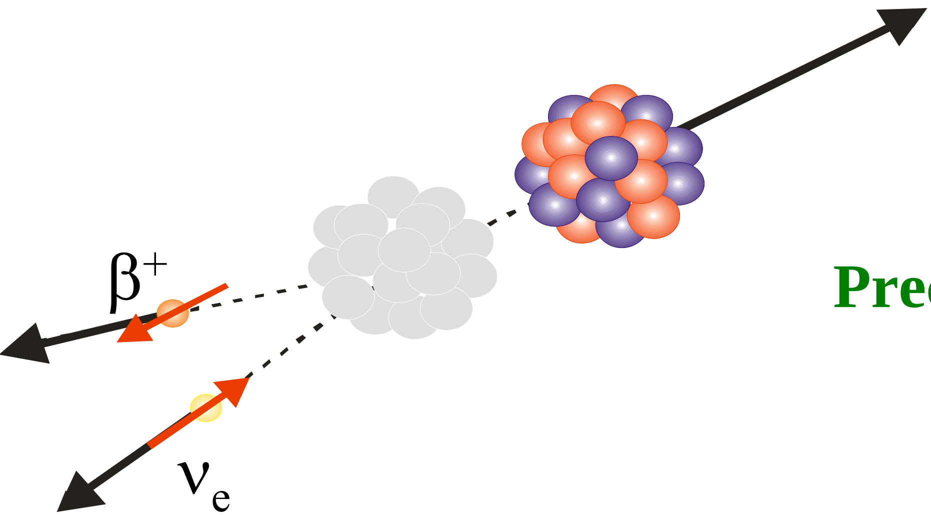
Probing exotic weak currents in nuclear β-decay



Workshop on

Precision Measurements at Low Energies

PSI, January 18-19, 2007

Nathal Severijns

Kath. University Leuven, Belgium

1. $Ft^{0^+\to 0^+}$ (D. Dubbers)

2. βν-correlation coefficient *a*

- neutron : *a*SPECT

- nuclei :
  - TRINAT / TRIUMF
  - Berkeley MOT (K. Jungmann)
  - KVI (K. Jungmann)
  - LPC-TRAP / GANIL
  - WITCH / ISOLDE

β-asymmetry parameter *A*

- neutron : (D. Dubbers - S. Paul)
- nuclei : Leuven – ISOLDE

3. symmetry tests

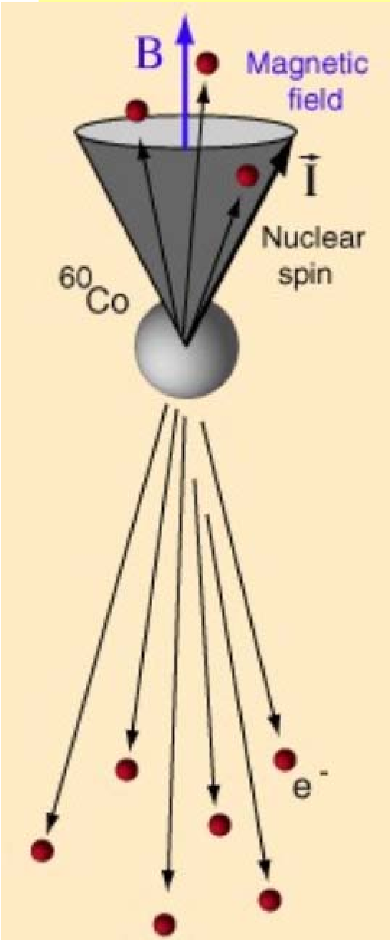
- parity
- TRV :
  - EDM (K. Jungmann)
  - D ($J.p_e x p_\nu$; V,A)
  - *R* ($\sigma.J x p_e$; S,T) ; neutron R-TRV / PSI

How it started:

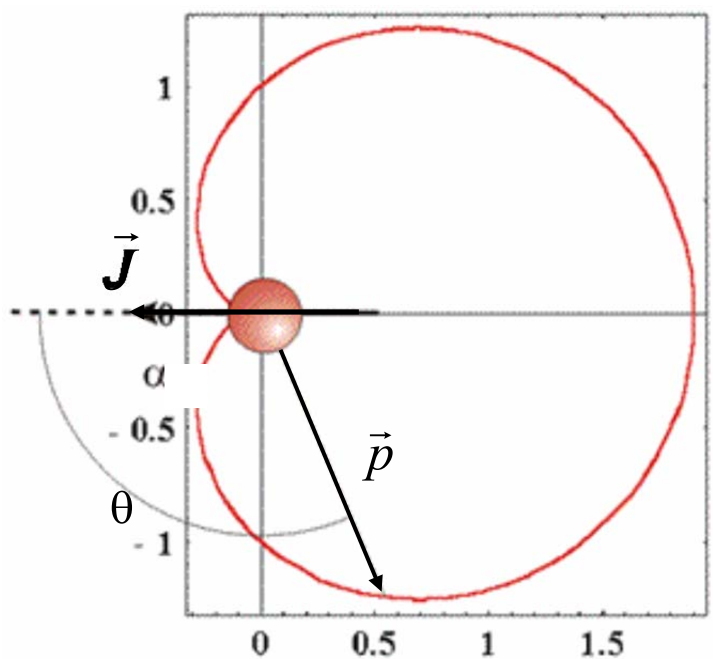
θ - τ **puzzle**: **one particle !? / P-violating decay !?**

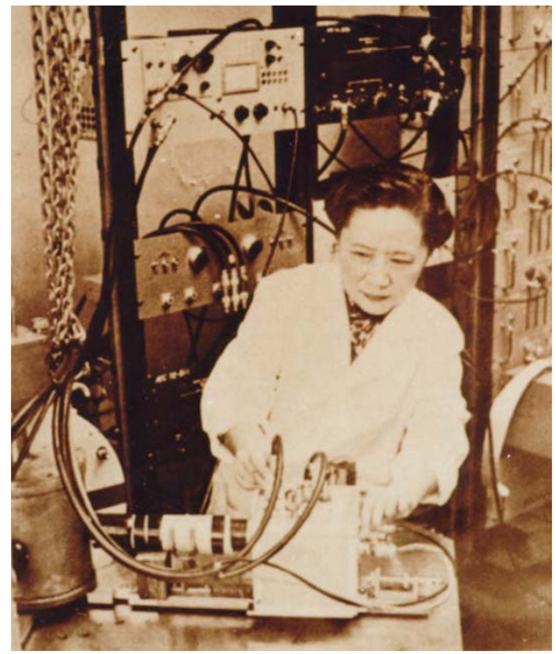
Oct.1956 **Lee & Yang**: **P-violation in weak interaction not yet tested !**
[PR 104 (1956) 254]

Jan.1957 **Wu et al.**: **^{60}Co β-decay P- violating !!**
[PR 105 (1957) 1413]



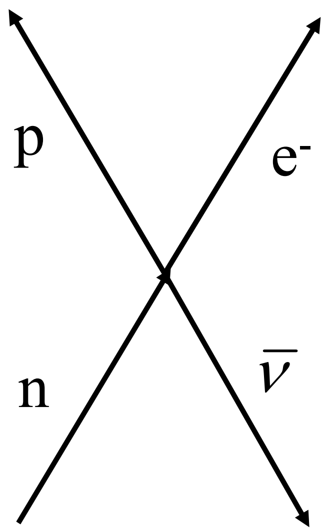
$$^{60}Co \rightarrow {}^{60}Ni + e^- + \bar{\nu}_e$$





STRUCTURE OF THE WEAK INTERACTION IN NUCLEAR BETA DECAY

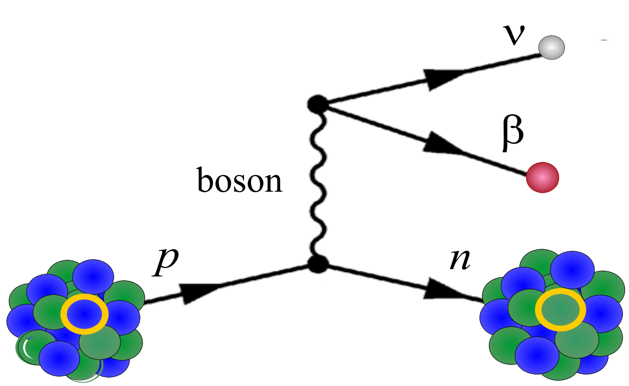
β-decay Hamiltonian (Lee & Yang) :



$$
\begin{aligned}
H_\beta / g \;\propto\;\; & (\bar{p}\, 1\, n)\;[\bar{e}\;\, 1\;\, (C_S + C_S'\gamma_5)\,\nu\,] \\
+\; & (\bar{p}\,\gamma_\mu\, n)\;[\bar{e}\;\, \gamma_\mu\;\, (C_V + C_V'\gamma_5)\,\nu\,] \\
+\; & \tfrac{1}{2}(\bar{p}\,\sigma_{\mu\nu}\, n)\;[\bar{e}\;\, \sigma_{\mu\nu}\;\, (C_T + C_T'\gamma_5)\,\nu\,] \\
-\; & (\bar{p}\,\gamma_\mu\gamma_5\, n)\;[\bar{e}\;\, \gamma_\mu\gamma_5 (C_A + C_A'\gamma_5)\,\nu\,] \\
+\; & \cancel{\underbrace{(\bar{p}\,\gamma_5\, n)}_{\approx 0}\;[\bar{e}\;\, \gamma_5\;\, (C_P + C_P'\gamma_5)\,\nu\,]}
\end{aligned}
$$

with γ_i (i = 1, 2, 3, 4) Dirac matrices $(\gamma_5 = \gamma_1\gamma_2\gamma_3\gamma_4)$

and $\sigma_{\mu\nu} = -\frac{i}{2}(\gamma_\mu\gamma_\lambda - \gamma_\lambda\gamma_\mu)$



P-violation if $C_i \neq 0$ and $C_i' \neq 0$

T-violation if $\mathrm{Im}(C_i^{(')} / C_j) \neq 0$

the Standard Model and beyond:

* $C_V = 1$ (CVC)
* $C_A = -1.27$ ($g_A/g_V = -1.2699(7)$ from n-decay)
* $C_V' = C_V$ & $C_A' = C_A$ (maximal P-violation)

* $C_S = C_S' = C_T = C_T' = C_P = C_P' \equiv 0$ (only V- and A-currents)

experimental upper limits:

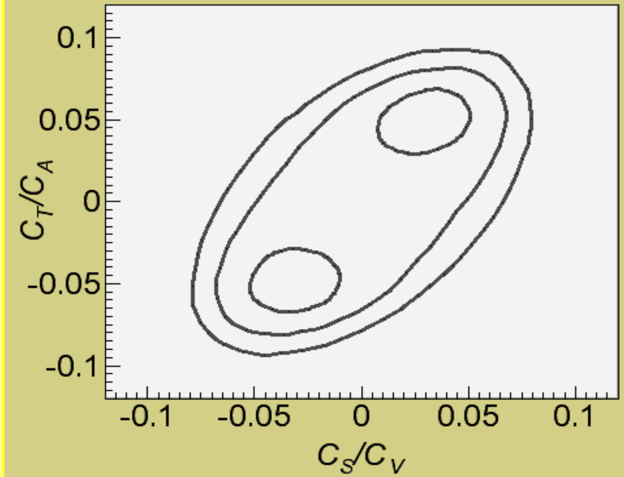
(neutron and nuclear β-decay)

$$\left| C_T^{(\,'\,)} / C_A \right| < 0.09$$

$$\left| C_S^{(\,'\,)} / C_V \right| < 0.07 \qquad (95\%\,\mathrm{CL})$$

from: N. Severijns, M. Beck, O. Naviliat-Cuncic, Rev. Mod. Phys. 78 (2006) 991

for right-handed exotic couplings

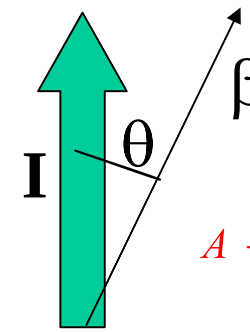


* no time reversal violation
(except for the CP-violation described by the phase in the CKM matrix)

distribution in

- **electron and neutrino directions** and in
- **electron energy**

from **polarized nuclei :**



$$A\,\frac{\vec{J}}{J}\cdot\frac{\vec{p}_e}{E_e}$$

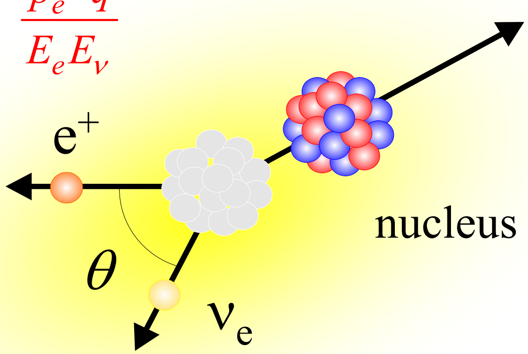
$$\omega\,(\langle\vec{J}\rangle\,|\,E_e,\Omega_e,\Omega_\nu)\;dE_e\;d\Omega_e\;d\Omega_\nu$$

$$\propto\;\underbrace{F(\pm Z,\,E_e)}_{\text{Fermi function}}\quad\underbrace{p_e\;E_e\;(E_0-E_e)^2\;dE_e\;d\Omega_e\;d\Omega_\nu}_{\text{phase space}}$$

$$\text{x}\quad\xi\;\left\{1\;+\;a\,\frac{\vec{p}_e\cdot\vec{q}}{E_eE_\nu}+b\,\frac{\gamma m_e}{E_e}+A\,\frac{\vec{J}}{J}\cdot\frac{\vec{p}_e}{E_e}+R\;\vec{\sigma}\cdot\frac{\vec{J}}{J}\,\text{x}\,\frac{\vec{p}_e}{E_e}+\ldots\right\}$$

β-ν correlation | **Fierz interference term (b ≡ 0 in standard model)** | **β-asymmetry** | **R-correlation**

$$a\,\frac{\vec{p}_e\cdot\vec{q}}{E_eE_\nu}$$

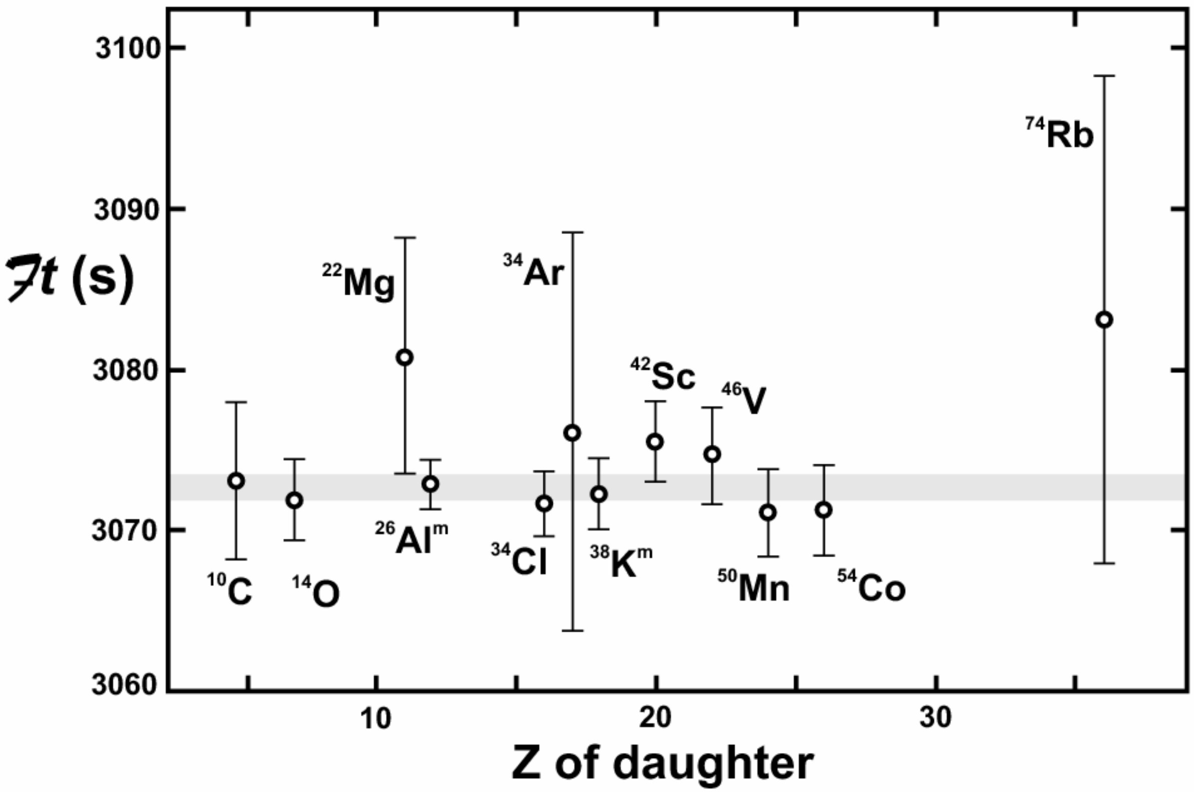


$$\tilde{X}=\frac{X}{1\;+\;b\,\dfrac{\gamma m_e}{E_e}}$$

J,D, Jackson, S.B. Treiman, H.W. Wyld, Nucl. Phys. 4 (1957) 206

1. $\mathfrak{F}$t-values of $0^+ \rightarrow 0^+$ superallowed Fermi transitions

$$\mathcal{F}t = ft\,(1+\delta_R)\,(1-\delta_C) = \frac{K}{2\,G_F^2\,V_{ud}^2\,(1+\Delta_R^V)}$$ = **3074.4(12) s** ([1,2])



$$\sum_i V_{ui}^2 = V_{ud}^2 + V_{us}^2 + V_{ub}^2 = \mathbf{0.9987(11)}$$

(with new values for V_{us})

