Beta decay probing weak interaction properties

Part 3

TU Darmstadt, Sept. 3-5, 2018

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Outline- 1

1. Introduction / 2 lectures

- role of beta decay in weak interaction physics
- beta decay Hamiltonian
- beta decay angular distribution

2. ft-values / 3 lectures

- definition
- corrected ft-values
- test of CKM matrix unitarity
- role of mirror beta transitions and neutron decay

3. Correlation measurements / 5 lectures

- correlation formula
- physics content and opportunities
- testing parity violation
- searching for time reversal violation
- probing the structure of the weak interaction (scalar and tensor currents)

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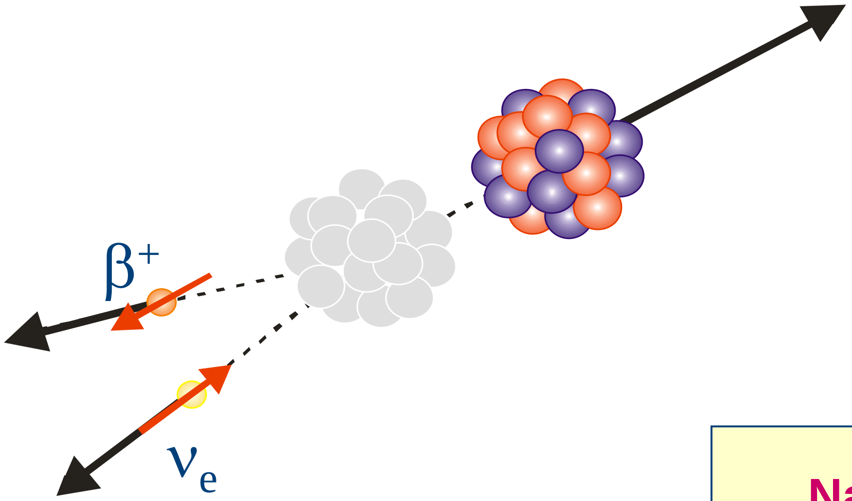
3. Correlation measurements in nuclear and neutron β decay



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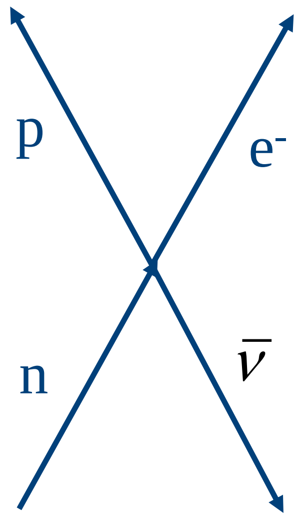
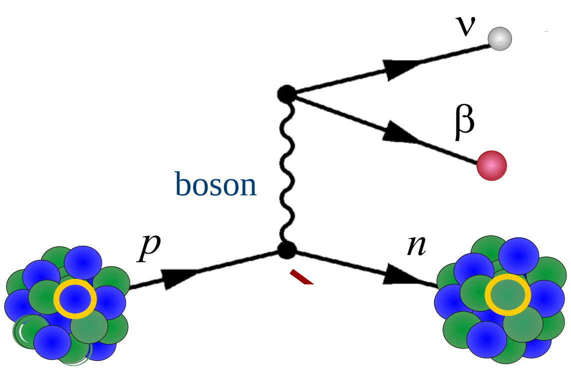
Structure of the weak interaction in β decay

β-decay Hamiltonian (Lee & Yang, 1956) :



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



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 $\mathrm{Im}(C_i^{(')} / C_j) \neq 0$

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Structure of the weak interaction in β decay

the Standard Model:

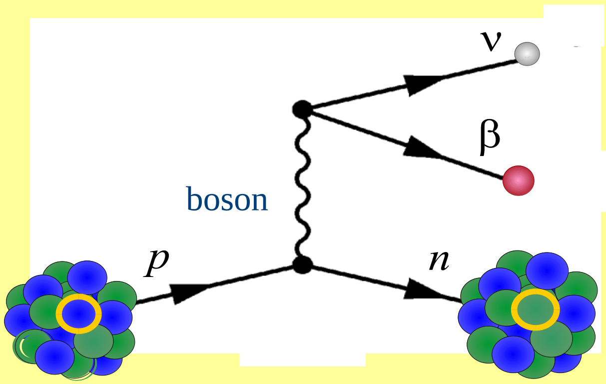
$C_i^{(')}$: coupling constants for the different types of weak interaction

* V-A interaction	$C_V \equiv 1$; $C_A = -1.27$ (C_A/C_V from n-decay)
* maximal P violation	$C_V' = C_V$ & $C_A' = C_A$
* no S, T, or P components	$C_S = C_S' = C_T = C_T' = C_P = C_P' \equiv 0$
* no time reversal violation	all C's are real

(except for the CP-violation included in the CKM matrix)

and Beyond:

experimental upper limits for $\left|C_T^{(')}/C_A\right|$ and $\left|C_S^{(')}/C_V\right|$ at few % level
(neutron and nuclear β-decay)



5% level → ~ 350 GeV
per mille level → ~ 2.5 TeV

$$C_i \propto \frac{M_W^2}{M_{new}^2}$$

Beta decay transition probability :

distribution in energy, emission angle and polarization of β-particles for allowed β-decay of polarized nuclei

$$d\Gamma = d\Gamma_0 \, \xi \left\{ 1 + \frac{\bar{p}\cdot\bar{q}}{E_e E_\nu} a + \frac{\Gamma m}{E_e} b \right.$$

βν-correlation — Fierz interference term

$$+ \bar{J}\cdot\left[\frac{\bar{p}}{E_e} A + \frac{\bar{q}}{E_\nu} B + \frac{\bar{p} \times \bar{q}}{E_e E_\nu} D \right]$$

β-asymmetry — ν-asymmetry

$$\left. + \bar{\sigma}\cdot\left[\frac{\bar{p}}{E_e} G + \hat{p}(\bar{J}\cdot\hat{p})Q' + \bar{J} \times \frac{\bar{p}}{E_e} R \right] \ldots \right\}$$

longitudinal polarization — transversal polarization

- $\vec{p}_e$ electron momentum
- $\vec{q}$ neutrino momentum
- E_e, E_ν electron/neutrino energy
- $\frac{\vec{J}}{J}$ nuclear spin polarization
- $\gamma = \sqrt{(1-(\alpha Z)^2}$
- m_e electron rest mass

(Z of daughter nucleus)

with $d\Gamma_0 \propto G_F^2 \, \underbrace{F(\pm Z, E_e)}_{\text{Fermi function}} \, \underbrace{(E_e - E_0)^2 \, p \, E_e \, dE \, d\Omega_e \, d\Omega_\nu}_{\text{phase space}}$

Fermi function — phase space

J.D. Jackson, S.B. Treiman, H.W. Wyld, Nucl. Phys. 4 (1957) 206 & Phys. Rev. 106 (1957) 517

$$\xi = M_F^2\left[|C_V|^2 + |C'_V|^2 + |C_S|^2 + |C'_S|^2\right] + M_{GT}^2\left[|C_A|^2 + |C'_A|^2 + |C_T|^2 + |C'_T|^2\right]$$

assuming time-reversal invariance (all C_i real)

$$a\,\xi = M_F^2\left[|C_V|^2 + |C'_V|^2 - |C_S|^2 - |C'_S|^2\right] - \frac{M_{GT}^2}{3}\left[|C_A|^2 + |C'_A|^2 - |C_T|^2 - |C'_T|^2\right]$$

$$b\,\xi = \pm 2\,\mathrm{Re}\left[M_F^2\left(C_S C_V^* + C'_S C'^*_V\right) + M_{GT}^2\left(C_T C_A^* + C'_T C'^*_A\right)\right]$$

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

$$A\,\xi = 2\,\mathrm{Re}\left[\mp\lambda_{J'J}\, M_{GT}^2\left(C_A C'^*_A - C_T C'^*_T\right) - \delta_{J'J}\sqrt{\frac{J}{J+1}}\, M_F M_{GT}\left(C_V C'^*_A + C'_V C_A^* - C_S C'^*_T - C'_S C_T^*\right)\right]$$

with: $M_{F(GT)}$ = Fermi(Gamow-Teller) nuclear matrix element,

C_i = coupling constants of the S, V, A, T weak interactions.

Note: - correlation coefficients (a, A, …) depend on physics ($C_i^{(')}$: coupling constants)

- 'kinematics' factors ($\frac{\vec{J}}{J}\cdot\frac{\vec{p}_e}{E_e}$, …) tell us how to organize the setup

Fierz interference term

$$b\,\frac{\gamma m_e}{E_e} \qquad (\gamma = \sqrt{1-(\alpha Z)^2})$$

- most experiments (because of the normalization) do not measure *X* = *a, A*, …

  but instead : $$\tilde{X} = \frac{X}{1 + b\,\frac{\gamma m_e}{E_e}}$$

- *b* depends <u>linearly</u> on the $C_i^{(')}$ coupling constants (instead of quadratically, as *a*)

- measurements of $\tilde{a},\ \tilde{A}, \ldots$ thus usually include also *b* *!!*

- sensitive to scalar and tensor weak currents via ($b = b_F + b_{GT}$):

$$b_F \cong Re\,\frac{C_S + C_S'}{C_V} \qquad b_{GT} \cong Re\,\frac{C_T + C_T'}{C_A}$$

<u>Note</u>: - b_F and b_{GT} are zero in the standard model

- for pure Fermi and Gamow-Teller transitions b_F and b_{GT} (and also *a, A,* …) do not depend on the nuclear matrix elements !!

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Fierz interference term

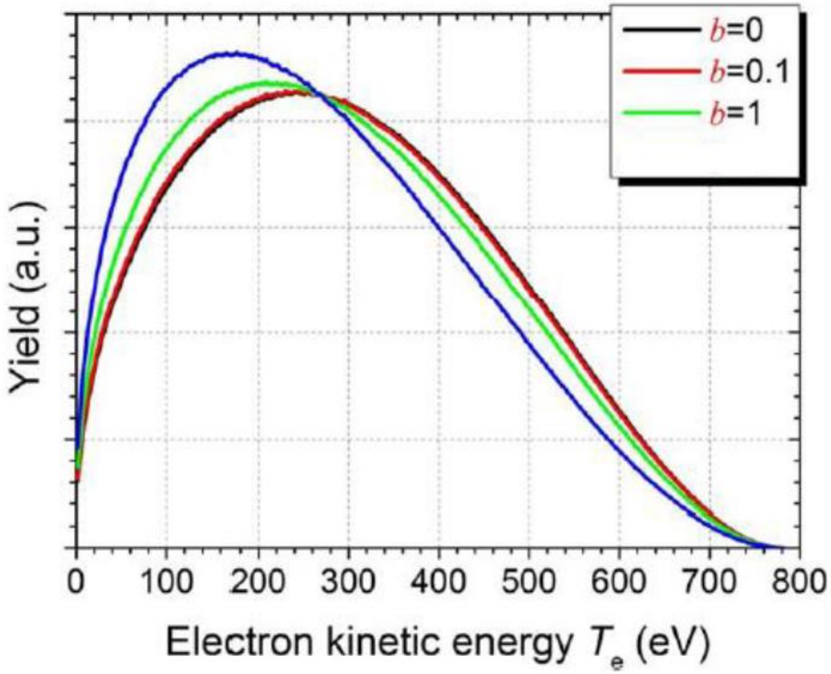
$$b \frac{\gamma m_e}{E_e}$$

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

- most experiments (because of the normalization) do not measure ***X* = *a*, *A*, …**

but instead : $$\tilde{X} = \frac{X}{1 + b \frac{\gamma m_e}{E_e}}$$

- **can also extract Fierz term *b* from beta spectrum shape, e.g. for neutron decay:**



recent result with UCNA:

$$b_n = 0.067(5)_{stat} \left(^{+90}_{-61}\right)_{syst}$$

with uncertainty dominated by absolute energy reconstruction and linearity of beta spectrometer energy response

K.P. Hickerson et al., Phys. Rev. C 96 (2017) 042501

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β-ν correlation / 1

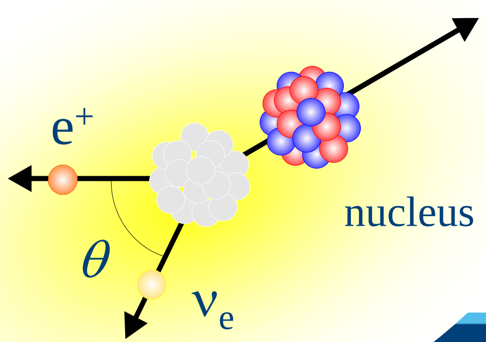
$$a\,\xi = M_F^2\left[|C_V|^2 + |C'_V|^2 - |C_S|^2 - |C'_S|^2\right] - \frac{M_{GT}^2}{3}\left[|C_A|^2 + |C'_A|^2 - |C_T|^2 - |C'_T|^2\right]$$

$$\xi = M_F^2\left[|C_V|^2 + |C'_V|^2 + |C_S|^2 + |C'_S|^2\right] + M_{GT}^2\left[|C_A|^2 + |C'_A|^2 + |C_T|^2 + |C'_T|^2\right]$$

$$a_F = \frac{a_F\,\xi_F}{\xi_F} = \frac{|C_V|^2 + |C'_V|^2 - |C_S|^2 - |C'_s|^2}{|C_V|^2 + |C'_V|^2 + |C_S|^2 + |C'_s|^2}$$

$$a_{GT} = \frac{a_{GT}\,\xi_{GT}}{\xi_{GT}} = -\frac{1}{3}\,\frac{|C_A|^2 + |C'_A|^2 - |C_T|^2 - |C'_T|^2}{|C_A|^2 + |C'_A|^2 + |C_T|^2 + |C'_T|^2}$$

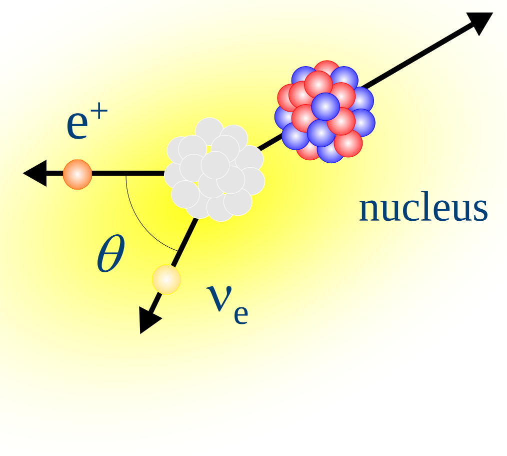
Interaction type	*a*
S	- 1
V	+ 1
T	+ 1/3
A	- 1/3



β-ν correlation / 2

$$a\,\frac{\vec{p}_e\cdot\vec{q}}{E_e E_\nu} \xrightarrow{\text{exp.}} \tilde{a} = \frac{a}{1 + b\,\dfrac{\gamma m_e}{E_e}}$$

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



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

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

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

Fierz term

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

!!! for pure transitions the results are independent of the nuclear matrix elements !!!

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

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

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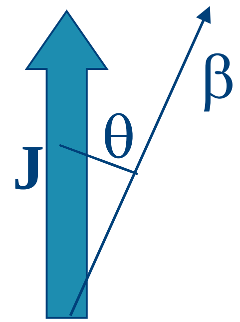
β-asymmetry parameter

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



$$\begin{aligned}
\tilde{A}^{\beta^{\mp}}_{\mathrm{GT}} &\equiv \frac{A}{1 \pm \frac{m}{E_e} b} \\
&\simeq A_{\mathrm{SM}} + \lambda \left[\frac{\alpha Z m}{p_e} \mathrm{Im}\left(\frac{C_T + C_T'}{C_A} \right) \right. \\
&\quad + \frac{\gamma m}{E_e} \mathrm{Re}\left(\frac{C_T + C_T'}{C_A} \right) \\
&\quad \left. \pm \mathrm{Re}\left(\frac{C_T C_T'^{*}}{C_A^2} \right) \pm \frac{|C_T|^2 + |C_T'|^2}{2 C_A^2} \right] \\
&\simeq A_{\mathrm{SM}} + \lambda \frac{\gamma m}{E_e} \mathrm{Re}\left(\frac{C_T + C_T'}{C_A} \right),
\end{aligned}$$

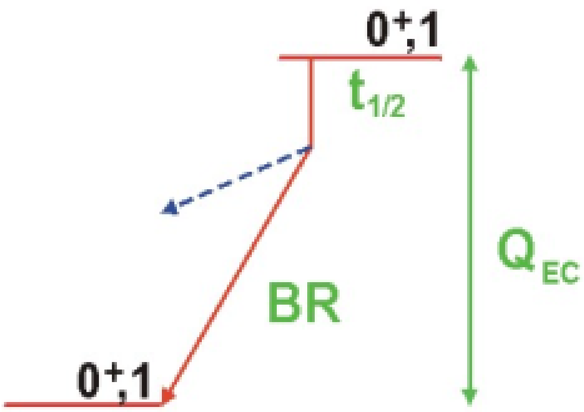
F. Wauters et al., Phys. Rev. C 82 (2010) 055502

Searching for charged scalar weak currents

ft value

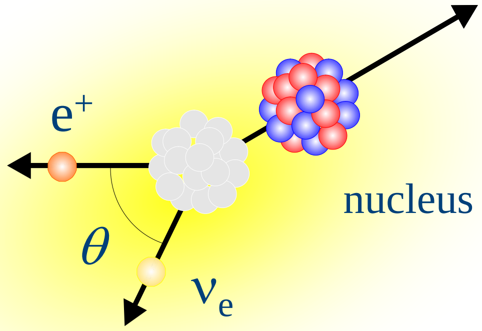
$$f_V t = \frac{K}{G_F^2 \, V_{ud}^2} \, \frac{1}{C_V^2 \, M_F^2 + C_A^2 \, M_{GT}^2}$$

with $t = t_{1/2} \left[\frac{1 + P_{EC}}{BR} \right]$



β-ν correlation

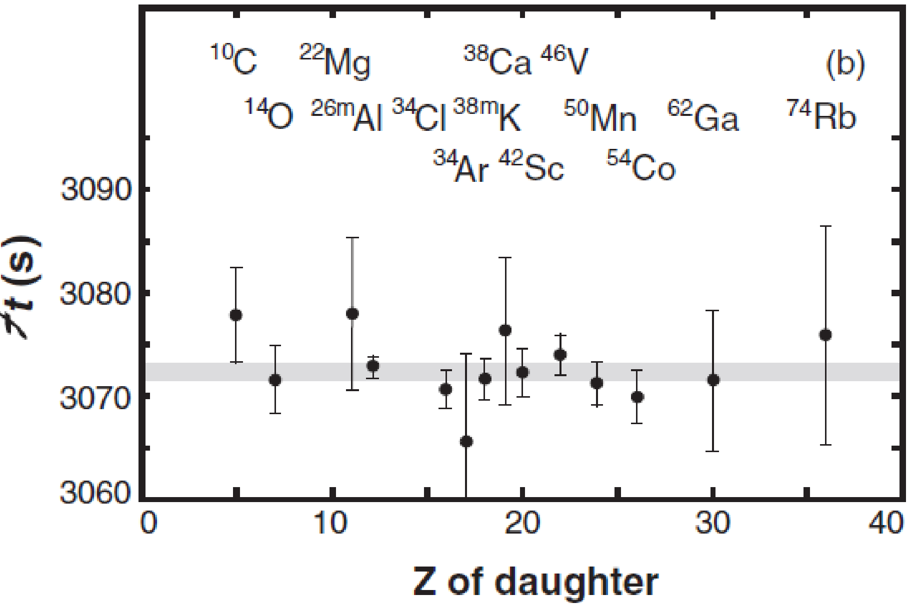
$$a \, \frac{\vec{p}_e \cdot \vec{q}}{E_e E_\nu}$$ and $$\tilde{a} = \frac{a}{1 + b \, \frac{\gamma m_e}{E_e}}$$



