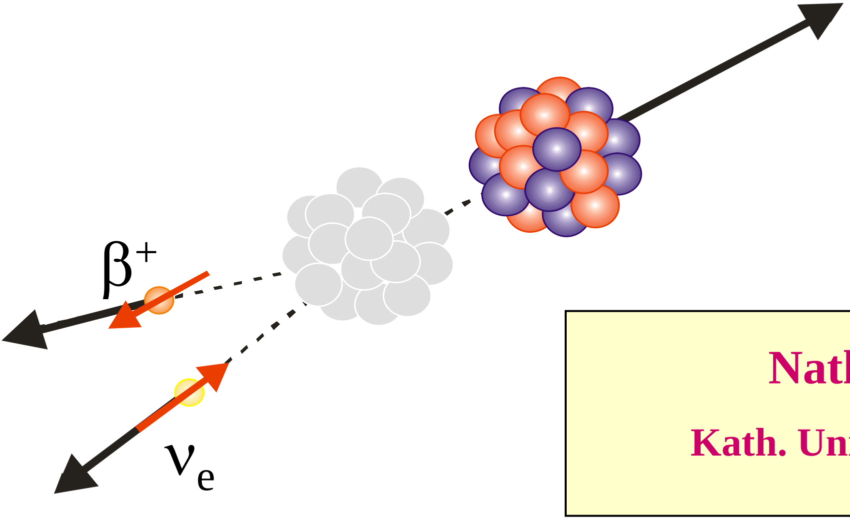
β spectrum shape measurements



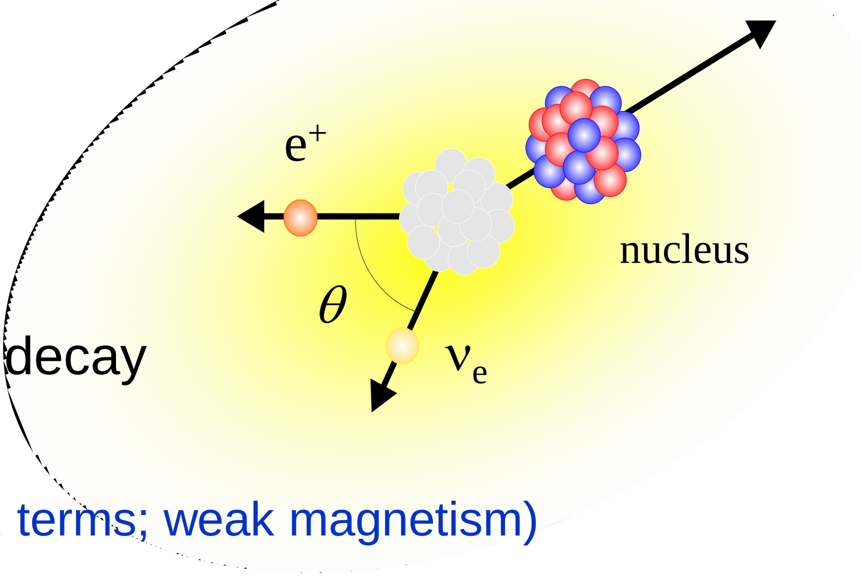
Solvay workshop

Brussels, Sept. 3-5, 2014

Nathal Severijns

Kath. Univ. Leuven, Belgium

Motivation



- $\mathcal{F}t^{0^+\to 0^+}$ & correlations (*a*, *A*, …) in β decay

  → scalar/tensor current searches

  (sensitivity limited by induced terms; weak magnetism)

1. induced terms (by strong interaction)
   - existing information
   - theoretical study **(in coll. with I.S. Towner and F. Glück)**
2. (new) experimental observable: β-spectrum shape

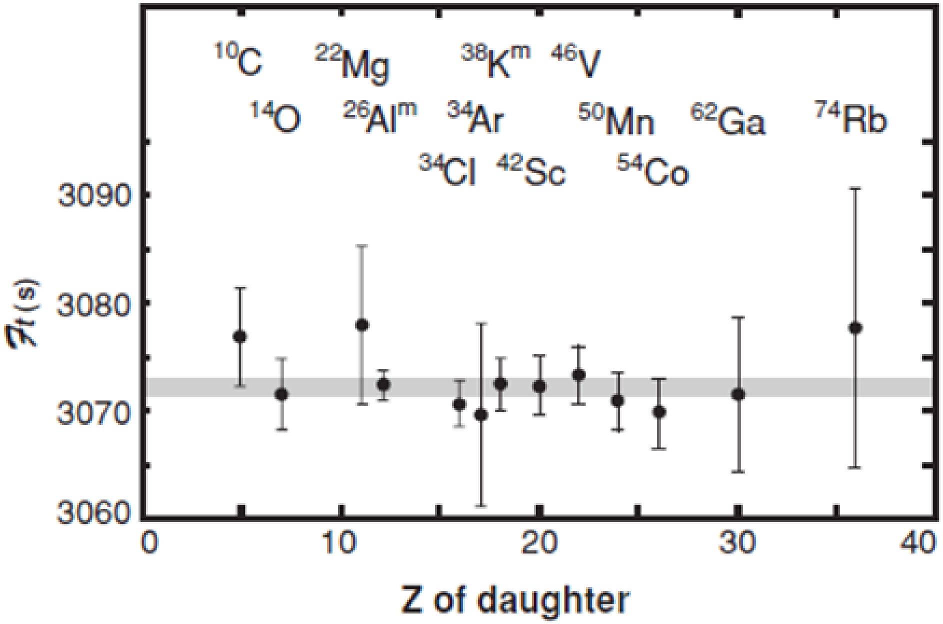
   → miniBETA spectrometer and Si detector based spectrometer

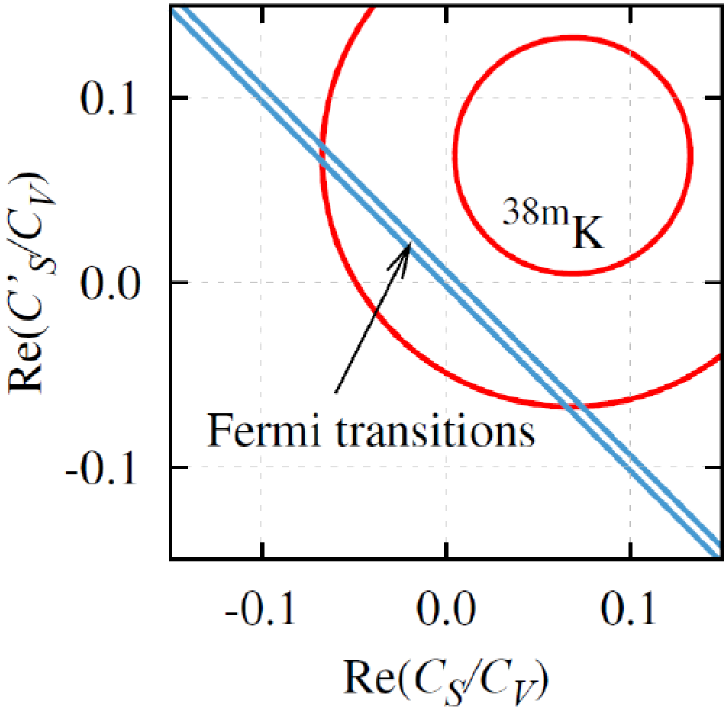
   (in coll. with K.Bodek et al., Jag. Univ. Krakow)

correlations and Ft-values in β decay

Ft value of $0^+ \rightarrow 0^+$ superallowed pure Fermi transitions

$$\mathcal{F}t^{0^+\to 0^+} = \frac{K}{2G_F^2 V_{ud}^2 C_V^2 (1+\Delta_R^V)} \frac{1}{(1+b_F')}$$ with $b_F' = \frac{\gamma m_e}{\langle E_e \rangle}\left(\frac{C_S + C_S'}{C_V}\right)$ **(Fierz term)**





$\mathcal{F}t^{0^+\to 0^+}$ = 3071.81(83) s

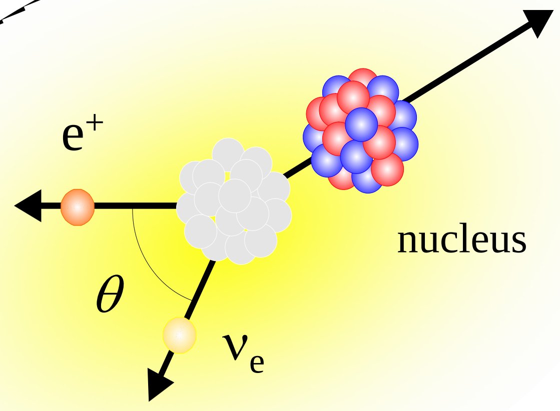
Towner & Hardy, Rep. Prog Phys. 73 (2010) 046301

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

2. β-ν correlation to probe scalar/tensor weak currents

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

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



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

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

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

Fierz term

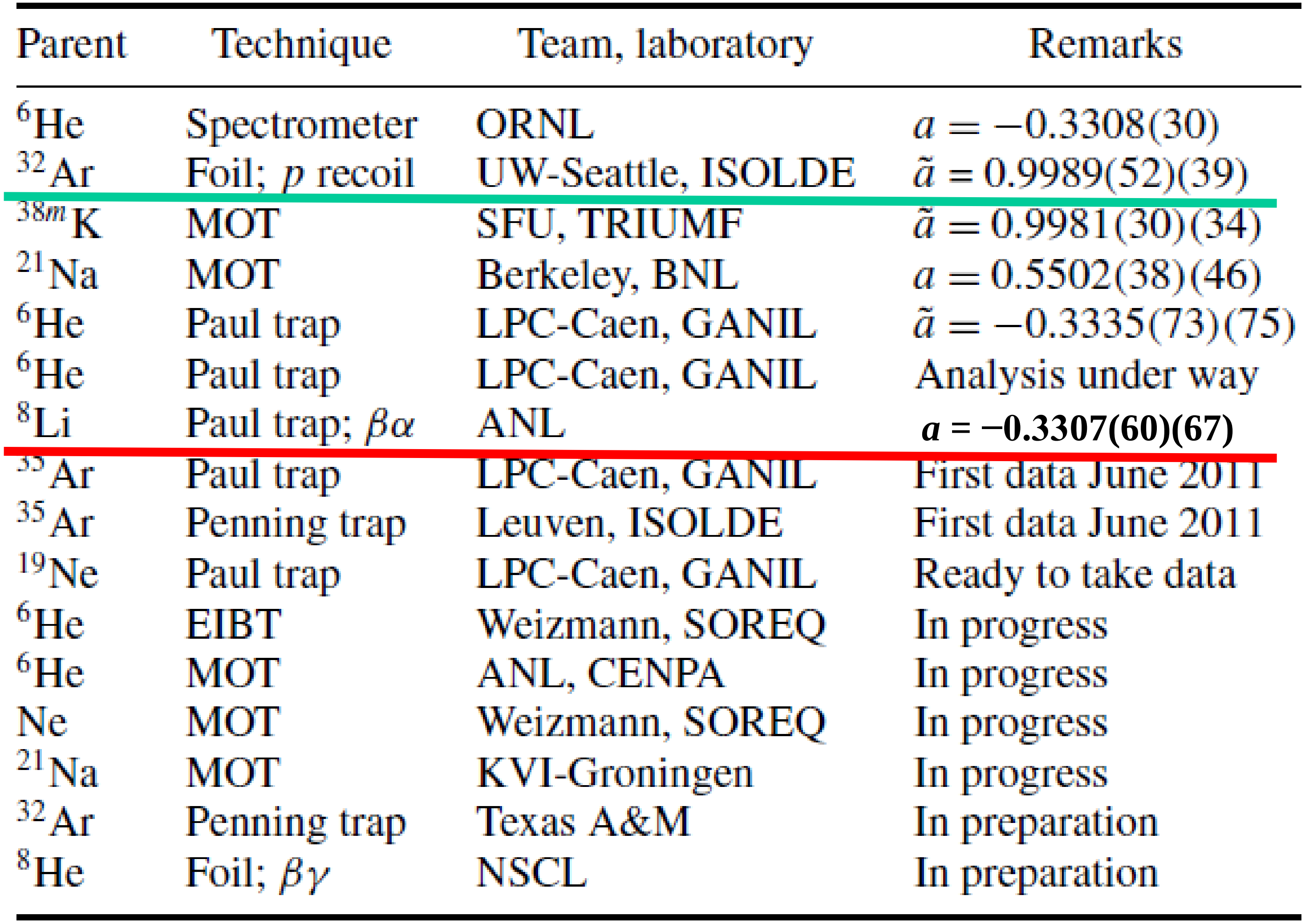
$$b_{GT} \cong Re\,\frac{C_T + C_T'}{C_A}$$

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

!!! for pure transitions weak interaction info independent of nuclear matrix elements !!!

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

Overview of β-ν correlation projects

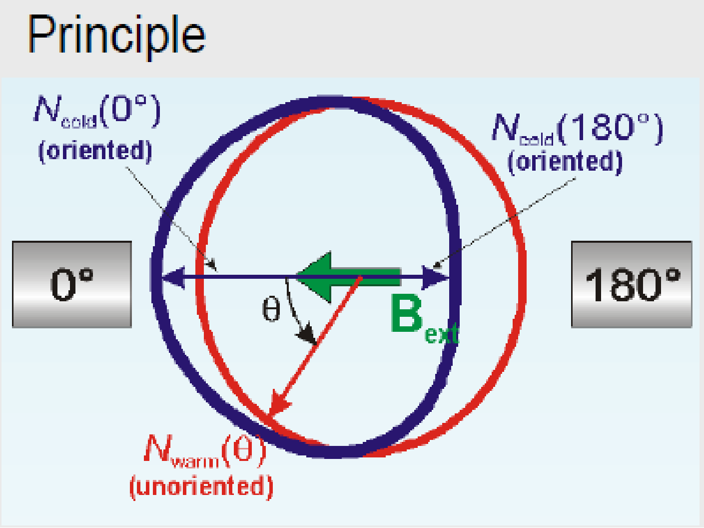


Parent	Technique	Team, laboratory	Remarks
^{6}He	Spectrometer	ORNL	$a = -0.3308(30)$
^{32}Ar	Foil; p recoil	UW-Seattle, ISOLDE	$\tilde{a} = 0.9989(52)(39)$
^{38m}K	MOT	SFU, TRIUMF	$\tilde{a} = 0.9981(30)(34)$
^{21}Na	MOT	Berkeley, BNL	$a = 0.5502(38)(46)$
^{6}He	Paul trap	LPC-Caen, GANIL	$\tilde{a} = -0.3335(73)(75)$
^{6}He	Paul trap	LPC-Caen, GANIL	Analysis under way
^{8}Li	Paul trap; $\beta\alpha$	ANL	$\boldsymbol{a} = \mathbf{-0.3307(60)(67)}$
^{35}Ar	Paul trap	LPC-Caen, GANIL	First data June 2011
^{35}Ar	Penning trap	Leuven, ISOLDE	First data June 2011
^{19}Ne	Paul trap	LPC-Caen, GANIL	Ready to take data
^{6}He	EIBT	Weizmann, SOREQ	In progress
^{6}He	MOT	ANL, CENPA	In progress
Ne	MOT	Weizmann, SOREQ	In progress
^{21}Na	MOT	KVI-Groningen	In progress
^{32}Ar	Penning trap	Texas A&M	In preparation
^{8}He	Foil; $\beta\gamma$	NSCL	In preparation

N.S. & O. Naviliat-Cuncic, Physica Scripta T152 (2013) 014018

3. β-asymmetry parameter in nuclear beta decay

(KU Leuven, NICOLE-ISOLDE, NPI Rez-Prague, Uni Bonn)



$$W(\theta) = \frac{N(\theta)_{pol}}{N(\theta)_{unpol}} = 1 + \tilde{A} \quad P \quad \frac{v}{c} \, Q\cos\theta$$

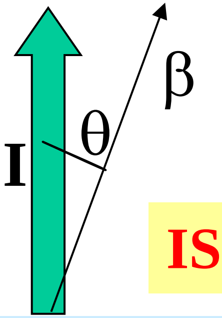
(P from anisotropy of γ-rays) **Geant4**

$$\tilde{A} = \frac{A}{1+b'_{GT}} \qquad \text{with} \qquad b'_{GT} = \frac{\gamma m_e}{\langle E_e \rangle}\left(\frac{C_T + C'_T}{C_A}\right)$$

