The Neutrino Electron Correlation Coefficient in Free Neutron Decay: Latest Results with the *a*SPECT Spectrometer

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The *a*SPECT collaboration

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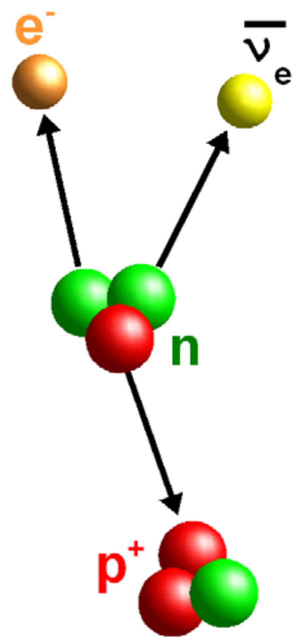
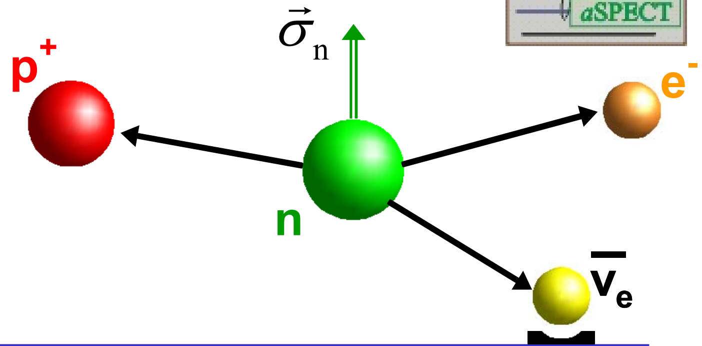


Outline

- The Antineutrino-electron angular correlation coefficient a in free neutron decay
- The Neutron decay spectrometer aSPECT
- Preliminary results from the beam time at ILL, Grenoble (Spring 2008)
- Improvements and Outlook
- Summary

Neutron Decay Parameters (SM)



$$H_{\text{weak}} = G_F V_{ud} \langle n | \gamma^\mu - \lambda \gamma^\mu \gamma^5 | p \rangle \langle \nu_e | \gamma_\mu - \gamma_\mu \gamma_5 | e^- \rangle$$

Jackson et al., PR **106**, 517 (1957)

$$dW \propto \underbrace{G_F^2 V_{ud}{}^2 \left(1 + 3|\lambda|^2\right)} \cdot \left\{ 1 + a \frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + b \frac{m_e}{E_e} + \vec{\sigma}_n \cdot \left(A \frac{\vec{p}_e}{E_e} + B \frac{\vec{p}_\nu}{E_\nu} + D \frac{\vec{p}_e \times \vec{p}_\nu}{E_e E_\nu} \right) \right\}$$

Neutron lifetime | Neutrino-Electron Correlation | Beta-Asymmetry

$$\tau_n^{-1} \propto G_F^2 V_{ud}{}^2 \left(1 + 3|\lambda|^2\right)$$

$$a = \frac{1 - |\lambda|^2}{1 + 3|\lambda|^2}$$

$$A = -2 \frac{|\lambda|^2 + |\lambda| \cos\phi}{1 + 3|\lambda|^2}$$

Coupling constant ratio $\lambda = \left| \frac{g_A}{g_V} \right| e^{i\phi}$, where phase ϕ = 180° (within the SM)

λ can be extracted from measurements of either a, A or B

$\Rightarrow$ over-determined process

Possible Tests of the Standard Model

- Search for Right-handed Currents
  - W_R?
- Search for Scalar and Tensor Interactions
  - Leptoquarks? Charged Higgs Bosons?
- Search for Supersymmetric Particles
  - (Loop corrections to Beta Decay change Coupling Constants)
- Test of the Unitarity of the Cabibbo-Kobayashi-Maskawa-Matrix

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{td} & V_{tb} \end{pmatrix} \cdot \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$|V_{ud}|^2 = \frac{(4908.7 \pm 1.9)\,s}{\tau_n (1 + 3\lambda^2)}$$