Ft-values of superallowed Fermi decays, and scalar currents

$$\mathcal{F}t^{0^+\to 0^+} \equiv f_V t^{0^+\to 0^+} \left(1+\delta_{NS}^V - \delta_C^V\right)\left(1+\delta_R'\right) = \frac{K}{2G_F^2\ V_{ud}^2\ C_V^2\ \left(1+\Delta_R^V\right)}$$

from experiment — **nucleus dependent corrections** — **nucleus independent**



$\mathcal{F}t^{0^+\to 0^+}$ **= 3072.27(72) s**

allowing for scalar currents

$$\mathcal{F}t^{0^+\to 0^+} = \frac{K}{2G_F^2 V_{ud}^2 C_V^2\left(1+\Delta_R^V\right)}\ \frac{1}{(1+b_F)}$$

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

JC Hardy & IS Towner , Phys. Rev. C 91 (2015) 025501

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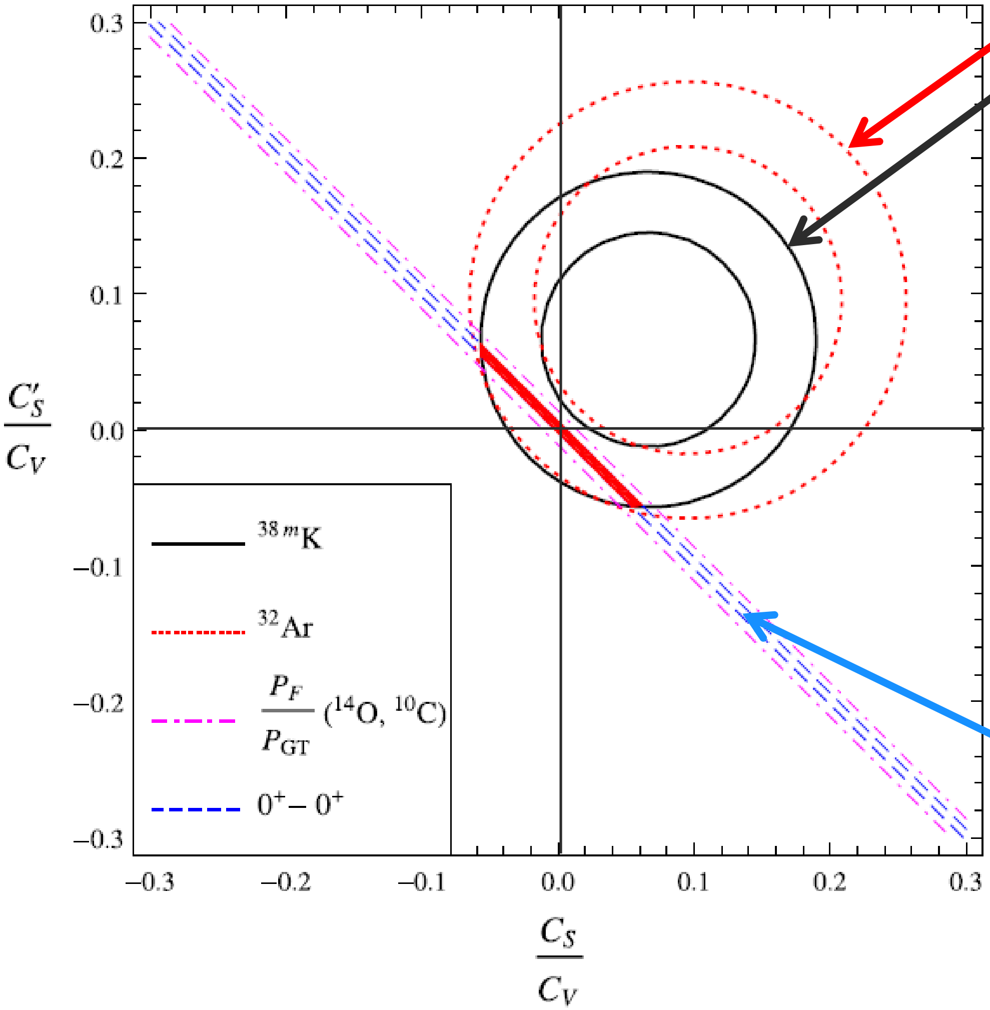
Limits on scalar currents



^{32}Ar: Adelberger et al., PRL 83 (1999) 1299

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

$$\tilde{a} = \frac{a}{1 + b\,\frac{\gamma m_e}{E_e}}$$

with:

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

$$b_F = \frac{\gamma m_e}{\langle E_e \rangle}\left(\frac{C_S + C'_S}{C_V}\right)$$

$$\mathcal{F}t^{0^+\to 0^+} = \frac{K}{2G_F^2 V_{ud}^2 C_V^2 \left(1+\Delta_R^V\right)}\,\frac{1}{(1+b_F)}$$

Hardy & Towner , Phys. Rev. C 91 (2015) 025501

B. R. Holstein, J. Phys. G 41 (2014) 114001

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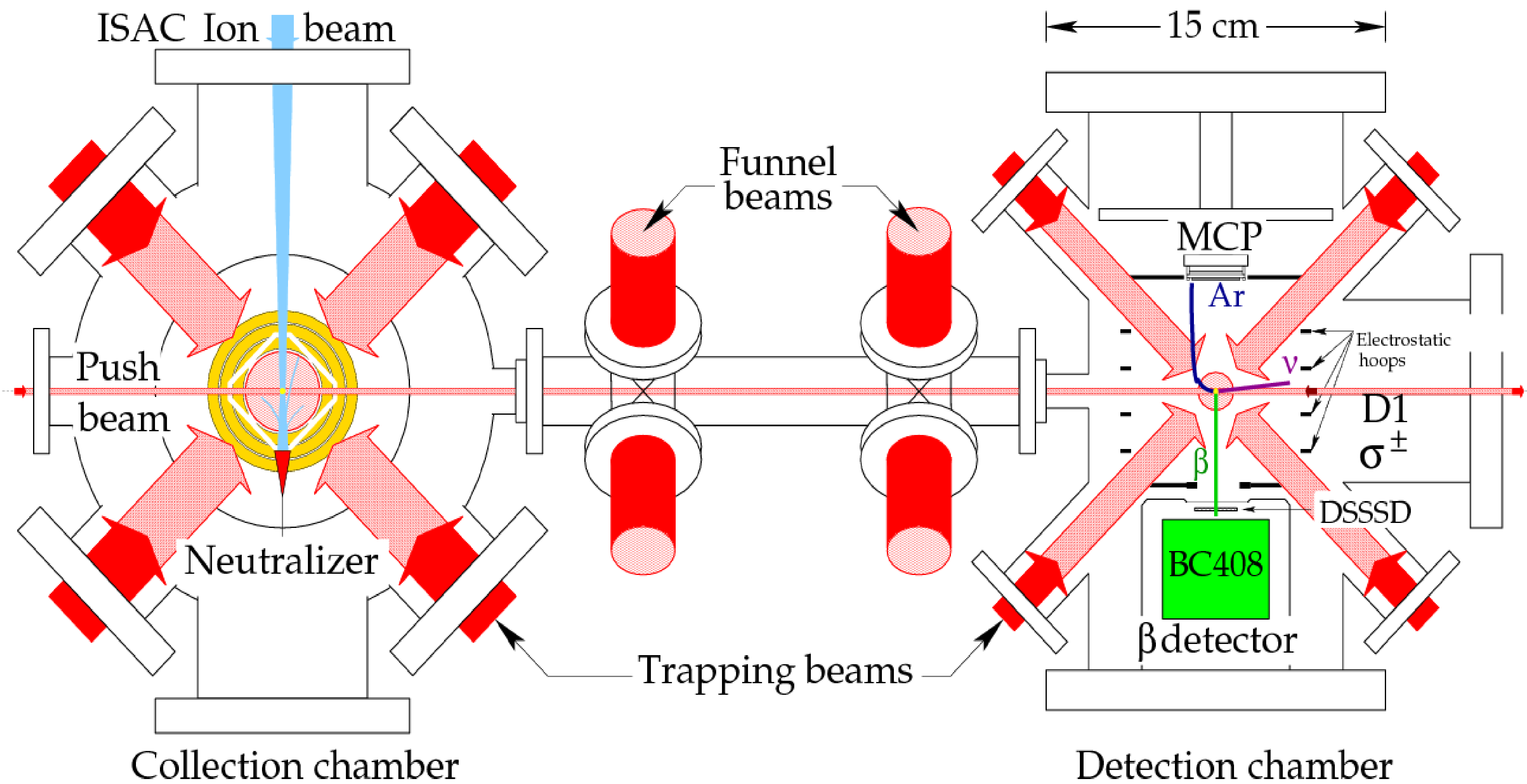
TRIUMF Neutral Atom Trap: *β-ν* correlation in the decay of ^{38m}K



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

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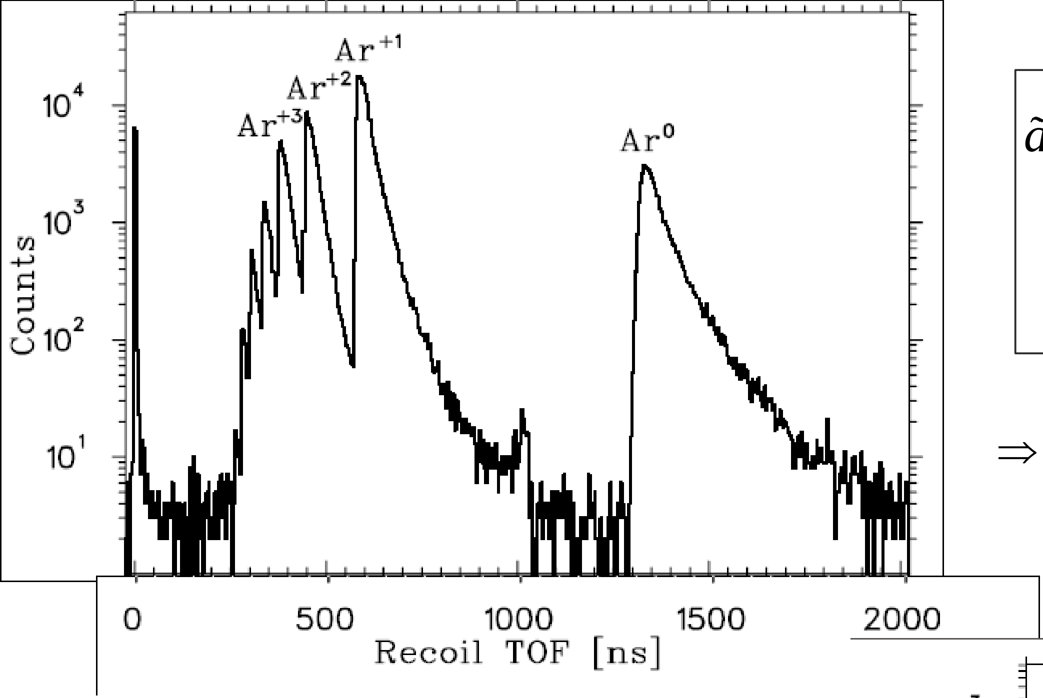


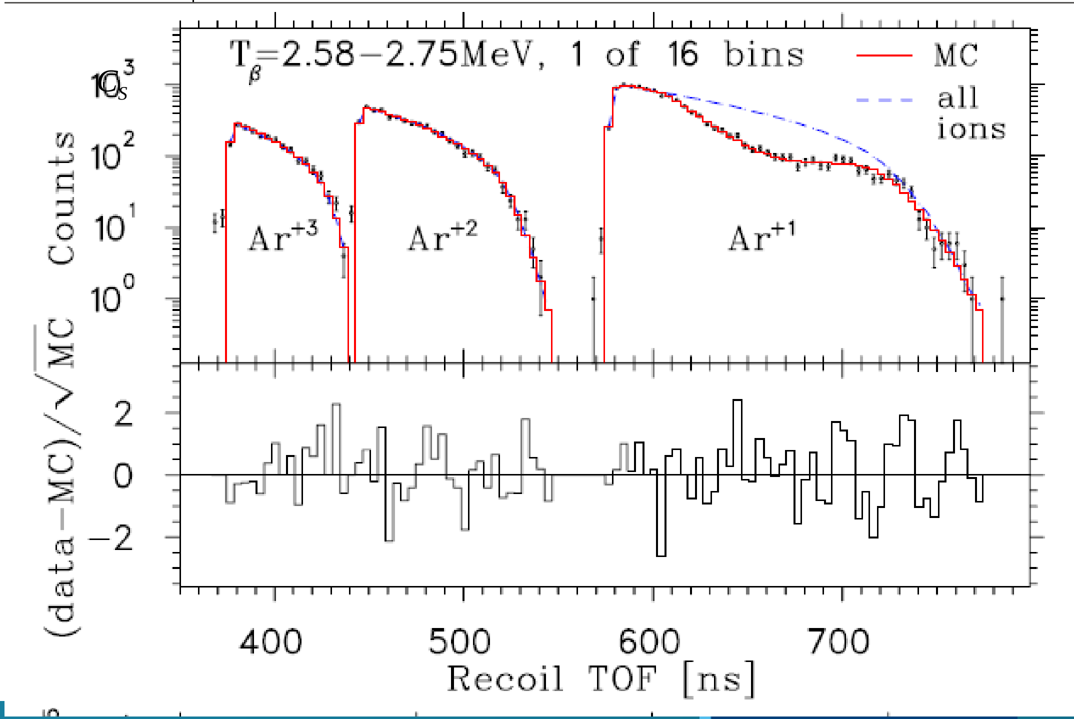
$$\tilde{a} = \frac{a}{1+\gamma \frac{m_e}{E_e} b} = 0.9981 \pm 0.0030 \pm 0.0035$$

$$(\tilde{a}_{SM} = 1)$$

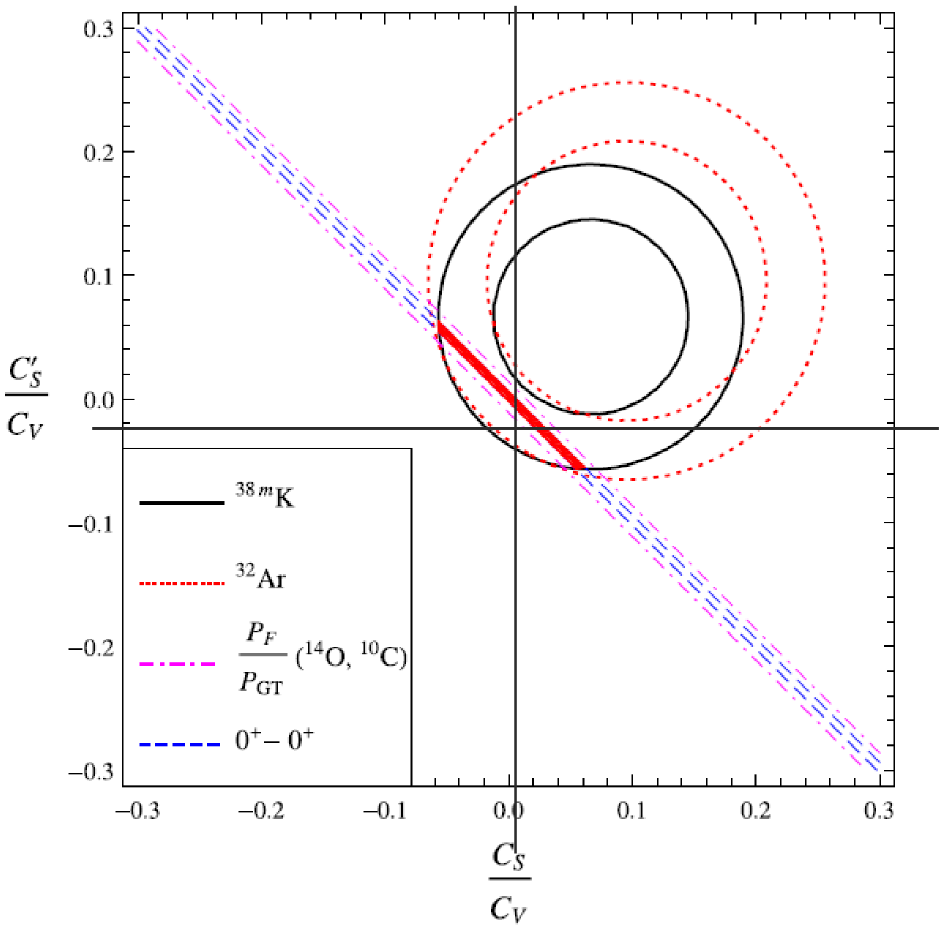
$$\Rightarrow \frac{|C_S|^2 + |C_S^{'}|^2}{|C_V|^2} \leq 0.097 \quad (90\% \text{ C.L.} \cong 1.65\sigma)$$

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

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



Future prospects for scalar current searches



band from $\mathcal{F}t^{0^+ \to 0^+}$ is already very narrow

→ more to be gained by reducing size of 'donut'-type allowed regions from βν-correlations (see next slide)

B. R. Holstein, J. Phys. G 41 (2014) 114001

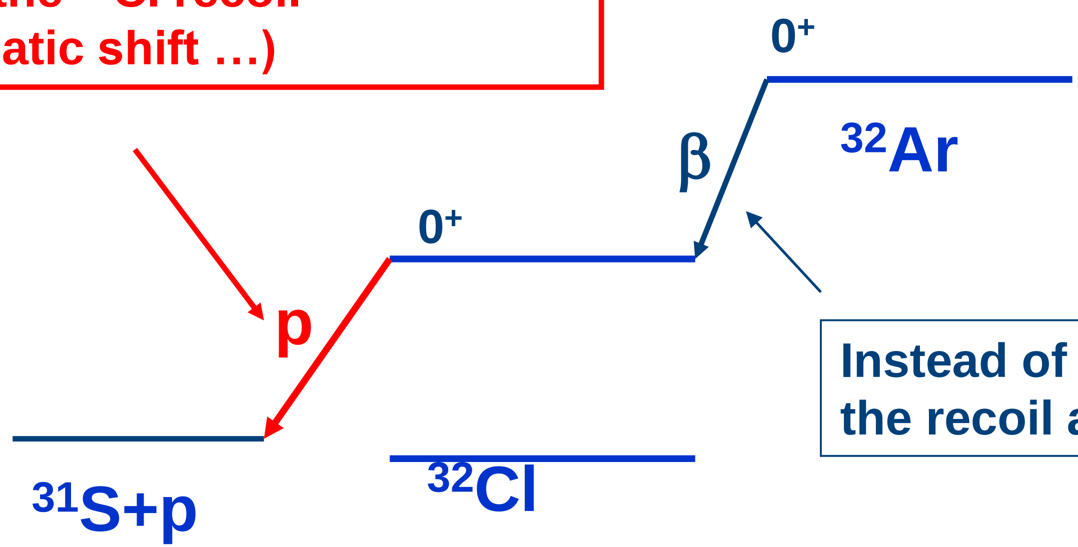
WISARD = Weak-interaction studies with Ar32 decay

(coll. Bordeaux, Leuven, LPC Caen, NPI-Prague)