^{60}CoCu , B_{ext} = 13 T

^{114}InFe , B_{hf} = 27 T

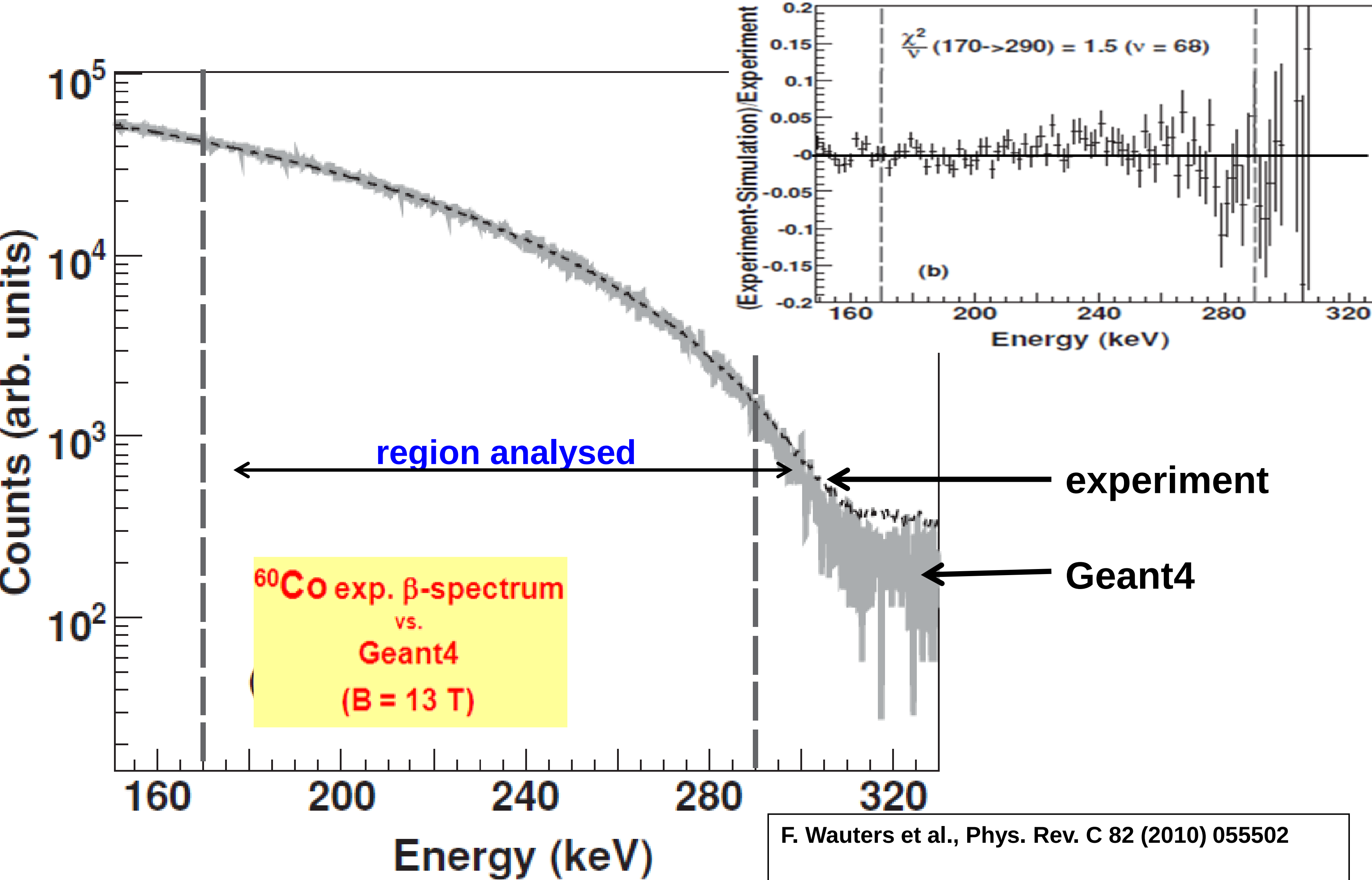
^{67}CuFe , B_{hf} = 21 T



IS431-experiment

Analysis:

$$\frac{\left[W(\theta) - 1\right]_{exp}}{\left[W(\theta) - 1\right]_{Geant}} = \frac{\left[\tilde{A} \quad P \quad \frac{v}{c} \, Q\cos\theta\right]_{exp}}{\left[\tilde{A}_{SM} \quad P \quad \frac{v}{c} \, Q\cos\theta\right]_{Geant}} = \frac{\tilde{A}}{\tilde{A}_{SM}}$$



region analysed

experiment

Geant4

^{60}Co exp. β-spectrum
vs.
Geant4
(B = 13 T)

F. Wauters et al., Phys. Rev. C 82 (2010) 055502

F. Wauters et al., Nucl. Instr. Meth. A 604 (2009) 563

$A_{exp}\ (^{60}\mathrm{Co})\ =\ -\,1.014\ (12)_{stat}\ (16)_{syst}$

$(A_{SM}\ =\ -0.987(9)\ )$

F. Wauters et al., Phys. Rev. C 82 (2010) 055502

$A_{exp}\ (^{114}\mathrm{In})\ =\ -\,0.990\ (10)_{stat}\ (10)_{syst}$

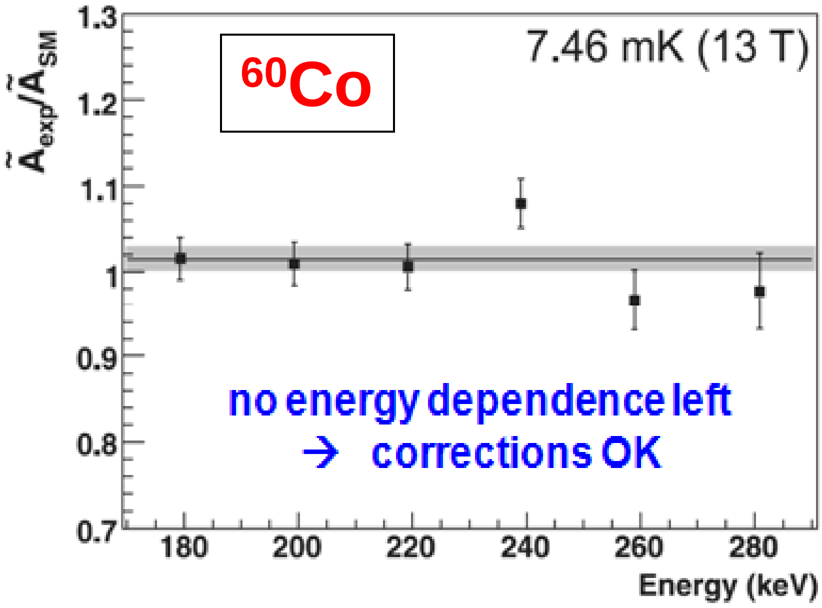
$(A_{SM}\ =\ -0.996(3)\ )$

F. Wauters et al., Phys. Rev. C 80 (2009) 062501(R)

$A_{exp}\ (^{67}\mathrm{Cu})\ =\ 0.584\ (6)_{stat}\ (11)_{syst}$

$(A_{SM}\ =\ 0.5993(2)\ )$

G. Soti et al., submitted



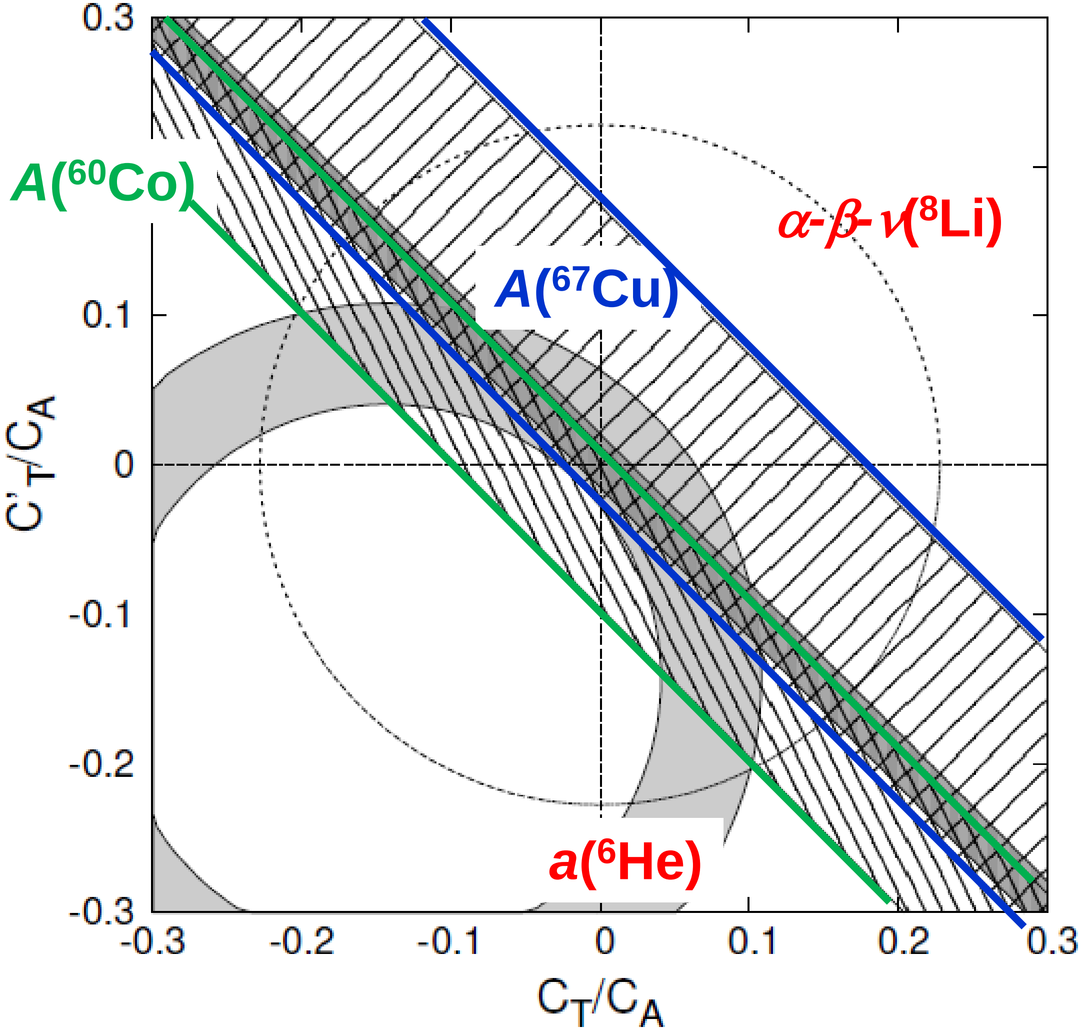
no energy dependence left

→ corrections OK

major systematic errors:

- performance of GEANT code (scattering)
- determination of nuclear polarization
- induced (recoil) terms

Constraints on tensor type weak couplings



a(^{6}He)
C. Johnston et al.,
PR 132 (1963) 1149

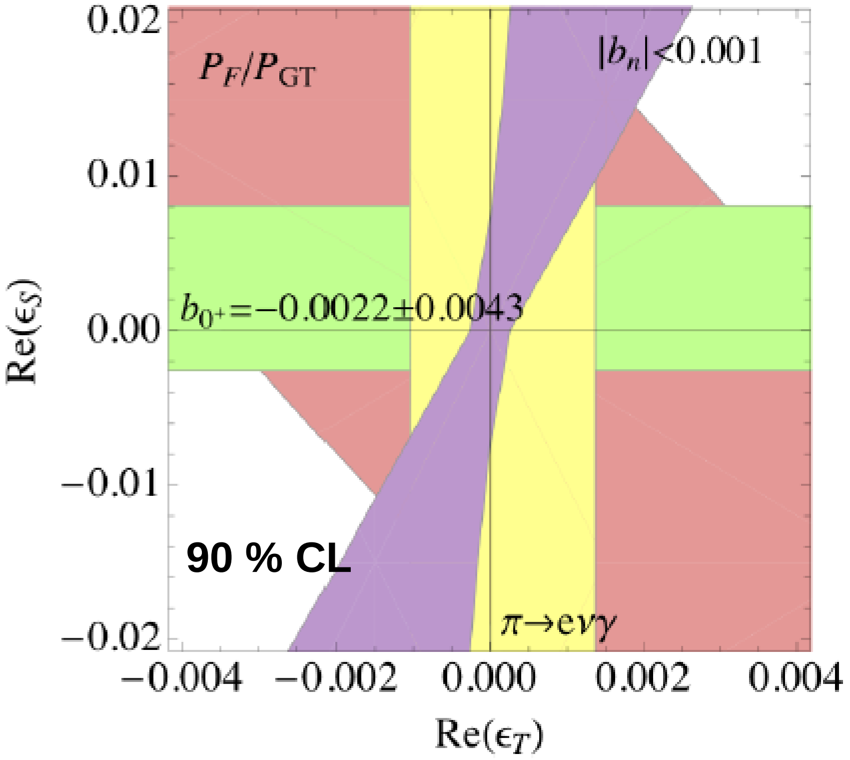
A(^{60}Co)
F. Wauters, N.S. et al.,
PR C 82 (2010) 055502

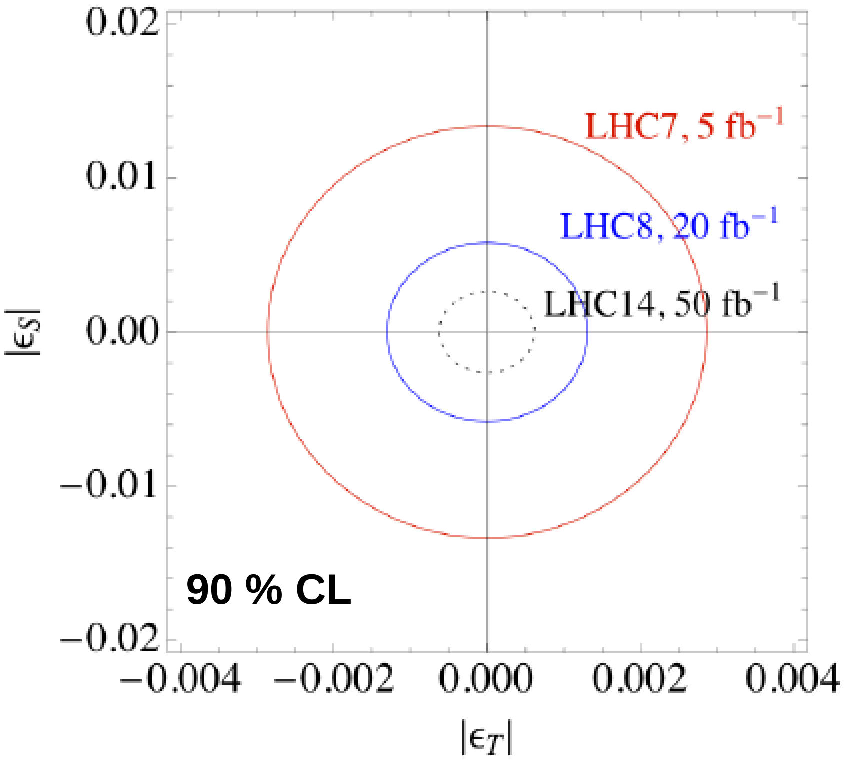
α-β-ν(^{8}Li)
G.Li, G.Savard et al.,
PRL 110 (2013) 082502

A(^{67}Cu)
G. Soti, N.S. et al., (2013) submitted

black band: P_F / P_{GT}
A.S. Carnoy et al.
PR C 43 (1991) 2825

Precision measurements in nuclear/neutron β decay in the LHC era





nuclear and neutron decay, pion decay

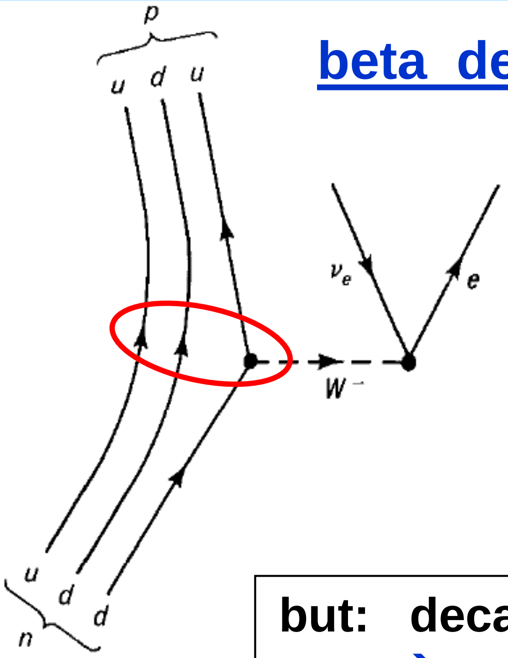
O. Naviliat-Cuncic and M. Gonzalez-Alonso
Annalen der Physik 525 (2013) 72.

