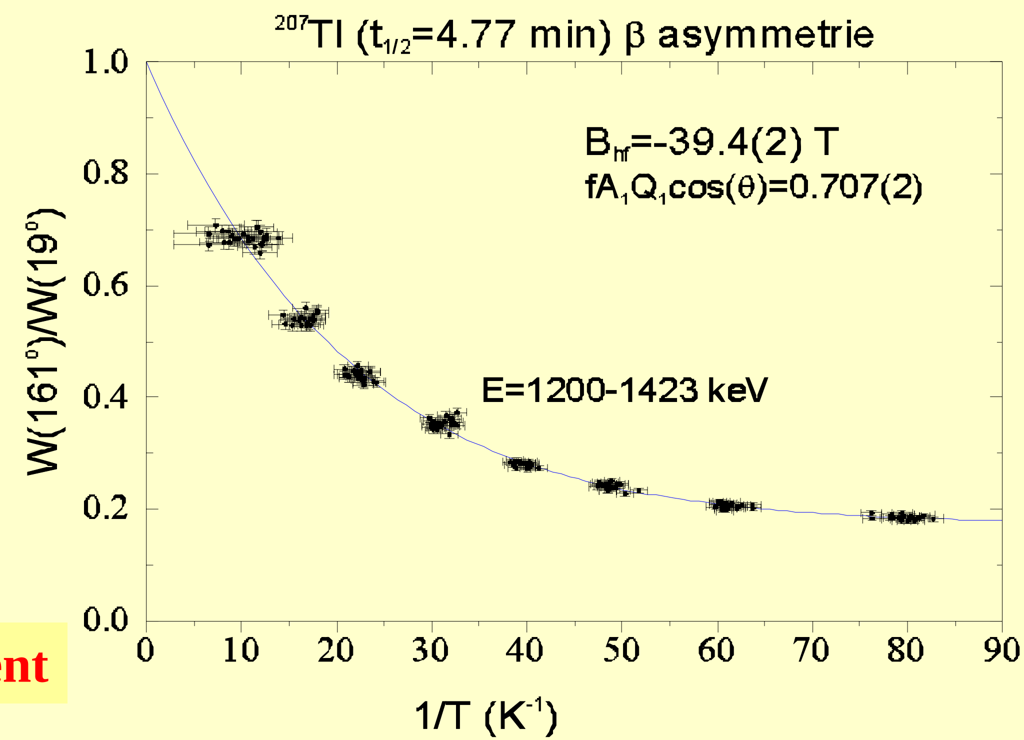
Low Temperature Nuclear Orientation @ NICOLE - ISOLDE



$$W(\theta) = \frac{N(\theta)_{pol}}{N(\theta)_{unpol}} = 1 + k\, A_{GT}^{\beta^m}\, P\, Q \frac{v}{c} \cos\theta$$



IS431-experiment

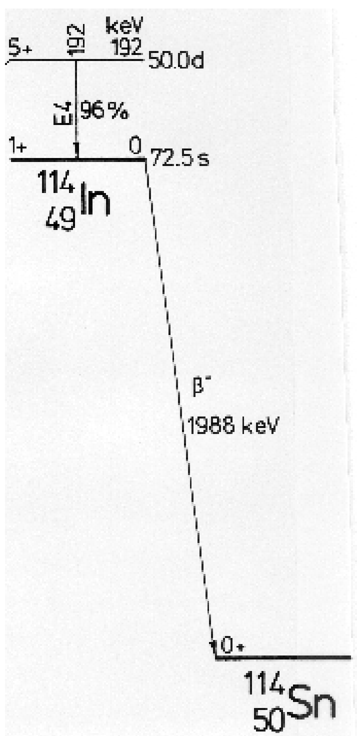


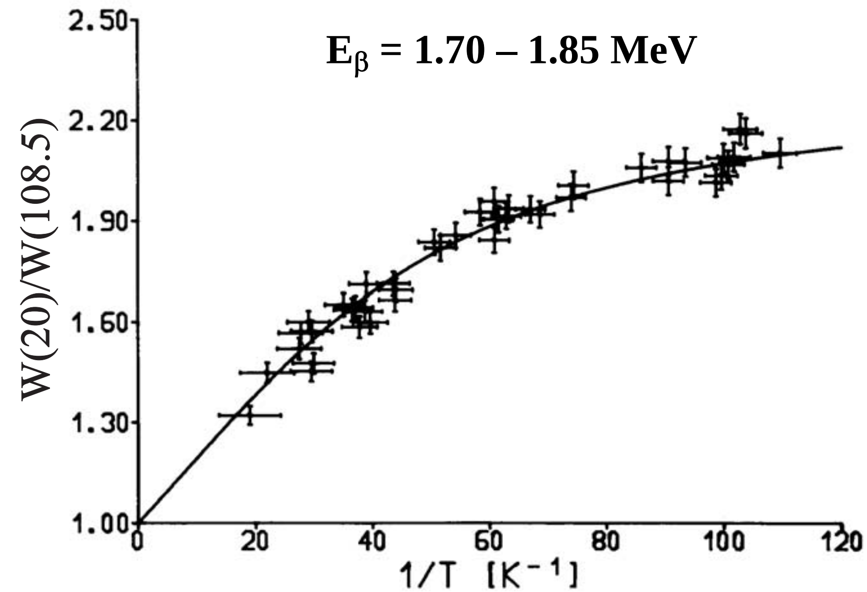
First case: ^{114}In

$1^+ \rightarrow 0^+$ pure GT

E_0 = 1.99 MeV

log *ft* = 4.473(5)





$$A_{GT} = -1.017(20)$$

↓ ($\gamma m/E$ = 0.210)

$-0.24 < \mathrm{Re}\,(C_T+C'_T)/C_A < 0.08$ **(90% CL)**

(best precision for A for a fast pure GT transition to date !)

N. Severijns et al., to be published