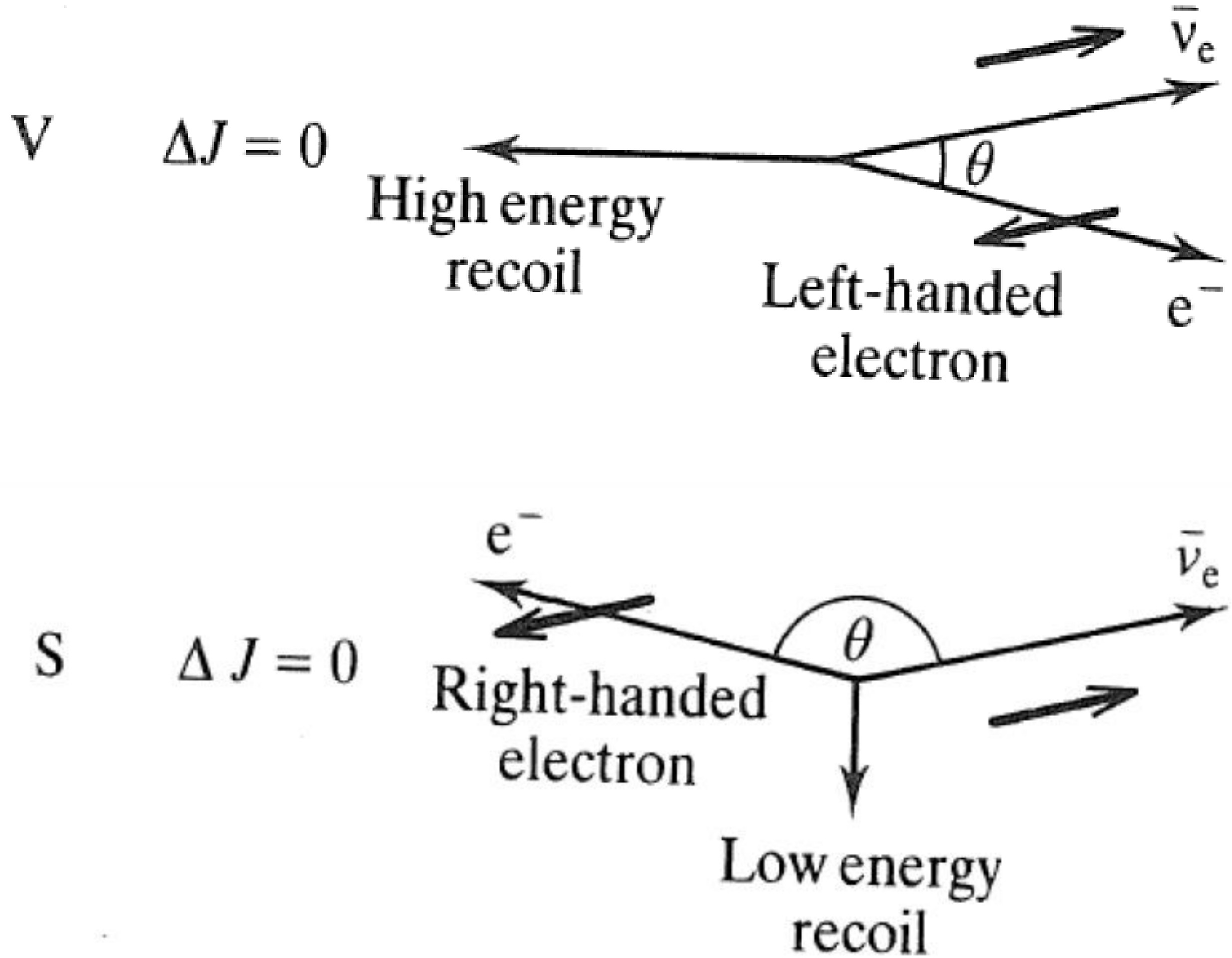
$$^{32}\mathrm{Ar} \rightarrow {}^{32}\mathrm{Cl}\; e^{+} \nu_{e}$$

$$^{32}\mathrm{Cl} \rightarrow {}^{32}\mathrm{S}\;\mathrm{p}$$

Detection of the proton that contains the information about the ^{32}Cl recoil (kinematic shift …)



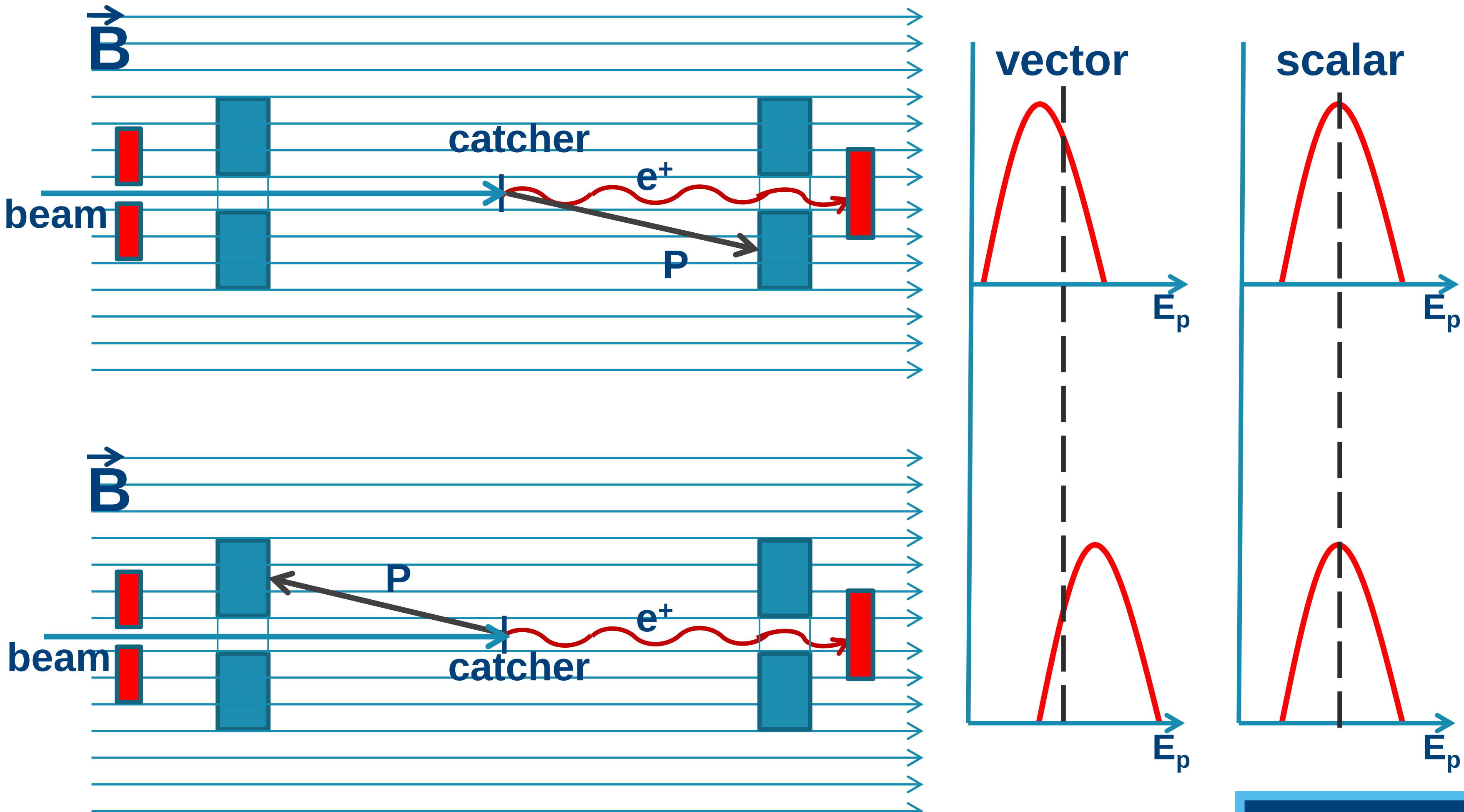
Instead of detecting the recoil and the positron


V
$\Delta J = 0$
$\bar{\nu}_e$
θ
High energy recoil
Left-handed electron
e^-
S
$\Delta J = 0$
e^-
$\bar{\nu}_e$
θ
Right-handed electron
Low energy recoil

WISARD = Weak-interaction studies with Ar32 decay

coll. Bordeaux, Leuven, LPC Caen, NPI-Prague

➔ measure protons and positrons in two hemispheres



1999: kinematic broadening in ^{32}Ar β-p decay

$$^{32}\text{Ar} \rightarrow {}^{32}\text{Cl}\, e^{+} \nu_{e}$$

$$^{32}\text{Cl} \rightarrow {}^{32}\text{S p}$$

observed kinematic broadening instead of kinematic shift

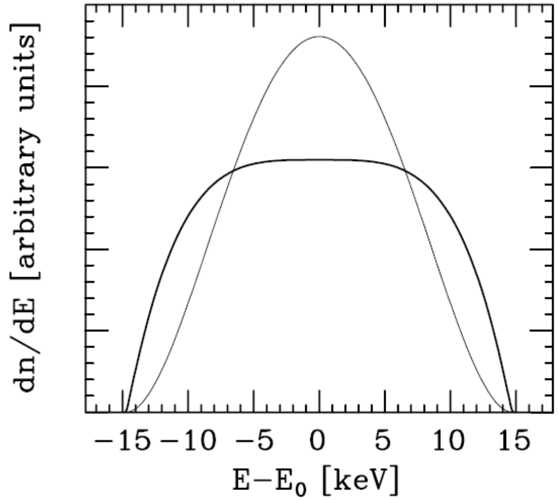
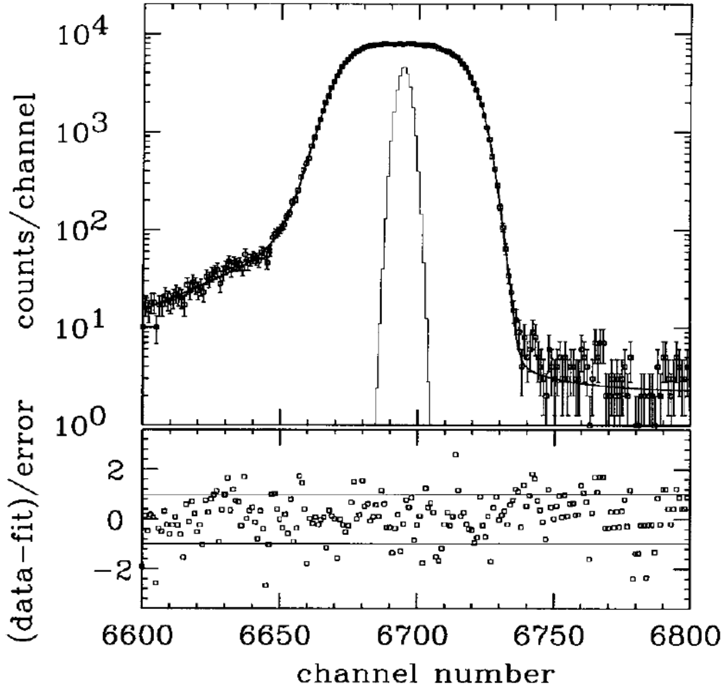


FIG. 1. Intrinsic shapes of the $0^{+} \rightarrow 0^{+}$ delayed proton group for $a = +1$, $b = 0$ (heavy curve) and $a = -1$, $b = 0$ (light curve). The daughter's 20 eV natural width is not visible on this scale.



$$\tilde{a}_{\text{exp}} = 0.9989(65)$$

E.G. Adelberger, et al., Phys. Rev. Lett. 83 (1999) 1299

A. Garcia et al., Hyperfine Interact. 129 (2000) 237

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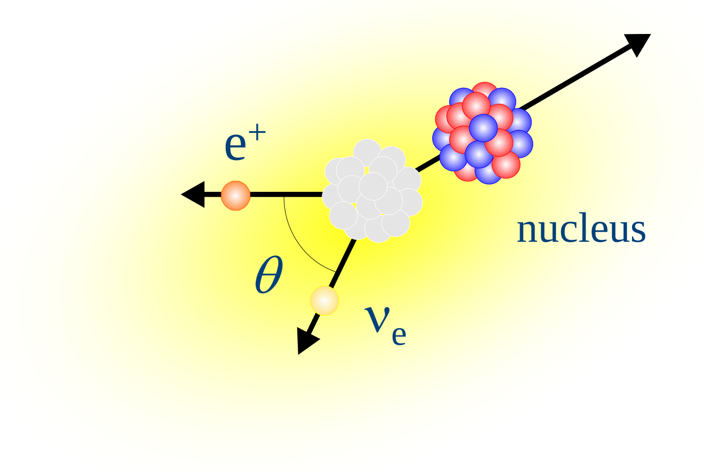
Searching for charged tensor weak currents

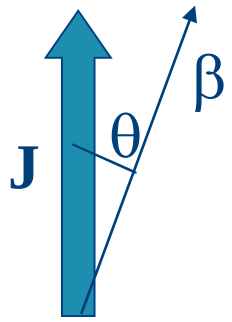
β-ν correlation

$$a \frac{\vec{p}_e \cdot \vec{q}}{E_e E_\nu} \quad \text{and} \quad \tilde{a} = \frac{a}{1 + b \dfrac{\gamma m_e}{E_e}}$$

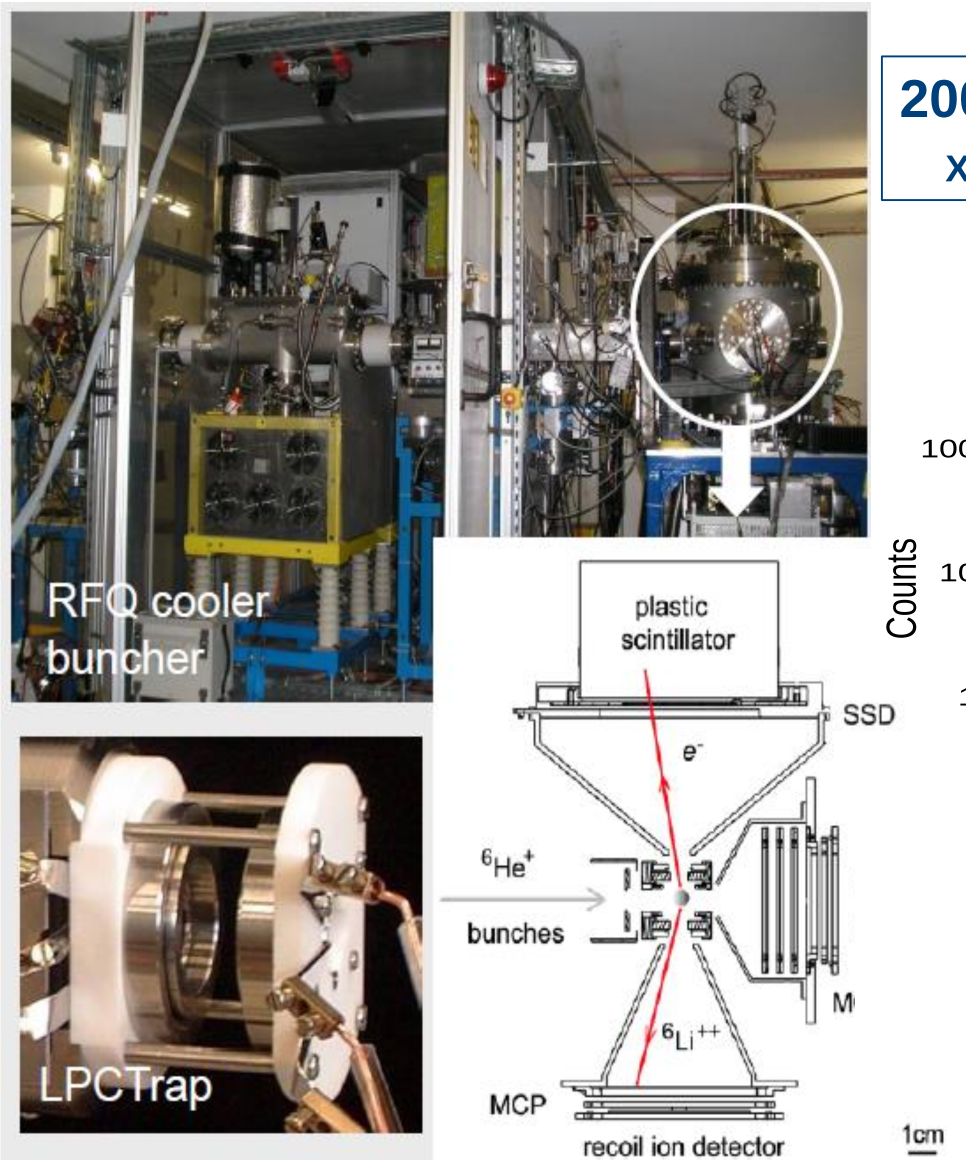


β-asymmetry parameter

$$A \frac{\vec{J}}{J} \cdot \frac{\vec{p}_e}{E_e} \quad \text{and} \quad \tilde{A} = \frac{A}{1 + b \dfrac{\gamma m_e}{E_e}}$$

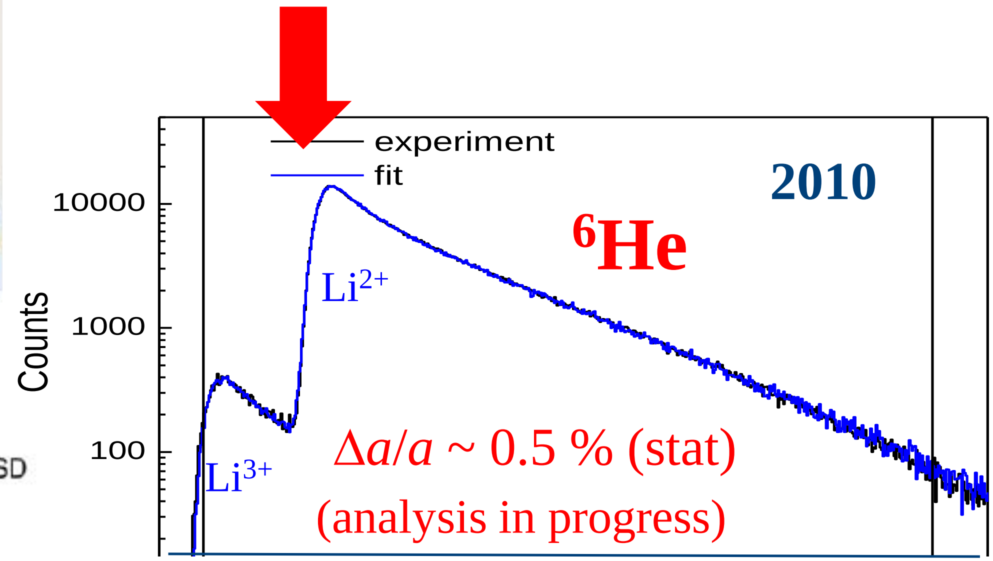


Exp. 2: LPC-Trap @ GANIL - ^{6}He



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 and comparison to atomic theory:

C. Couratin et al., PRL 108 (2012) 243201

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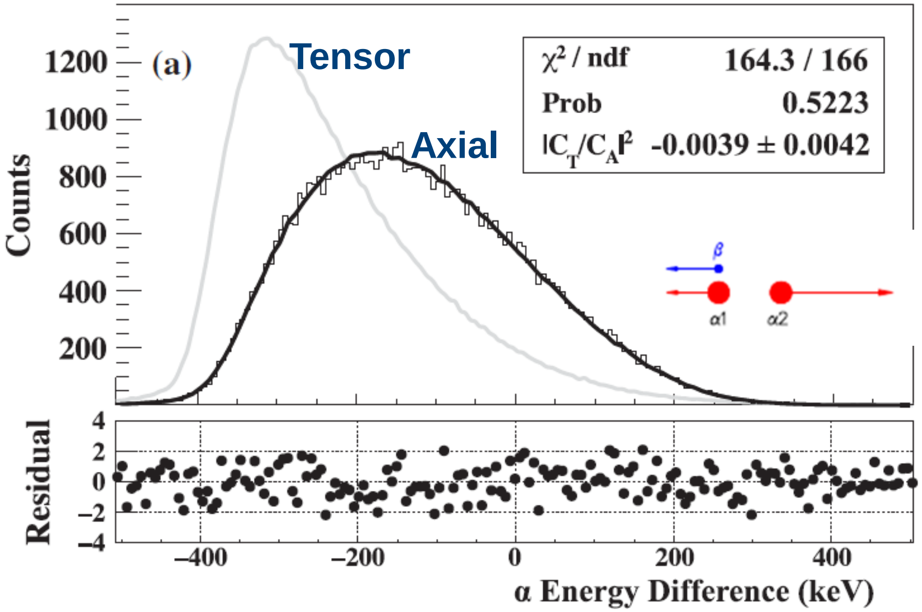
α-β-ν correlation from α-particle breakup of ^{8}Be* after ^{8}Li β decay in a Paul trap