V. Cirigliano, et al.,
J. High. Energ. Phys. 1302 (2013) 046

limits on scalar/tensor couplings obtained by CMS collaboration in *pp* → *e* + MET + *X* channel

- **S. Chatrchyan et al. (CMS Collab.)**
  J. High. Energ. Phys. 1208 (2012) 023;
- **CERN Rep. nr. CMS-PAS-EXO-12-060 (2013)**

induced / recoil terms



beta decay: $H = G_F \langle \psi_f | V_\mu(0) + A_\mu(0) | \psi_i \rangle l^\mu$

with $l^\mu = \bar{e}(p)\gamma^\mu(1+\gamma_5)v(k)$

free quark:

$$V_\mu(q^2) = \bar{u}[g_V(q^2)\gamma_\mu]d\ ,$$

$$A_\mu(q^2) = \bar{u}[g_A(q^2)\gamma_\mu\gamma_5]d$$

but: decaying quark is not free but bound in a nucleon
→ extra terms induced by strong interaction

neutron decay:

$$V_\mu(q^2) = \bar{p}[g_V(q^2)\gamma_\mu + \overset{\text{weak magnetism}}{\boxed{g_M(q^2)\sigma_{\mu\nu}\frac{q_\nu}{2M}}} + ig_S(q^2)\frac{q_\mu}{m_e}]n$$

$$A_\mu(q^2) = \bar{p}[g_A(q^2)\gamma_\mu\gamma_5 + g_T(q^2)\sigma_{\mu\nu}\gamma_5\frac{q_\nu}{2M} + ig_P(q^2)\frac{q_\mu}{m_e}\gamma_5]n$$

weak magnetism (CVC)

T = 1/2 Jπ → Jπ mirror β transitions

$$b(\beta^{\mp}) = A\sqrt{\frac{J}{J+1}}\, M_F^0\ \mu^{\mp}$$

$$\mu^{\mp} = \mp(\mu_M - \mu_D)$$

e.g. F.P. Calaprice and B.R. Holstein
Nucl. Phys. A 273 (1976) 301

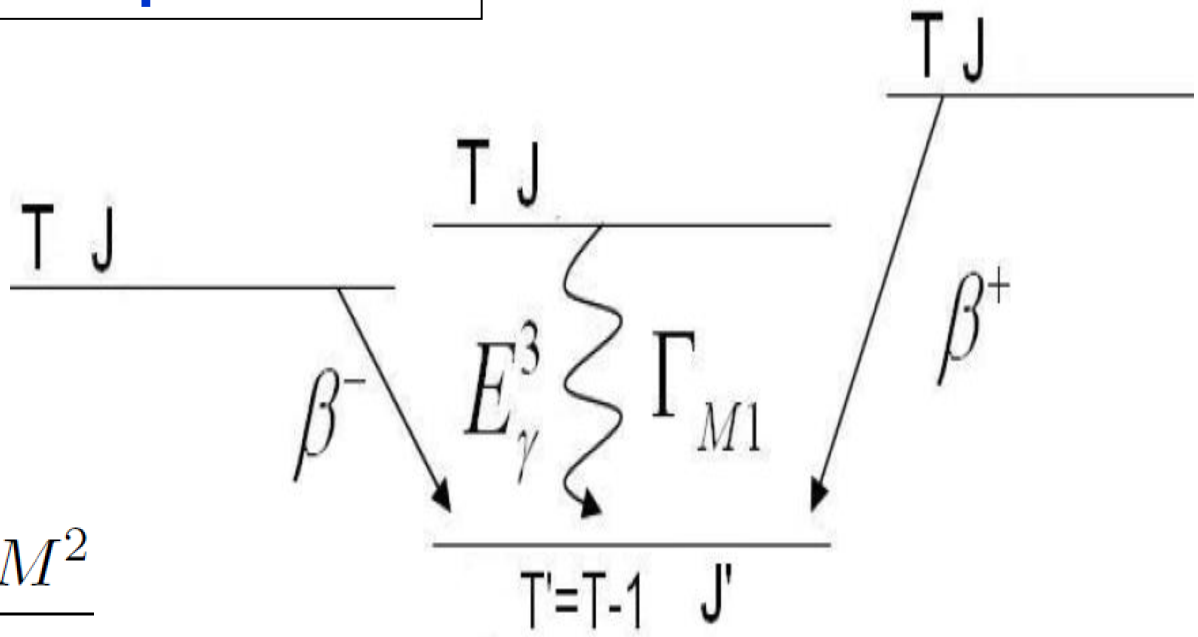
$$\mathcal{F}t^{mirror} \equiv f_V t(1+\delta_R')(1+\delta_{NS}^V - \delta_C^V) = \frac{2\mathcal{F}t^{0^+\to 0^+}}{\left(1+\frac{f_A}{f_V}\rho^2\right)}$$

$$\rho \cong g_A M_{GT}^0 = c$$

N. Severijns, I.S. Towner et al.,
Phys. Rev. C 78 (2008) 055501

weak magnetism (CVC)

GT β decays of triplet states

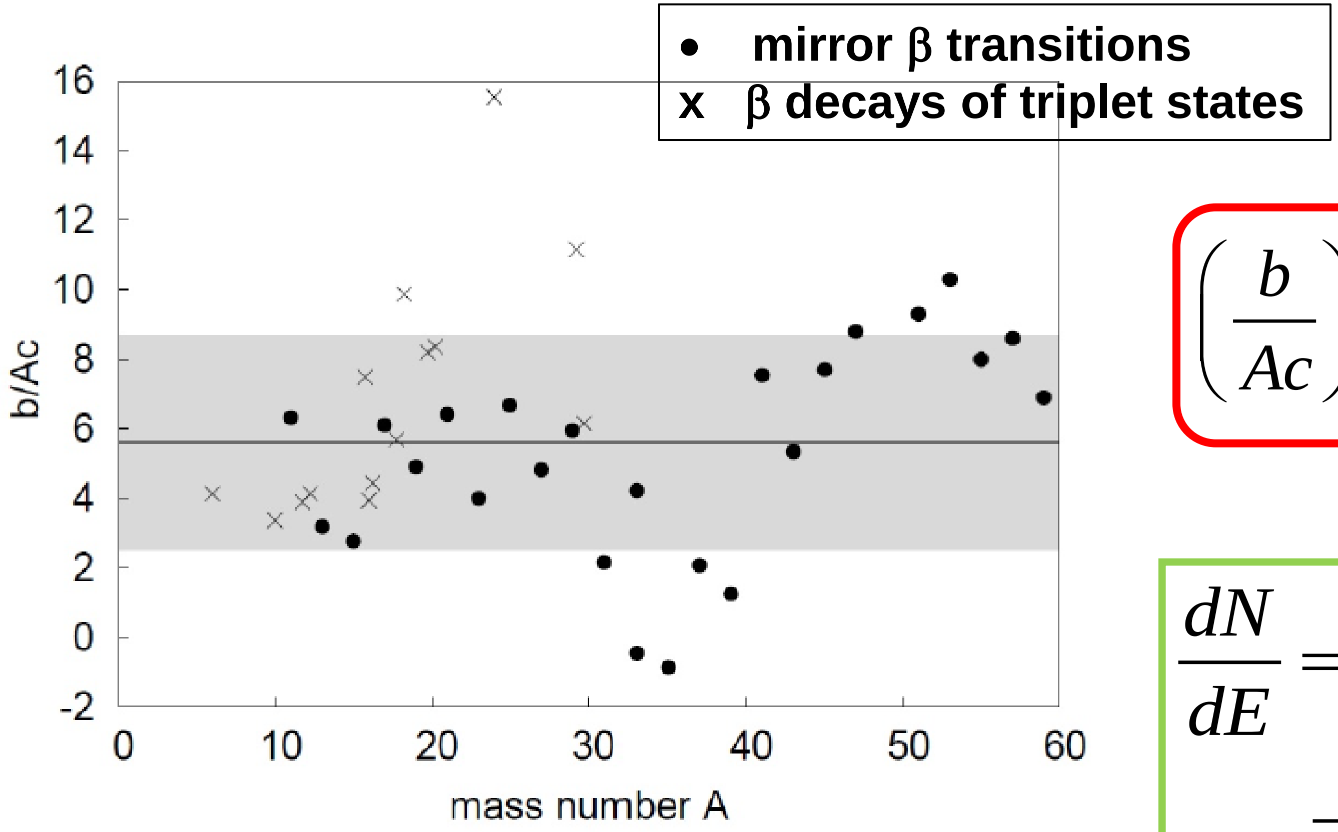


$$b_\gamma^2 = 6\frac{\Gamma_{M1} M^2}{E_\gamma^3 \alpha}$$

$$c^2 = \frac{2\mathcal{F}t^{0^+\to 0^+}}{ft}$$

e.g. F.P. Calaprice and B.R. Holstein
Nucl. Phys. A 273 (1976) 301

weak magnetism (CVC) - experimental data



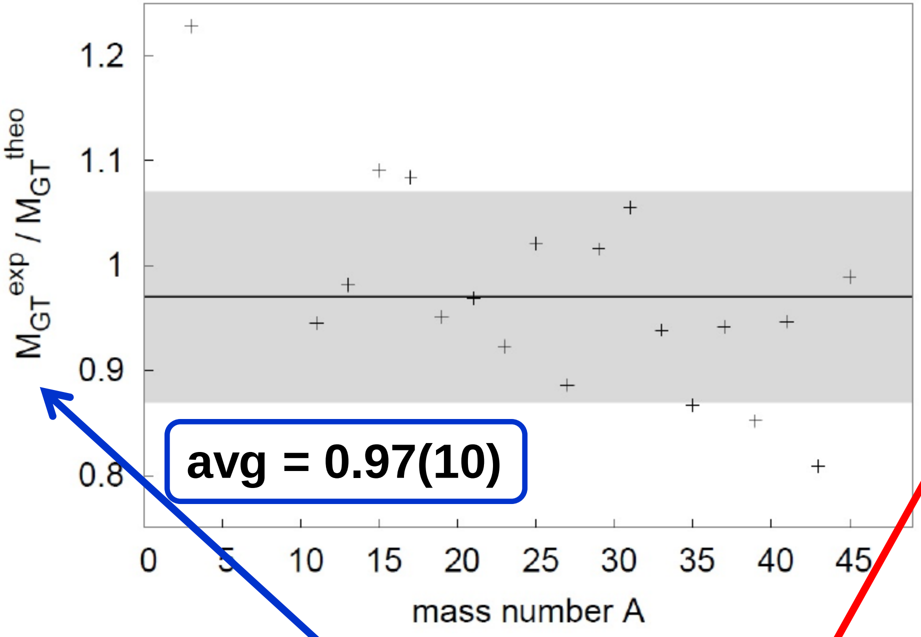
$$\left(\frac{b}{Ac}\right)_{avg} = 5.6 \pm 3.0$$

$$\frac{dN}{dE} = \frac{4}{3M_n}\frac{b}{Ac}$$

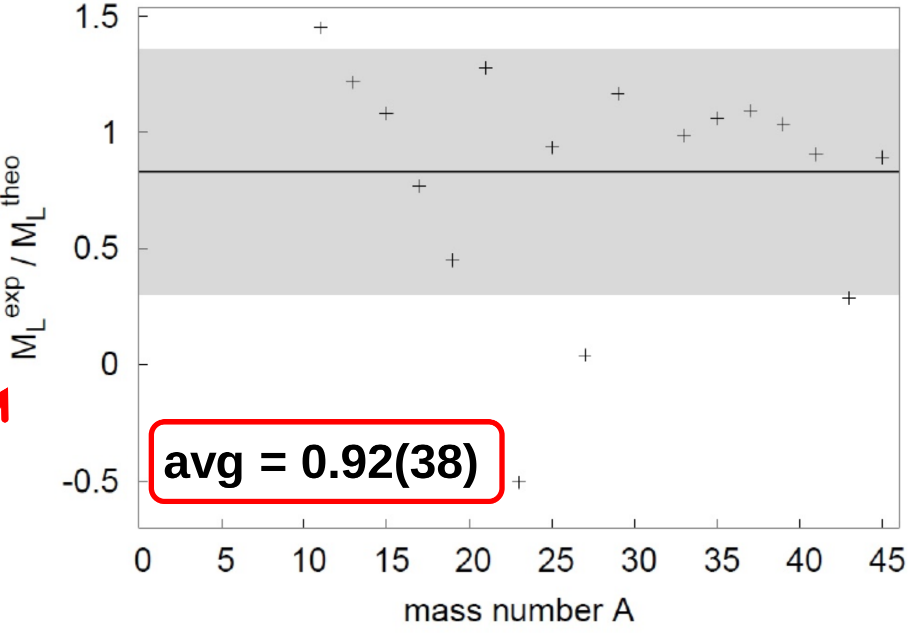
$$= 0.8(4)\%\ \mathrm{MeV}^{-1}$$

V. De Leebeeck, I.S. Towner, N.S., et al., to be published

weak magnetism (CVC) - mirror β transitions



avg = 0.97(10)



avg = 0.92(38)

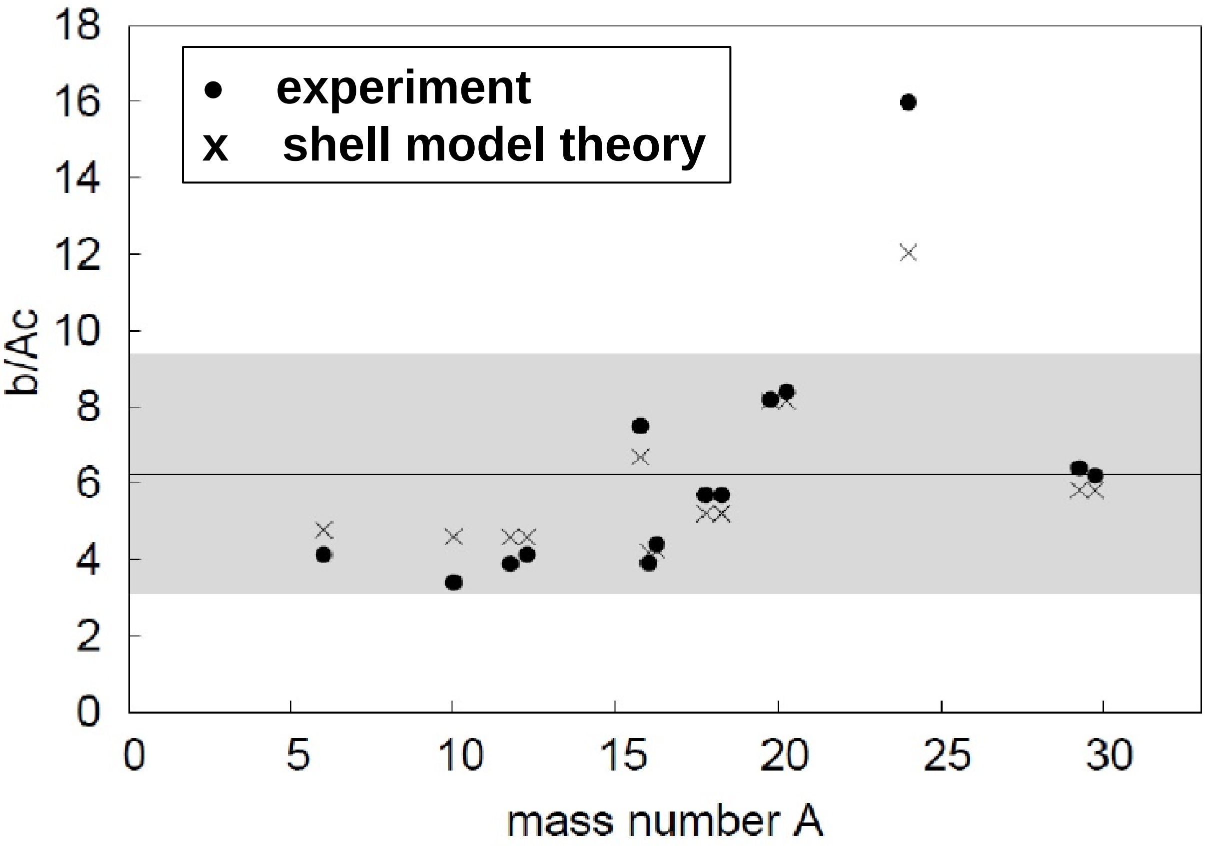
$$\frac{b}{Ac} \cong \left[\frac{g_M}{g_V} + \frac{g_V}{g_A} \frac{\boxed{M_L}}{M_{GT}} \right]$$

$$c \cong g_A \boxed{M_{GT}}$$

	$(b/Ac)^{exp}/(b/Ac)^{theo}$
mirror (A = 3-45)	**1.20(49)**

V. De Leebeeck, I.S. Towner, N.S., et al., to be published

weak magnetism (CVC) - β decays of triplet states



$(b/Ac)^{exp}/(b/Ac)^{theo}$

----

triplet **1.01(15)**

(A = 6-30)