B/ D mesons

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$$

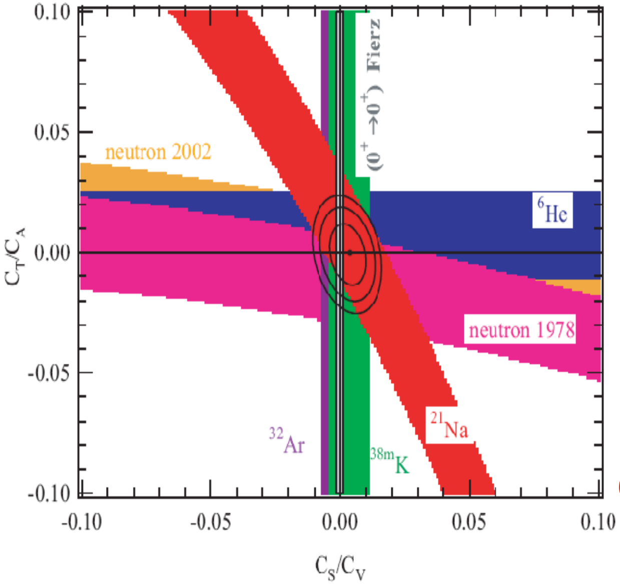
Kaon decays

Search for Scalar and Tensor Interactions

Left-handed Scalar and Tensor Model:

(Time reversal invariance)

$$\frac{g_V'}{g_V}=1,\quad \frac{g_A'}{g_A}=1,\quad \frac{g_S'}{g_V}=\frac{g_S}{g_V},\quad \text{and}\quad \frac{g_T'}{g_A}=\frac{g_T}{g_A}$$

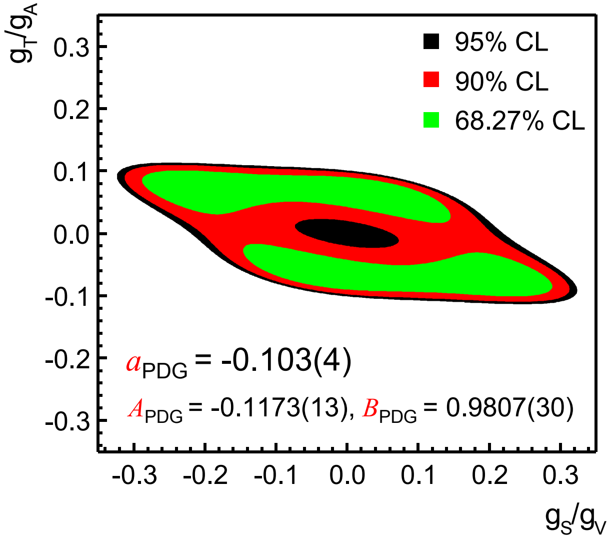


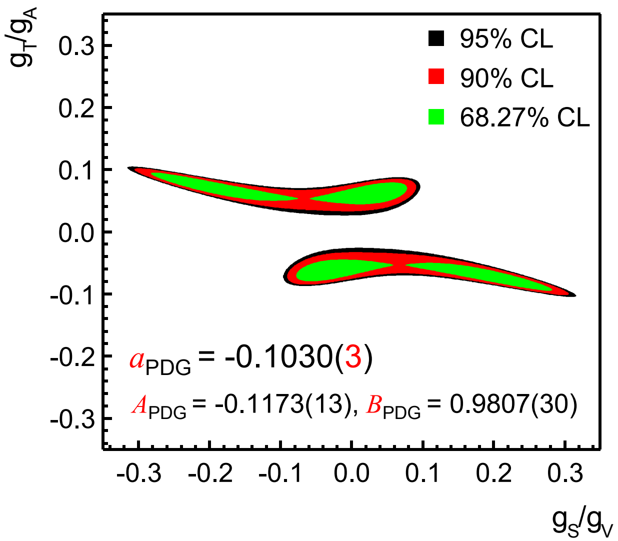
P.A. Vetter et al., Phys. Rev. C **77,** 035502 (2008)