(ANL Argonne)



$$^8\text{Li} \rightarrow {}^8\text{Be}^* \, e^- \bar{\nu}_e$$

$$^8\text{Be}^* \rightarrow 2\alpha$$

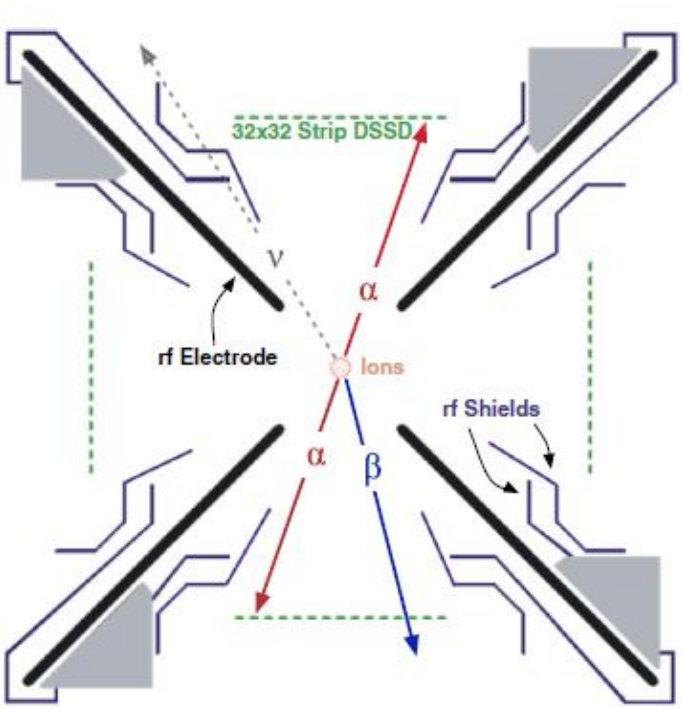


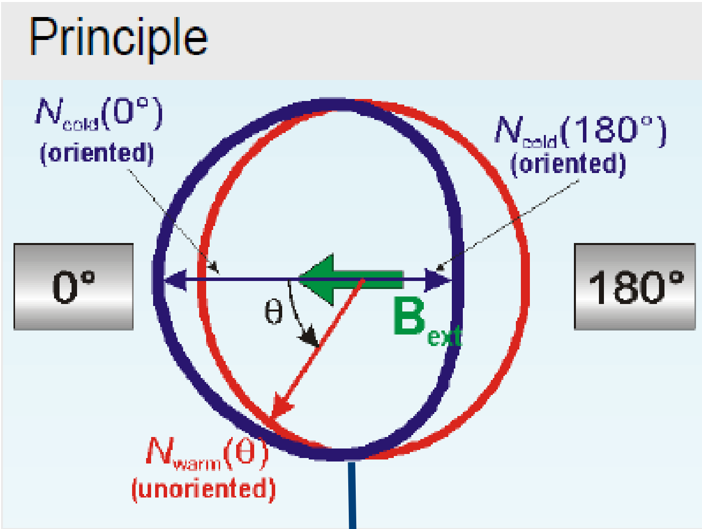
FIG. 1 (color online). Cross-sectional view of the BPT and detector system in the rf plane. The direction of the emitted α's and β's is determined by the vector between the trap center and detector pixels.

$a_{\beta\nu}$ = −0.3342 (26)$_{stat}$ (29)$_{sys}$

M.G. Sternberg, G.Savard et al., PRL 115 (2015) 182501

β-asymmetry with polarized nuclei

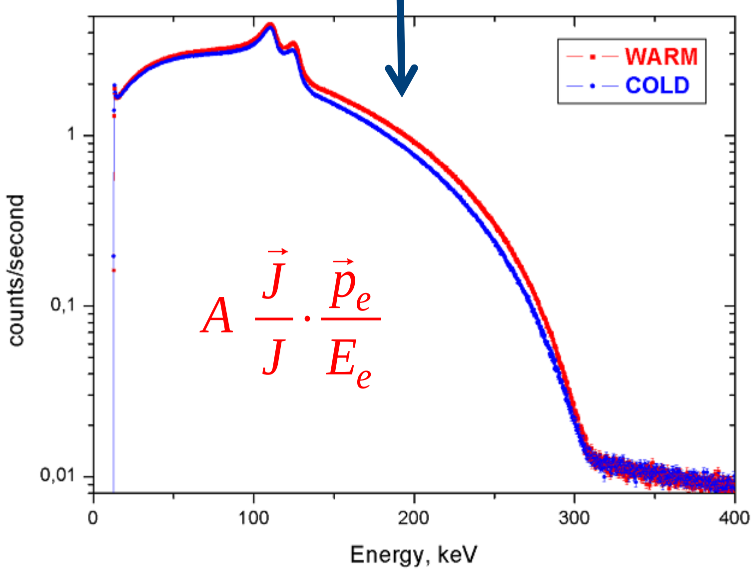
(Leuven / ISOLDE / Bonn / Prague)



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

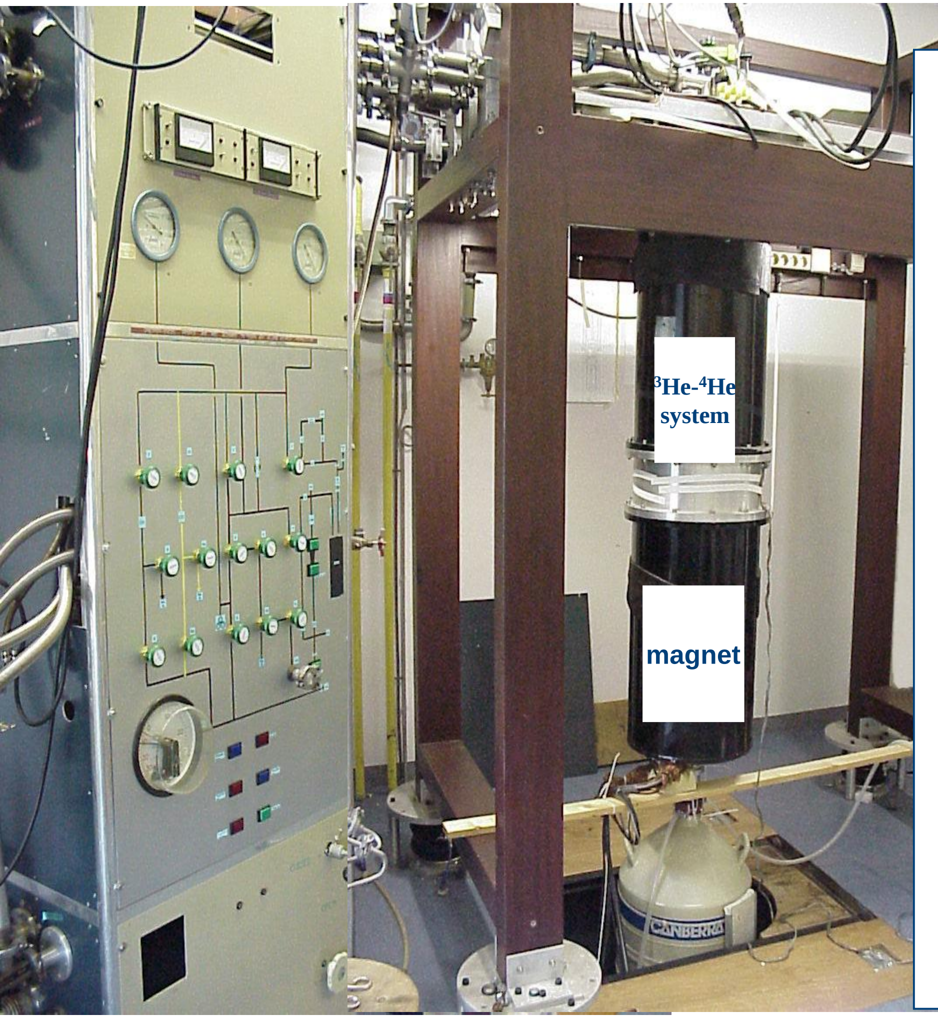
(P from anisotropy of γ-rays) Geant4

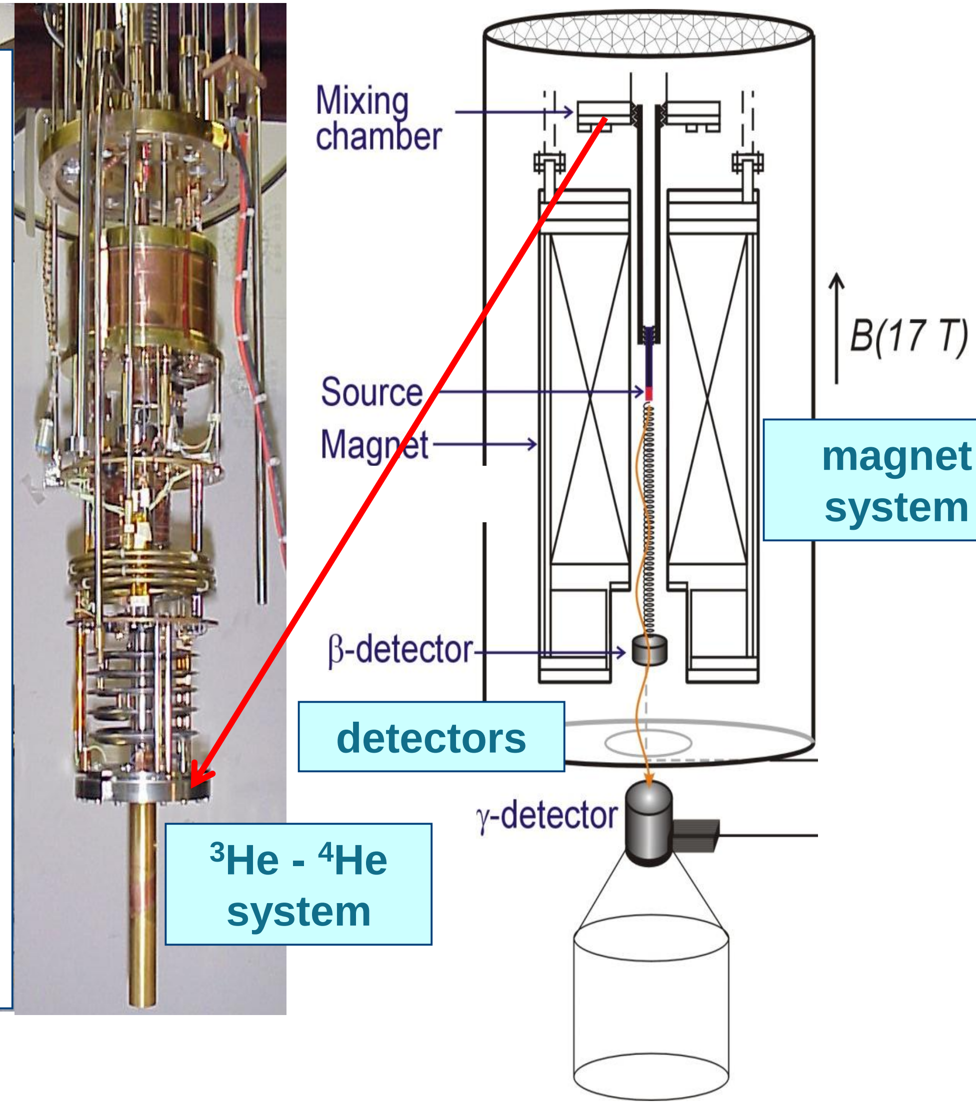
$$\tilde{A} = \frac{A}{1+b'_{GT}} \quad \text{with} \quad b'_{GT} = \frac{\gamma m_e}{\langle E_e \rangle}\left(\frac{C_T + C'_T}{C_A}\right)$$



Analysis:

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



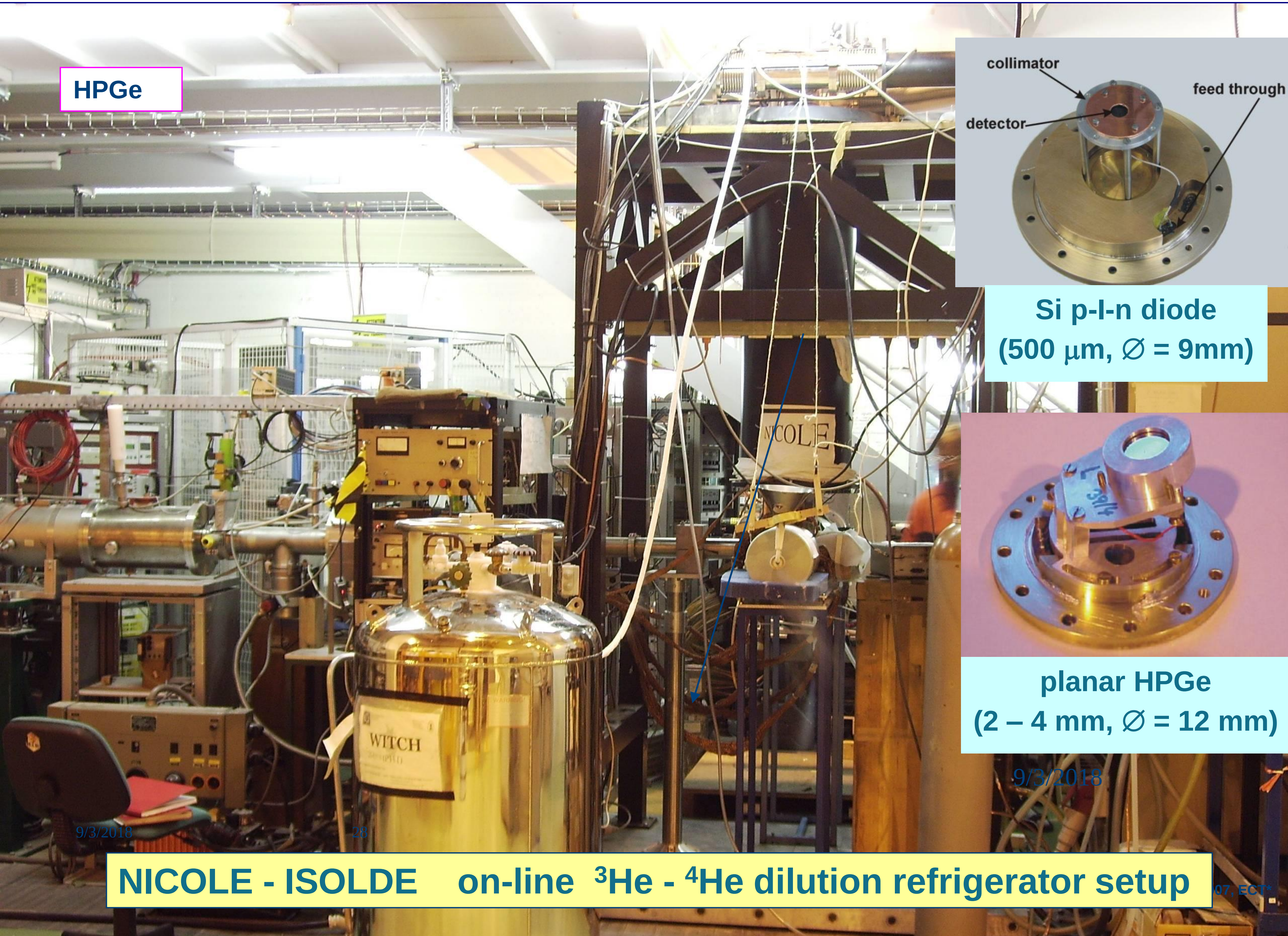


^{3}He - ^{4}He dilution refrigerator set-up

polarized nuclei ; 5 – 100 mK

Leuven – ISOLDE ; IS431

KU LEUVEN

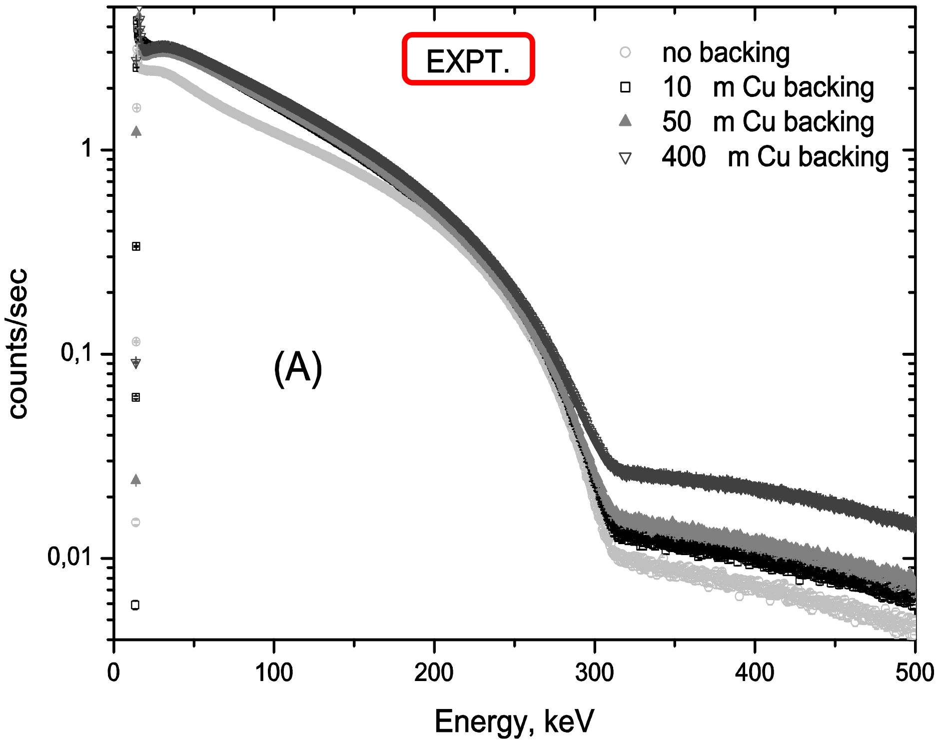


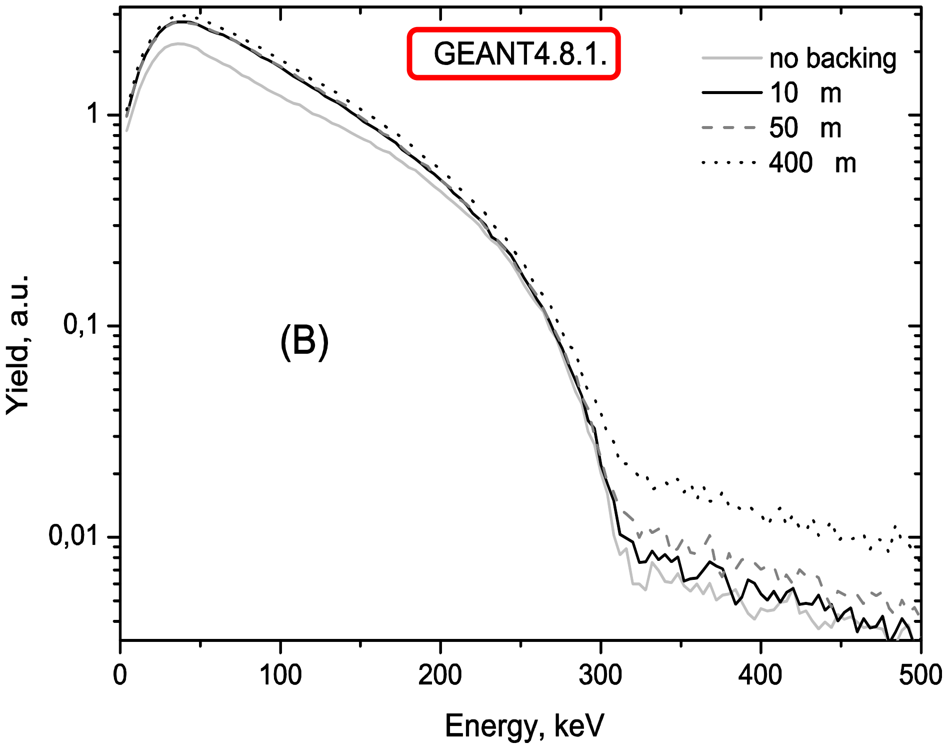
Si p-I-n diode
(500 μm, ∅ = 9mm)

planar HPGe
(2 – 4 mm, ∅ = 12 mm)