V. De Leebeeck, I.S. Towner, N.S., et al., to be published

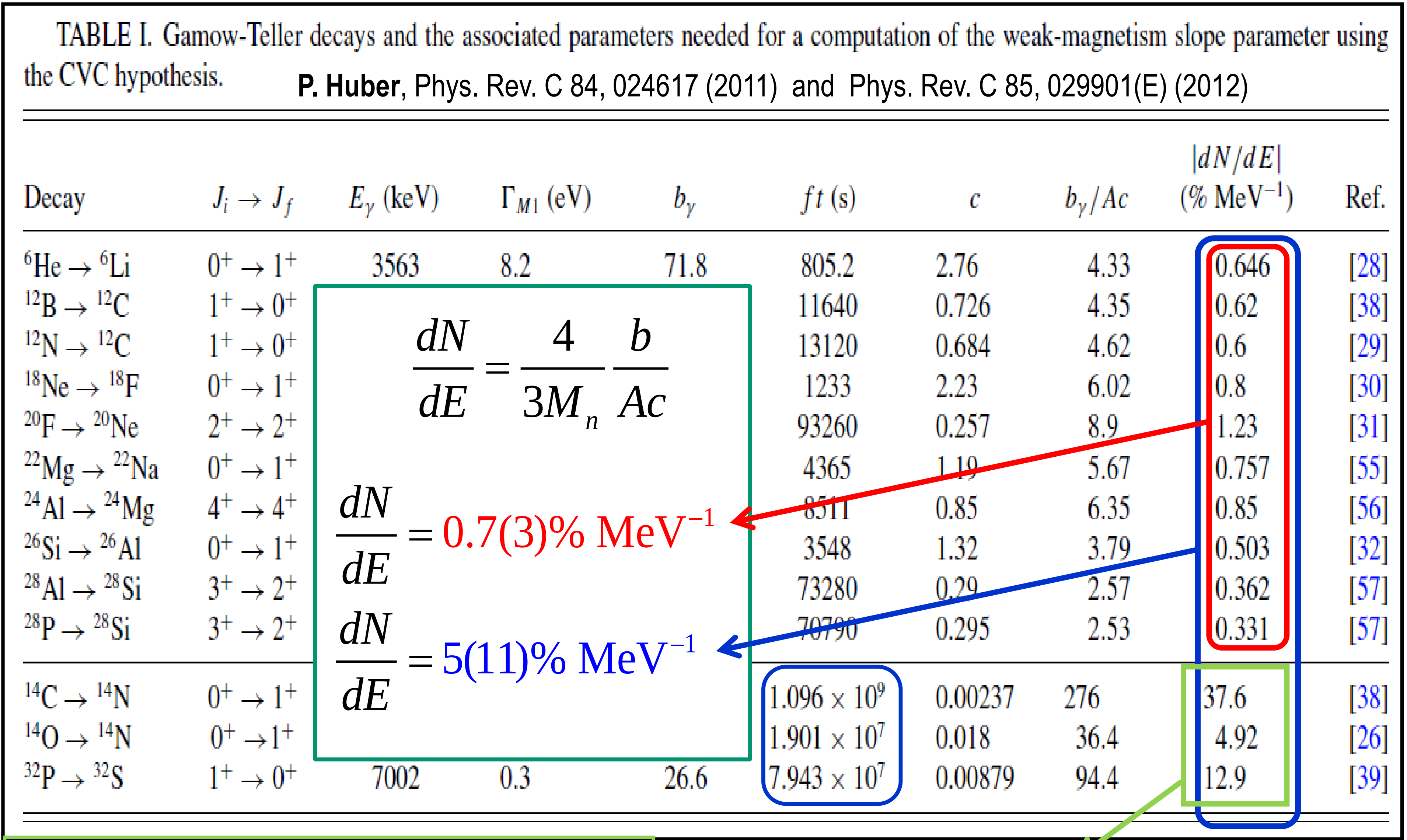


TABLE I. Gamow-Teller decays and the associated parameters needed for a computation of the weak-magnetism slope parameter using the CVC hypothesis.

P. Huber, Phys. Rev. C 84, 024617 (2011) and Phys. Rev. C 85, 029901(E) (2012)

Decay	$J_i \to J_f$	E_γ (keV)	Γ_{M1} (eV)	b_γ	ft (s)	c	b_γ/Ac	$\lvert dN/dE \rvert$ (% MeV^{-1})	Ref.
$^{6}\mathrm{He} \to {}^{6}\mathrm{Li}$	$0^+ \to 1^+$	3563	8.2	71.8	805.2	2.76	4.33	0.646	[28]
$^{12}\mathrm{B} \to {}^{12}\mathrm{C}$	$1^+ \to 0^+$				11640	0.726	4.35	0.62	[38]
$^{12}\mathrm{N} \to {}^{12}\mathrm{C}$	$1^+ \to 0^+$				13120	0.684	4.62	0.6	[29]
$^{18}\mathrm{Ne} \to {}^{18}\mathrm{F}$	$0^+ \to 1^+$				1233	2.23	6.02	0.8	[30]
$^{20}\mathrm{F} \to {}^{20}\mathrm{Ne}$	$2^+ \to 2^+$				93260	0.257	8.9	1.23	[31]
$^{22}\mathrm{Mg} \to {}^{22}\mathrm{Na}$	$0^+ \to 1^+$				4365	1.19	5.67	0.757	[55]
$^{24}\mathrm{Al} \to {}^{24}\mathrm{Mg}$	$4^+ \to 4^+$				8511	0.85	6.35	0.85	[56]
$^{26}\mathrm{Si} \to {}^{26}\mathrm{Al}$	$0^+ \to 1^+$				3548	1.32	3.79	0.503	[32]
$^{28}\mathrm{Al} \to {}^{28}\mathrm{Si}$	$3^+ \to 2^+$				73280	0.29	2.57	0.362	[57]
$^{28}\mathrm{P} \to {}^{28}\mathrm{Si}$	$3^+ \to 2^+$				70790	0.295	2.53	0.331	[57]
$^{14}\mathrm{C} \to {}^{14}\mathrm{N}$	$0^+ \to 1^+$				1.096×10^9	0.00237	276	37.6	[38]
$^{14}\mathrm{O} \to {}^{14}\mathrm{N}$	$0^+ \to 1^+$				1.901×10^7	0.018	36.4	4.92	[26]
$^{32}\mathrm{P} \to {}^{32}\mathrm{S}$	$1^+ \to 0^+$	7002	0.3	26.6	7.943×10^7	0.00879	94.4	12.9	[39]

$$\frac{dN}{dE} = \frac{4}{3M_n}\frac{b}{Ac}$$

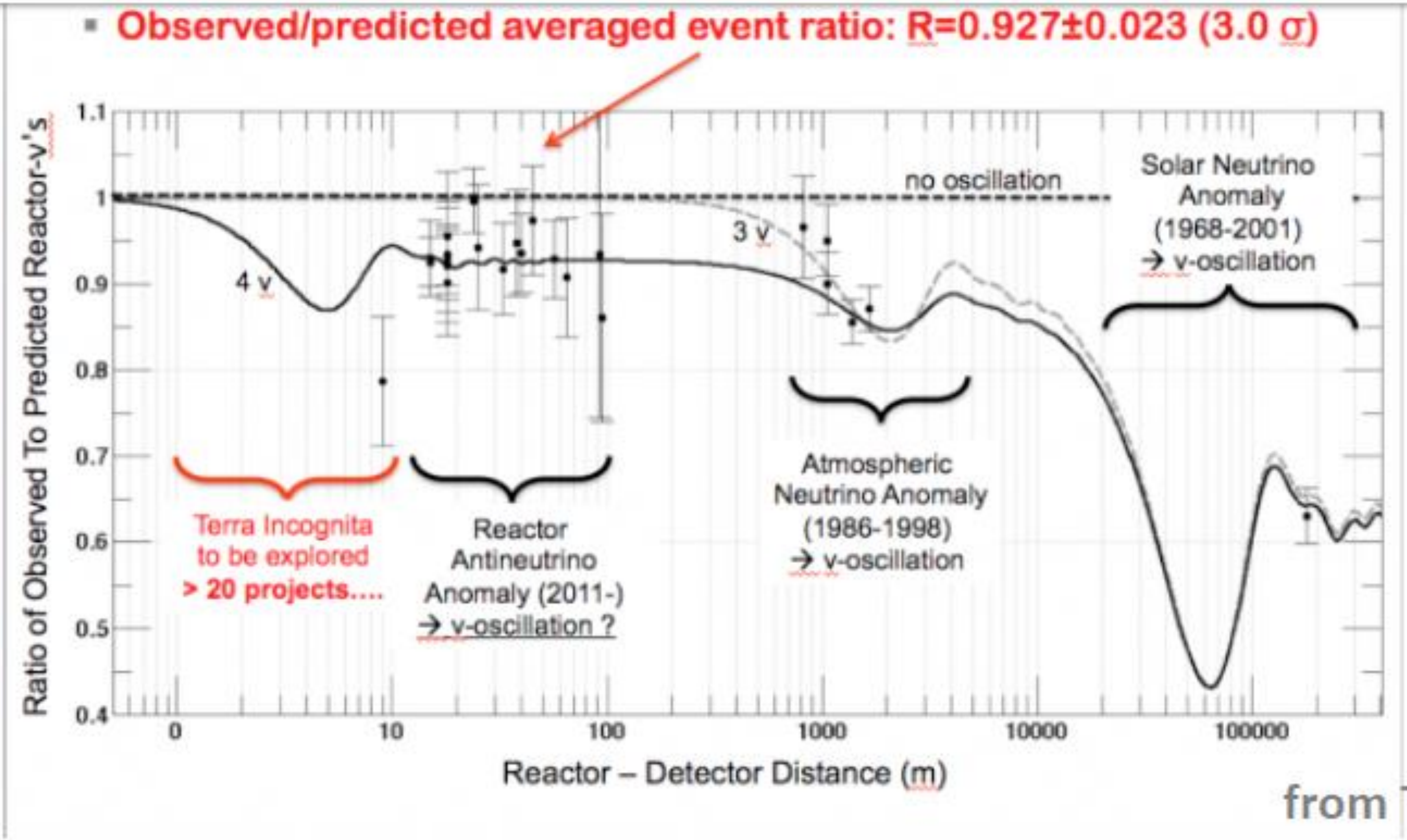
$$\frac{dN}{dE} = 0.7(3)\%\ \mathrm{MeV}^{-1}$$

$$\frac{dN}{dE} = 5(11)\%\ \mathrm{MeV}^{-1}$$

Note: shift of dN/dE by +0.5% MeV^{-1} causes a shift of the reactor anti-neutrino rate by -1%

Could indicate breakdown of impulse approx. if log *ft* is large, or be due to electromagnetic interaction which is then very much amplified because of the hindrance of the decays.

The Reactor Antineutrino Anomaly



- **Observed/predicted averaged event ratio: R=0.927±0.023 (3.0 σ)**

from Th. Lasserre

The effect mostly comes from the detailed physics involved in the nuclear beta-decay of fission fragments in the reactor

β spectrum shape measurements

$$N(p)dp = Kp^2(W - W_0)^2 \cdot F(Z,p) \cdot L_0 \cdot C \cdot R_n \cdot RC \cdot S(E)dp$$

- phase space factor x constants
- ***F(Z,p)*: Fermi function**
- ***L_0* & *C*: finite size of nucleus**
- ***R_n* : finite mass of nucleus**
- ***RC*: radiative corrections**
- ***S(E)*: spectrum shape factor**

$$\boxed{S(E) \approx 1 + \frac{2}{3M_n}\left(5 \pm 2\frac{b}{Ac}\right)E_e \;\propto\; 1\,\%\,\mathrm{MeV}^{-1}}$$

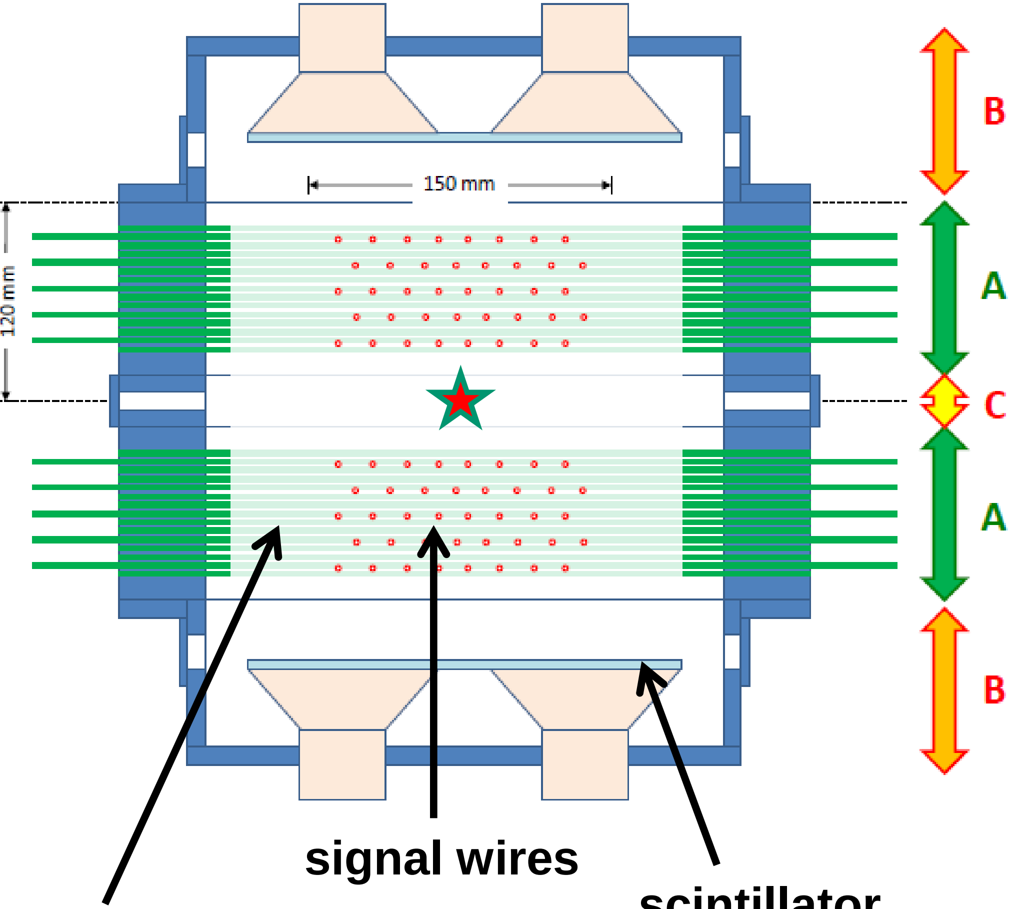
(for a pure GT transition and neglecting terms ∝ 1/M^2 and ∝ m_e^2/E)

→ $$d\Gamma \propto G_F\ F(Z,E)\left[1 + k' \boxed{b_{WM}\ E_\beta} + k'' \boxed{\frac{b_{Fierz}}{E_\beta}}\right]$$

β spectrum shape measurements with the miniBETA spectrometer

Univ. Krakow – Univ. Leuven

$$d\Gamma \propto G_F\ F(Z,E)\left[1 + k'\boxed{E_\beta\ b_{WM}} + k''\boxed{\frac{b_{Fierz}}{E_\beta}}\right]$$



signal wires

scintillator

multi-wire drift chamber

1. high β-endpoint energies (^{14}O, ^{32}P, ^{68}Cu, ^{114}In, …) :

   → weak magnetism

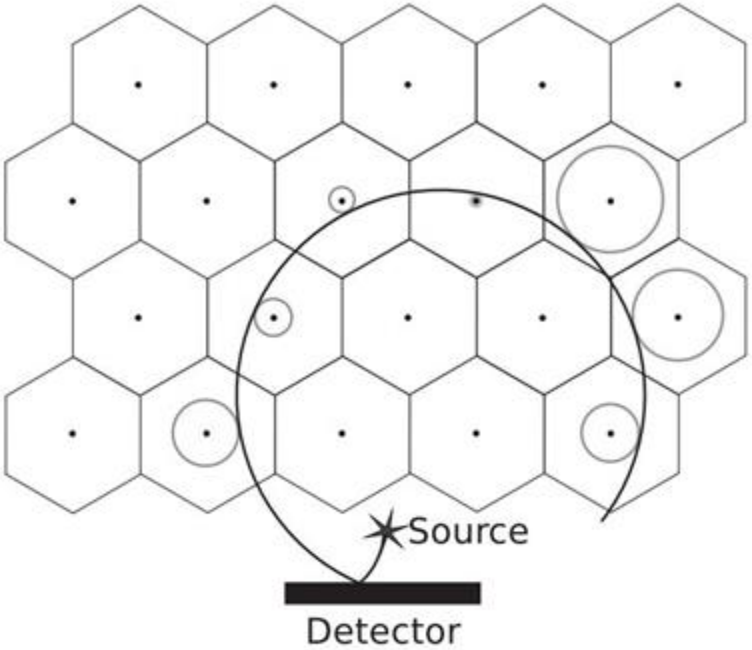
2. low β-endpoint energies (^{45}Ca, ^{60}Co, ^{67}Cu …) :