([1]) Towner and Hardy (0^+->0^+), PRL 94 (2003) 092501, PR C71 (2005) 055501
([2]) Savard et al., PRL 95 (2005) 102501

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

1. **right-handed currents:**

$$-0.0005 < \zeta < 0.0015 \quad \text{(90\% C.L.)}$$

2. **scalar currents:**

$$-0.005 < \mathrm{Re}\left(\frac{C_S + C_S'}{C_V}\right) < 0.011$$

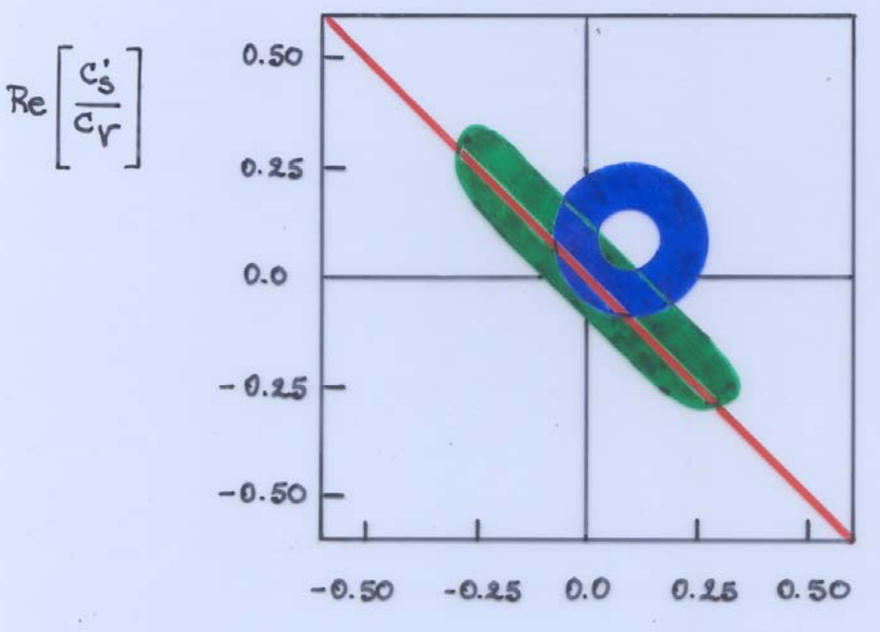
(90% CL)

Ad 1: Left Right Symm.-models

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

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

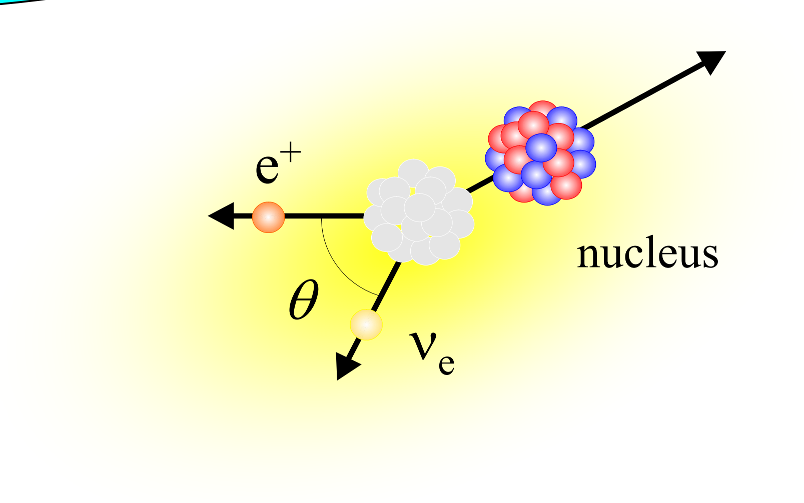
$$\delta = m_1^2 / m_2^2$$



Ad 2: scalar currents

2a. βν-correlation

$$a \, \frac{\vec{p}_e \cdot \vec{q}}{E_e E_\nu}$$



or $\tilde{a} = \dfrac{a}{1 + b \dfrac{\gamma m_e}{E_e}}$ with $\gamma = \sqrt{1-(\alpha Z)^2}$

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

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

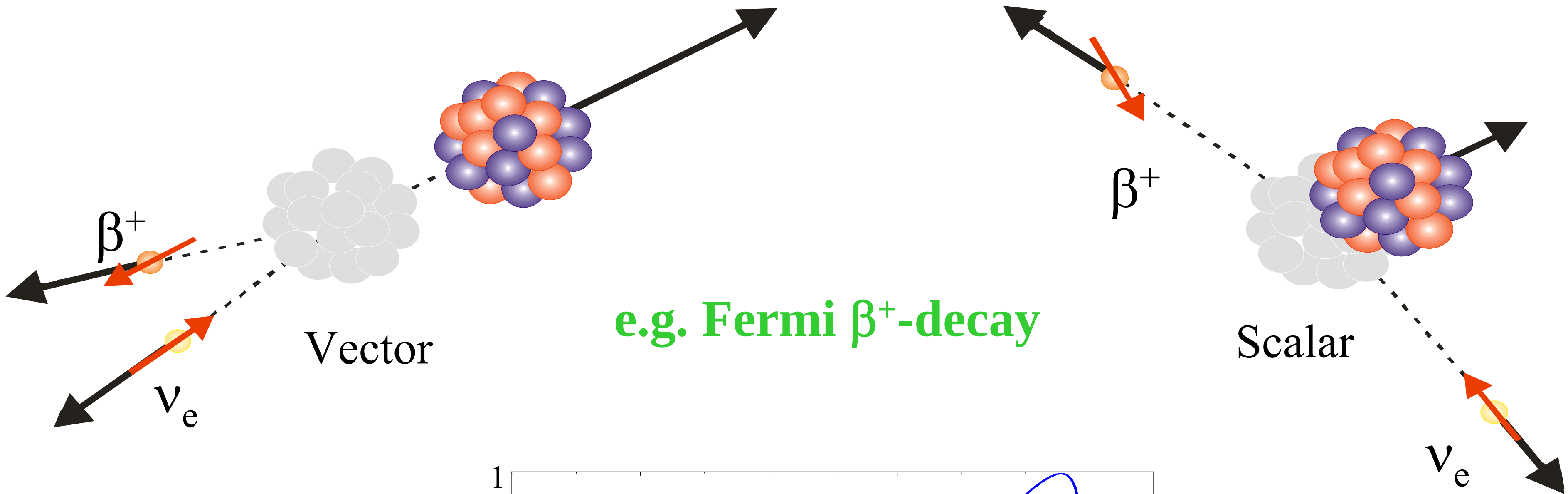
$$b_F \cong Re \, \frac{C_S + C_S'}{C_V}$$

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

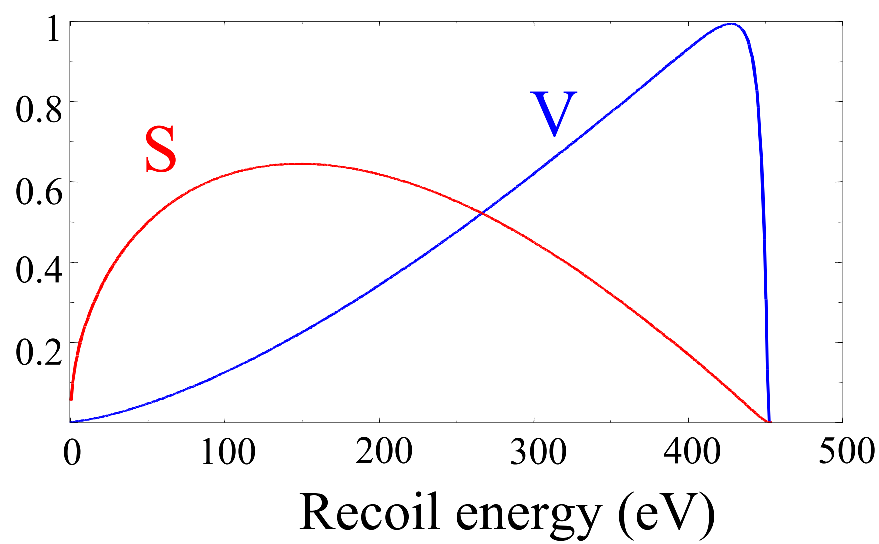
(assuming maximal P-violation and T-invariance for V and A interactions)

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

recoil ion energy spectrum :

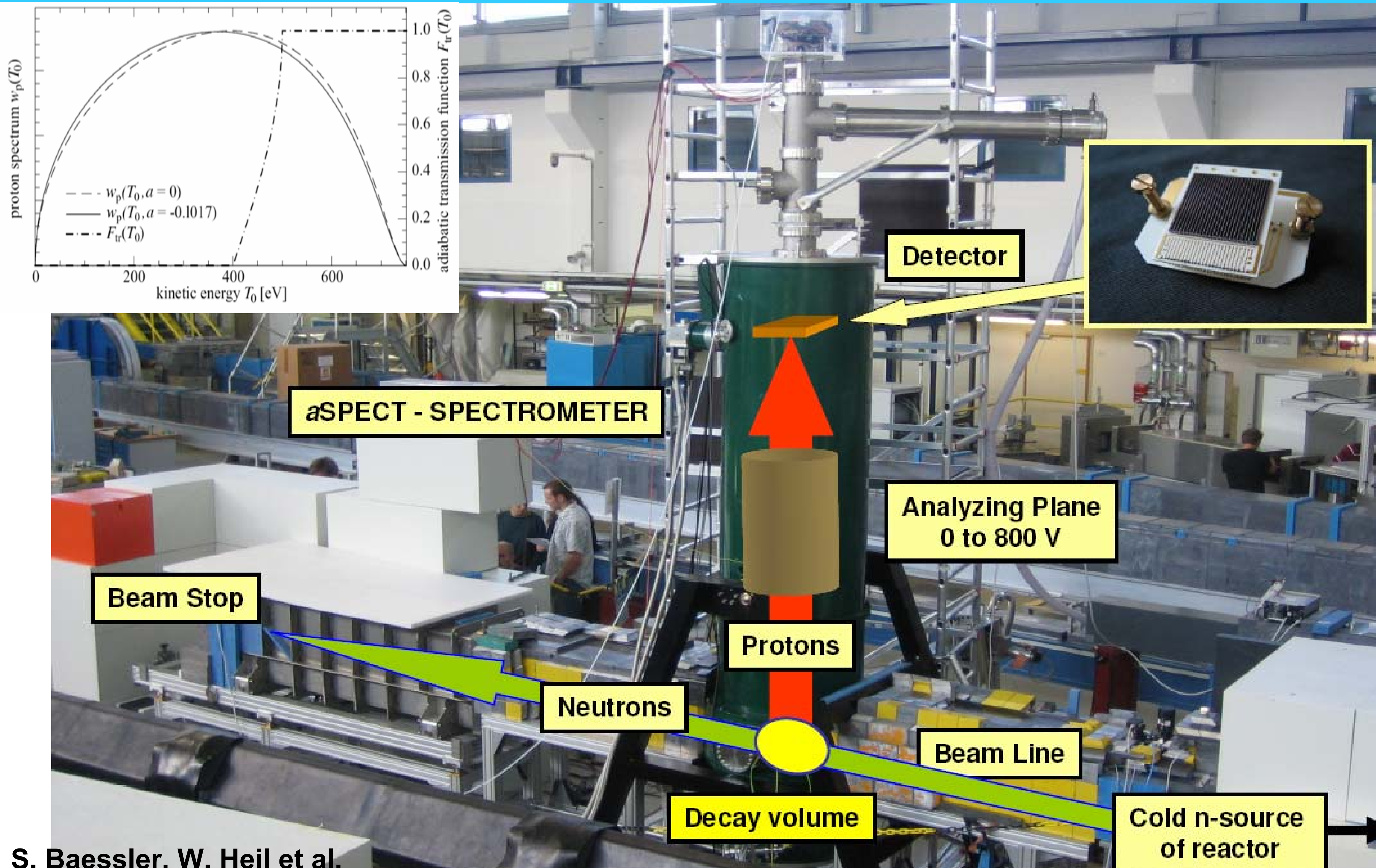


e.g. Fermi β+-decay



*a*SPECT experiment (FRM-II München)

(Mainz, Budapest, Karlsruhe, München, Sussex)

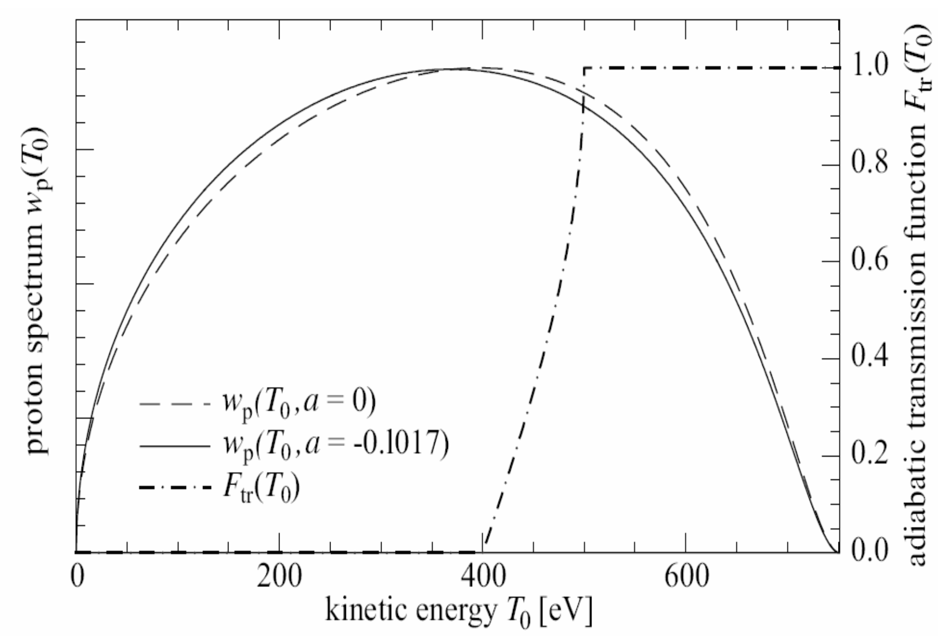


S. Baessler, W. Heil et al.

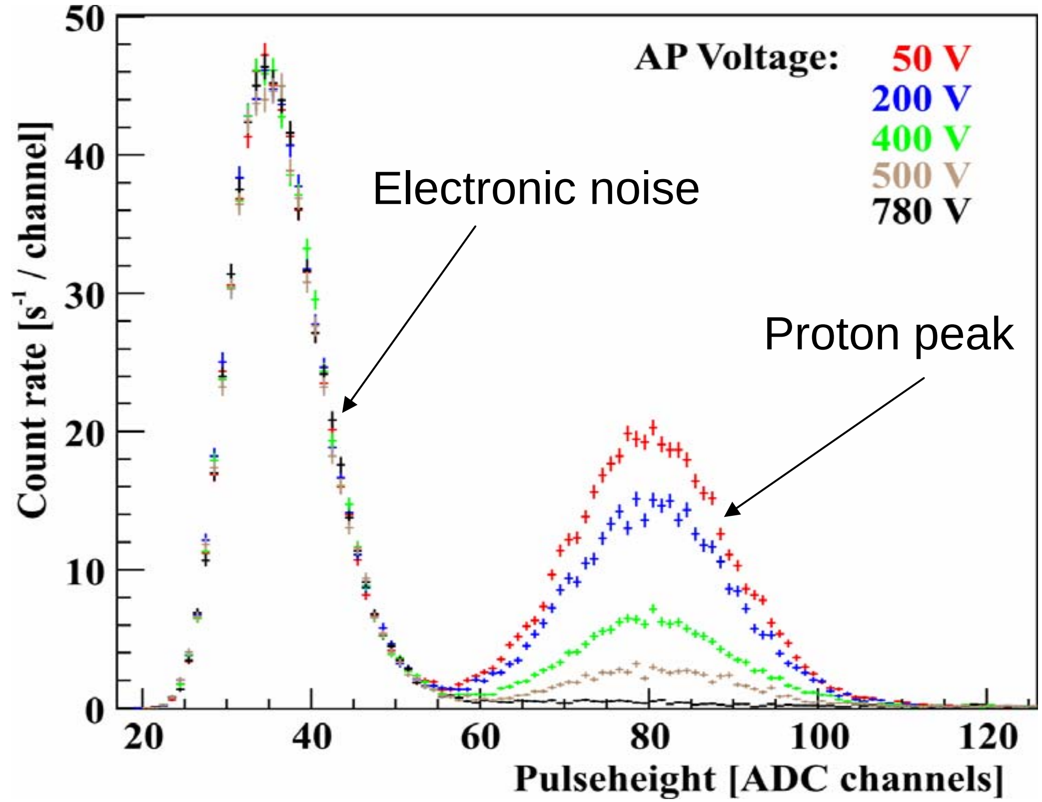
aSPECT - proton spectra

$a_{n\text{-}wavg}$ =-0.103(4)   (PDG)