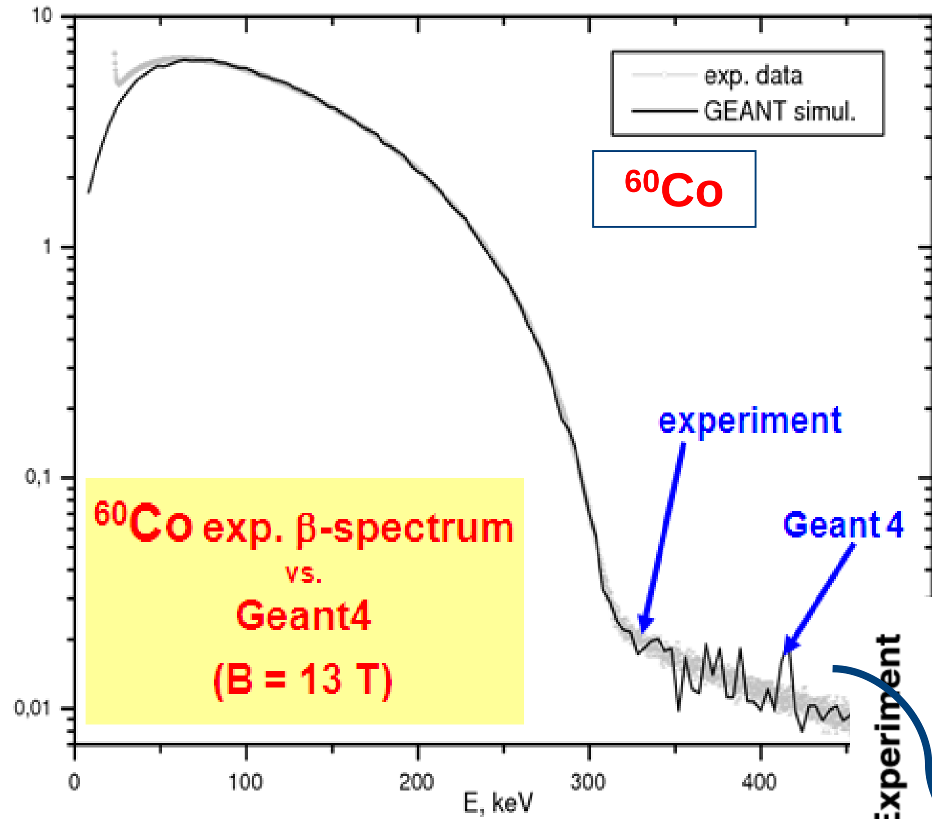
NICOLE - ISOLDE on-line ^{3}He - ^{4}He dilution refrigerator setup

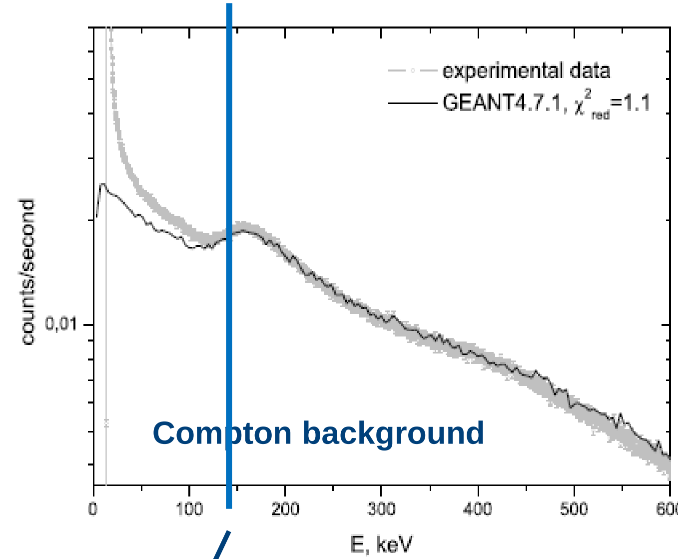
development of GEANT4.8 based simulation code

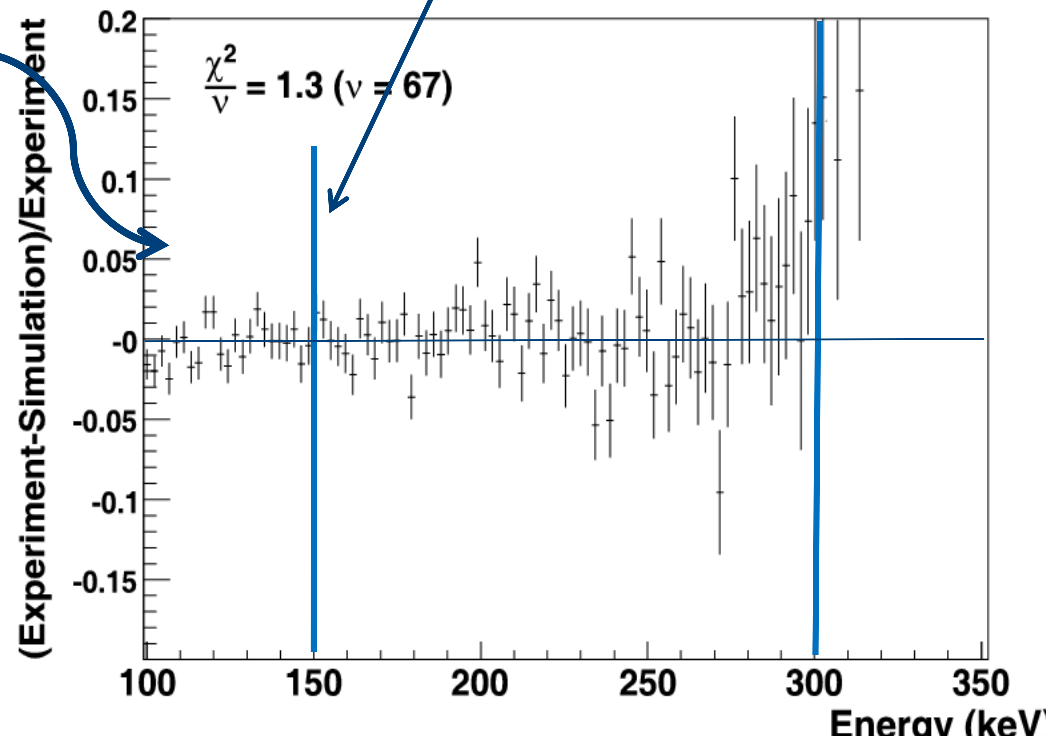




KU LEUVEN



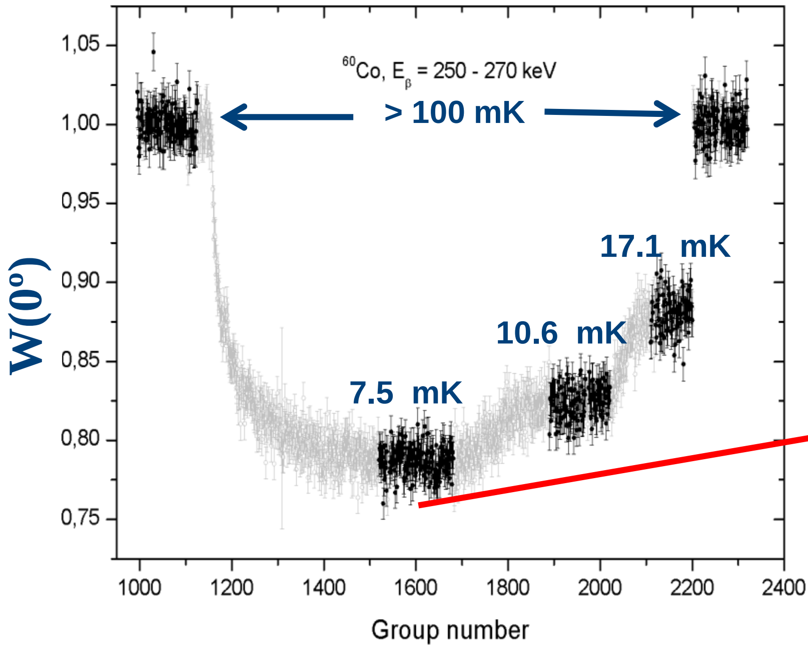


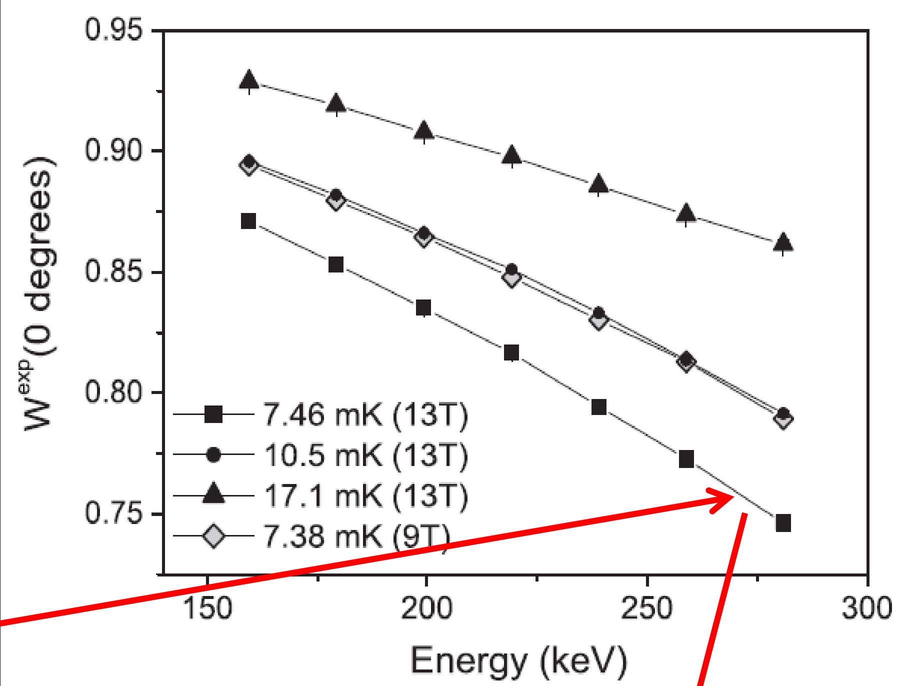


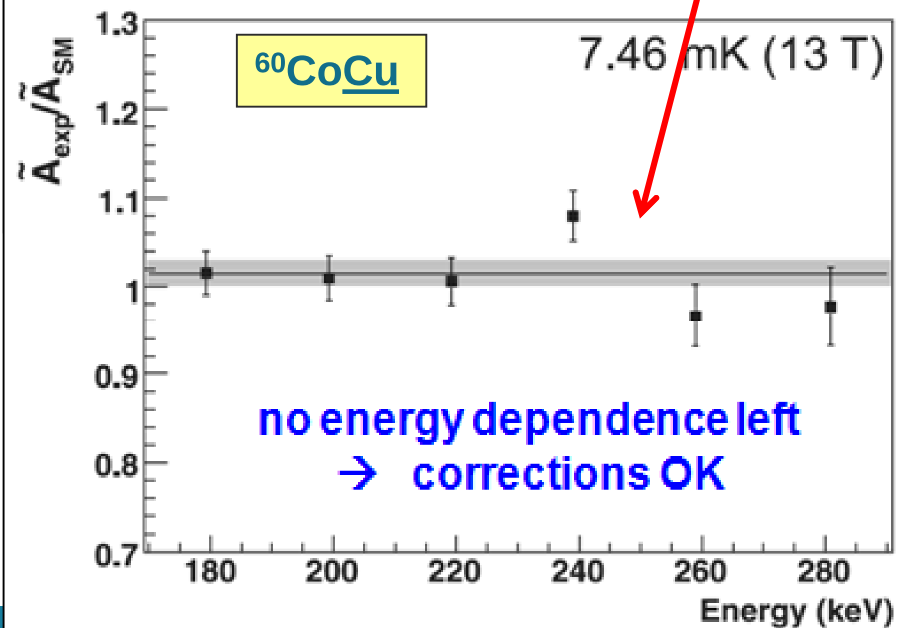
performance of GEANT4.8 simulation code

F. Wauters et al., NIM A609 (2009) 156

β-anisotropy - raw data - bin 6







B_{ext} = 13 Tesla

W(0°) = $N(0°)_{pol}$ / $N(0°)_{unpol}$

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

A_{exp} (^{60}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}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}Cu) = 0.584 $(6)_{stat}$ $(11)_{syst}$

(A_{SM} = 0.5993(2))

G. Soti et al., submitted

Limits (90% C.L.) :

^{60}Co : $-0.088 < (C_T + C_T')/C_A < 0.014$

^{114}In : $-0.082 < (C_T + C_T')/C_A < 0.139$

if $\Delta A = 0.01$

$\downarrow$ (for $\gamma m/E_e \cong 0.5$)

$$\mathrm{Re}\left(\frac{C_T + C_T'}{C_A}\right) < 0.033 \quad \text{(90\% CL)}$$

major systematic errors:

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

^{60}Co$\underline{\text{Cu}}$, B_{ext} = 13 T

^{114}In$\underline{\text{Fe}}$, B_{hf} = 27 T

^{67}Cu$\underline{\text{Fe}}$, B_{hf} = 21 T

major systematic errors:

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

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

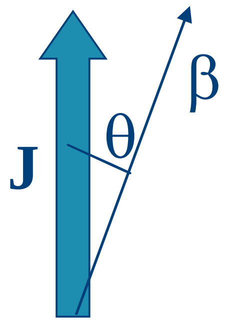
F. Wauters et al., Phys. Rev. C 82 (2010) 055502

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

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

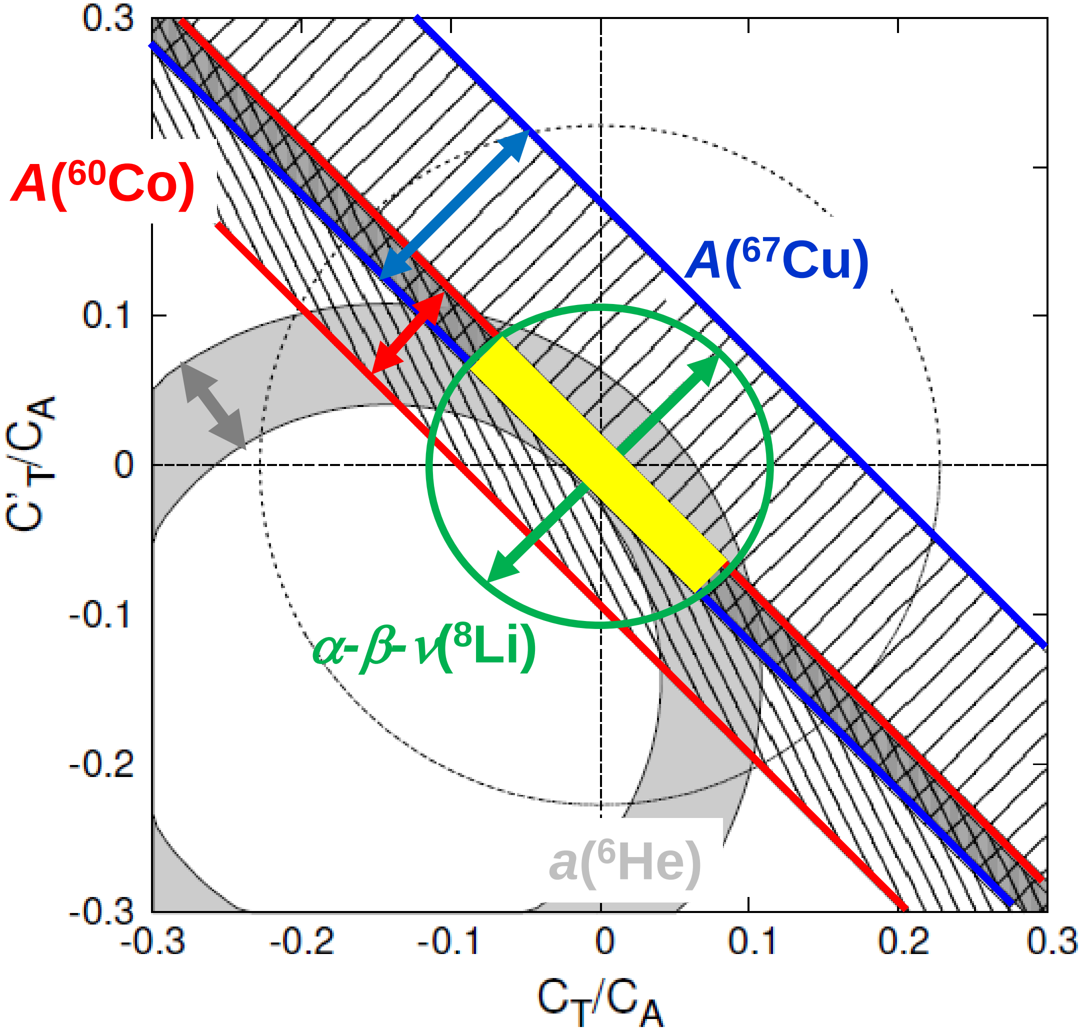
$$A_{exp}\,(^{67}\text{Cu}) = 0.587(8)_{stat}\,(12)_{syst}$$

G. Soti et al., Phys. Rev. C 90 (2014) 035502



IS431-experiment

Limits on tensor currents



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

α-β-ν(^{8}Li)
M.G. Sternberg, G.Savard et al.,
PRL 115 (2015) 182501

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

A(^{67}Cu)
G. Soti, N.S. et al.,
PR C 90 (2014) 035502

Testing Parity Violation

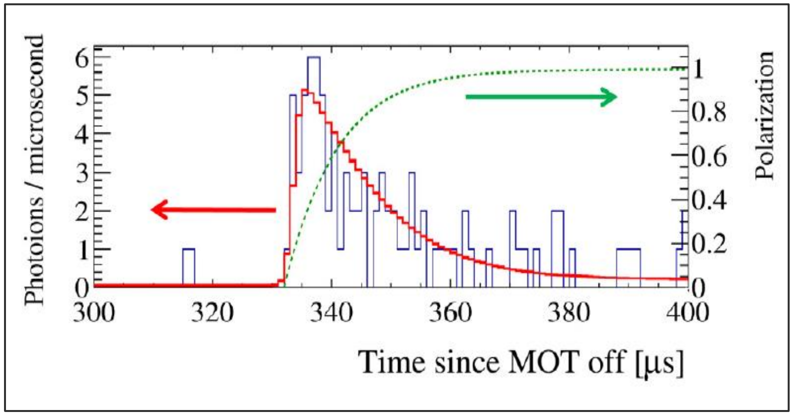
Focus on pseudoscalar observables, e.g. $\vec{J} \cdot \vec{p}$ **(Mme. Wu exp with ^{60}Co), e.g. :**