   → scalar / tensor type weak interactions

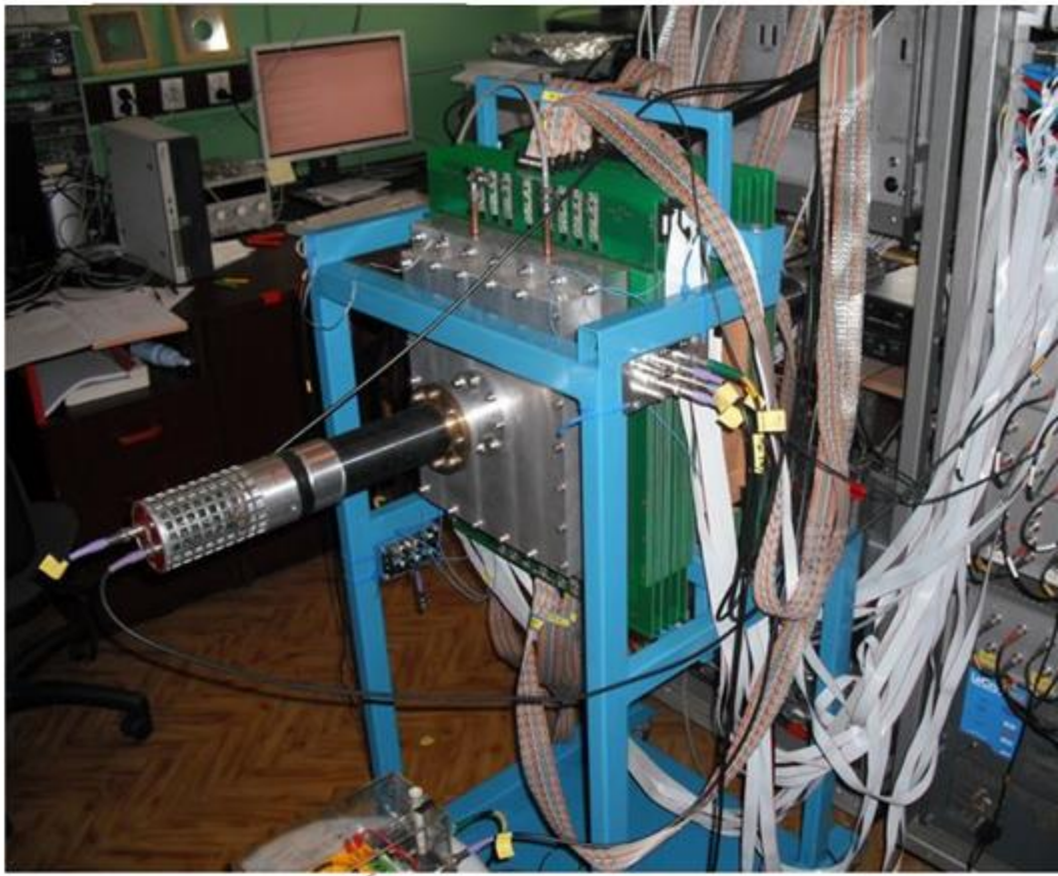
3. improve current knowledge on electron scattering

   → improve precision of Geant4

miniBETA spectrometer

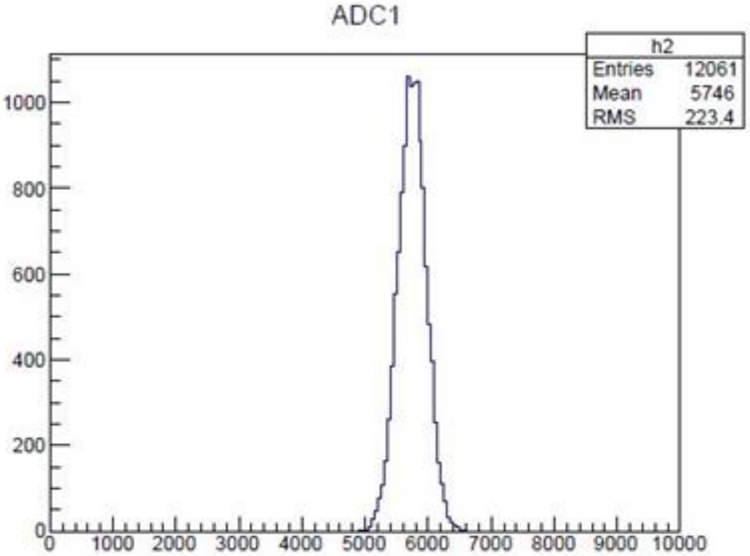


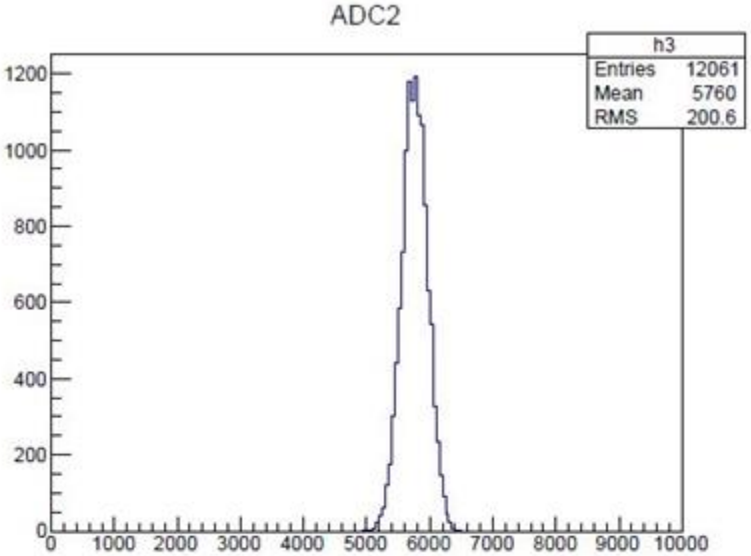
- 80 hexagonal cells
  (10 planes with 8 signal wires
  [$\phi = 25\mu\mathrm{m}$, NiCr 8020])
- X-Y space resolution 0.5mm
- Z position from charge division
- energy resolution <10keV.

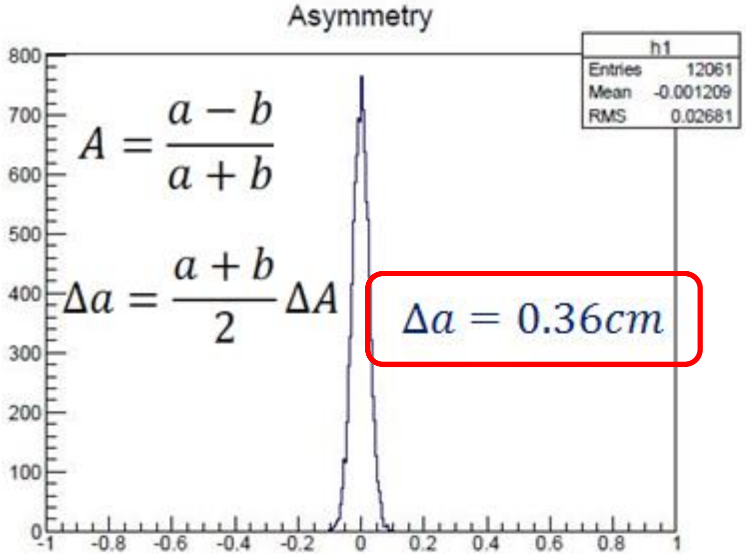


commissioning ongoing

Test of the electronics



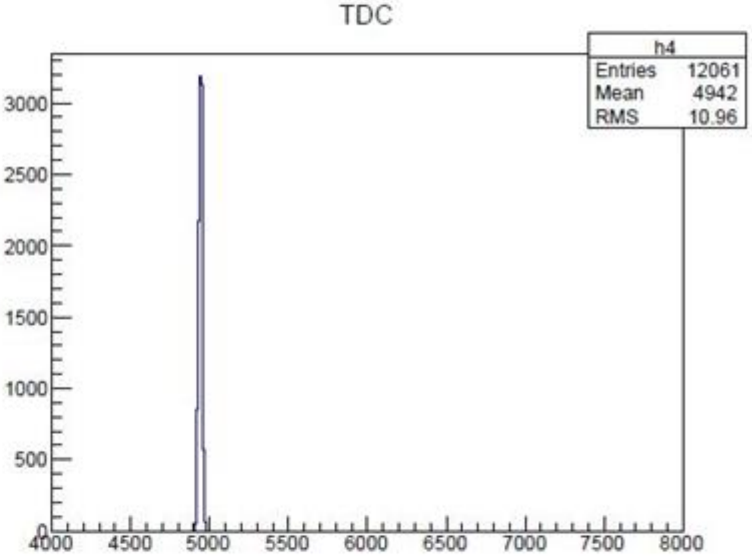




$$A = \frac{a-b}{a+b}$$

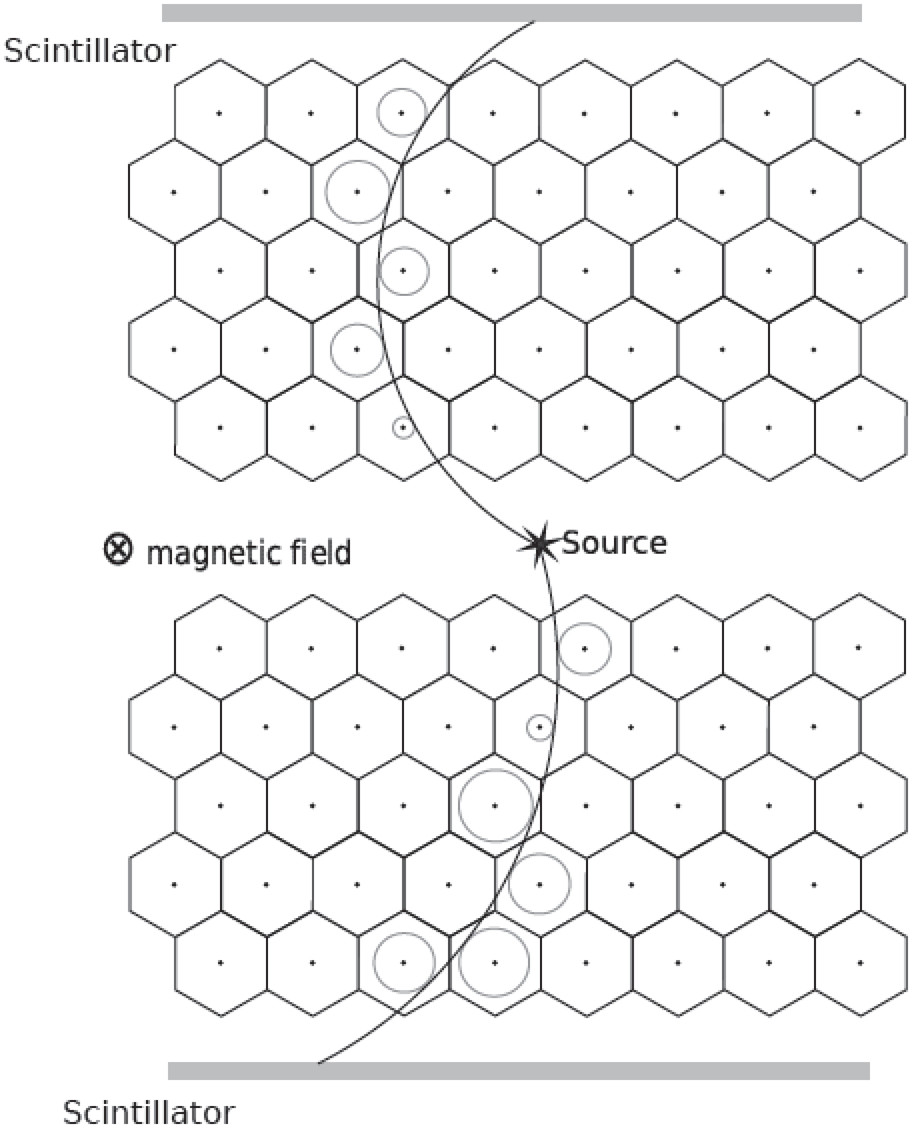
$$\Delta a = \frac{a+b}{2}\Delta A$$

$$\Delta a = 0.36cm$$



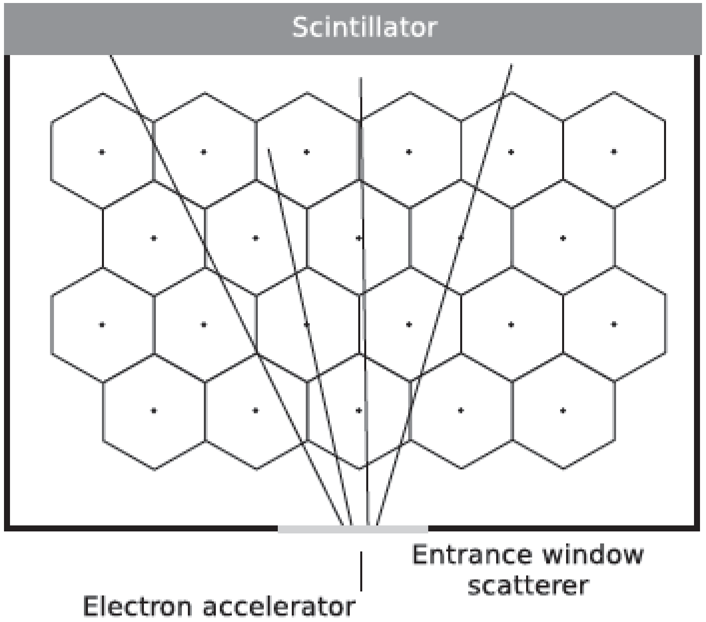
β spectrum shape measurements with the **miniBETA spectrometer**

principle:



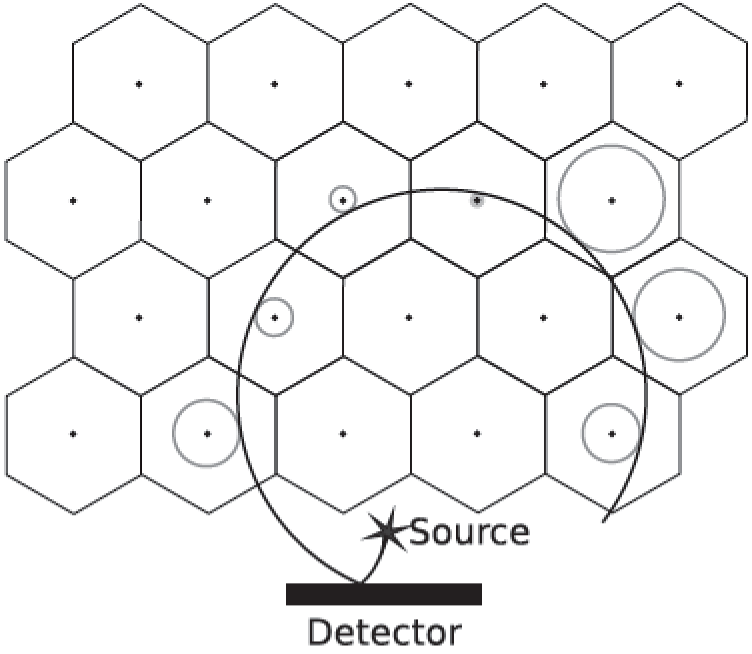
electron scattering / transmission studies with miniBETA

transmission



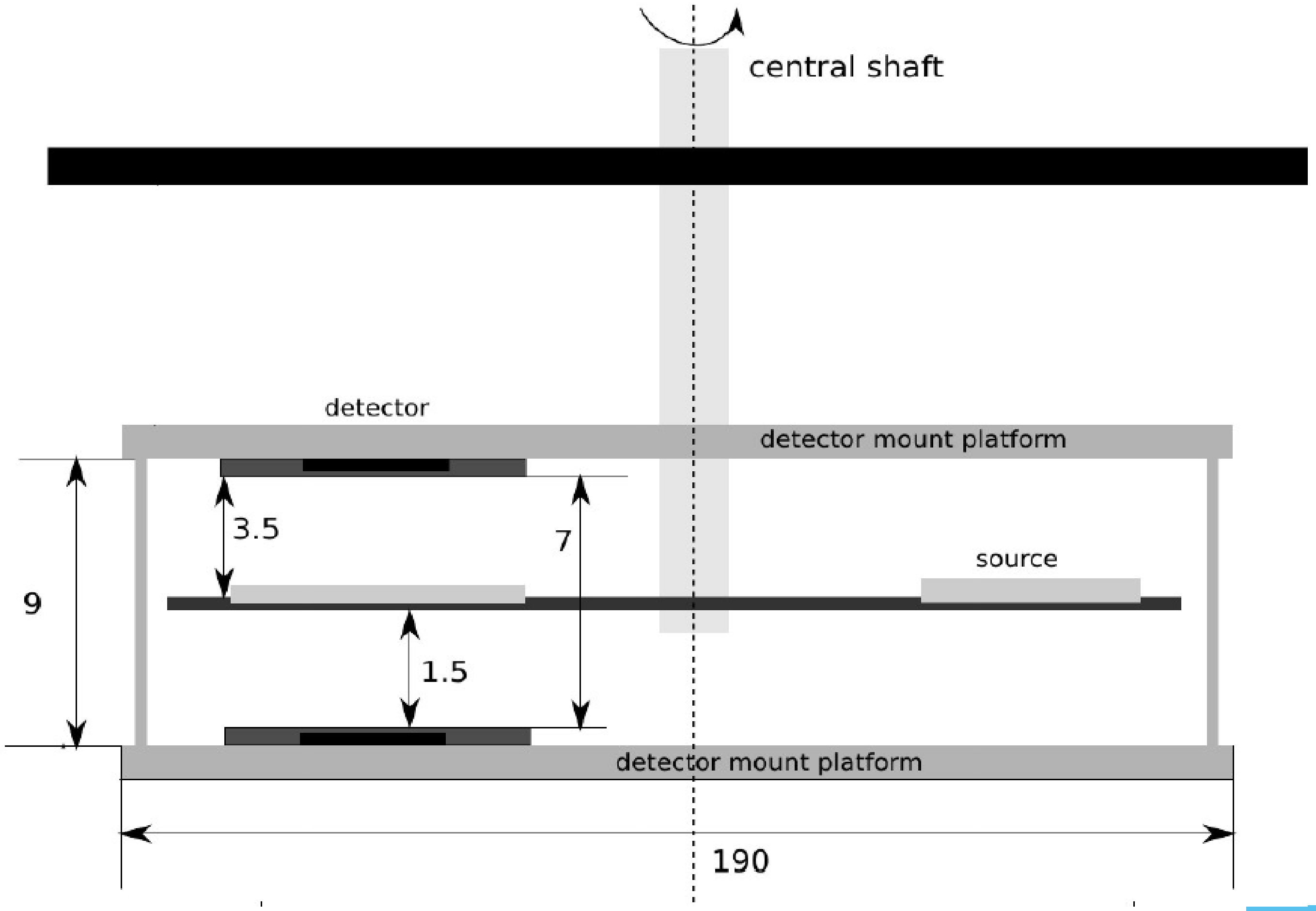
- measure the angular distribution of electrons after transmission through thin foils
- provide high precision data for the Geant4 collaboration to tune the electron multiple scattering models
- conversion electrons or electron accelerator

scattering

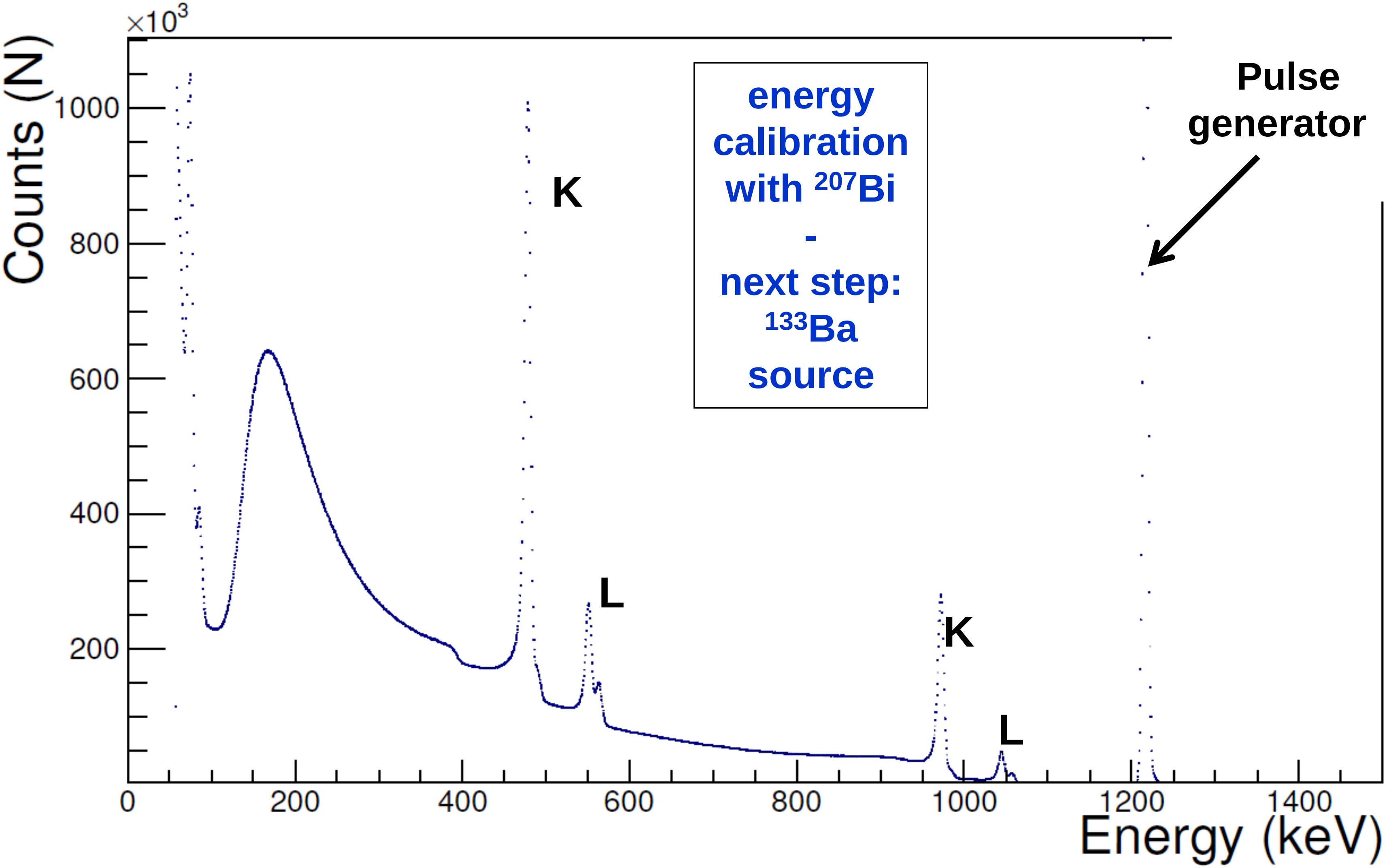


- initial electron energy from detector + track curvature
- conversion electrons for high precision measurement of the backscattering probability

Experimental setup



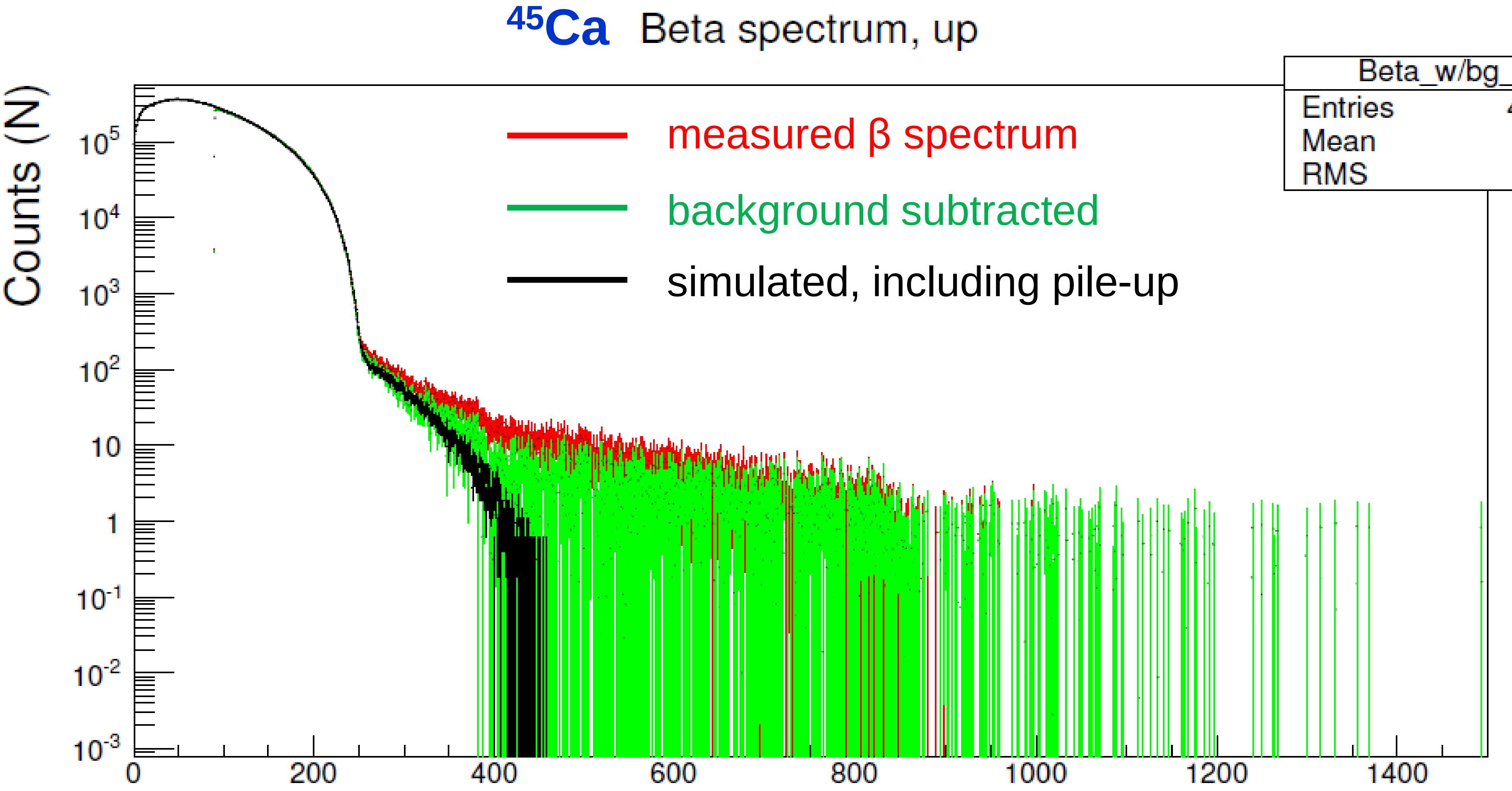
β spectrum shape measurements with Si detectors spectrometer



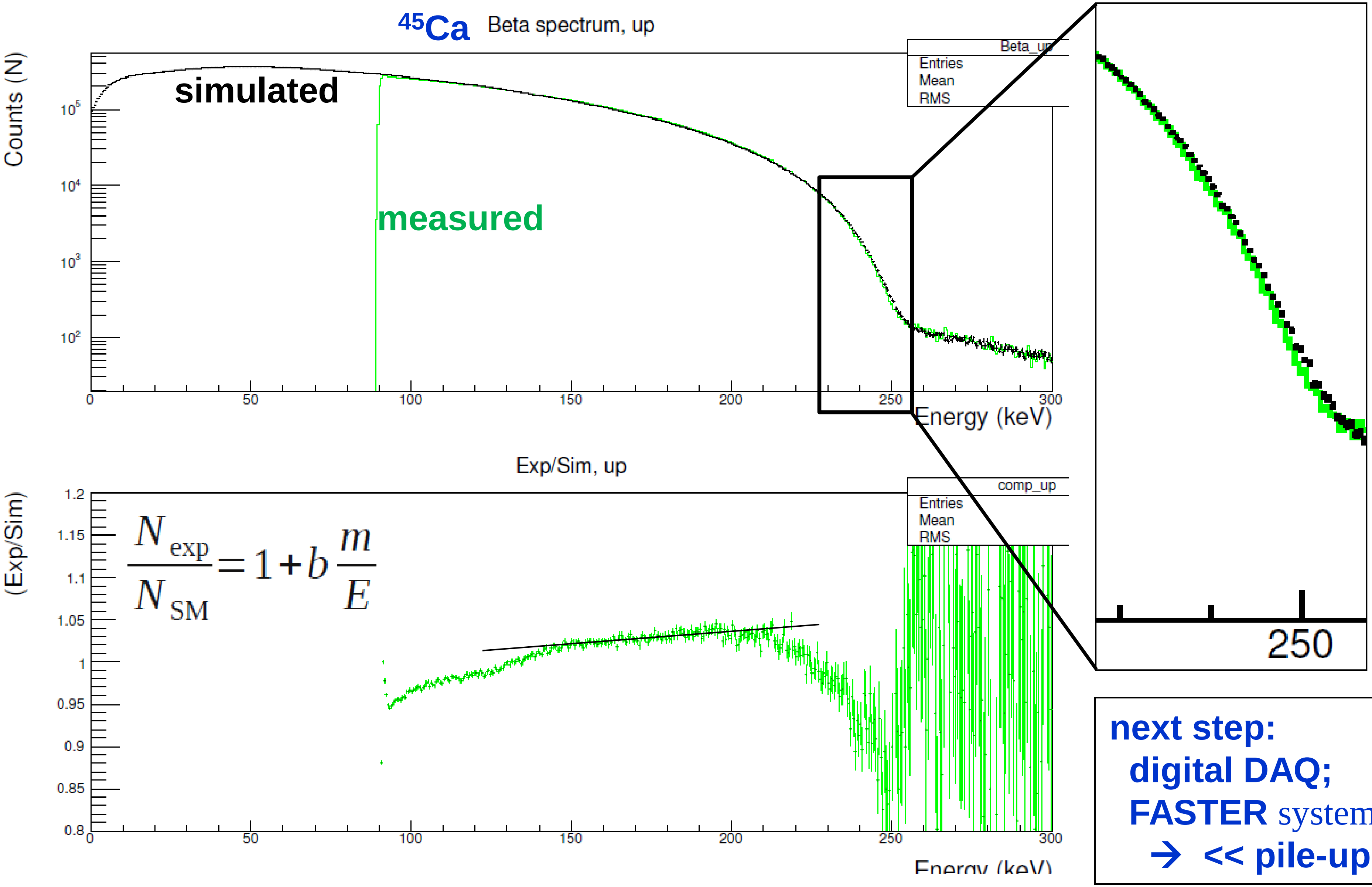
energy calibration with ^{207}Bi
-
next step: ^{133}Ba source