- about factor 10 improvement necessary to have same sensitivity to g_A/g_V as A_n-parameter
- sensitive to C_S and C_T



Pulse hight spectrum:

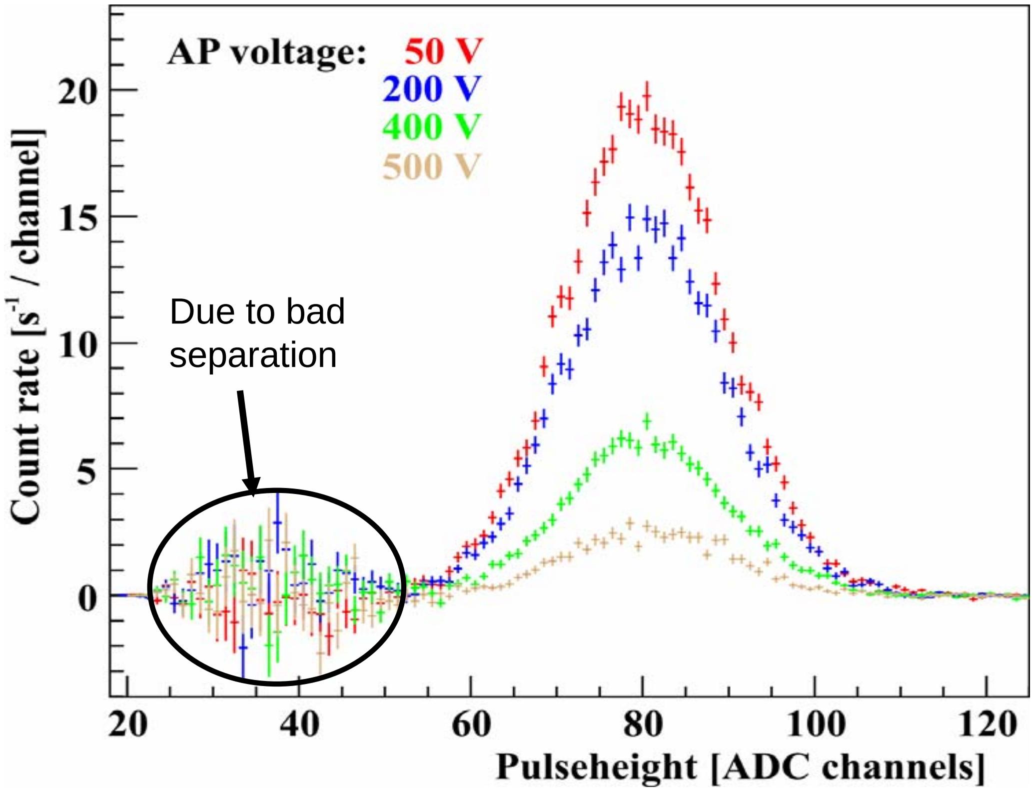


- Proton spectrum looks ok, Countrate ~ 500 Hz
- Signal to background ratio > 10:1
- Proton Signal not well separated from electronic noise

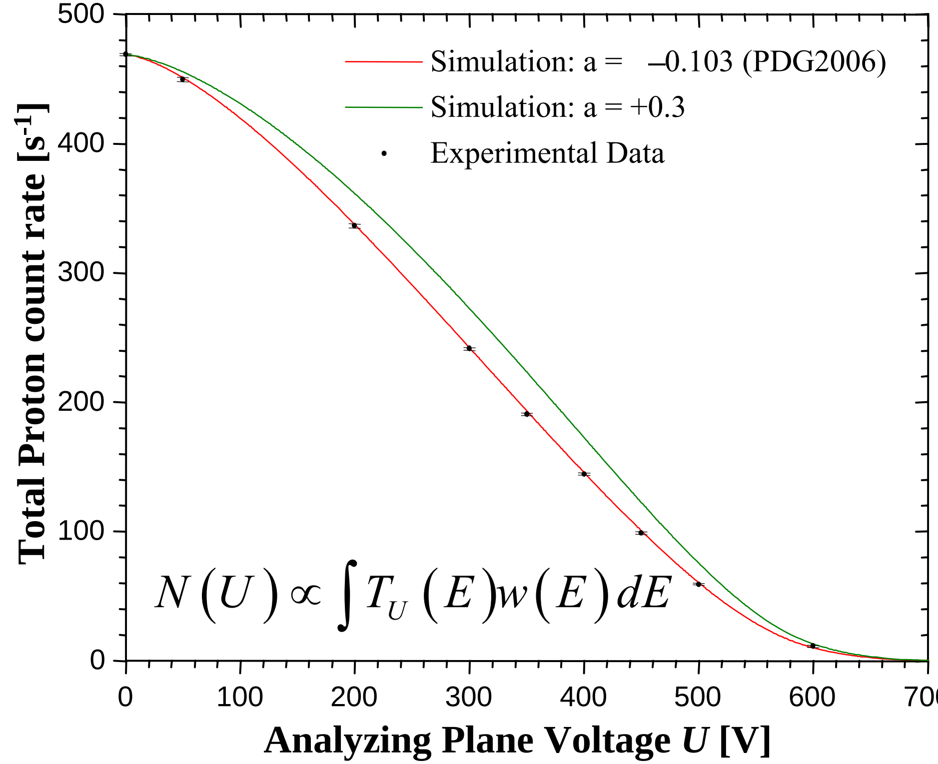
S. Baessler

Extraction of *a*

after background subtraction



integral proton spectrum



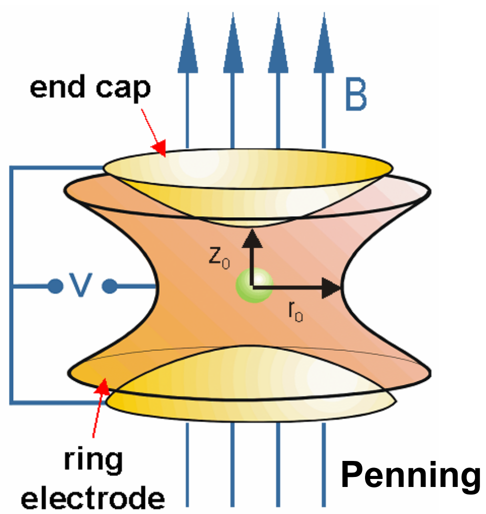
- Fulfills requirements for statistical accuracy
- Instabilities (Electronic Noise?)

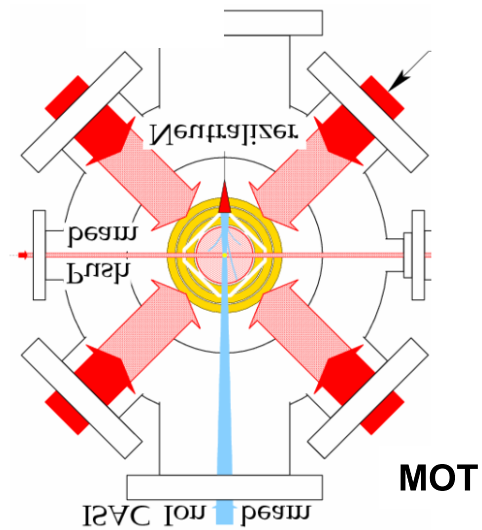
traps for correlations in nuclear beta decay

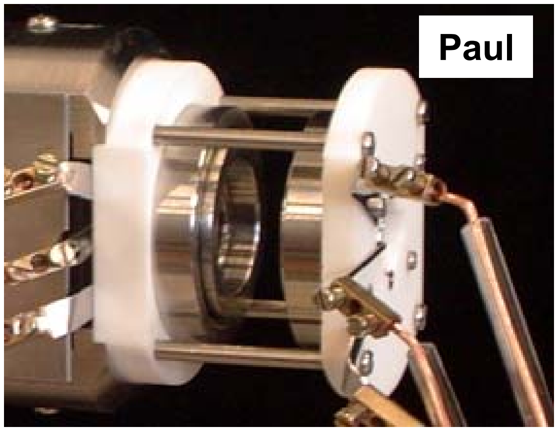
isotope	trap	meas.	lab
^{21}Na	MOT	a_F [(1)]	LBNL
^{38m}K	MOT	a_F [(2)]	TRIUMF
^{6}He	Paul	a_{GT}	LPC/GANIL
^{35}Ar	Penning	a_F	KUL/ISOLDE
^{21}Na, ^{19}Ne, ^{23}Mg	MOT	a, D	KVI
^{82}Rb	MOT	A_{GT}	LANL

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

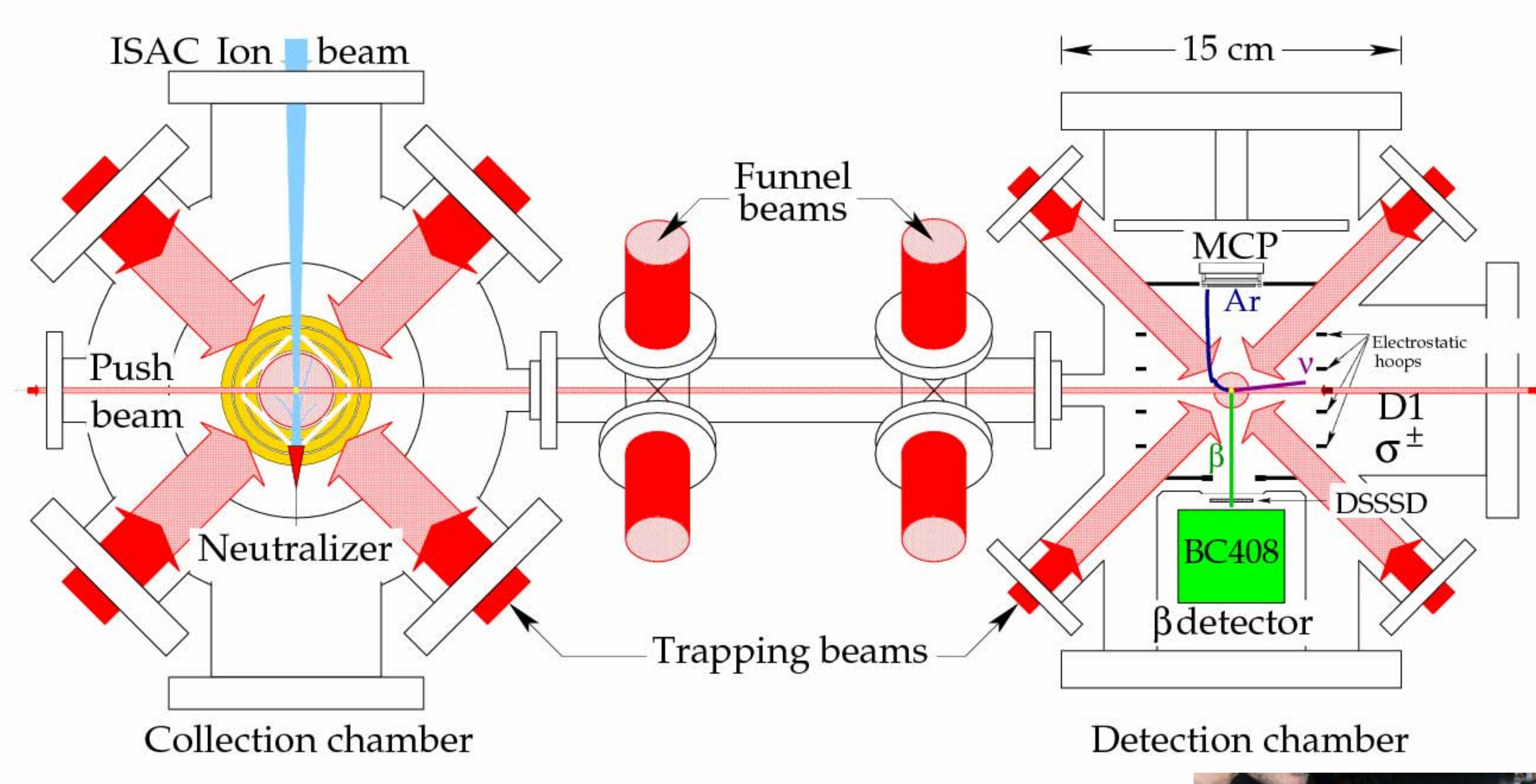
N. Scielzo, S.J. Freedman et al., PRL 93 (2004) 102501
A. Gorelov, J. Behr et al., PRL 94 (2005) 142501
R. Rodriguez, O. Naviliat et al., NIM A565 (2006) 876
M. Beck, N. Severijns et al., NIM A503 (2003) 567
G.P. Berg, K. Jungmann et al., NIM B204 (2003) 52
S.G. Crane, D.J. Vieira et al., PRL 86 (2001) 2967

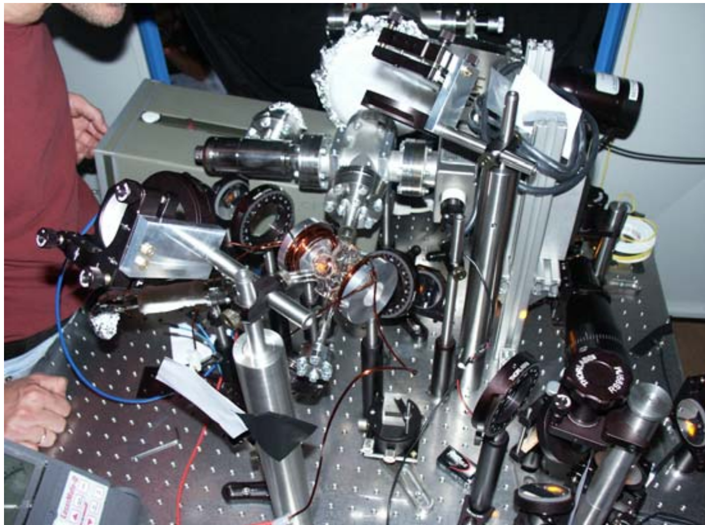






TRINAT MOT trap at TRIUMF-ISAC (Vancouver)