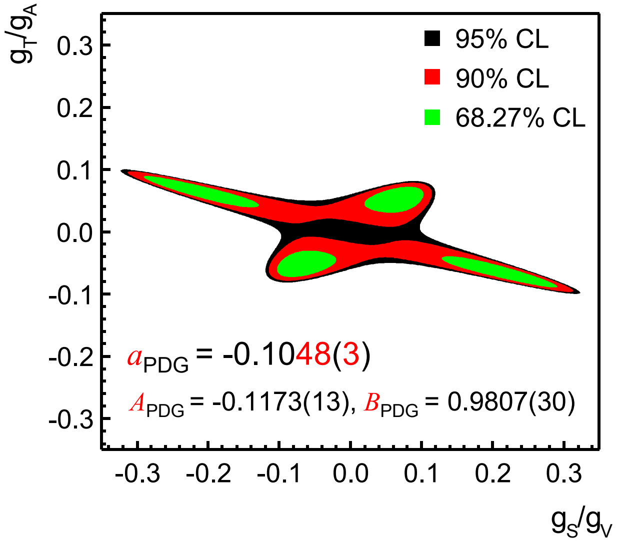
Right-handed Scalar and Tensor Model:

(Time reversal invariance and b = 0)

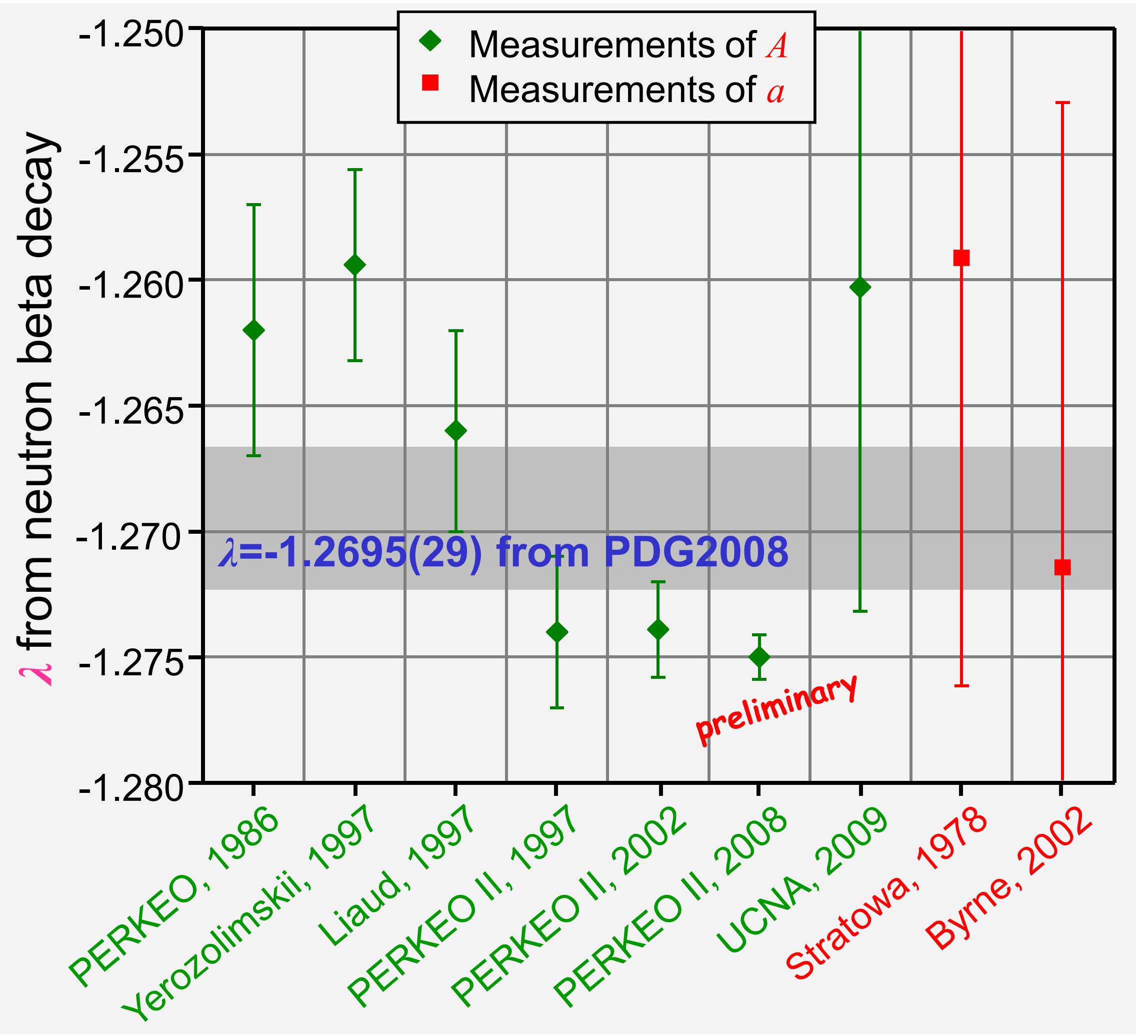
$$\frac{g_V'}{g_V}=1,\quad \frac{g_A'}{g_A}=1,\quad \frac{g_S'}{g_V}=-\frac{g_S}{g_V},\quad \text{and}\quad \frac{g_T'}{g_A}=-\frac{g_T}{g_A}$$