Pulse generator

β spectrum shape measurements with Si detectors spectrometer



β spectrum shape measurements with Si detectors spectrometer

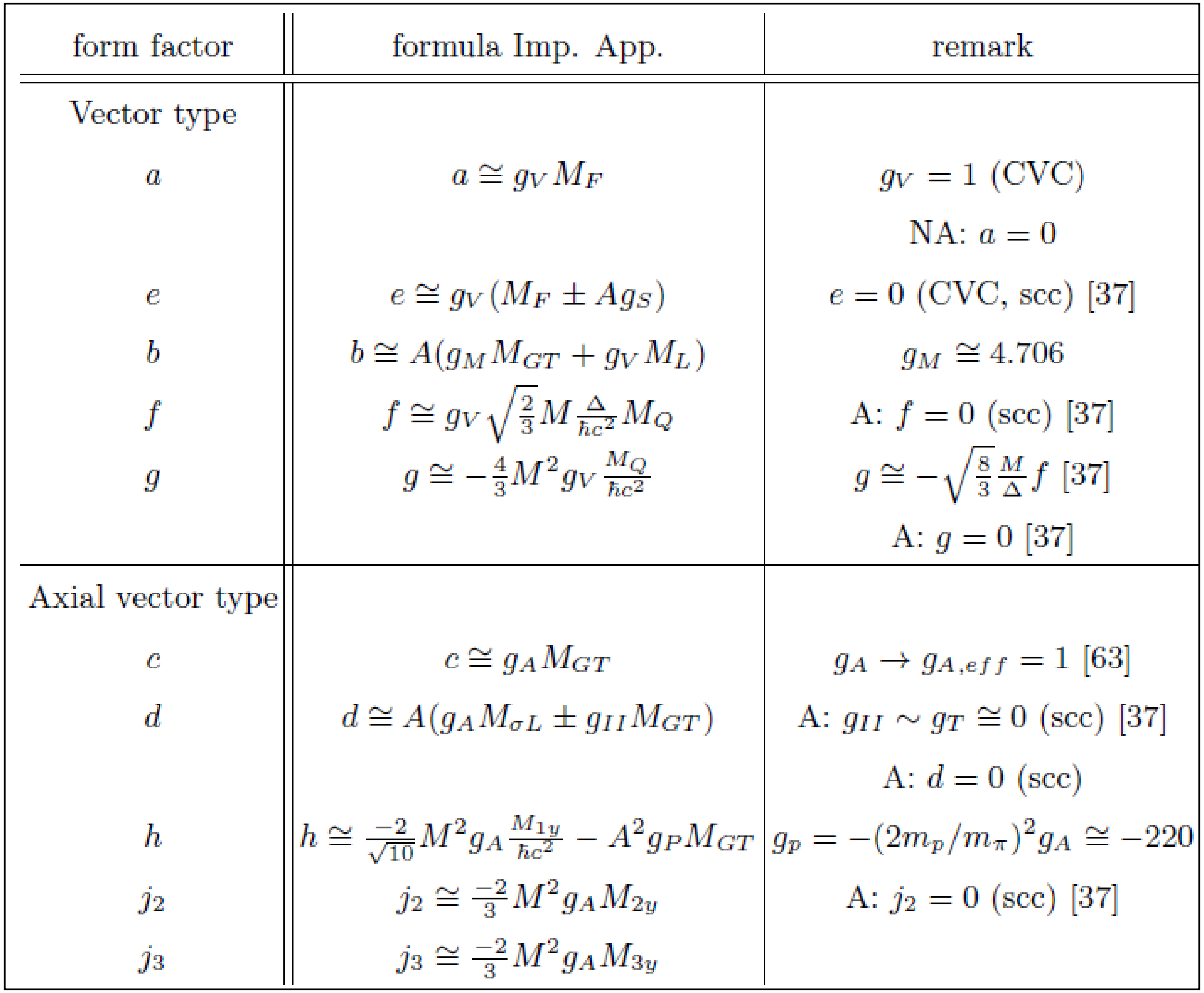


$$\frac{N_{\mathrm{exp}}}{N_{\mathrm{SM}}} = 1 + b\,\frac{m}{E}$$

next step:
digital DAQ;
FASTER system
→ **<< pile-up**

induced / recoil terms

nuclear β decay:



form factor	formula Imp. App.	remark
Vector type		
a	$a \cong g_V M_F$	$g_V = 1$ (CVC)
		NA: $a = 0$
e	$e \cong g_V (M_F \pm A g_S)$	$e = 0$ (CVC, scc) [37]
b	$b \cong A(g_M M_{GT} + g_V M_L)$	$g_M \cong 4.706$
f	$f \cong g_V \sqrt{\frac{2}{3}} M \frac{\Delta}{\hbar c^2} M_Q$	A: $f = 0$ (scc) [37]
g	$g \cong -\frac{4}{3} M^2 g_V \frac{M_Q}{\hbar c^2}$	$g \cong -\sqrt{\frac{8}{3}} \frac{M}{\Delta} f$ [37]
		A: $g = 0$ [37]
Axial vector type		
c	$c \cong g_A M_{GT}$	$g_A \rightarrow g_{A,eff} = 1$ [63]
d	$d \cong A(g_A M_{\sigma L} \pm g_{II} M_{GT})$	A: $g_{II} \sim g_T \cong 0$ (scc) [37]
		A: $d = 0$ (scc)
h	$h \cong \frac{-2}{\sqrt{10}} M^2 g_A \frac{M_{1y}}{\hbar c^2} - A^2 g_P M_{GT}$	$g_p = -(2m_p/m_\pi)^2 g_A \cong -220$
j_2	$j_2 \cong \frac{-2}{3} M^2 g_A M_{2y}$	A: $j_2 = 0$ (scc) [37]
j_3	$j_3 \cong \frac{-2}{3} M^2 g_A M_{3y}$	

for a pure GT transition,

and neglecting terms ∝ $1/M^2$ and ∝ m_e^2/E :

$$H_0(E) = c^2 - \frac{2}{3}\frac{E_0}{M}c(c+d\pm b) + \frac{2}{3}\frac{E}{M}c(5c\pm 2b)$$

→ $H_0(E) = f_1 + f_2 E$

→ $S(E) \equiv \dfrac{H_0(E)}{H_0(E=0)}$

$$\boxed{S(E) \approx 1 + \frac{2}{3M}\left(5 \pm 2\frac{b}{c}\right)E_e}$$

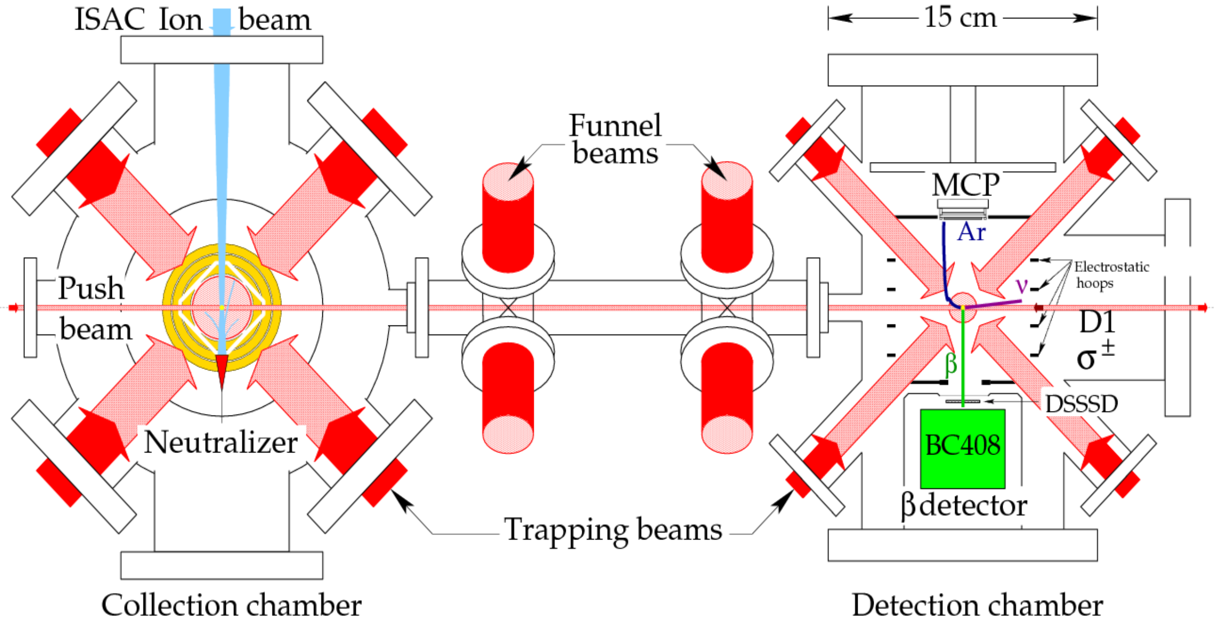
TRINAT MOT trap at TRIUMF-ISAC – ^{38m}K - scalar

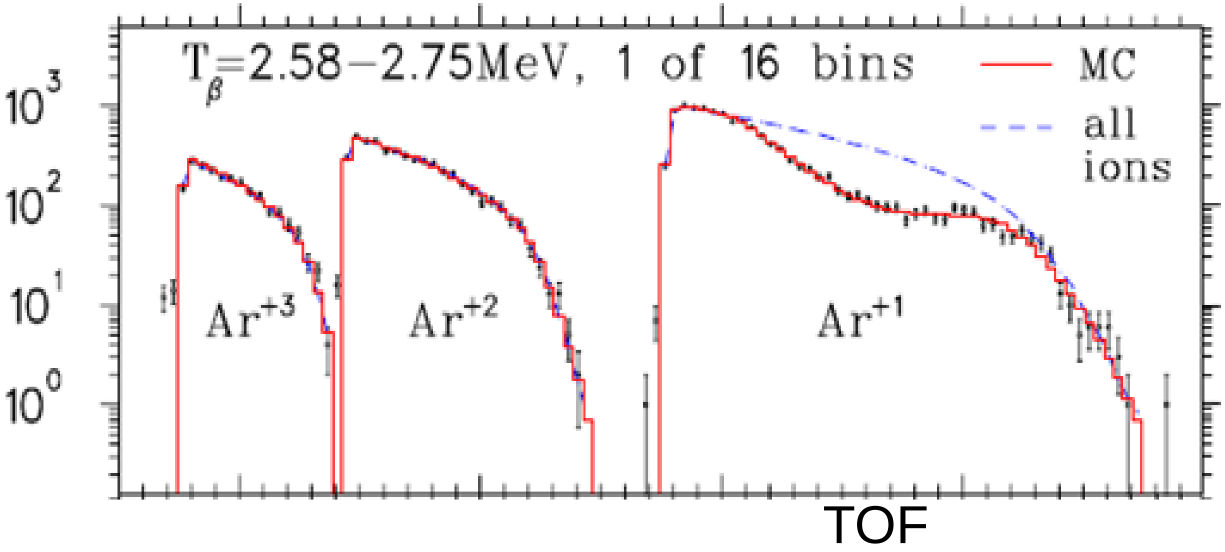
search for scalar couplings

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

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

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





$$\tilde{a} = \frac{a}{1+\frac{\gamma m_e}{E_e} b} = 0.9981(30)(35)$$

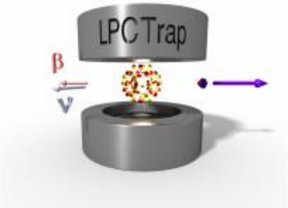
$$\Rightarrow \quad \frac{|C_S|^2 + |C_S'|^2}{|C_V|^2} \leq 0.097$$

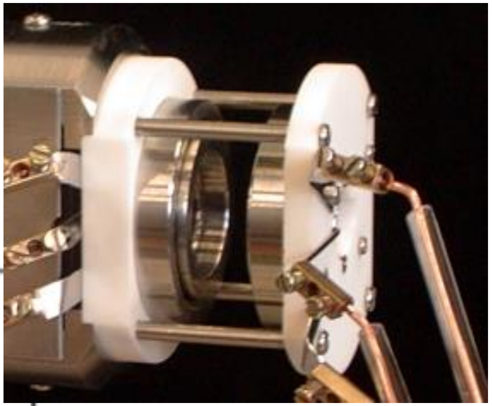
(90% C.L.)

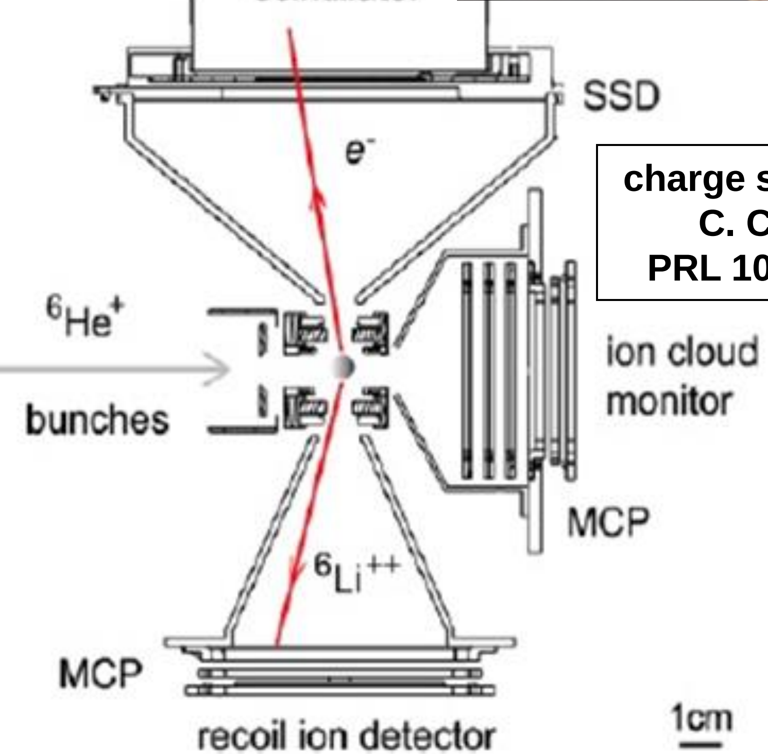
LPCTrap @ GANIL - ^{6}He / ^{35}Ar - tensor / scalar

2006 (^{6}He): $a_{\beta\nu} = -0.3335(73)_{stat}(75)_{syst}$

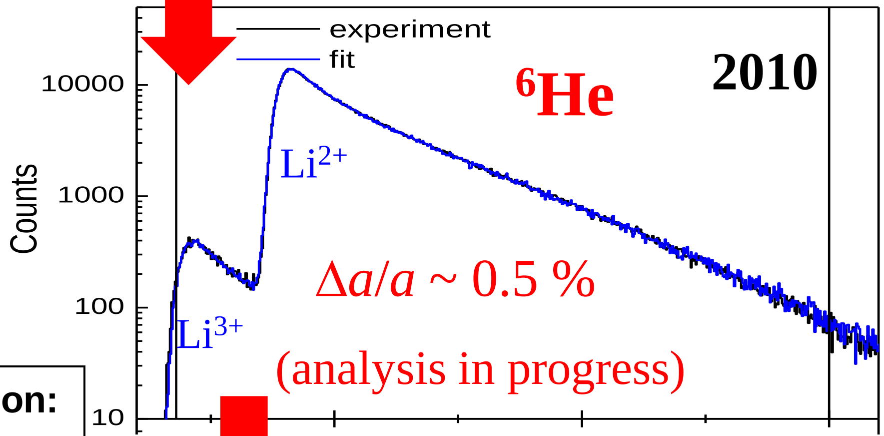
X. Fléchard et al., J. Phys. G 38 (2011) 055101





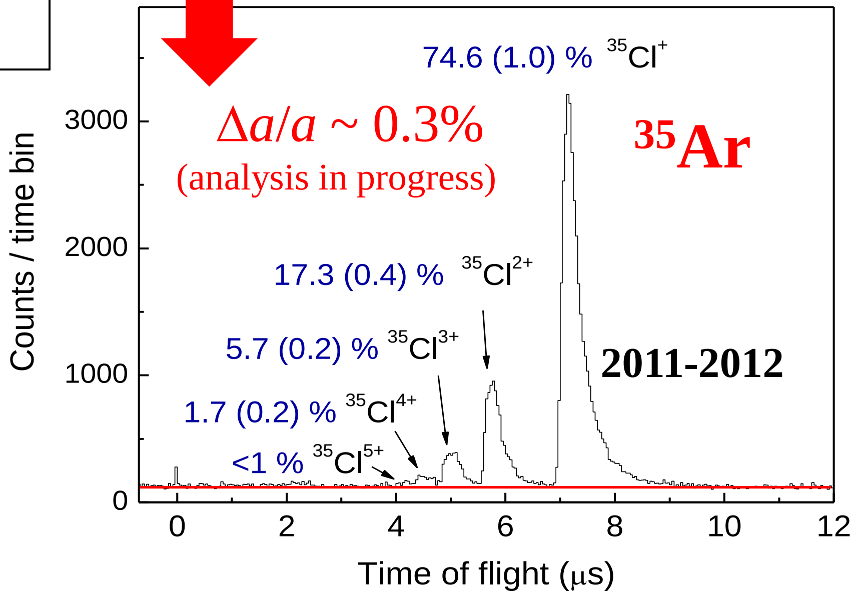


charge state distribution:
C. Couratin et al.
PRL 108 (2012) 243201



$\Delta a/a \sim 0.5$ %

(analysis in progress)



$\Delta a/a \sim 0.3$%

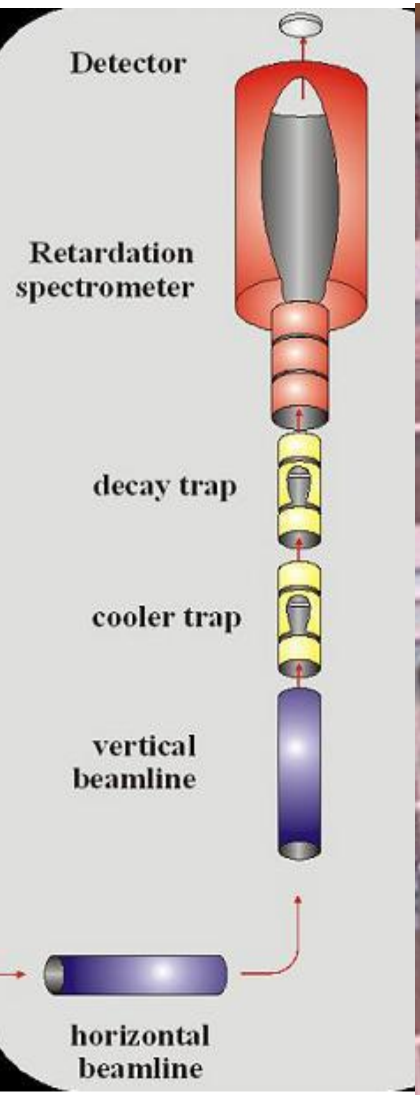
(analysis in progress)