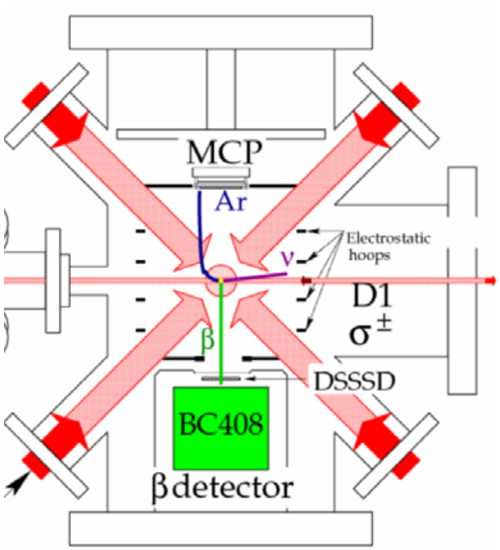
search for exotic scalar couplings with ^{38m}K **(J. Behr et al.)**

$$^{38m}K \rightarrow {}^{38}Ar + e^{+} + \nu$$

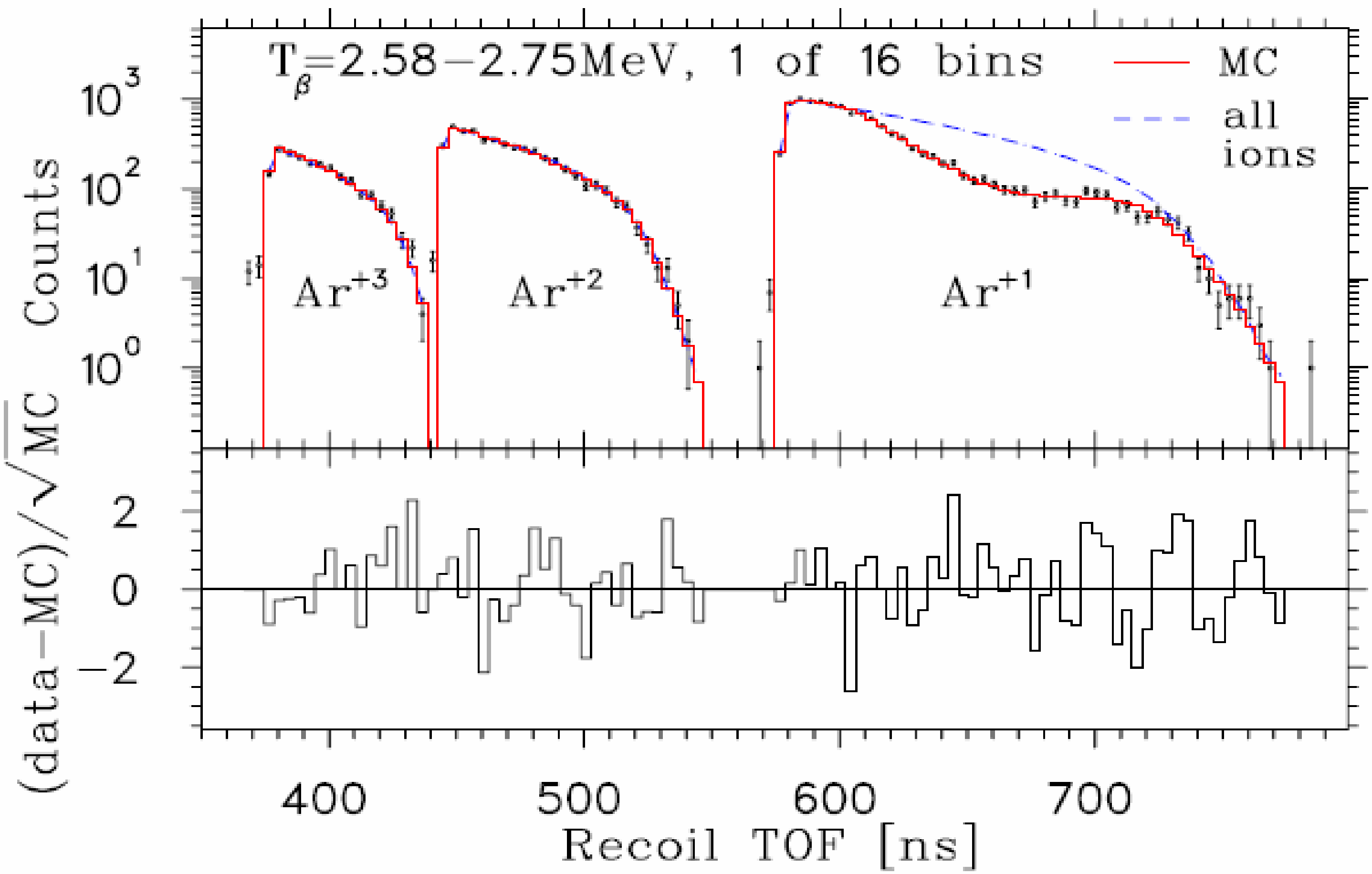
superallowed $0^+ \rightarrow 0^+$ pure Fermi transition ($t_{1/2}$ = 0.95 s)

$$\tilde{a} = \frac{a}{1+\gamma \dfrac{m_e}{E_e} b} = 0.9981 \pm 0.0030 \pm 0.0035 \quad \Rightarrow \quad \frac{|C_S|^2 + |C'_S|^2}{|C_V|^2} \leq 0.097$$

$$(\tilde{a}_{SM} = 1) \qquad (90\% \text{ C.L. } \cong 1.65\sigma)$$



A. Gorelov, J. Behr et al.,
Phys. Rev. Lett. 94 (2005) 142501

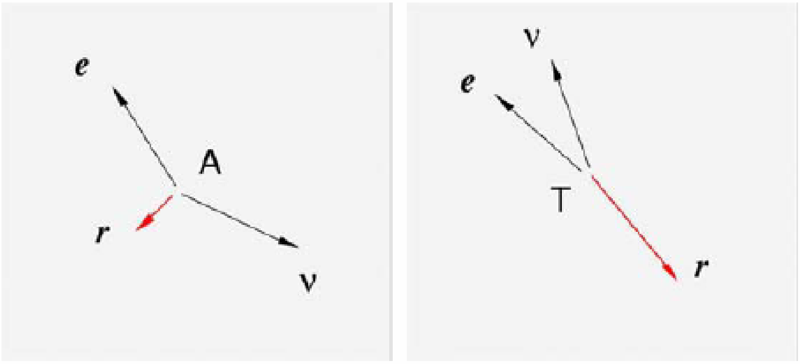


LPC-Caen Paul trap at GANIL (O. Naviliat, G. Ban et al.)

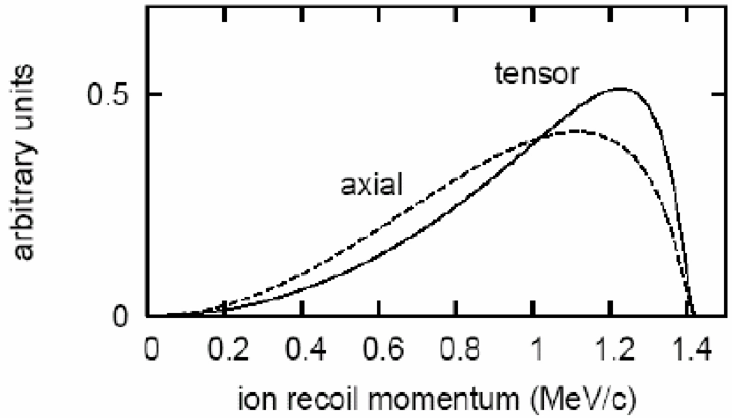
- search for exotic tensor couplings

$$a\left(\frac{\mathbf{p_e}\cdot\mathbf{p}_\nu}{E_e E_\nu}\right)$$ in a Gamow-Teller transition

standard (Axial) exotic (Tensor)

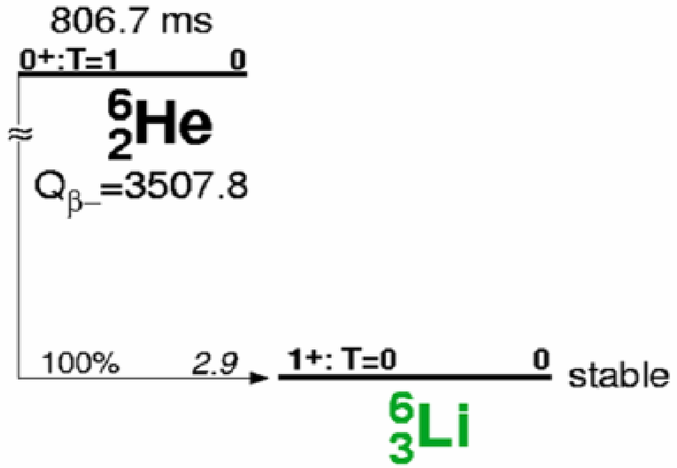


the signature is in the ion recoil spectrum



- candidate

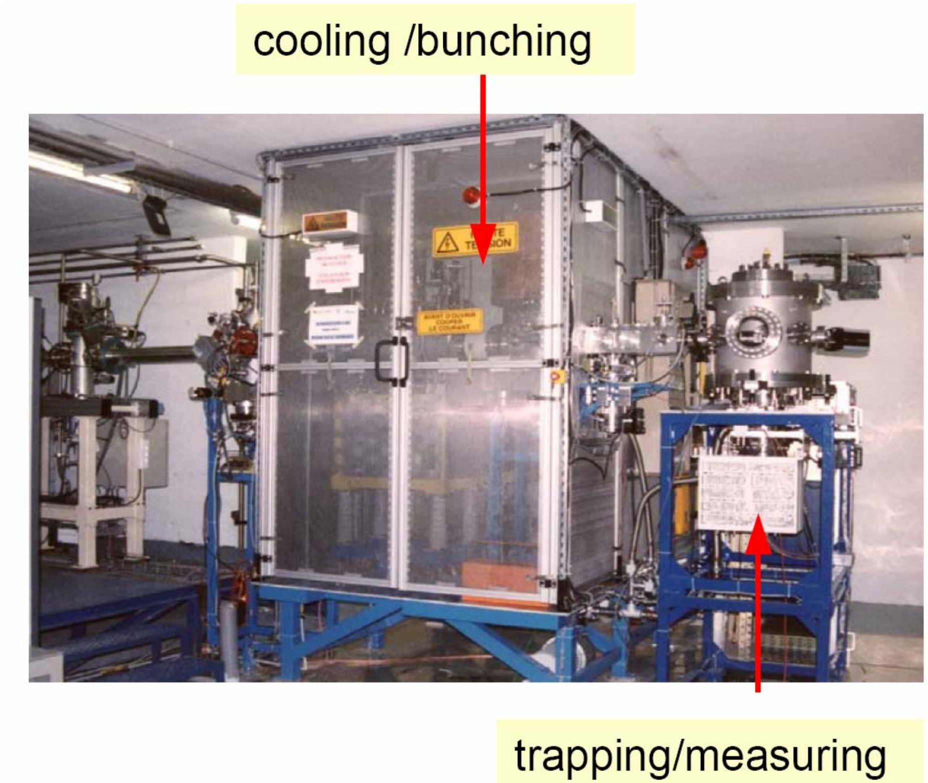
$$^{6}\mathrm{He} \rightarrow {}^{6}\mathrm{Li} + e^{-} + \bar{\nu}_e$$

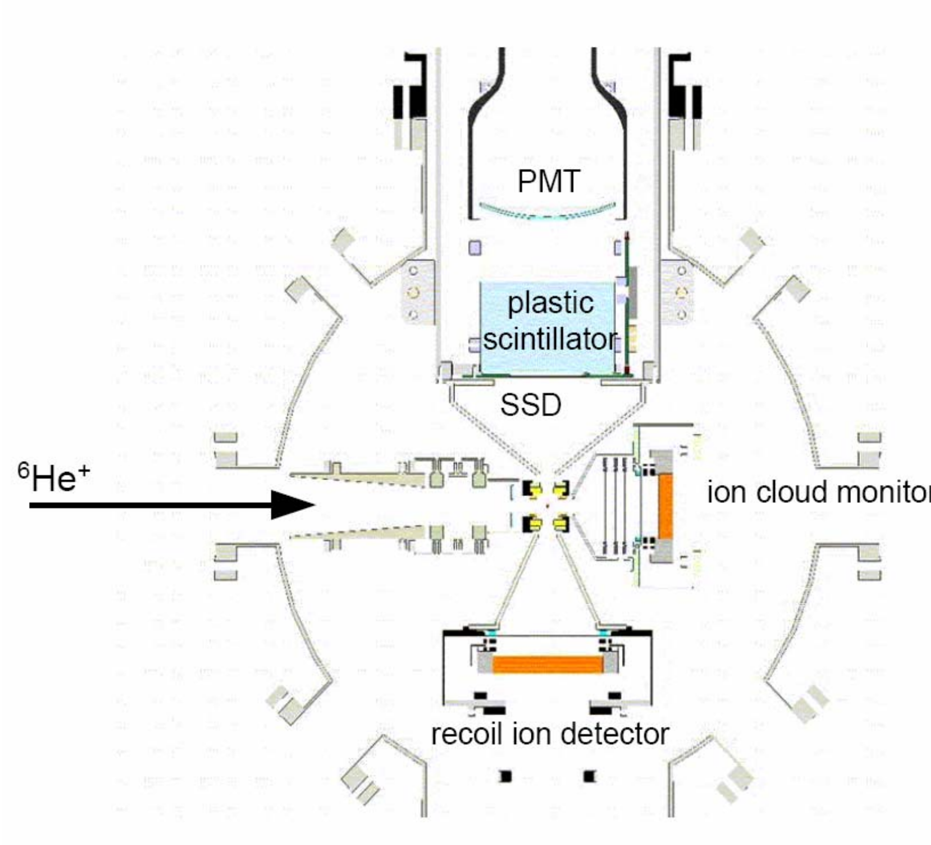


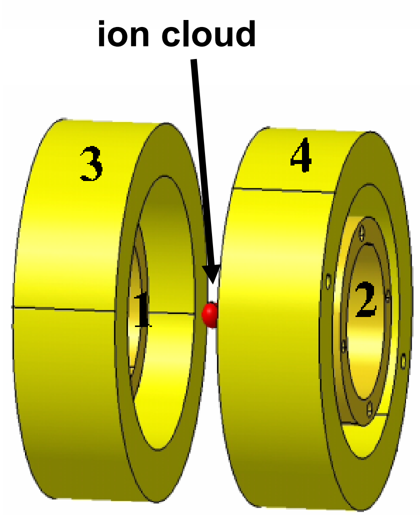
- general principle

- produce ^{6}He nuclei
- trap the ions (requires beam cooling)
- measure recoil ^{6}Li TOF (E_R<1.4 keV)