Determination of $\lambda = g_A / g_V$



- PERKEO II is the systematically cleanest experiment
- Still the disagreement with older measurements is not explained
- A measurement of a is independent of possible unknown errors in A; systematics are entirely different

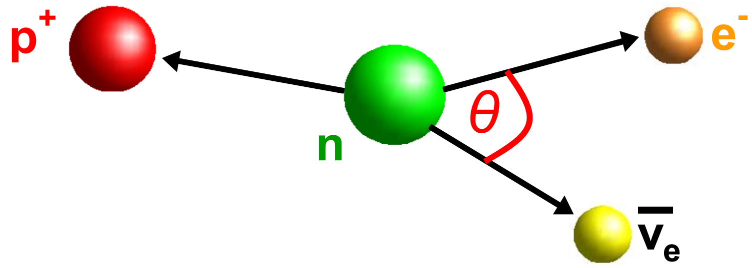
Present best experiments have $\Delta a/a \sim 5\ \%$

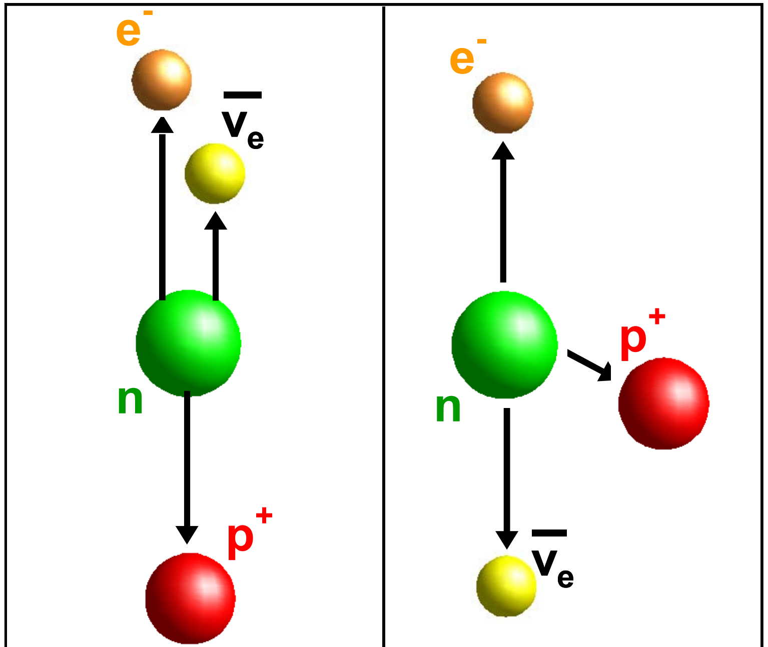
Aim of aSPECT is $\Delta a/a \sim 0.3\%$ ≙