1. Polarization-asymmetry correlation for beta-particles

P.A. Quin and T.A. Girard, Phys. Lett. B 229 (1989) 29

$$\mathrm{d}W(\boldsymbol{J}, \hat{\boldsymbol{\sigma}}, E) \propto \xi \left\{ 1 + \frac{\boldsymbol{p}}{E} \cdot \boldsymbol{J} A + \hat{\boldsymbol{\sigma}} \cdot \left[\frac{\boldsymbol{p}}{E} G + \boldsymbol{J} N + \frac{\boldsymbol{p}}{E+m} \left(\frac{\boldsymbol{p}}{E} \cdot \boldsymbol{J} \right) Q \right] \right\}$$

2. Beta-asymmetry parameter in ^{37}K decay at ISAC-TRINAT



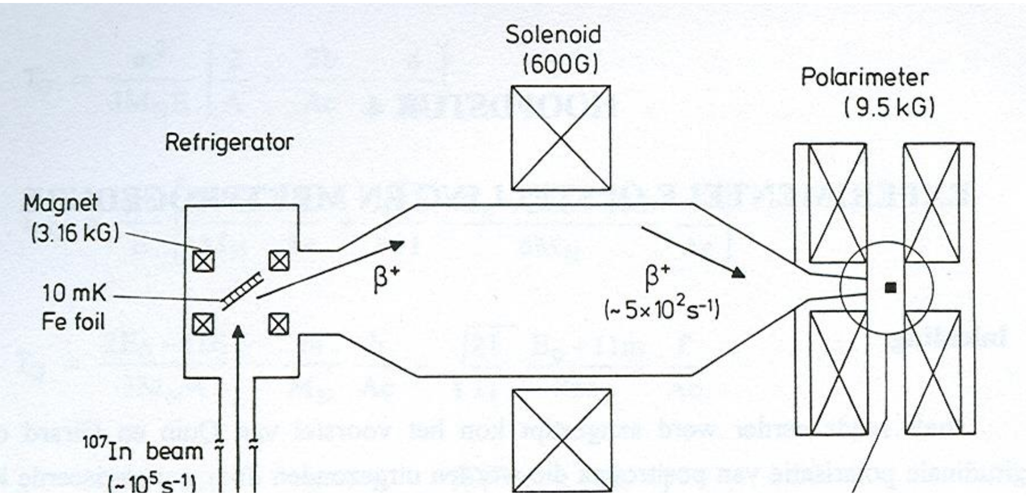
Longitudinal polarization of positrons emitted by polarized nuclei
(precision test of parity violation / searches for right-handed currents)

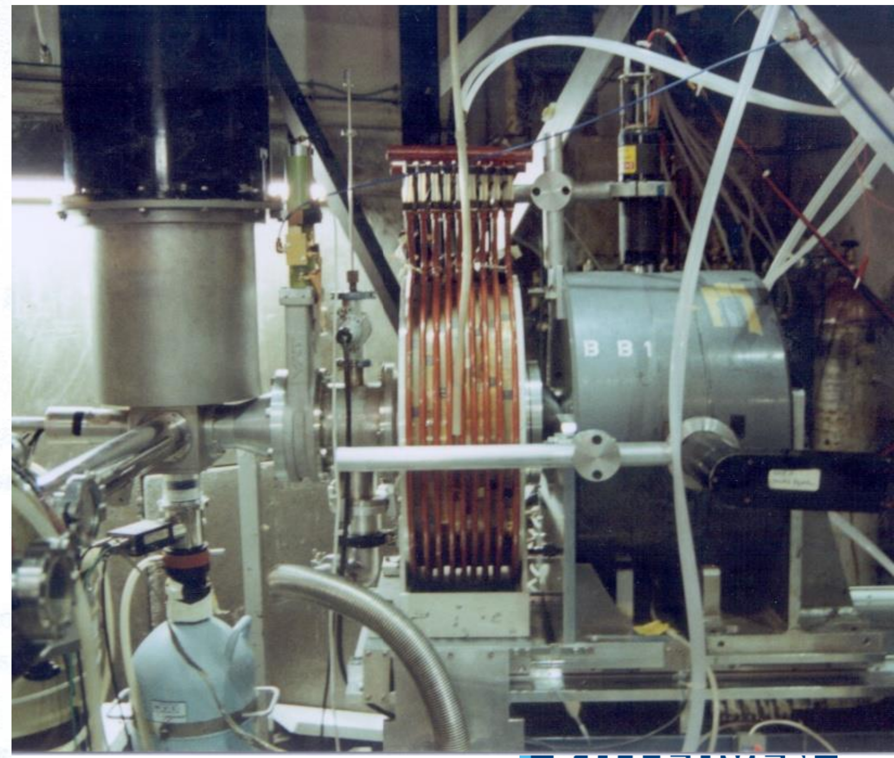
experimental quantity

$$R \equiv P^- / P^+ = R_{SM} [1 + k \Delta]$$

$$\Delta = (\delta + \zeta)^2$$

with : P^- (P^+) the β particle longitudinal polarization for β's emitted opposite to (in the direction of) the polarized nuclear spin vector (P^0 for unpolarized nuclei)





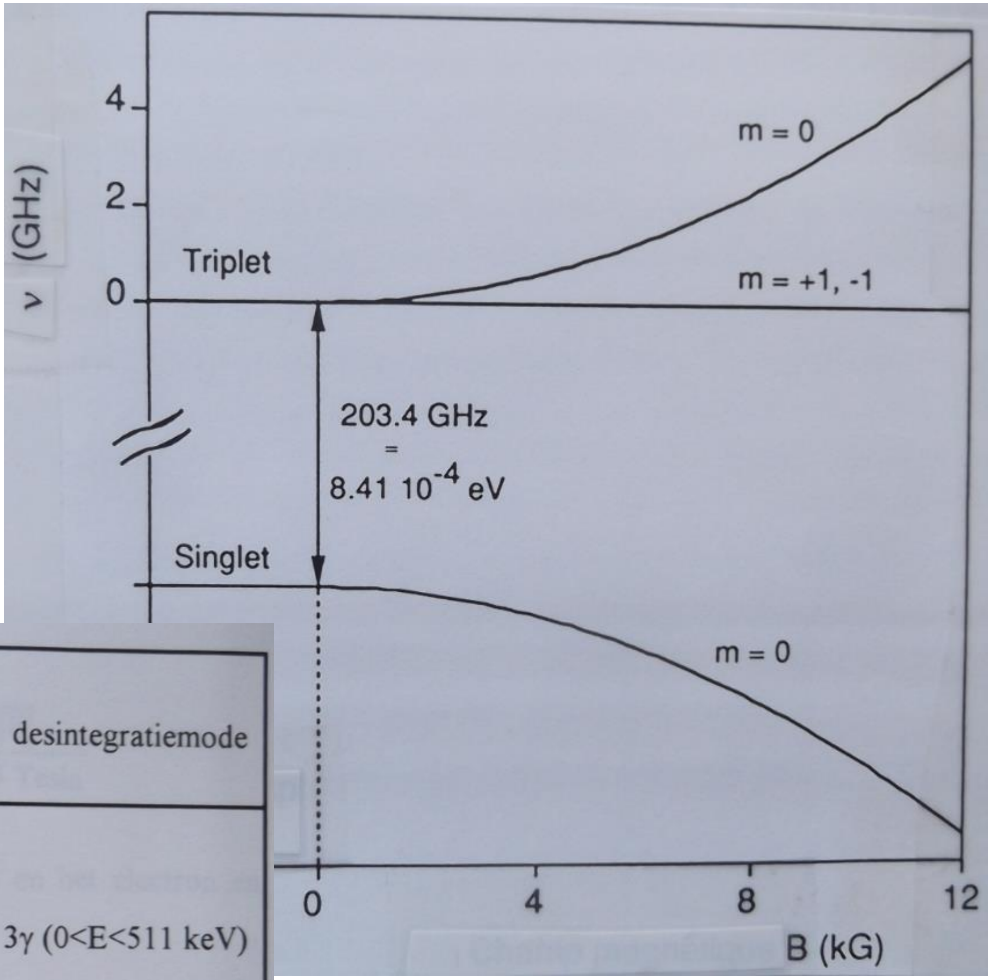
(Minimal) Left Right Symmetric models

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

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

$$\delta = (m_{W1})^2 / (m_{W2})^2$$

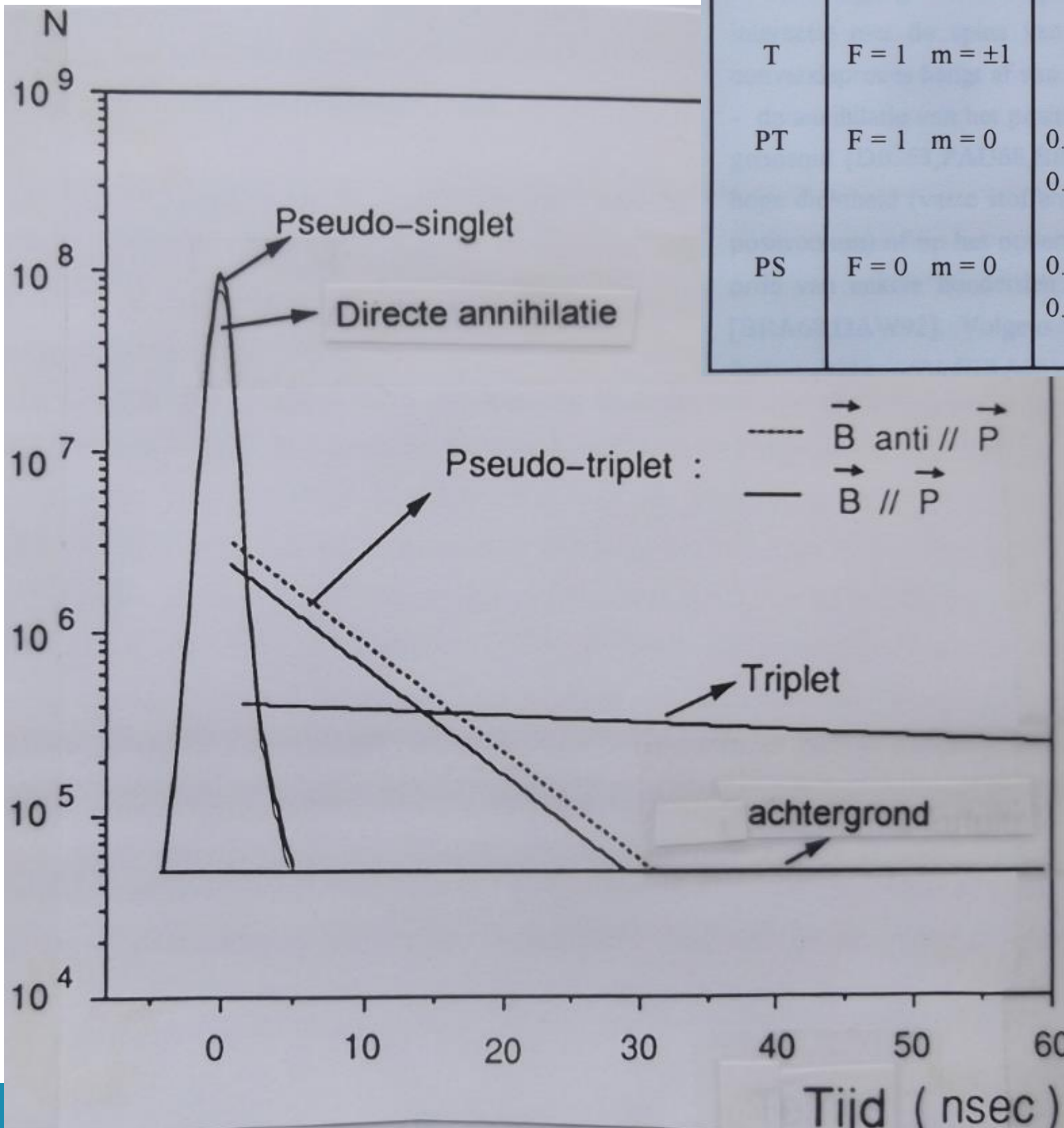
Positronium hyperfine structure

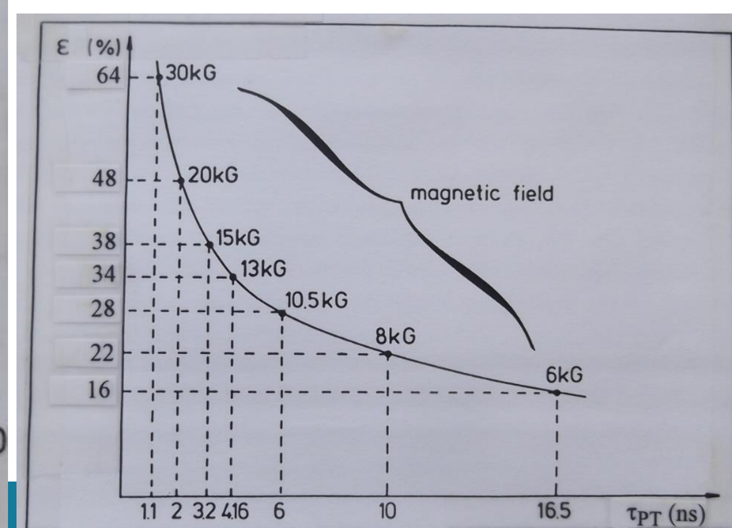


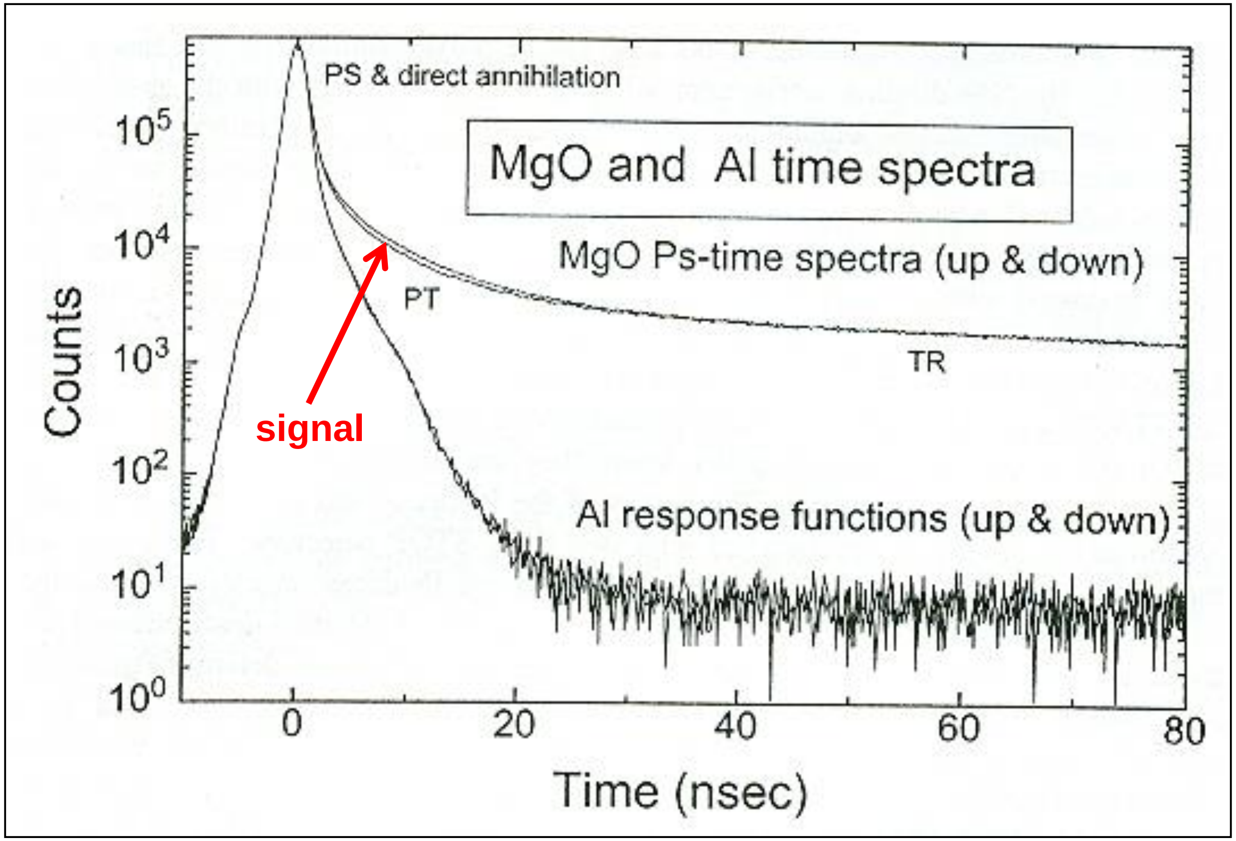
toestand	spin	populatie	levensduur	desintegratiemode
Triplet (ortho-Ps)	F = 1 m = +1 m = 0 m = -1	0.25 0.25 0.25	τ_T =142 ns	3γ (0<E<511 keV)
Singlet (para-Ps)	F = 0 m = 0	0.25	τ_S =0.125 ns	2γ (E=511 keV)

Positronium decay in a magnetic field

toestand	spin	populatie	levensduur	desintegratiemode
T	F = 1 m = ±1	0.50	τ_T = 142 ns	3γ (0<E<511 keV)
PT	F = 1 m = 0	0.25(1-εP) als $\overline{B} /\!/ \overline{P}$ 0.25(1+εP) als $\overline{B}$ anti $/\!/ \overline{P}$	τ_{PT} = f(B)	2γ (3γ)
PS	F = 0 m = 0	0.25(1+εP) als $\overline{B} /\!/ \overline{P}$ 0.25(1-εP) als $\overline{B}$ anti $/\!/ \overline{P}$	τ_{PS} = f(B)	2γ (E=511 keV)







Louvain-la-Neuve, Madison, Leuven, ETH-Zurich, PSI collaboration

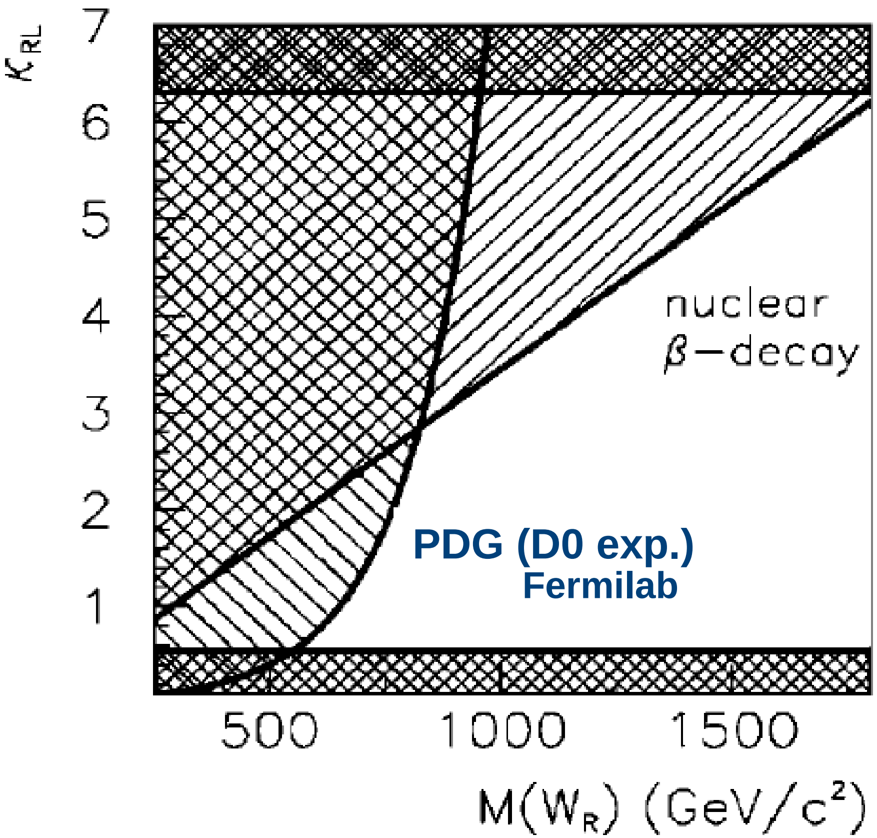
Results :