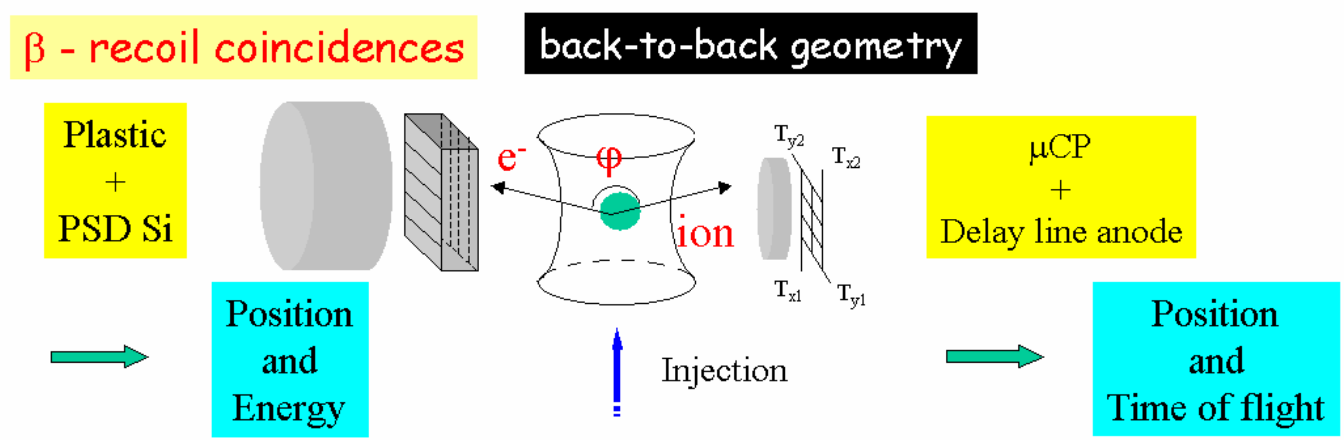
O. Naviliat





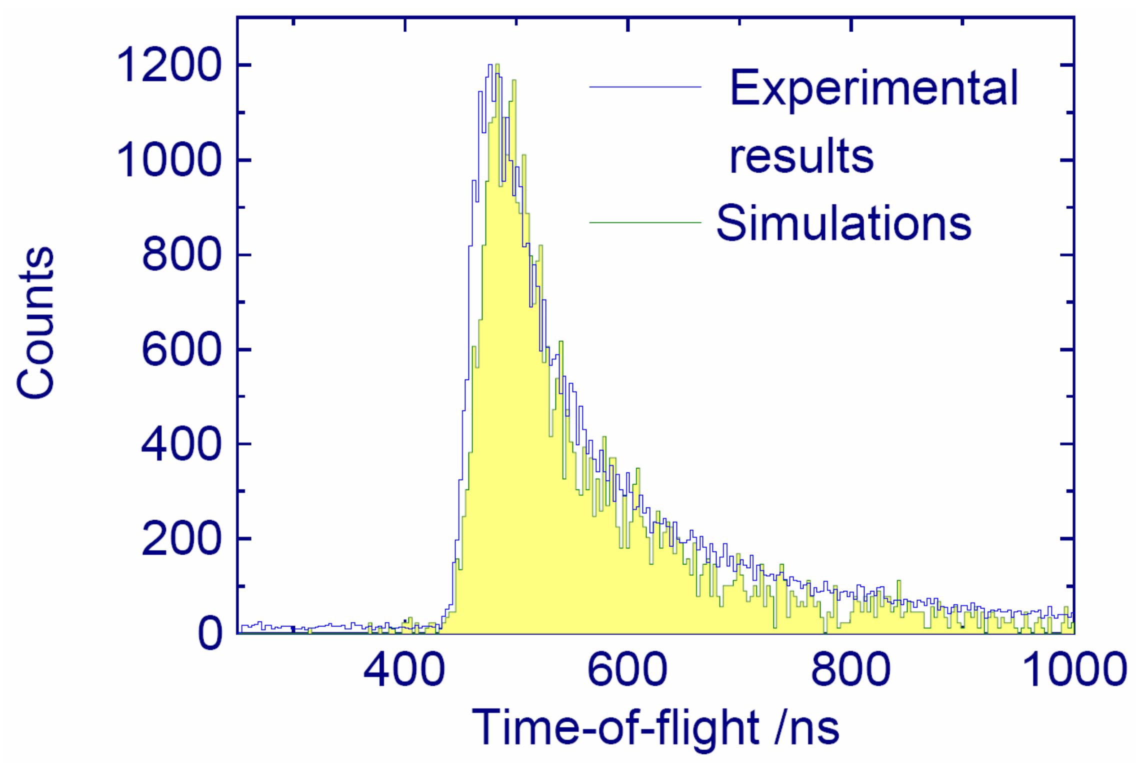


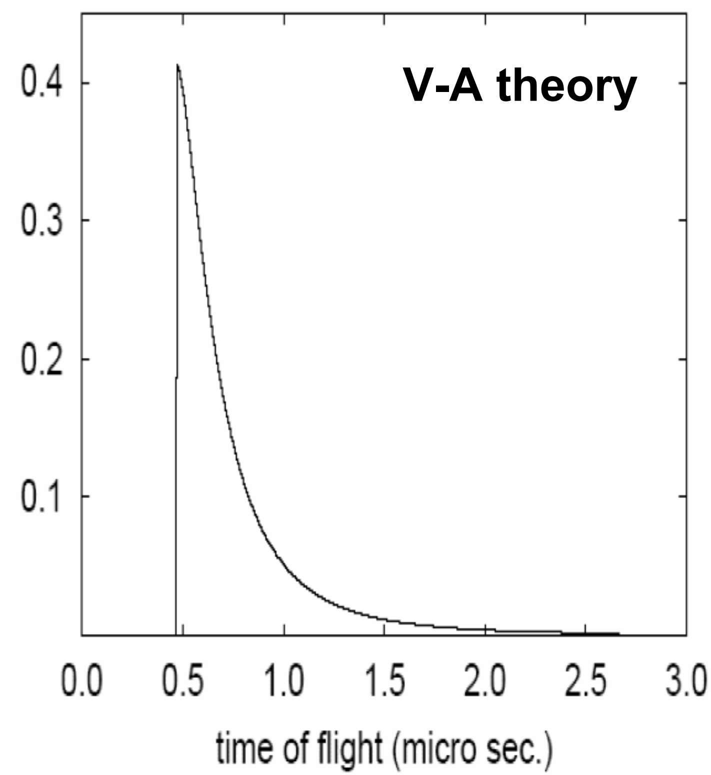
LPC-Caen Paul trap



O. Naviliat

first results from LPC-Caen trap at GANIL :





- **2005: proof of principle**
- **2006: first data**
- **difference between experiment and simulation due to main systematic effect, i.e. rf-field**

O. Naviliat

WITCH double-Penning trap system at ISOLDE-CERN

K.U.Leuven, ISOLDE-CERN, Uni Münster, GSI, NPI-Řež (Prague)

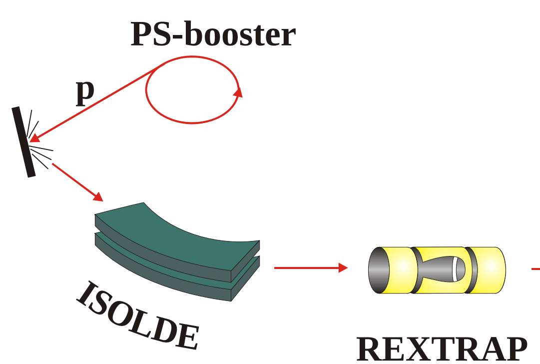
Weak Interaction Trap for CHarged particles

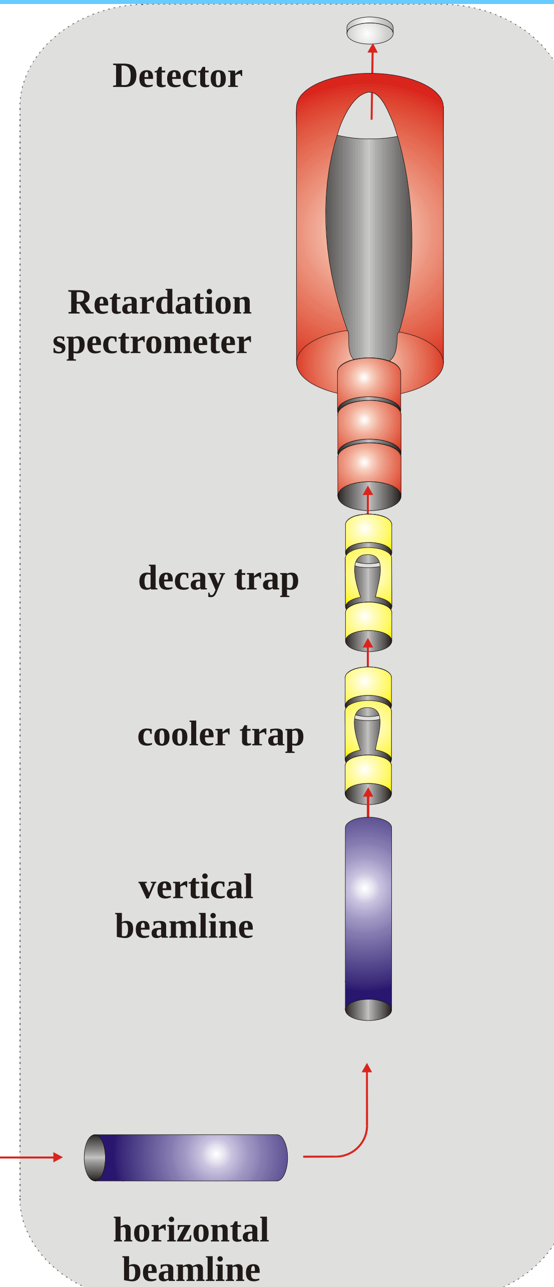
cooler & decay Penning traps + retardation spectrometer

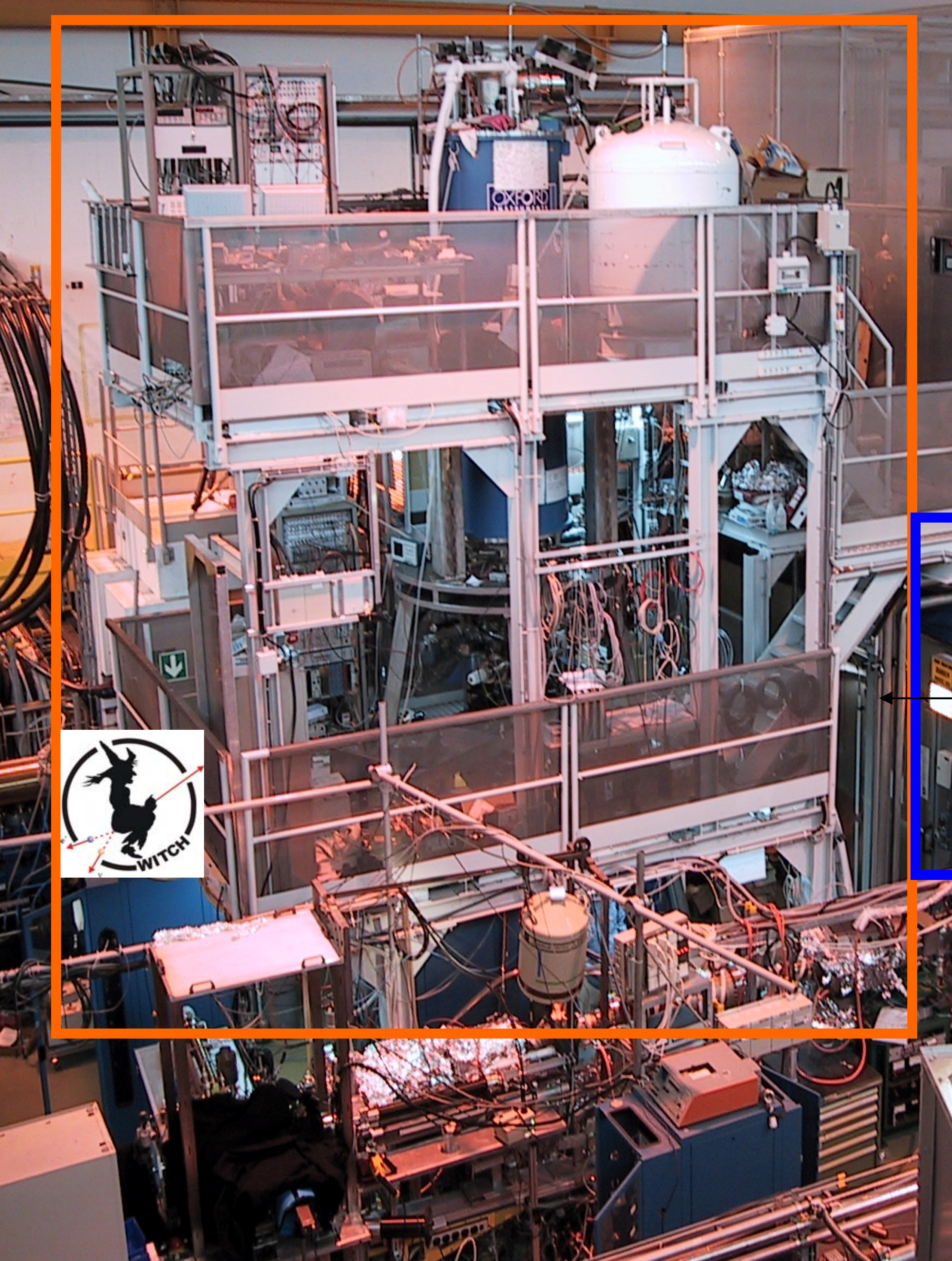
search for exotic scalar/tensor couplings
in the beta-neutrino correlation by
recoil ion energy spectrum shape

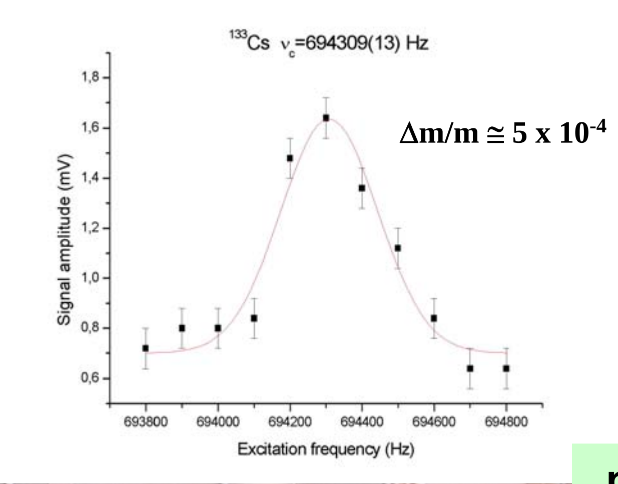
WITCH-Collaboration:

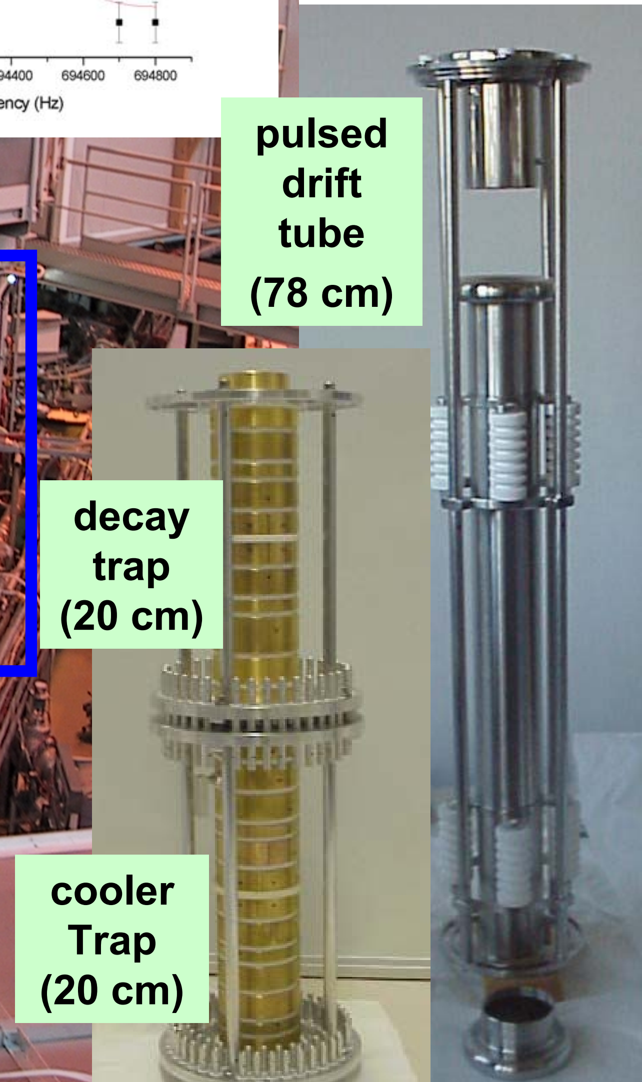
S. Coeck, V. Kozlov, M. Herbane, M. Tandecki, N. Severijns (K.U.Leuven);
M. Beck, P. Friedag, C. Weinheimer (Univ. Münster);
F. Wenander, P. Delahaye, A. Herlert (ISOLDE-CERN);
D. Beck (GSI-Darmstadt);
D. Zakoucky (NPI-Rez, Prague).