The Neutrino-Electron Correlation *a* and the Proton Spectrum in Neutron Decay

The Correlation coefficient *a*

$$dW \propto \left(1 + a \frac{v_e}{c} \cos\left(\vec{p}_e, \vec{p}_\nu\right)\right)$$

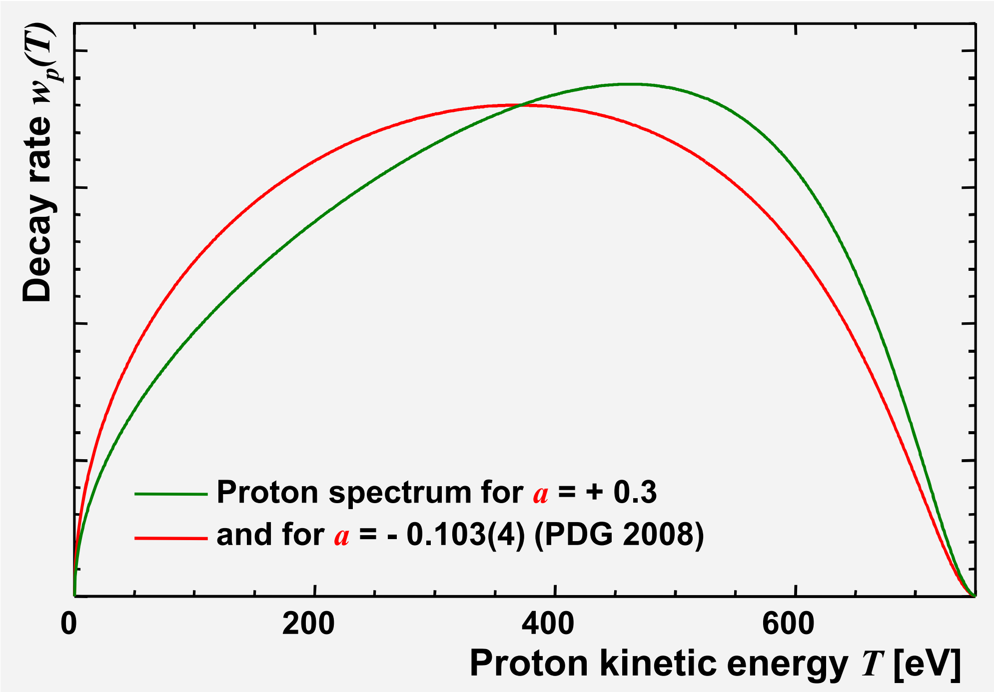




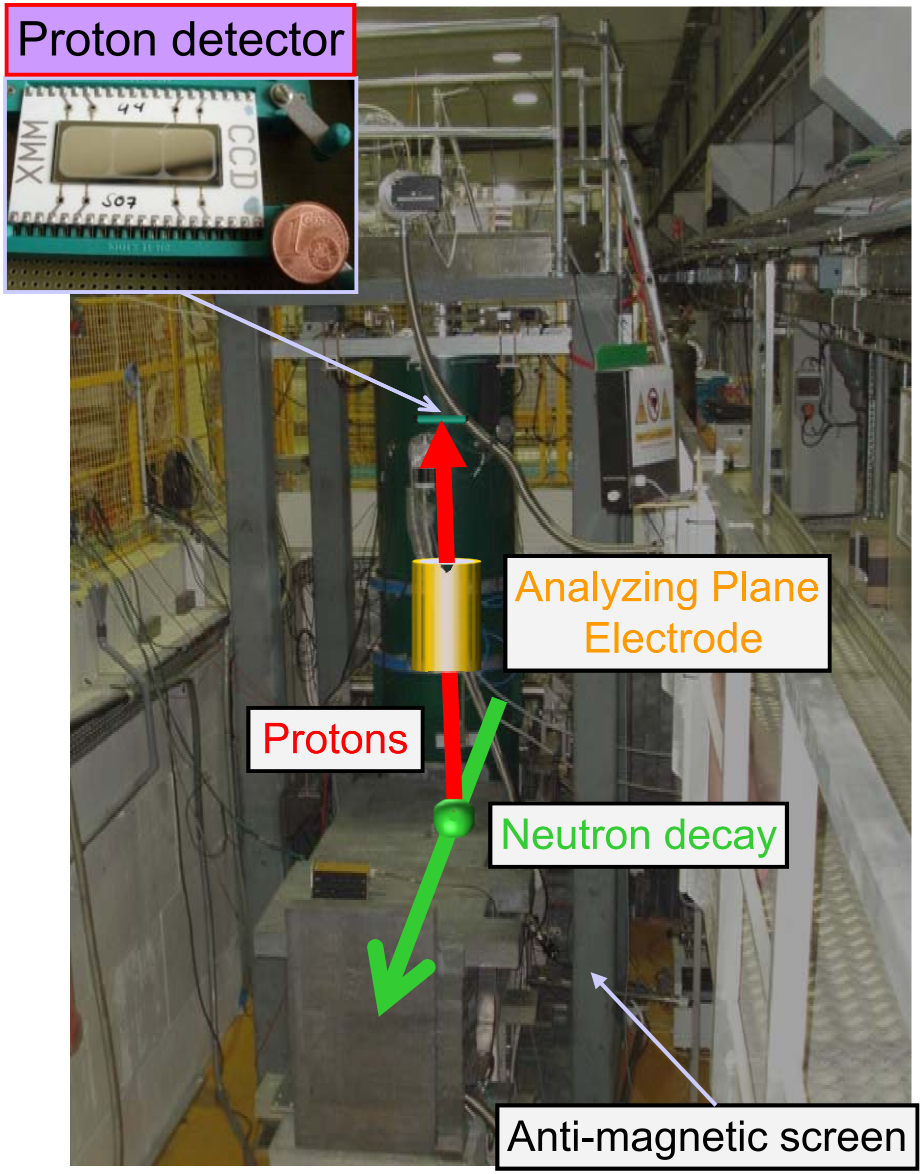
Proton kinetic energy is big

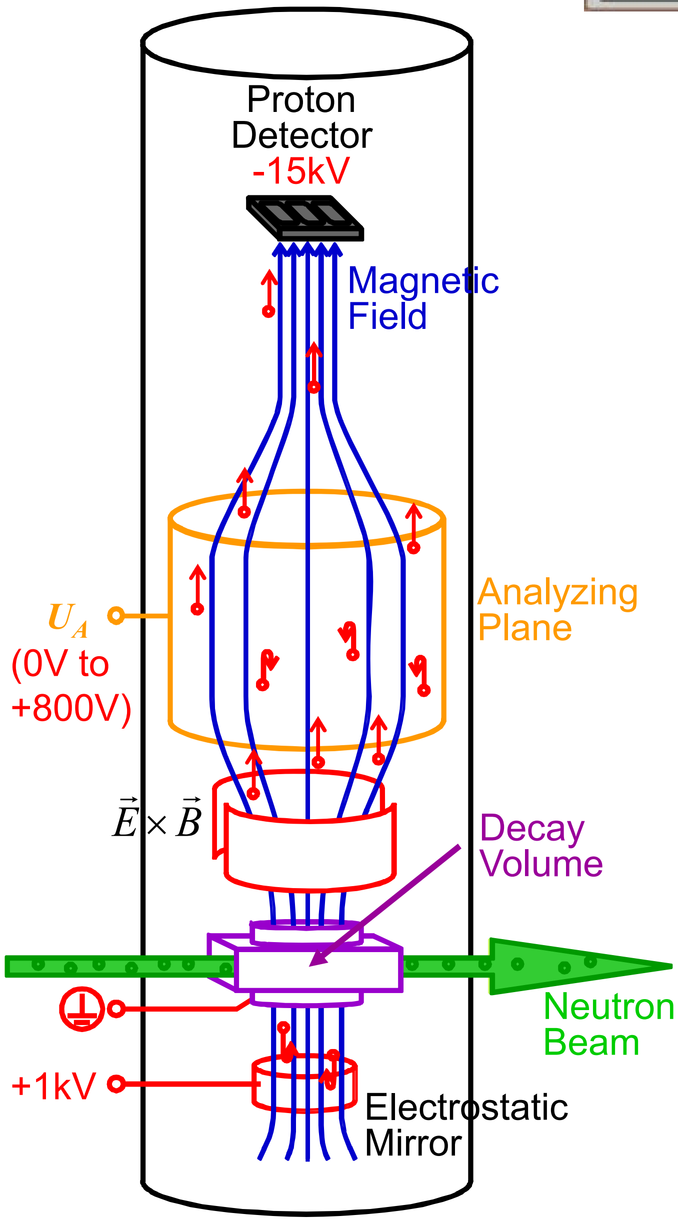