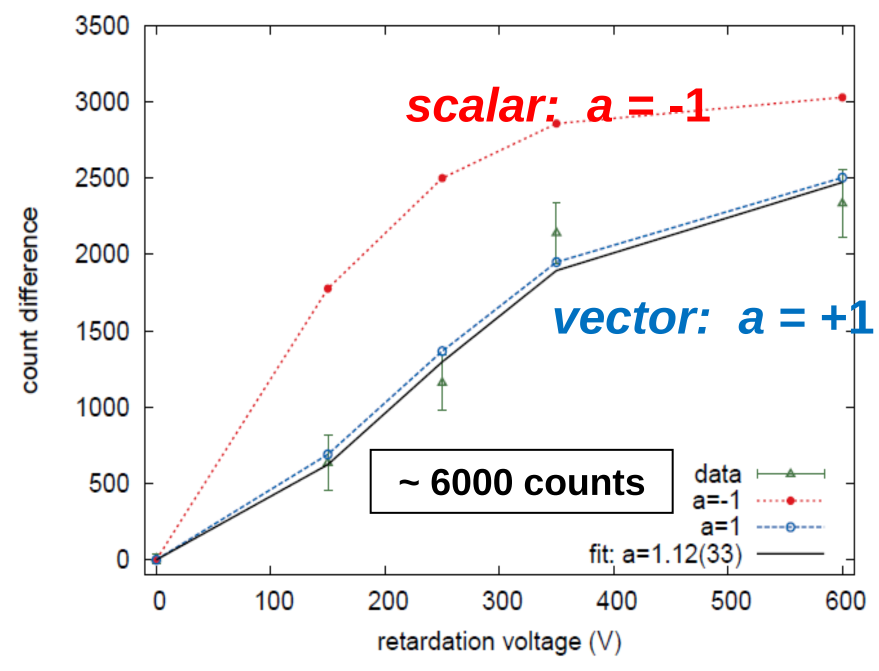
WITCH @ ISOLDE - ^{35}Ar - scalar

(KU Leuven, Univ. Munster, ISOLDE, NPI Rez-Prague, LPC-Caen)

Goal : determine βν correlation for ^{35}Ar with $(\Delta a/a)_{stat} \leq 0.5$ %

→ measure energy spectrum of recoiling ions with a retardation spectrometer




scalar: a = -1

vector: a = +1

~ 6000 counts

M. Beck et al., Eur. Phys. J. A47 (2011) 45

M. Tandecki et al., NIM A629 (2011) 396

S. Van Gorp et al., NIM A638 (2011) 192

induced / recoil terms

$$V_\mu(q^2) = \bar{p}[g_V(q^2)\gamma_\mu + \overset{\text{weak magnetism}}{\boxed{g_M(q^2)\sigma_{\mu\nu}\frac{q_\nu}{2M}}} + ig_S(q^2)\frac{q_\mu}{m_e}]n$$

$$A_\mu(q^2) = \bar{p}[g_A(q^2)\gamma_\mu\gamma_5 + g_T(q^2)\sigma_{\mu\nu}\gamma_5\frac{q_\nu}{2M} + ig_P(q^2)\frac{q_\mu}{m_e}\gamma_5]n$$

induced / recoil terms

nuclear β decay:

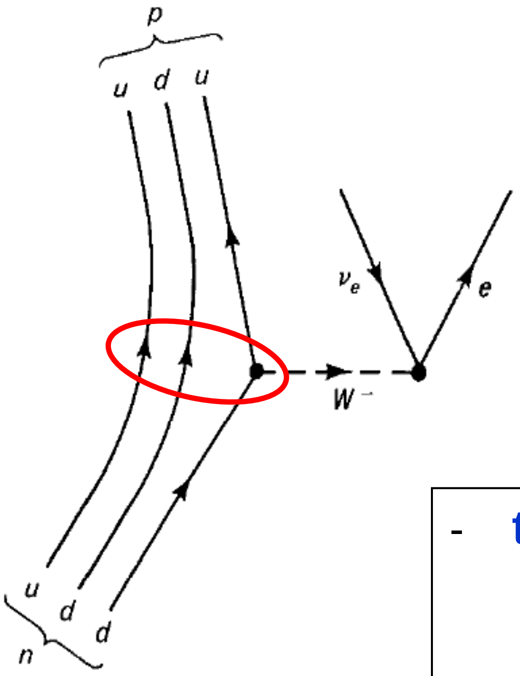
form factor	formula Imp. App.
Vector type	
a	$a \cong g_V M_F$
e	$e \cong g_V (M_F \pm A g_S)$
b	$b \cong A(g_M M_{GT} + g_V M_L)$
f	$f \cong g_V \sqrt{\frac{2}{3}} M \frac{\Delta}{\hbar c^2} M_Q$
g	$g \cong -\frac{4}{3} M^2 g_V \frac{M_Q}{\hbar c^2}$
Axial vector type	
c	$c \cong g_A M_{GT}$
d	$d \cong A(g_A M_{\sigma L} \pm g_{II} M_{GT})$
h	$h \cong \frac{-2}{\sqrt{10}} M^2 g_A \frac{M_{1y}}{\hbar c^2} - A^2 g_P M_{GT}$
j_2	$j_2 \cong \frac{-2}{3} M^2 g_A M_{2y}$
j_3	$j_3 \cong \frac{-2}{3} M^2 g_A M_{3y}$

Matrix element	Operator form
M_F	$\langle \beta \| \Sigma \tau_i^{\pm} \| \alpha \rangle$
M_{GT}	$\langle \beta \| \Sigma \tau_i^{\pm} \vec{\sigma}_i \| \alpha \rangle$
M_L	$\langle \beta \| \Sigma \tau_i^{\pm} \vec{l}_i \| \alpha \rangle$
$M_{\sigma r^2}$	$\langle \beta \| \Sigma \tau_i^{\pm} \vec{\sigma}_i r_i^2 \| \alpha \rangle$
$M_{\sigma L}$	$\langle \beta \| \Sigma \tau_i^{\pm} i \vec{\sigma}_i \times \vec{l}_i \| \alpha \rangle$
M_Q	$\left(\frac{4\pi}{5}\right)^{\frac{1}{2}} \langle \beta \| \Sigma \tau_i^{\pm} r_i^2 Y_2(\hat{r}_i) \| \alpha \rangle$
M_{ky}	$\left(\frac{16\pi}{5}\right)^{\frac{1}{2}} \langle \beta \| \Sigma \tau_i^{\pm} \sigma_i^2 C_{12k}^{nn'k} \sigma_{in} Y_2^{n'}(\hat{r}_i) \| \alpha \rangle$

B. R. Holstein, Rev. Mod. Phys. 46 (1974) 789

F.P. Calaprice et al., Phys. Rev. C 15 (1977) 2178

induced / recoil terms



due to **strong interaction**;
decaying **quark** is not free but **bound in a nucleon**

- effects of **few per mille** typically
- dominant = ‘**weak magnetism**’

- **theoretical study**:

  induced terms for mirror decays and
  T = 1 triplet decays, up to A = 45:

  (V. De Leebeeck, I.S. Towner, N.S., to be published)

- **experimental study**:

  new spectrometer for β spectrum shape
  measurements (MWDC + E-detectors)

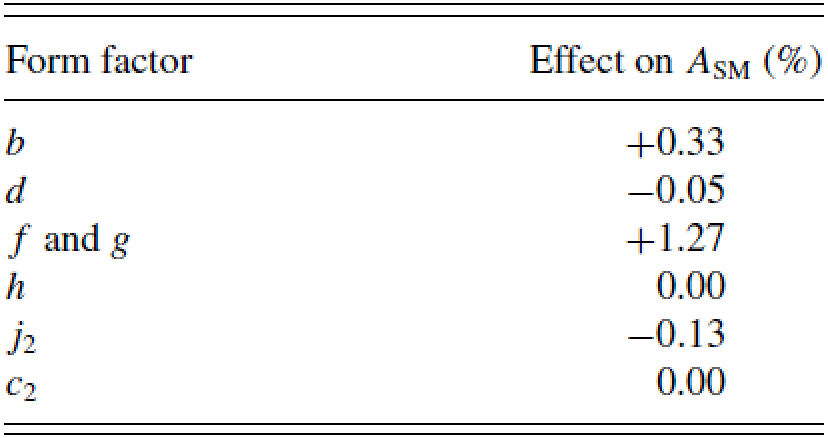
  Leuven-Krakow collaboration

effect on e.g. ^{60}Co asymmetry parameter (log *ft* = 7.5)

F. Wauters et al., Phys. Rev. C 82 (2010) 055502

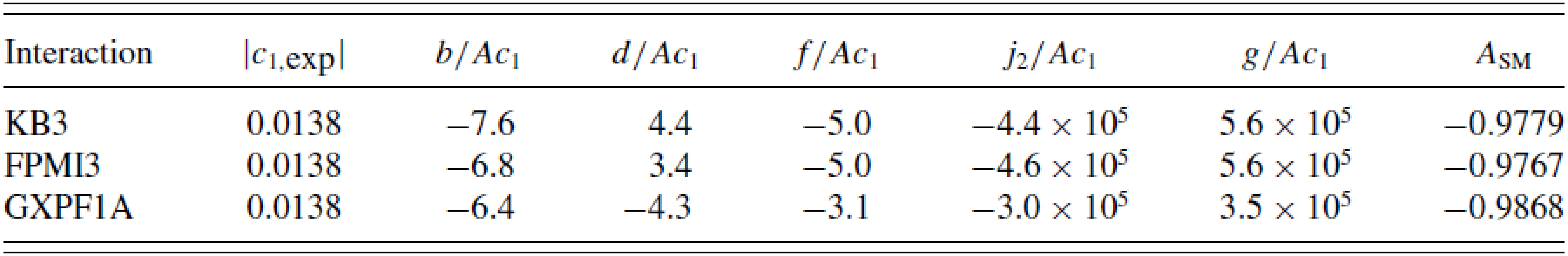
β asymmetry parameter:

$$A^{\beta\mp}_{SM,GT} = \mp\frac{\gamma_{JJ'}}{J+1}\Big[1 + \frac{1}{A}\Big[\frac{E+2m_e^2/E}{3M_n}\Big] \boxed{\mp\frac{b}{Ac_1}}\Big[\frac{\boxed{E}+2m_e^2/E}{3M_n}\Big] + \frac{d}{Ac_1}\Big[\frac{-E+m_e^2/E}{3M_n}\Big] \mp\frac{f}{Ac_1}\Big[\frac{\lambda_{JJ'}}{\gamma_{JJ'}}\frac{5E}{M_n}\Big]\Big] + \ldots$$



Form factor	Effect on A_{SM} (%)
b	+0.33
d	−0.05
f and g	+1.27
h	0.00
j_2	−0.13
c_2	0.00

A_{SM} (^{60}Co) = -0.987(9)

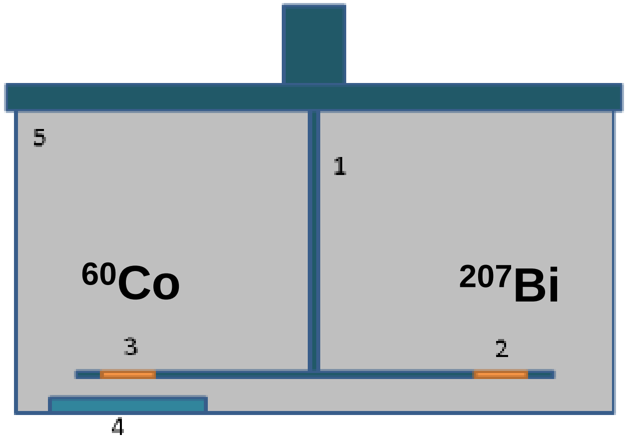


Interaction	$\lvert c_{1,\exp}\rvert$	b/Ac_1	d/Ac_1	f/Ac_1	j_2/Ac_1	g/Ac_1	A_{SM}
KB3	0.0138	−7.6	4.4	−5.0	-4.4×10^5	5.6×10^5	−0.9779
FPMI3	0.0138	−6.8	3.4	−5.0	-4.6×10^5	5.6×10^5	−0.9767
GXPF1A	0.0138	−6.4	−4.3	−3.1	-3.0×10^5	3.5×10^5	−0.9868

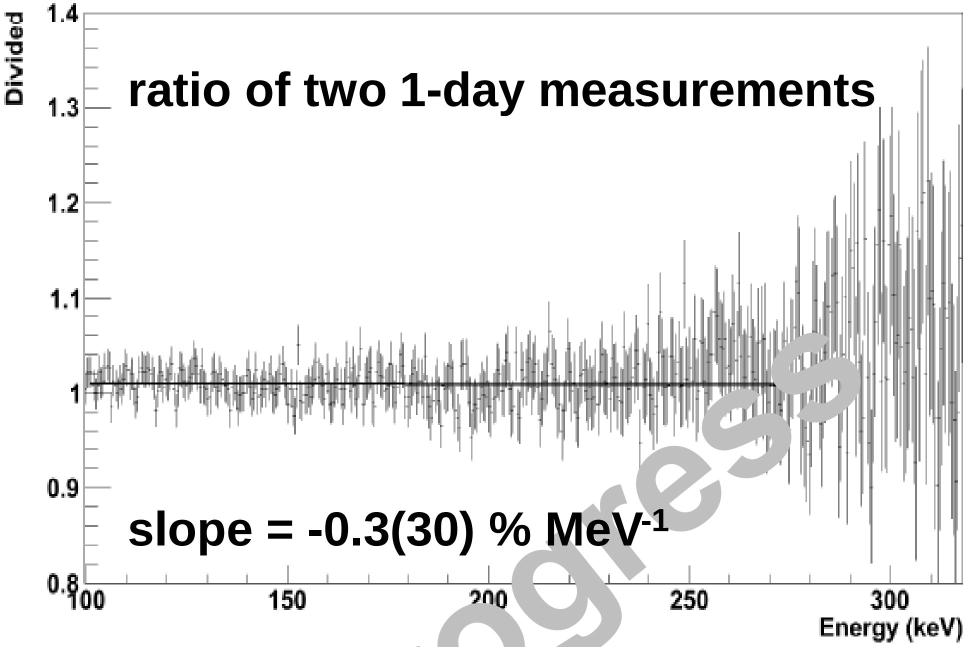
with experimental precisions ~ 0.5 to 1%

→ precision has reached the level where the induced terms have to be included and quite well known, to further gain sensitivity to new physics

β spectrum shape measurements with a Si detector

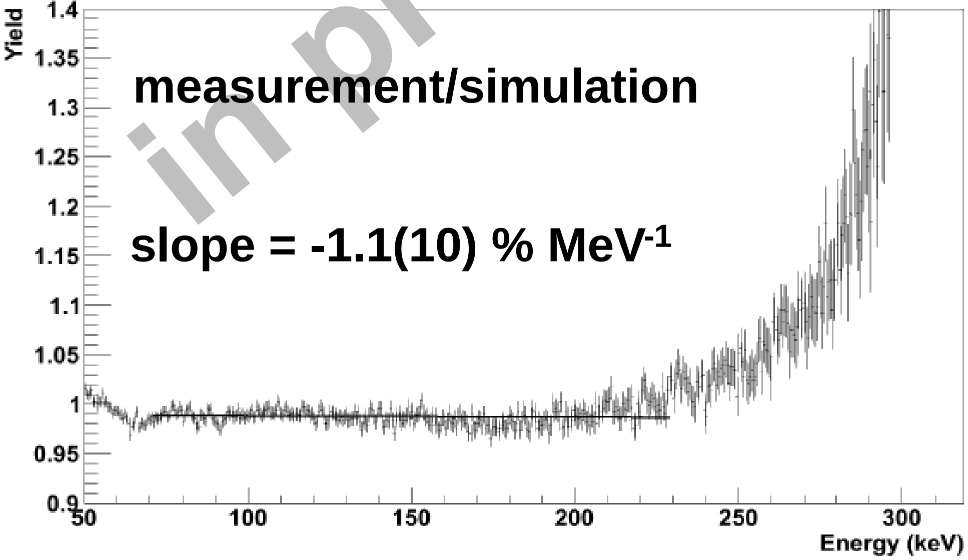


Si pin-diode
0.5 mm



ratio of two 1-day measurements

slope = -0.3(30) % MeV^{-1}



measurement/simulation

slope = -1.1(10) % MeV^{-1}