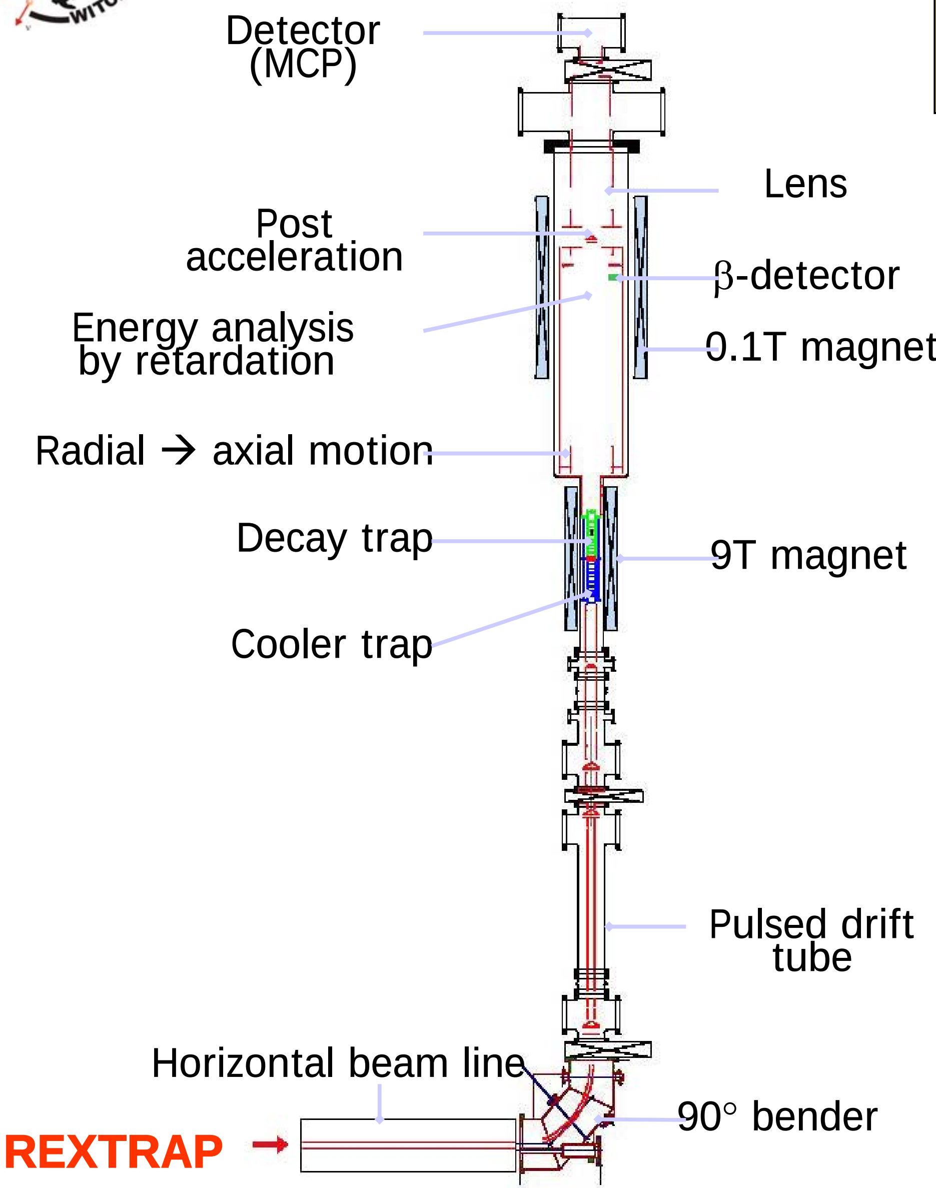



Rextrap


^{133}Cs ν_c=694309(13) Hz
$\Delta m/m \cong 5 \times 10^{-4}$
Signal amplitude (mV)
Excitation frequency (Hz)
0,6
0,8
1,0
1,2
1,4
1,6
1,8
693800
694000
694200
694400
694600
694800


pulsed drift tube (78 cm)
decay trap (20 cm)
cooler Trap (20 cm)

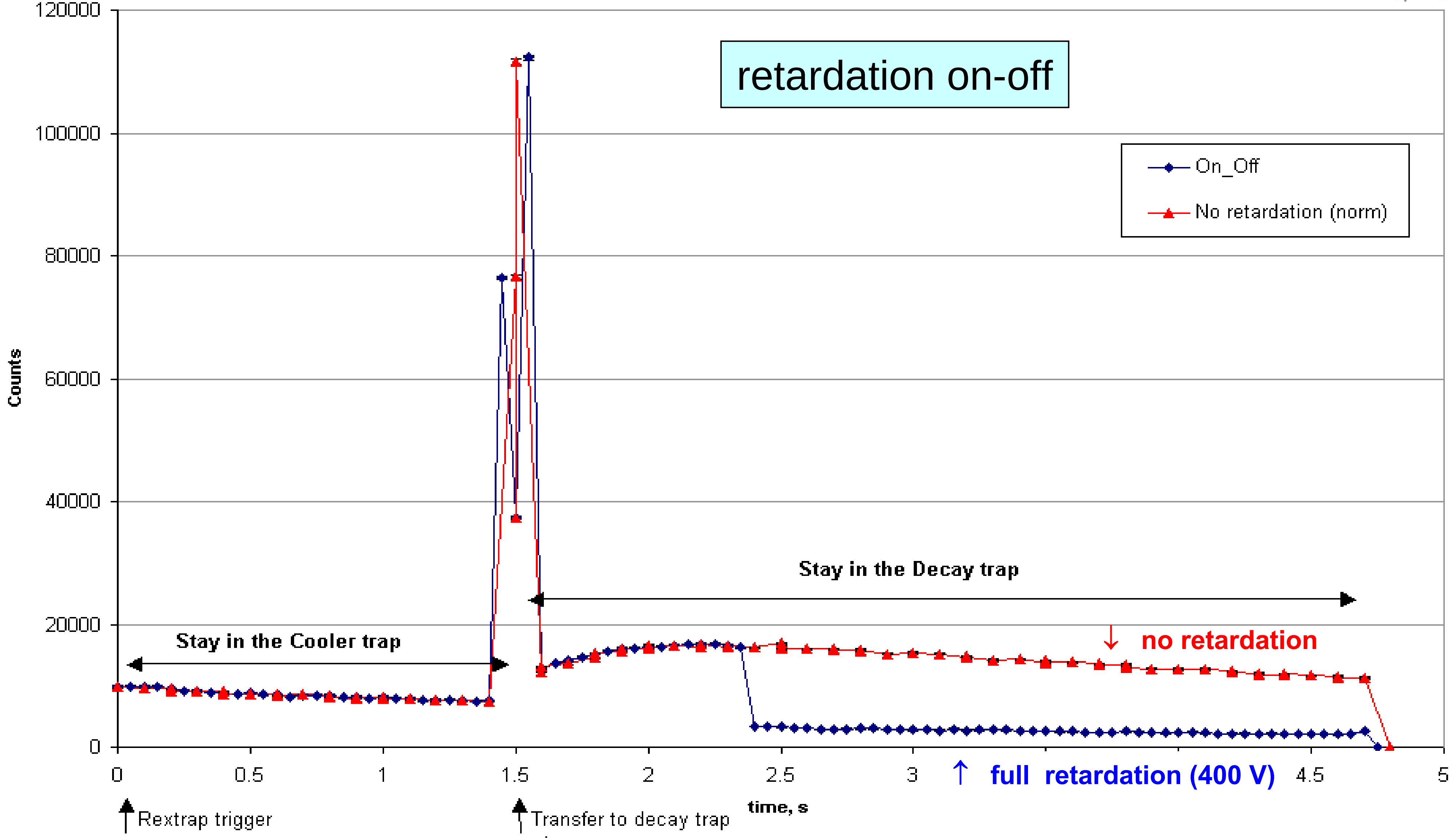
Commissioning results (status November 2006)



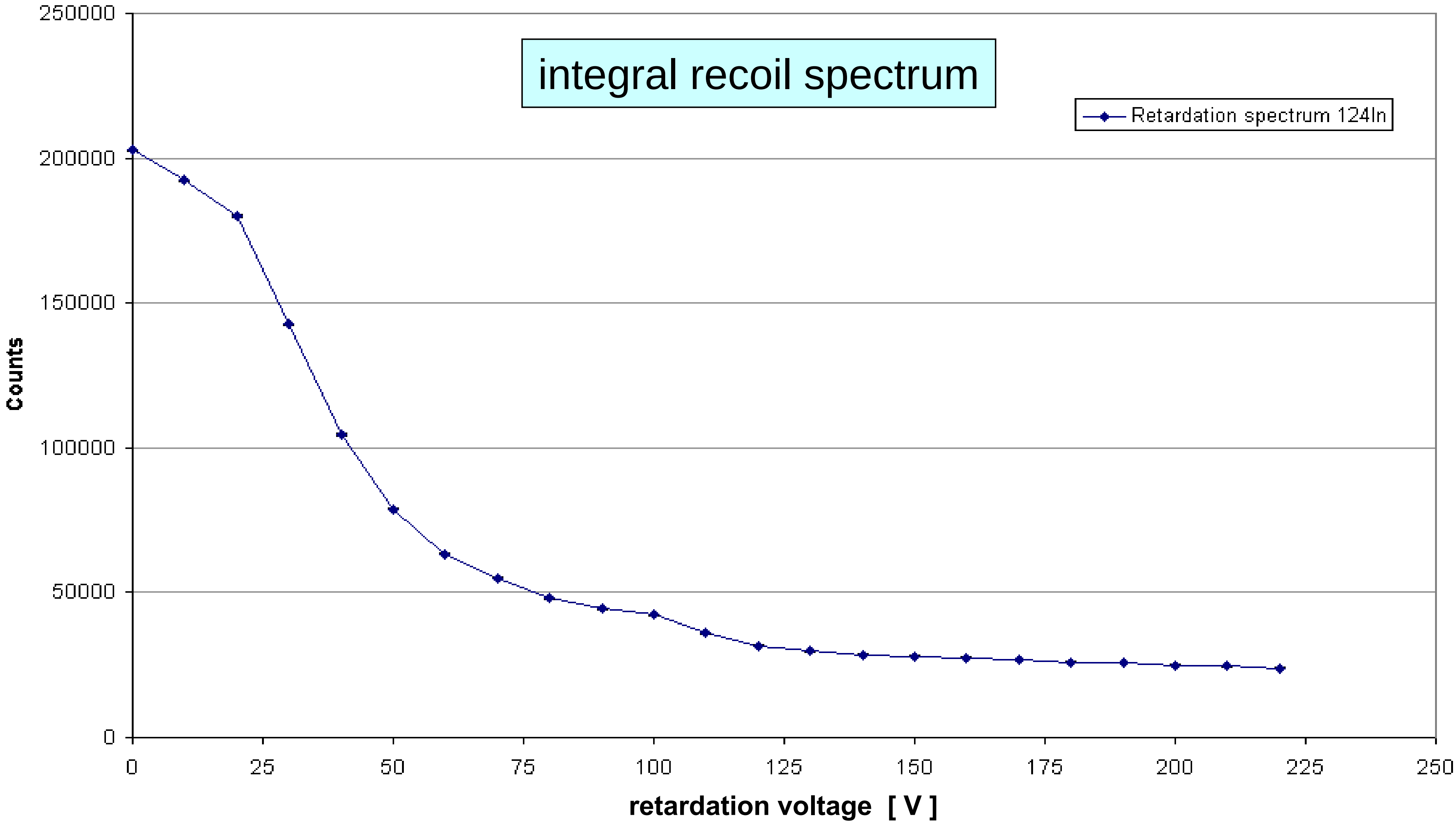
Section	Efficiency
Transport through horizontal beam line and pulse down (30 keV → ~0.2 keV)	**~ 80 %**
Injection of 0.2 kV beam in 9 T magnetic field	**~ 20 %**
Trapping of ions in cooler Penning trap	**~ 60 %**
Transfer to and storage in decay trap	**~ 80 %**
Shake-off + fraction leaving the trap	**~ 30 %**
Transmission of retardation spectrometer **MCP efficiency**	**~ 50 %** **~ 50 %**
Total efficiency **(REXTRAP to recoil ion MCP detector)**	**~ 0.6 %** **(ideal: ≈ 12 %)**

WITCH-experiment 03 nov 2006

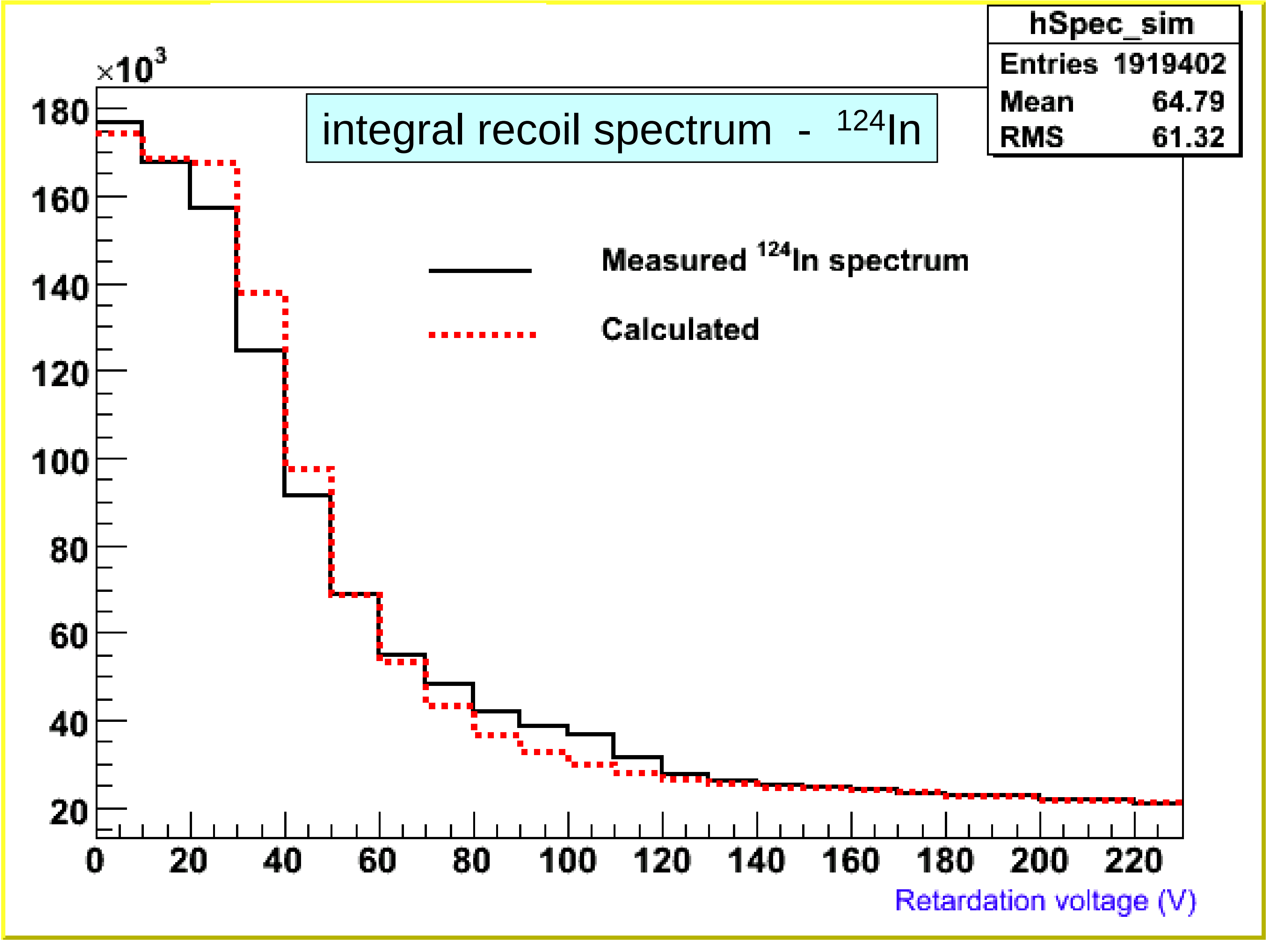
V. Kozlov, S. Coeck, M. Tandecki, S. Van Gorp,
M. Beck, P. Friedag, C. Weinheimer, F. Wenander,
P. Delahaye, D. Beck, N. Severijns



WITCH-experiment nov 2006

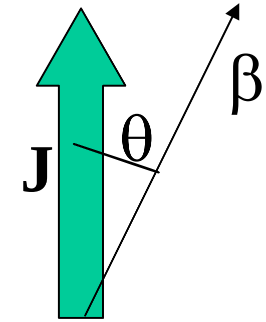


WITCH-experiment nov 2006



2b. β asymmetry

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



for a pure Gamow-Teller transition :

$$\tilde{A}_{GT}^{\beta^{\mp}} \cong \lambda_{J'J} \left[\mp 1 + \frac{\alpha Z m}{p} \mathrm{Im}\left(\frac{C_T + C_T'}{C_A} \right) + \frac{\gamma m}{E_e} \mathrm{Re}\left(\frac{C_T + C_T'}{C_A} \right) \right]$$

$$\left[\gamma = \sqrt{1 - (\alpha Z)^2} \right]$$

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

$\Delta A = 0.01 \rightarrow$ (for $\gamma m/E_e \cong 0.5$) $\mathrm{Re}\,[(C_T + C_T')\,/\,C_A] < 0.033$ (90% CL)