Proton kinetic energy is small

Sensitivity of the Proton Spectrum to *a*

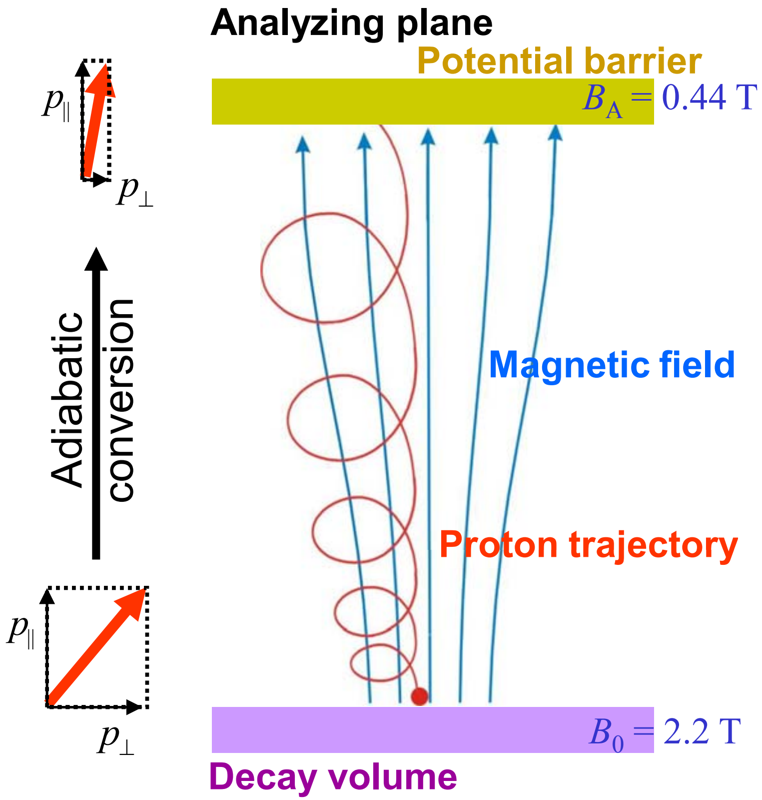


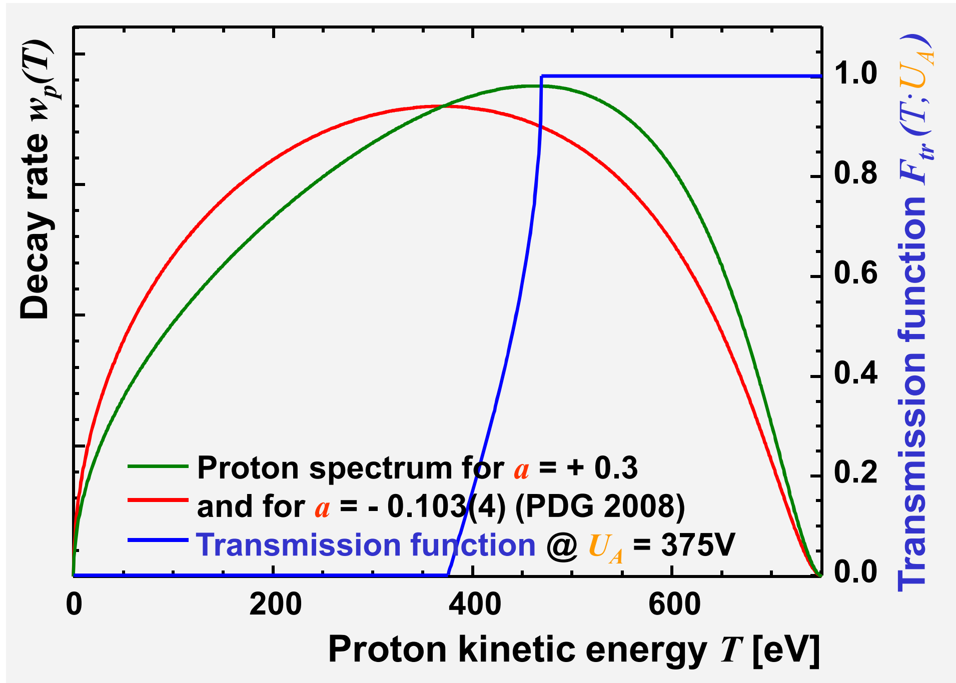