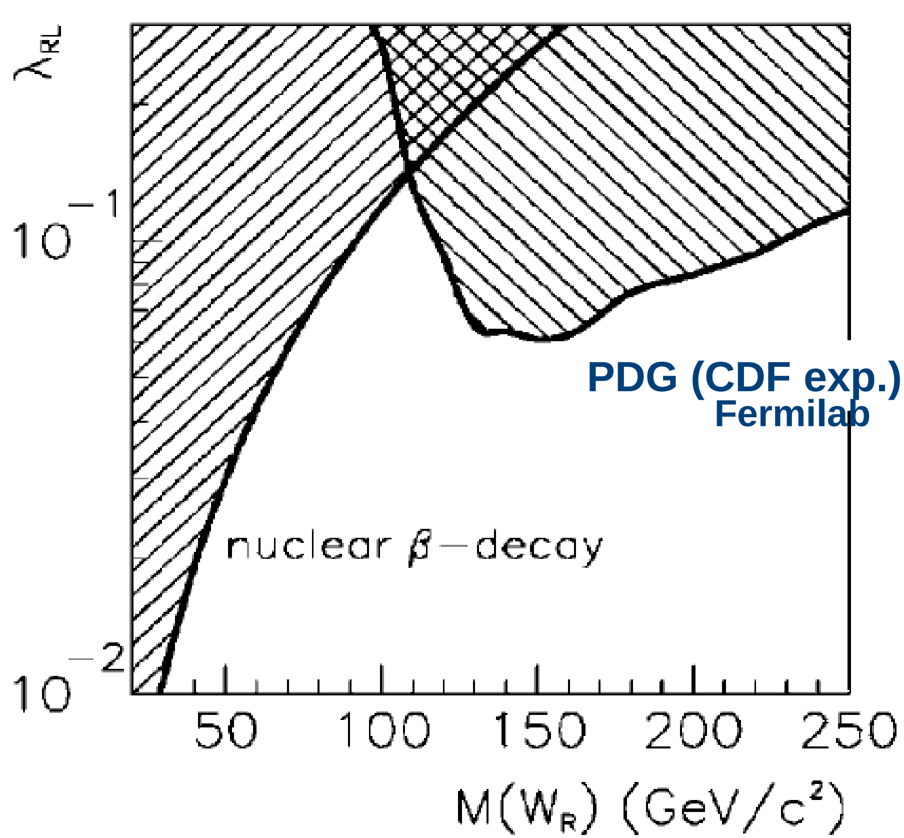
observable	nucleus	$(\delta + \zeta)^2$	
P^- / P^+	^{107}In	-0.0003(58)	1)
P^- / P^+	^{12}N	0.0064(76)	2)
P^- / P^+	^{12}N	-0.0001(34)	3)
P^- / P^0	^{107}In	0.0021(17)	4)
average		0.0017(14)	

$M_{W_2} > 320$ GeV/c^2 (90 % C.L.)

1) N. Severijns et al., PRL 70 (1993) 4047, 73 (1994) 611
2) M. Allet et al., Phys. Lett. B363 (1996) 139
3) E. Thomas et al., Nucl. Phys. A694 (2001) 559
4) N. Severijns et al., Nucl. Phys. A629 (1998) 423c

Complementarity of beta decay RHC results and collider results, in general LRS models





$\kappa_{RL} = g_R / g_L$

shaded areas are excluded

$\lambda_{RL} = V_{ud}^R / V_{ud}^L$

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Beta-asymmetry parameter in ^{37}K decay

^{37}K @ ISAC-TRINAT: A = -0.5707(13)$_{stat}$(12)$_{syst}$(5)$_{pol}$ = -0.5707(18)

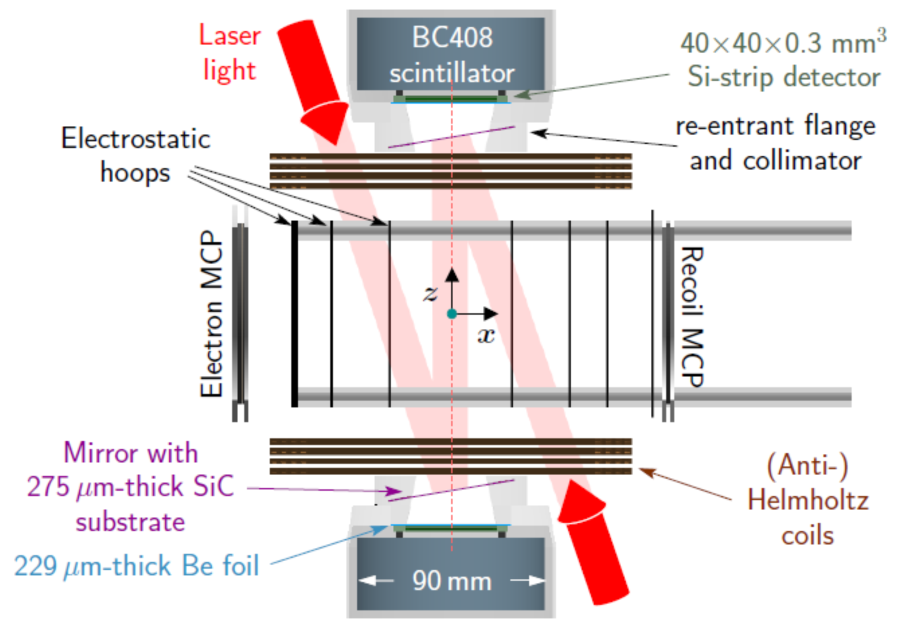
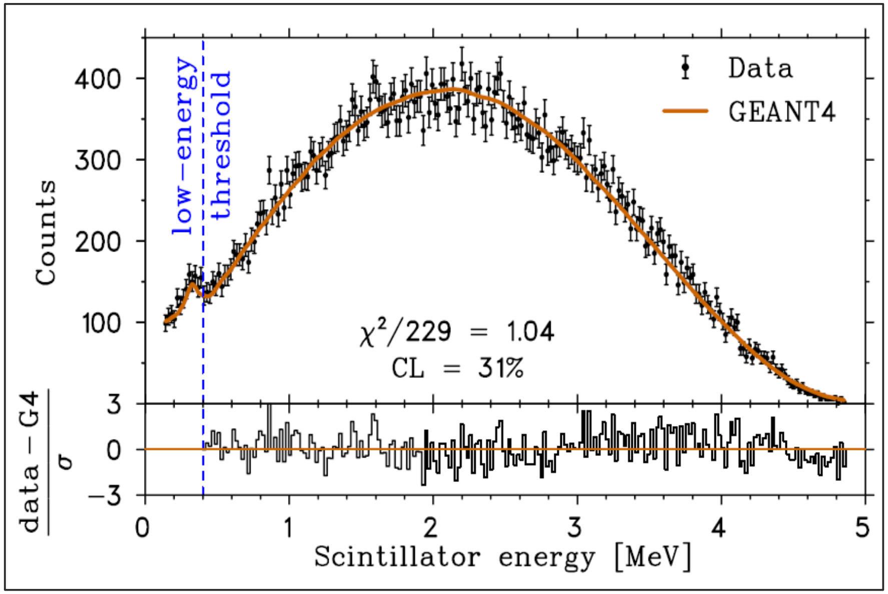


FIG. 1. The TRINAT detection chamber (color online). To polarize the atoms along the β-detection ($\hat{z}$-) axis, optical pumping light is brought in at a 19° angle with respect to the $\hat{z}$-axis and reflected off thin mirrors mounted within a β collimator on the front face of the re-entrant flanges. Thin Be foils behind the mirrors separate the Si-strip and scintillator β detectors from the 1×10^{-9} Torr vacuum of the chamber. Magnetic field coils provide the Helmholtz (optical pumping, 2 Gauss) and anti-Helmholtz (MOT) fields. Glassy carbon and titanium electrostatic hoops produce a uniform electric field of 150 to 535 V/cm in the $\hat{x}$ direction to guide shakeoff electrons and ions towards microchannel plate detectors.



Fenker, Behr, Melconian et al., PRL 120 (2018) 062502

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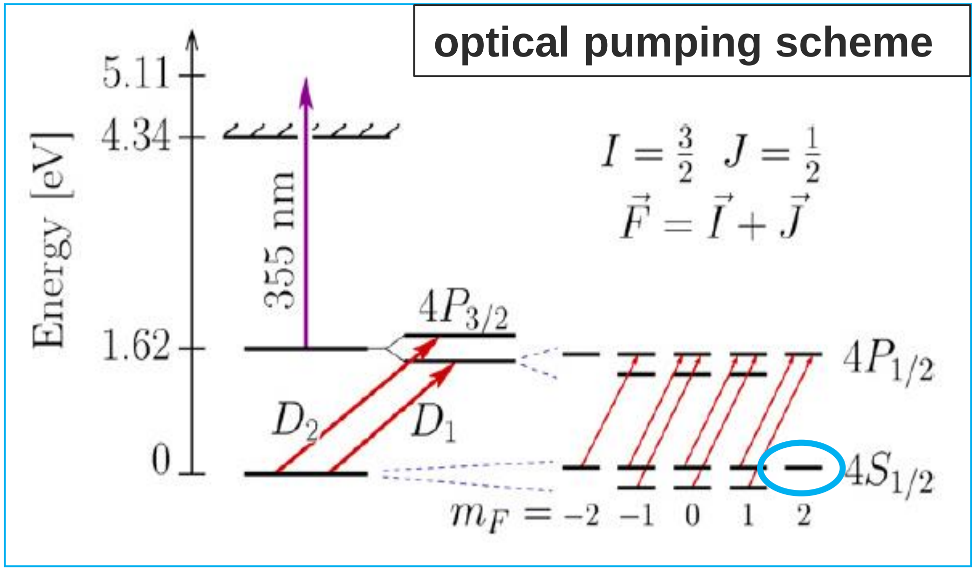
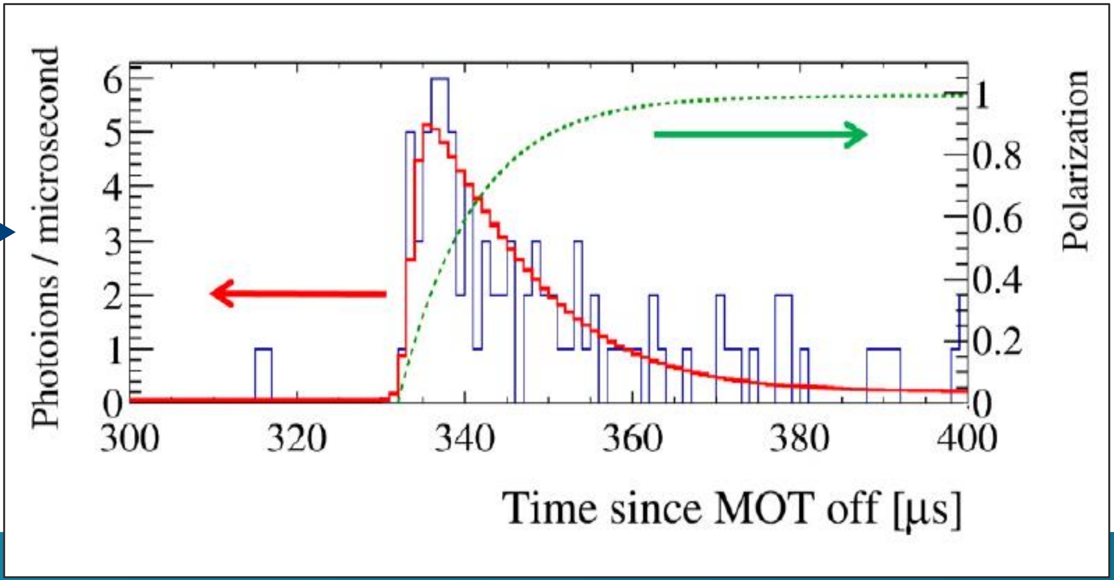
Polarization by optical pumping and determination of nuclear polarization via photoionization in a MOT



reached 99.12(9) % nuclear polarization by optical pumping in the MOT magneto-optical trap

# of photoions produced from $4P_{1/2}$ state with 355 nm laser light



Fenker, Behr, Melconian et al., New J. Phys. 18 (2016) 073028

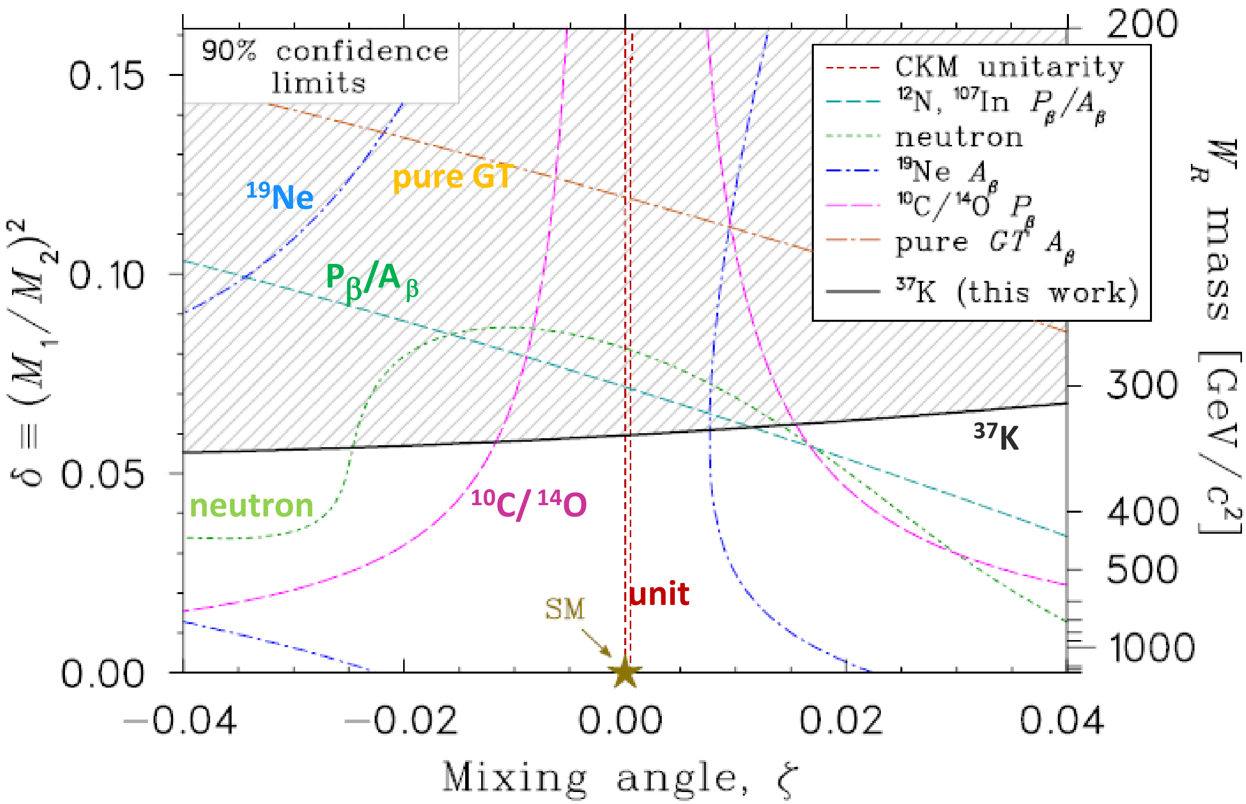


FIG. 5. (Color online) Constraints on manifest L-R symmetric models from nuclear and neutron [34] β decay. We show complementarity of our result with: CKM unitarity [16]; the ratio of β^+ polarization to A_β of ^{12}N and ^{107}In [2, 35]; A_β of mixed GT/F ^{19}Ne [14, 36–38]; the β^+ polarization of ^{10}C compared to ^{14}O [39]; and the weighted average of A_β of three recent GT cases [40–42]. All present results include SM, i.e. $\zeta = 0$ and $\delta = 0$, at 90%.

Fenker, Behr, Melconian et al., PRL 120 (2018) 062502

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Testing Time-Reversal Invariance

Focus on triple-correlation coefficients (zero in Standard Model):

D $\frac{\langle \mathbf{J} \rangle}{J} \cdot \frac{\mathbf{p}_e \times \mathbf{p}_\nu}{E_e E_\nu}$

$$D\xi = \delta_{J'J} M_F M_{GT} \sqrt{\frac{J}{J+1}} \Big[2\,\mathrm{Im}\,(C_S C_T^* - C_V C_A^* + C'_S C'^*_T - C'_V C'^*_A) \mp \frac{\alpha Z m}{p_e} 2\,\mathrm{Re}\,(C_S C_A^* - C_V C_T^* + C'_S C'^*_A - C'_V C'^*_T) \Big]$$

R $\sigma \cdot \frac{\langle \mathbf{J} \rangle}{J} \times \frac{\mathbf{p}_e}{E_e}$

$$R\xi = |M_{GT}|^2 \lambda_{J'J} \Big[\pm 2\,\mathrm{Im}\,(C_T C'^*_A + C'_T C_A^*) - \frac{\alpha Z m}{p_e} 2\,\mathrm{Re}(C_T C'^*_T - C_A C'^*_A) \Big] + \delta_{J'J} M_F M_{GT} \sqrt{\frac{J}{J+1}} \Big[2\,\mathrm{Im}\,(C_S C'^*_A + C'_S C_A^* - C_V C'^*_T - C'_V C_T^*) \mp \frac{\alpha Z m}{p_e} 2\,\mathrm{Re}\,(C_S C'^*_T + C'_S C_T^* - C_V C'^*_A - C'_V C_A^*) \Big]. \quad \text{(A.16)}$$

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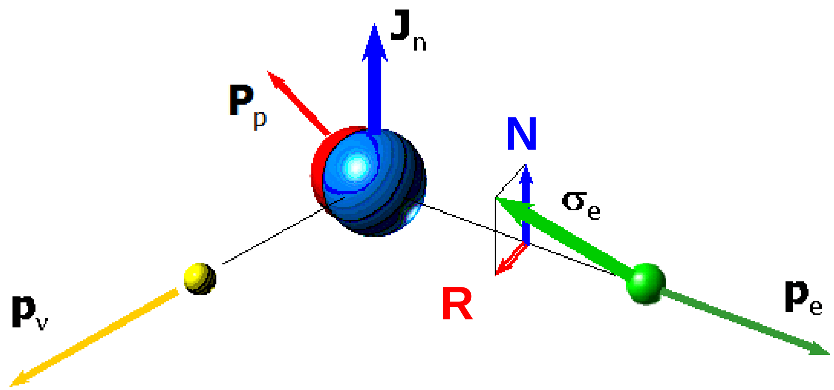
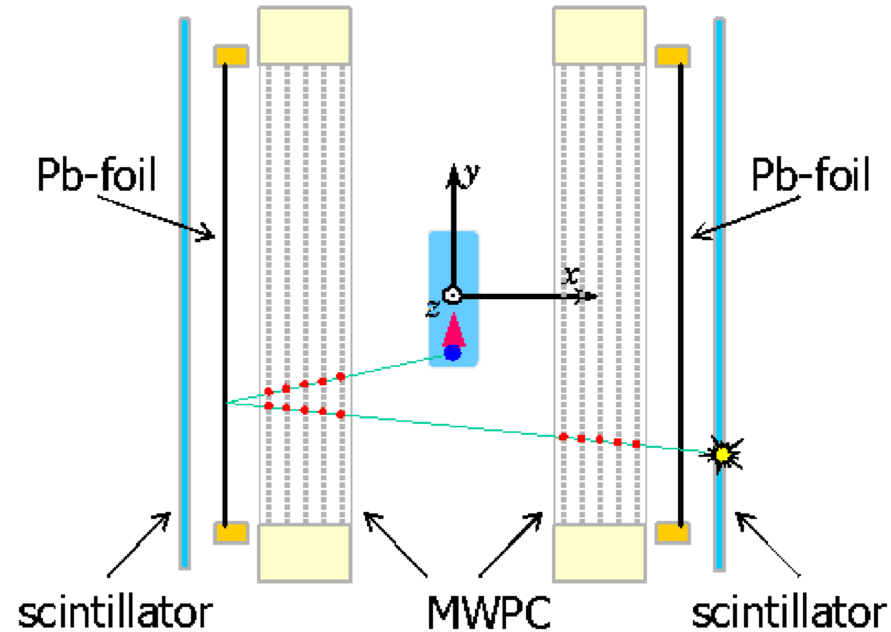
The nTRV experiment at the Paul Scherrer Institute