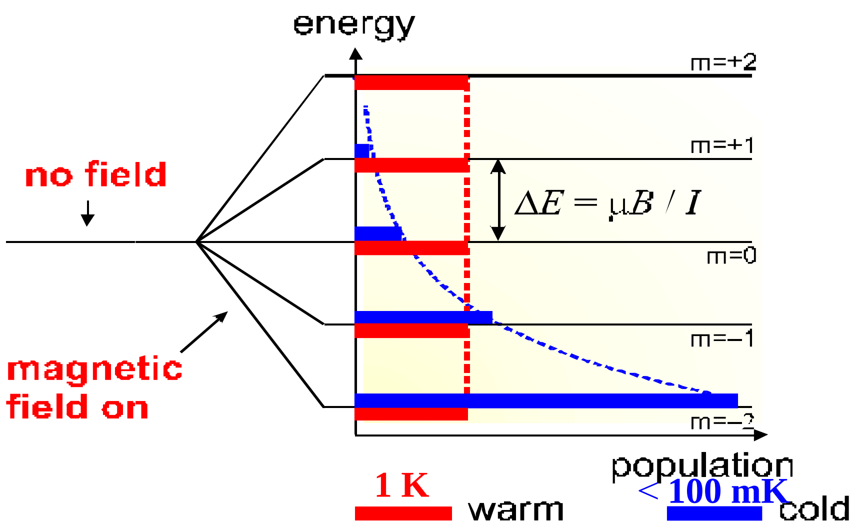
(assuming maximal P-violation and T-invariance for V and A interactions)

recoil corr. (induced form factors) ≈ 10^{-3} ; radiative corrections ≈ 10^{-4} / A_{GT} independent of nuclear matrix elements

Low Temperature Nuclear Orientation + Geant 4

(NICOLE-ISOLDE, K.U.Leuven, NPI Rez-Prague, Uni Bonn)

I. Kraev, F. Wauters, D. Zakoucky, N. Severijns et al.



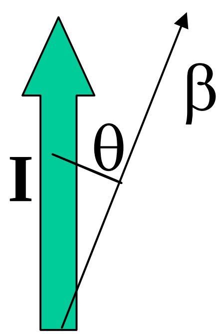
$$W(\theta) = \frac{N(\theta)_{pol}}{N(\theta)_{unpol}} = 1 + A_{GT}^{\beta^{\mp}} \; P \; \frac{v}{c} \, Q \cos\theta$$

(P from anisotropy of γ-rays)

Geant 4

Leuven: ^{60}Co<u>Cu</u> , B_{ext} = 13 T

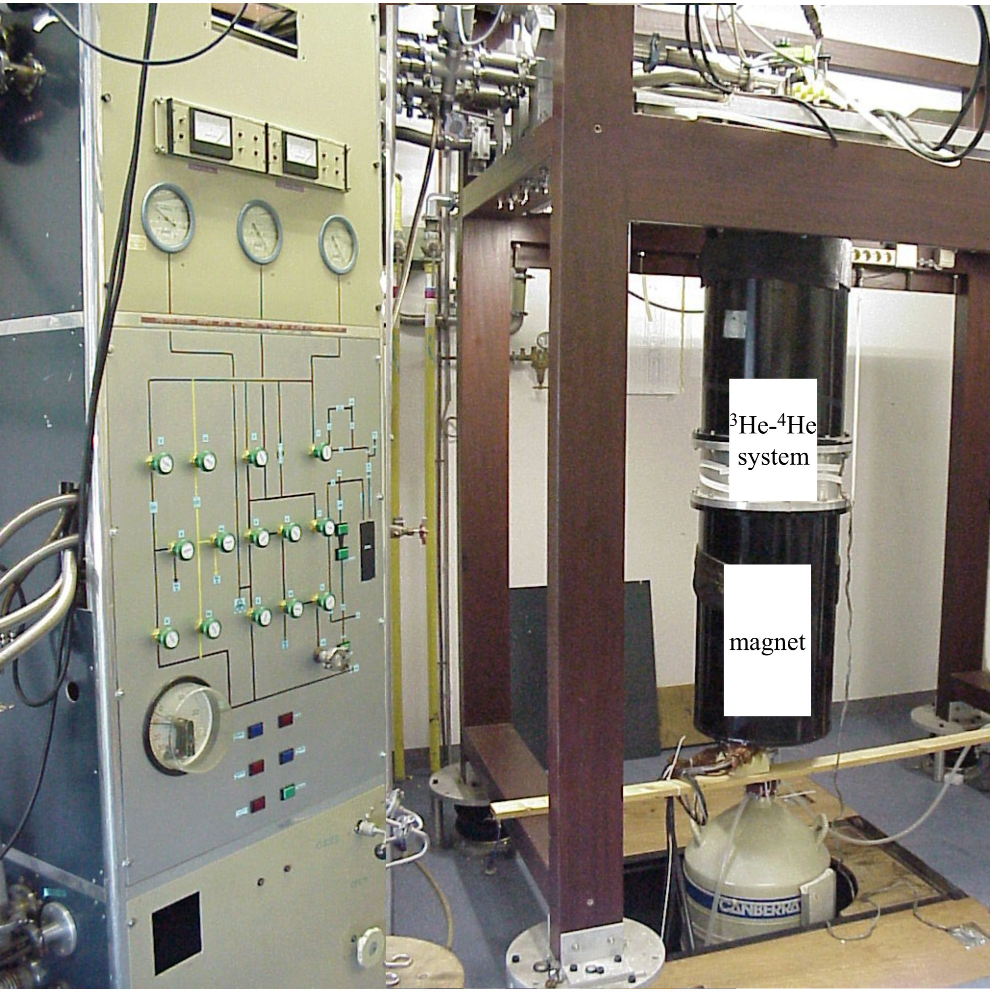
ISOLDE: ^{63}Cu<u>Fe</u> , B_{hf} = 22 T

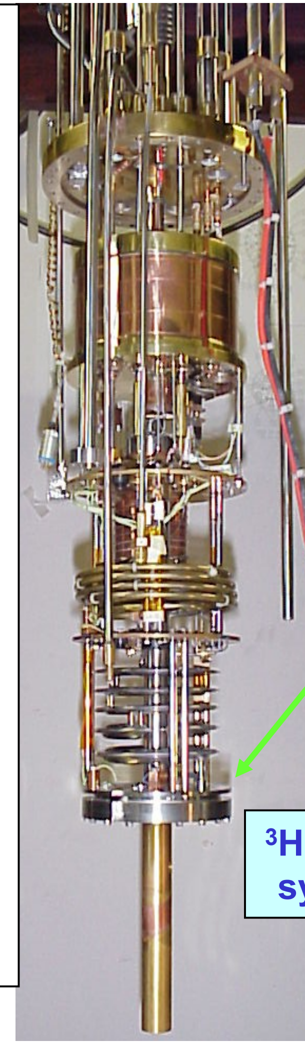


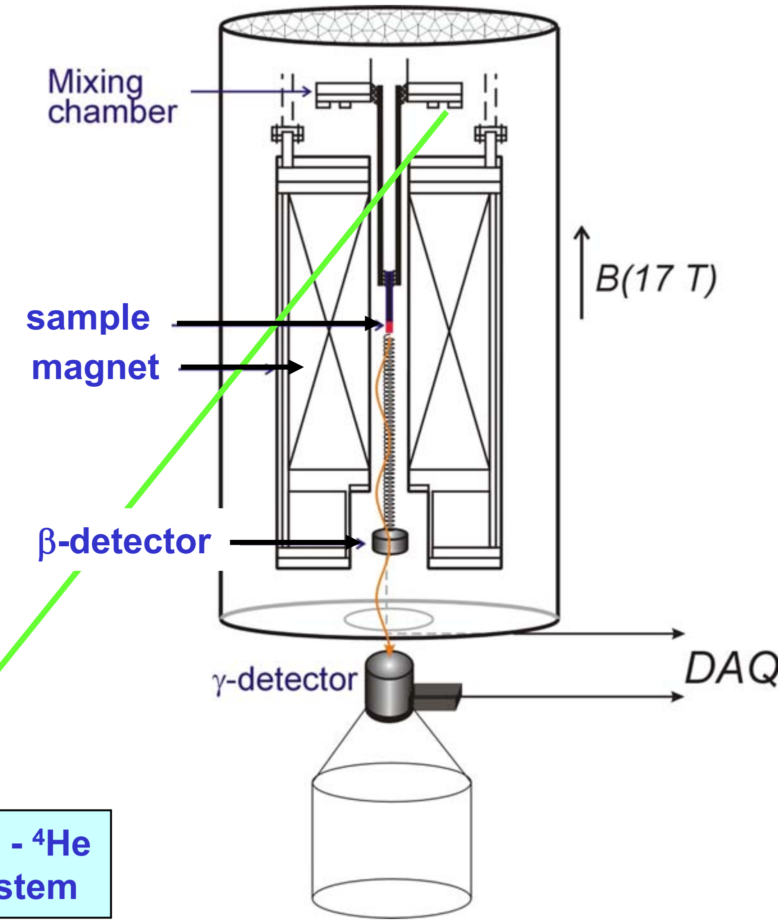
<u>Analysis:</u>

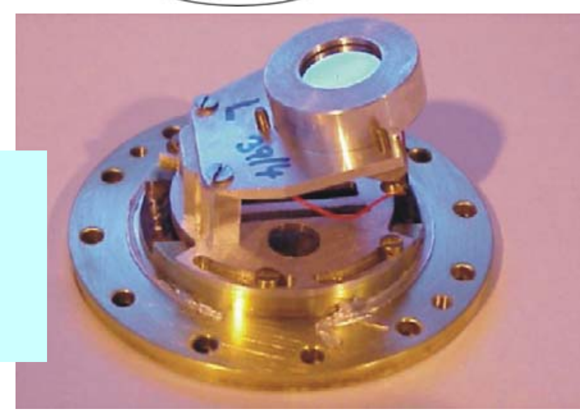
$$\frac{\left[\,W(\theta) - 1\right]_{exp}}{\left[\,W(\theta) - 1\right]_{sim}} = \frac{\left[A_{GT}^{\beta^{m}} \; P \; \frac{v}{c} \, Q\cos\theta\right]_{exp}}{\left[A_{GT,SM}^{\beta^{\mp}} \; P \; \frac{v}{c} \, Q\cos\theta\right]_{sim}} = \frac{A_{GT}^{\beta^{\mp}}}{A_{GT,\,SM}^{\beta^{\mp}}}$$

IS431-experiment





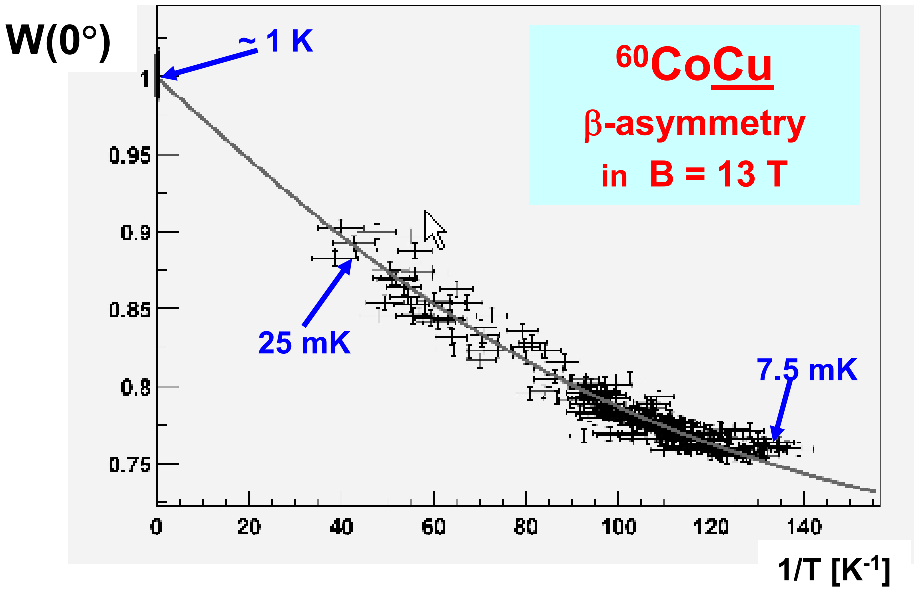


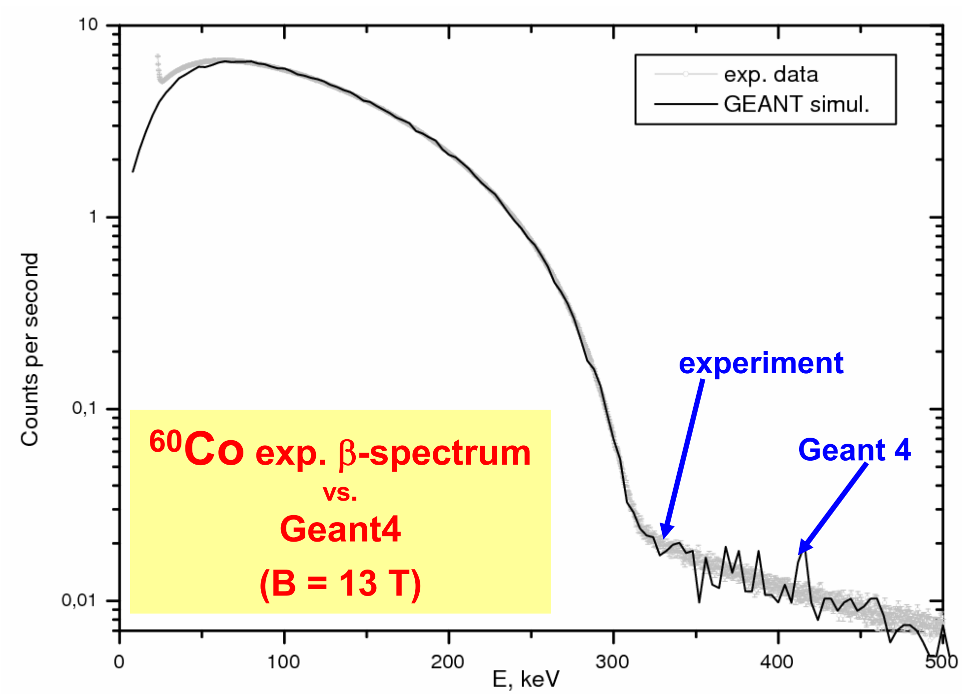


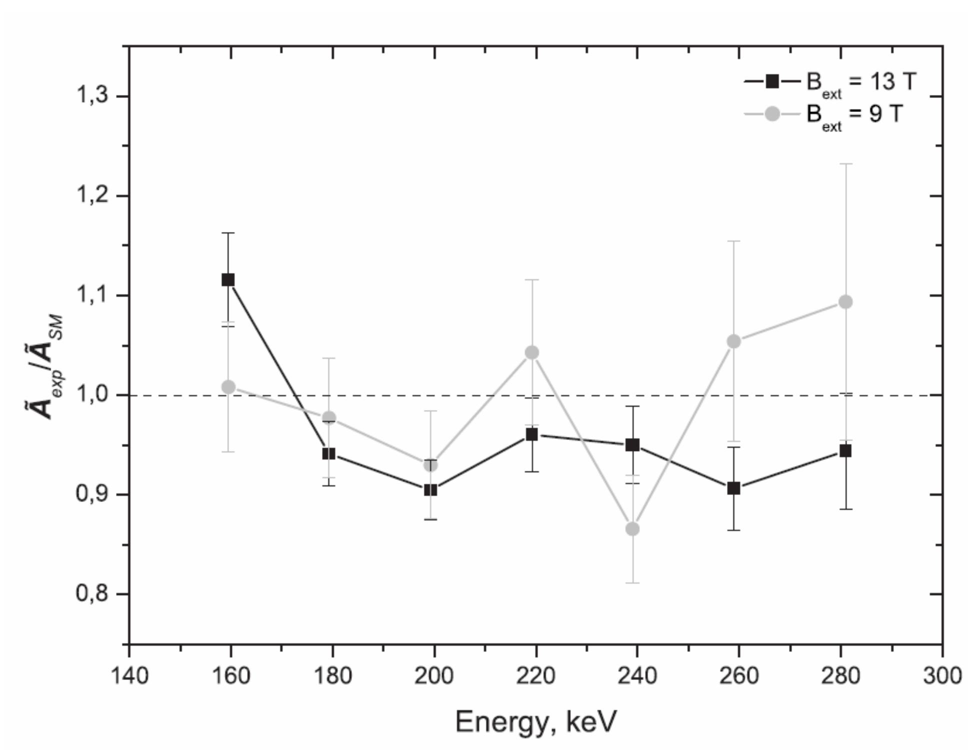
^{3}He - ^{4}He dilution refrigerator set-up

β-detector:

Si p-I-n diode (∅ = 9 mm), at T ~ 10 K







From ratio $\dfrac{[\ W(\theta)-1\ ]_{\text{exp}}}{[\ W(\theta)-1\ ]_{\text{Geant}}}$ **get :**

$$\tilde{A}_{\text{exp}} / \tilde{A}_{\text{SM}} = -0.953\ (22)$$

(preliminary; limited by statistics of GEANT simulation)

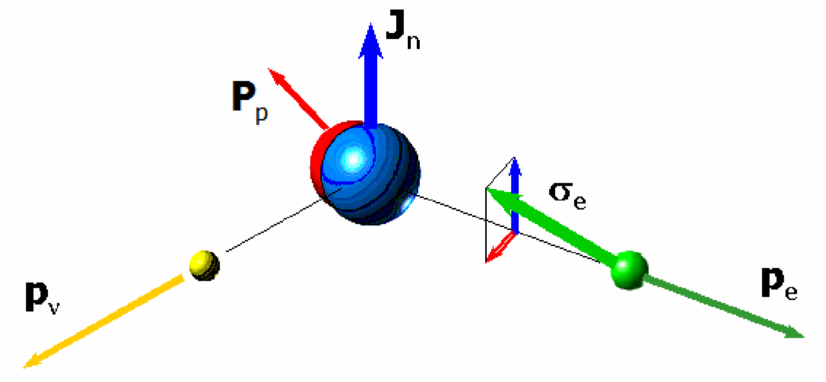
A = -1.010 (20) [Chirovsky, Wu et al., NIM 219 (1984) 103]

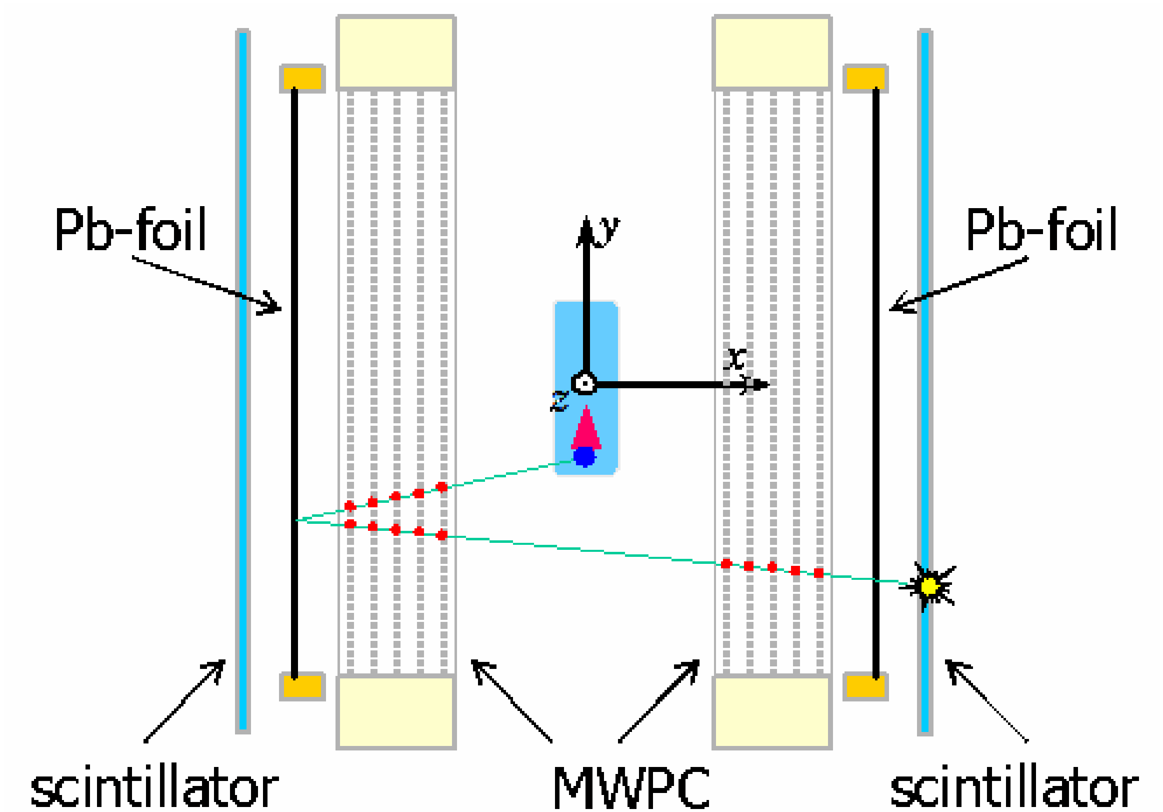
A = -0.972 (34) [Hung et al., PR C14 (1976) 1162]

3. Testing time reversal violation in free neutron decay
(Univ. Krakow, PSI, LPC-Caen, K.U.Leuven, …)

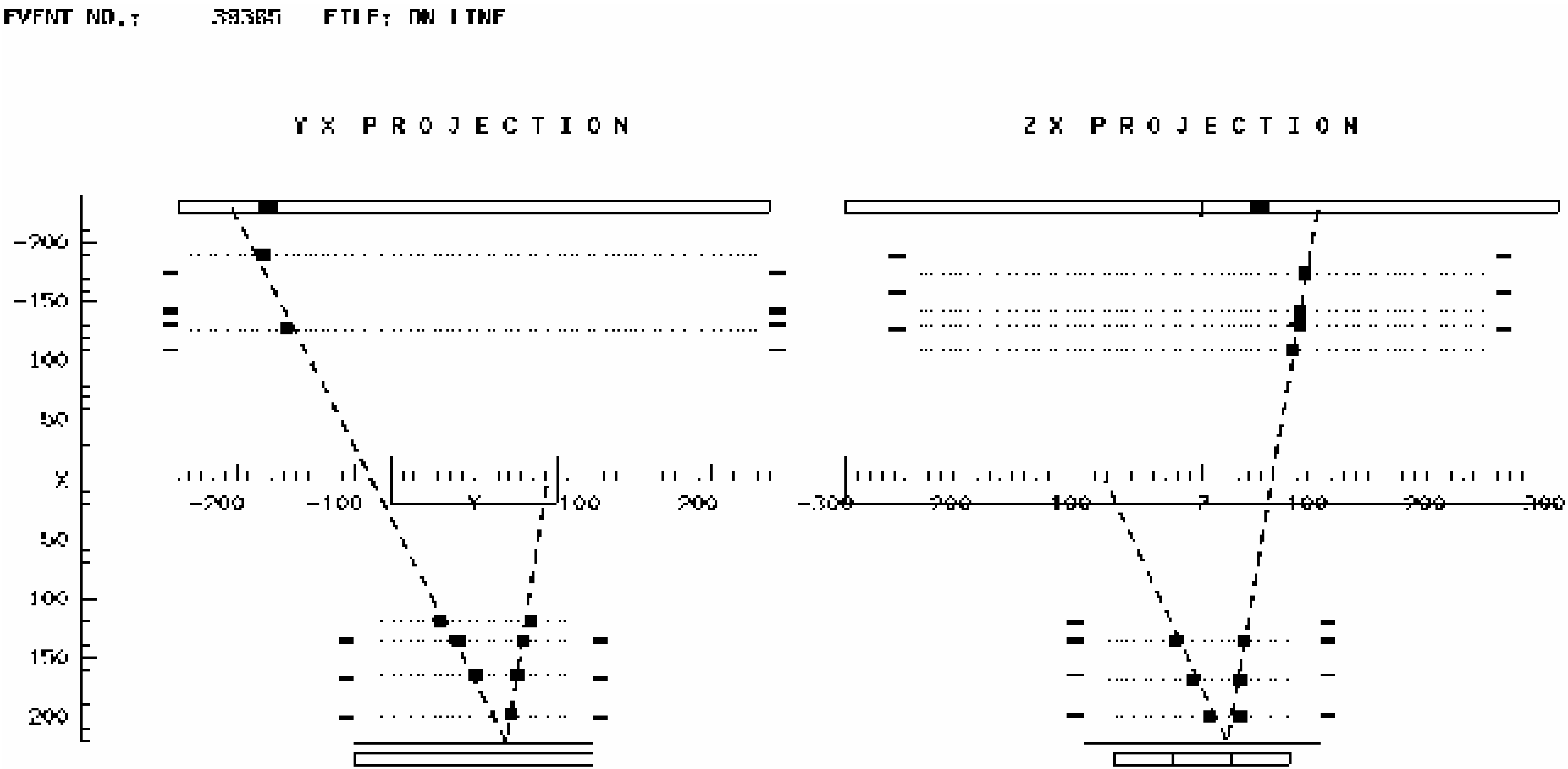
(SINQ-FUNSPIN)

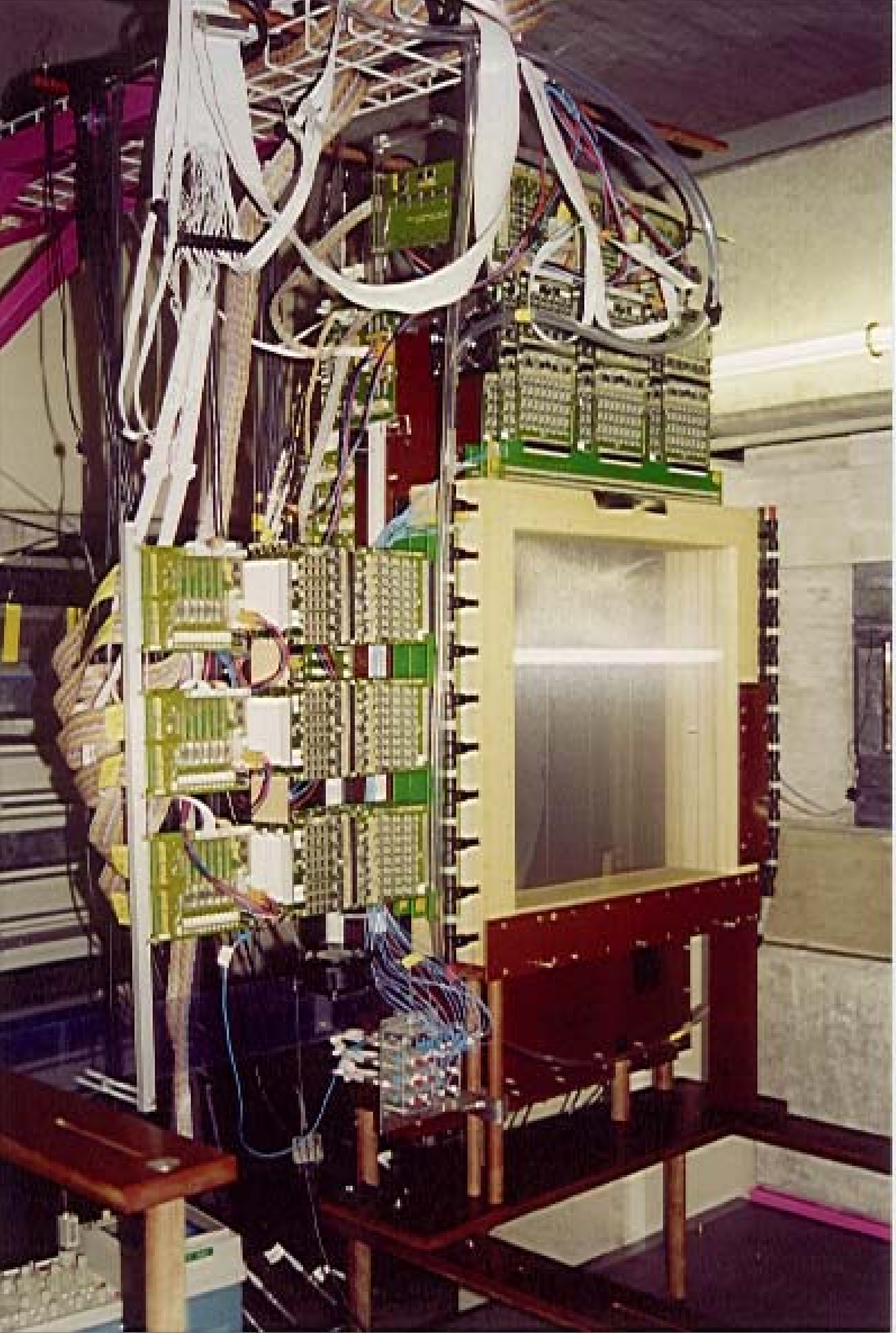
$$R\,\frac{\vec{J}\cdot(\vec{p}\times\vec{\sigma})}{E}$$





$$R = 0.28\ \mathrm{Im}\left(\frac{C_S + C_S'}{C_A}\right) + 0.33\ \mathrm{Im}\left(\frac{C_T + C_T'}{C_A}\right)$$

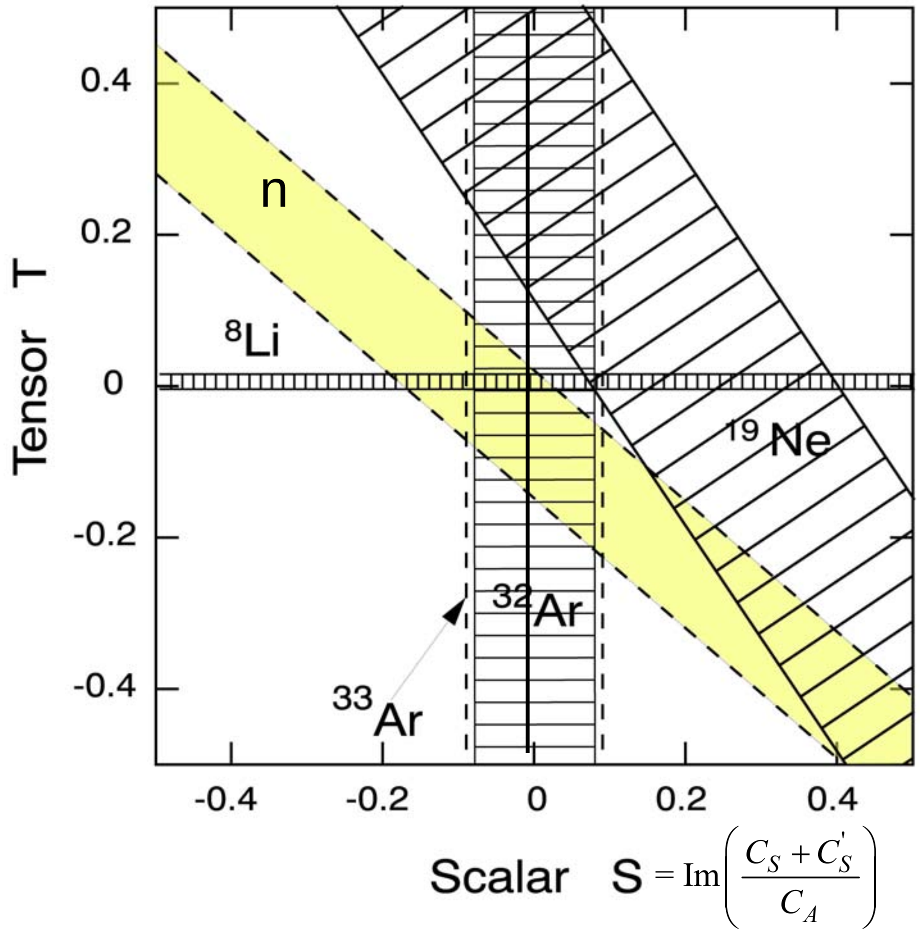

Y X P R O J E C T I O N
Z X P R O J E C T I O N
-200
-150
100
50
50
100
150
200
-200
-100
100
200
100
200



R = -0.021(28) (preliminary)

(1/4 of statistics from test run 2006)

N = 0.085(39) (N **J.σ** ; N_{SM} = 0.078)



^{8}Li : Sromicki et al., PSI – ETH Zurich

^{19}Ne : F. Calaprice et al., Princeton

^{32,33}Ar : E.G. Adelerger et al., ISOLDE

1. $Ft^{0^+ \rightarrow 0^+}$

2. βν-correlation coefficient *a*

- neutron : *a*SPECT
- nuclei :
  - TRINAT / TRIUMF
  - LPC-TRAP / GANIL
  - WITCH / ISOLDE

β-asymmetry parameter *A*

nuclei : Leuven – ISOLDE

3. symmetry tests

TRV : *R* ($\sigma.Jxp_e$; S,T) ; neutron R-TRV / PSI