(Univ. Krakow, PSI, LPC-Caen, K.U.Leuven, …)

(SINQ-FUNSPIN)

$$W(\mathbf{J}, \hat{\boldsymbol{\sigma}}, E, \mathbf{p}) \propto 1 + \frac{\mathbf{J}}{J} \cdot \left(A \frac{\mathbf{p}}{E} + R \frac{\mathbf{p} \times \hat{\boldsymbol{\sigma}}}{E} + N \hat{\boldsymbol{\sigma}} \right)$$





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

$$R = -0.218 \ \mathrm{Im}\left(\frac{C_S + C_S'}{C_A}\right) + 0.335 \ \mathrm{Im}\left(\frac{C_T + C_T'}{C_A}\right) \boxed{- \frac{m_e}{137\, p} A} \rightarrow R_{SM}$$

$$N \ \bar{\sigma} \cdot \bar{J}$$

$$N = -0.218 \ \mathrm{Re}\left(\frac{C_S + C_S'}{C_A}\right) + 0.335 \ \mathrm{Re}\left(\frac{C_T + C_T'}{C_A}\right) \boxed{- \frac{m_e}{E} A} \rightarrow N_{SM}$$

A. Kozela et al., Phys. Rev. Lett. 102 (2009) 172301;
A. Kozela et al., Phys. Rev. C 85 (2012) 045501

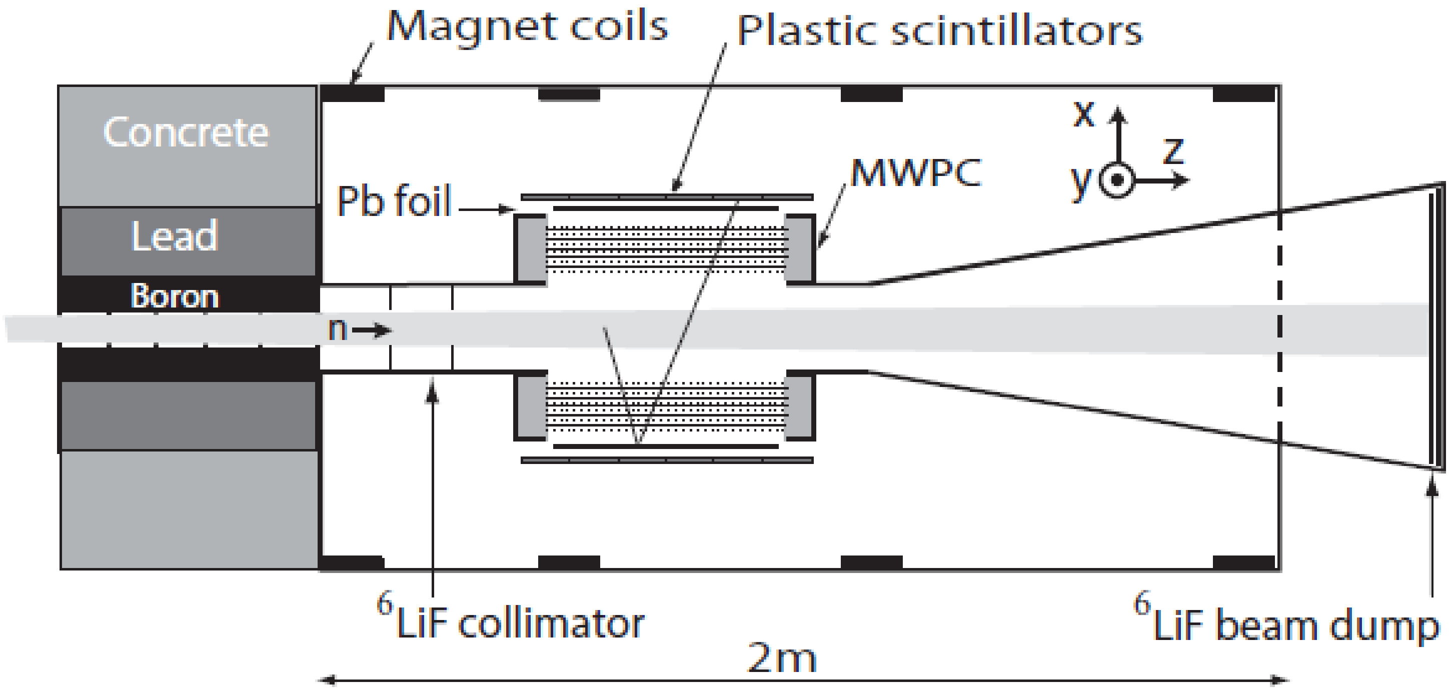
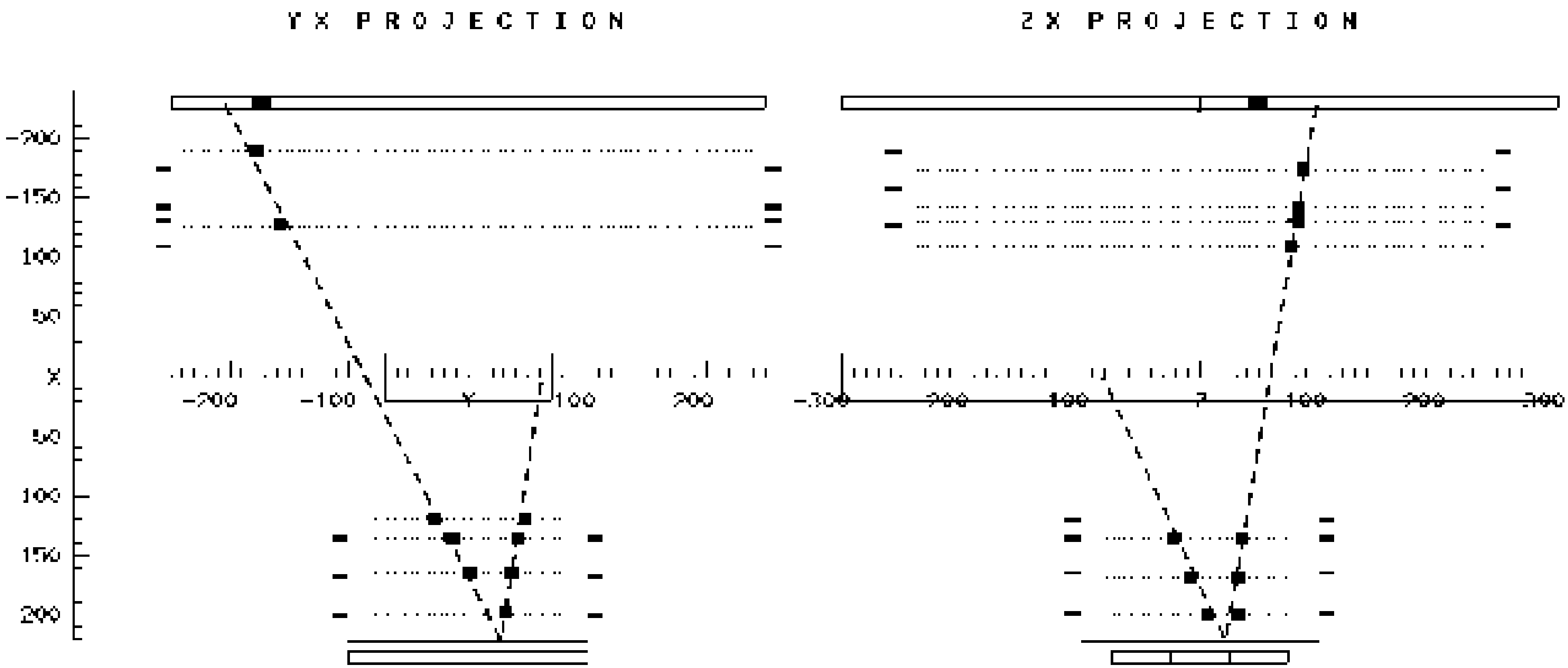


FIG. 3. Schematic top view of the experimental setup. A sample projection of an electron V-track event is shown. The coordinate system used throughout this paper is indicated.

A. Kozela et al., Phys. Rev. Lett. 102 (2009) 172301;
A. Kozela et al., Phys. Rev. C 85 (2012) 045501

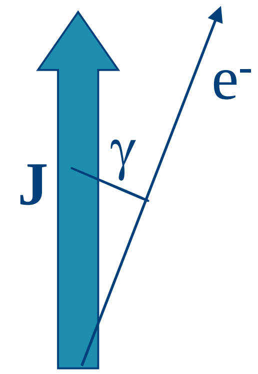
‘V-tracks’



Left-right asymmetry for Mott-scattering of electrons in the field of a spin-zero nucleus (Pb)
For electrons with spin perpendicular to the scattering plane, allows to determine the size of this transverse electron polarization.

nuclear polarization determined from β asymmetry

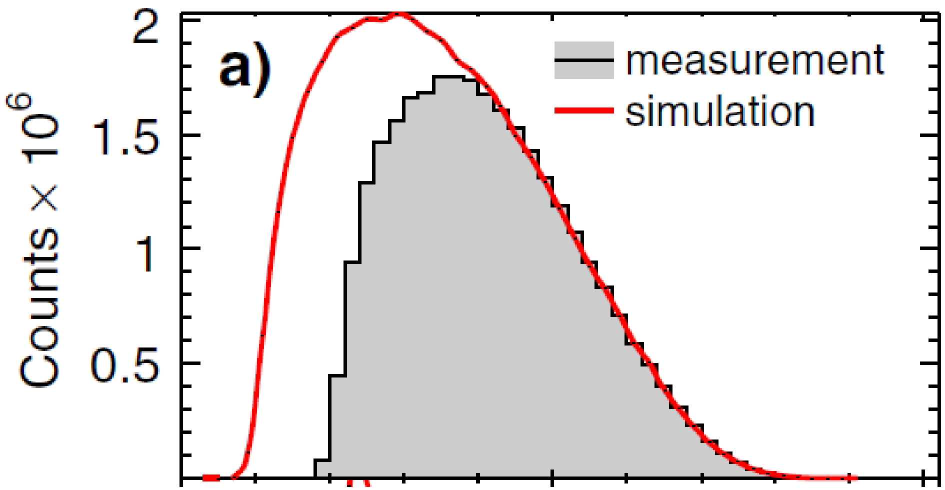
$$\mathcal{E}(\beta,\gamma) = \frac{N^+(\beta,\gamma) - N^-(\beta,\gamma)}{N^+(\beta,\gamma) + N^-(\beta,\gamma)} = P\beta A\cos(\gamma)$$



$N^{+,-}$: singles electron count rate for the two neutron spin directions

β = v/c

A = -0.1173(13) from PDG(2008)



→ P = 0.774 (2) (7)

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determination of *N* and *R* correlation coefficients

$$\mathcal{A}(\alpha) = [n^+(\alpha) - n^-(\alpha)]/[n^+(\alpha) + n^-(\alpha)]$$

$n^{+,-}$: V-track count rate for the two neutron spin directions

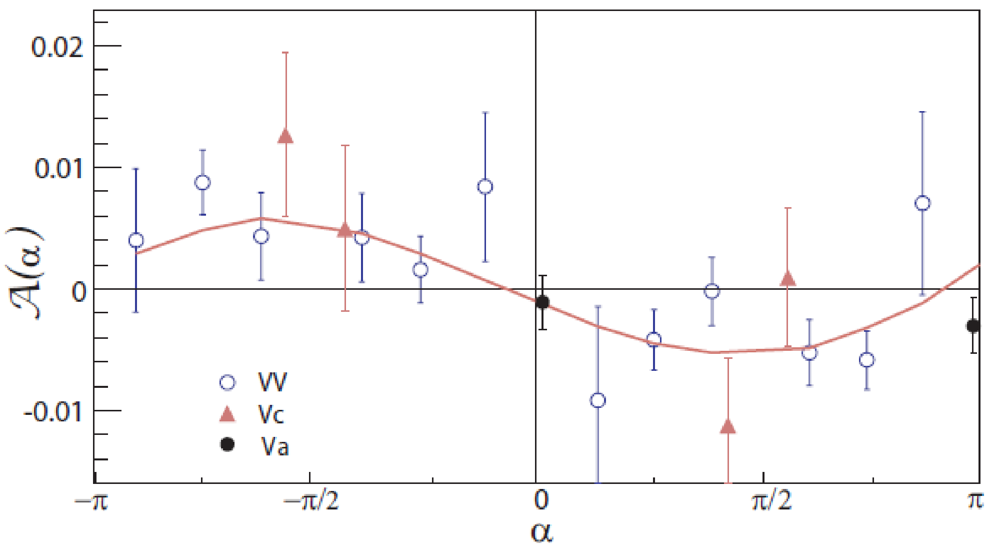
α : angle between electron scattering and neutrons decay planes

$$\mathcal{A}(\alpha) - P\bar{\beta}A\bar{\mathcal{F}}(\alpha) = P\bar{S}(\alpha)[N\bar{\mathcal{G}}(\alpha) + R\bar{\beta}\bar{\mathcal{H}}(\alpha)]$$

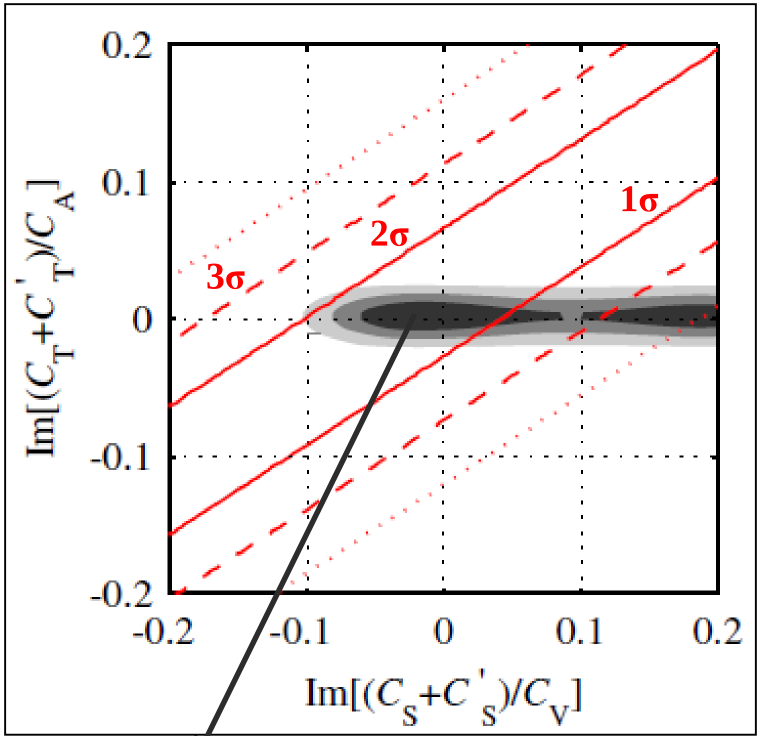
$\langle \hat{\mathbf{J}} \cdot \hat{p} \rangle$ — ***A***

$\langle \hat{\mathbf{J}} \cdot \hat{\boldsymbol{\sigma}} \rangle$ — ***N***

$\langle \hat{\mathbf{J}} \cdot \hat{\mathbf{p}} \times \hat{\boldsymbol{\sigma}} \rangle$ — ***R***



$$W(\mathbf{J}, \hat{\boldsymbol{\sigma}}, E, \mathbf{p}) \propto 1 + \frac{\mathbf{J}}{J} \cdot \left(A \frac{\mathbf{p}}{E} + R \frac{\mathbf{p} \times \hat{\boldsymbol{\sigma}}}{E} + N \hat{\boldsymbol{\sigma}} \right)$$



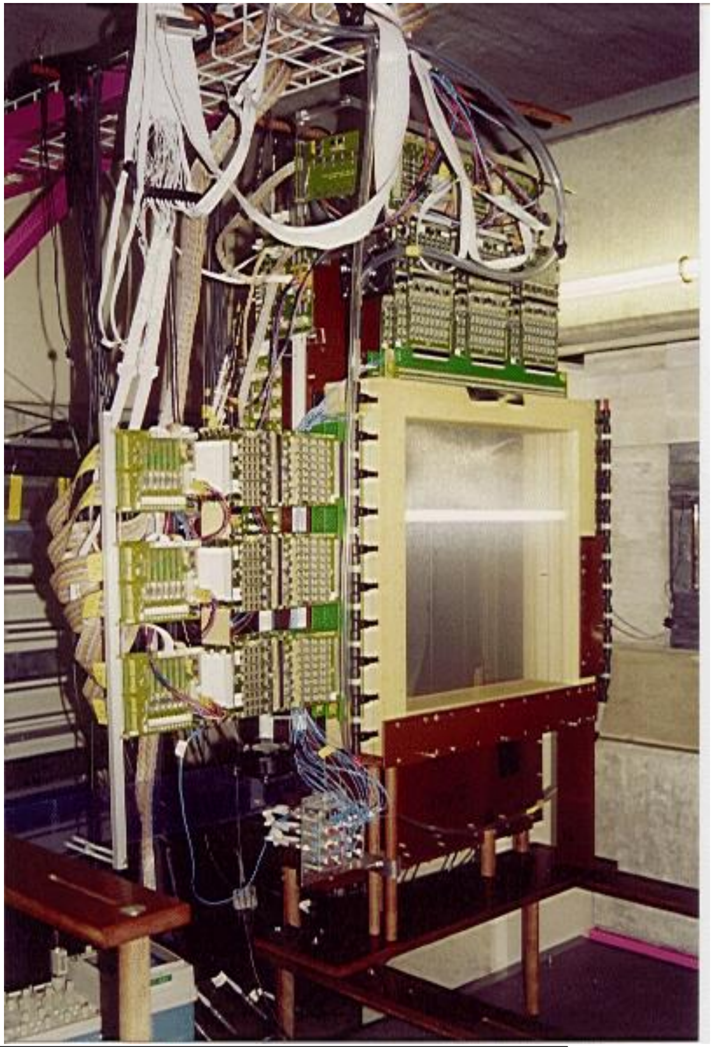
R_{exp} = 0.004(13)

R_{SM} = 0.0006(2)

N_{exp} = 0.067(12)

N_{SM} = 0.068(1)

most precise determinations of N and R to date



limits from N. Severijns et al., Rev. Mod. Phys. 78 (2006) 991

The result for R improves the constraints on time-reversal violating (imaginary) scalar couplings as shown in the figure above (red bands are allowed regions from R; black/grey is situation before).

The result for N is the first result ever for N. It served to check the quality of the method and data analysis, but is not significantly precise to contribute to existing limits for scalar/tensor currents).

A. Kozela et al., Phys. Rev. Lett. 102 (2009) 172301; A. Kozela et al., Phys. Rev. C 85 (2012) 045501

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