Setup of *a*SPECT at PF1b/ ILL and Spectrometer sketch





Principle of a Retardation spectrometer



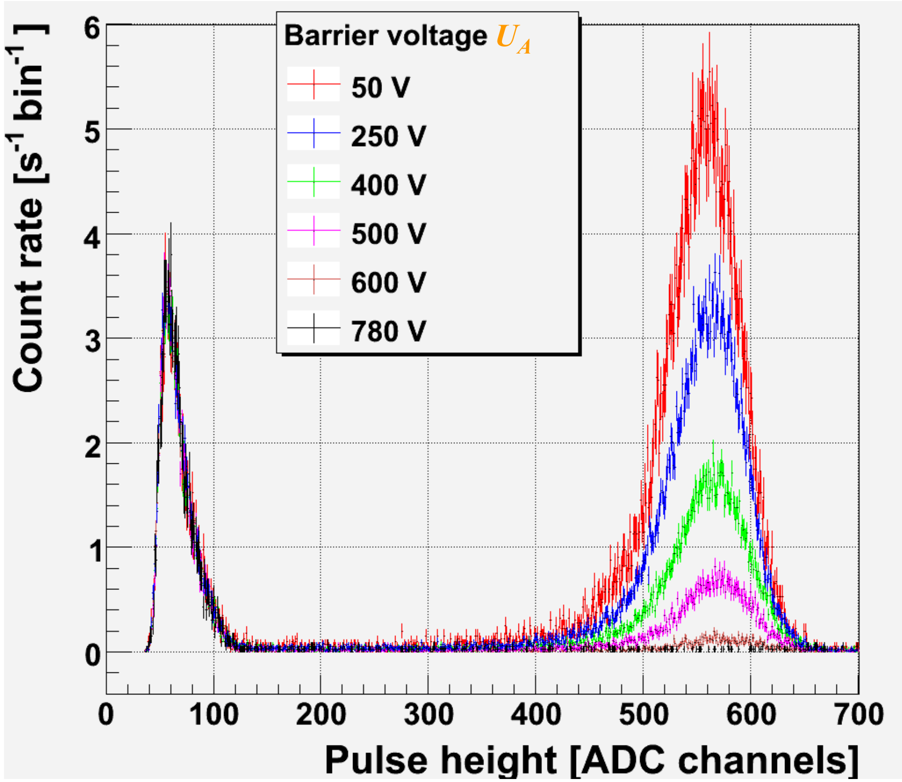


Transmission function $F_{tr}(T;U_A)$ in the adiabatic limit

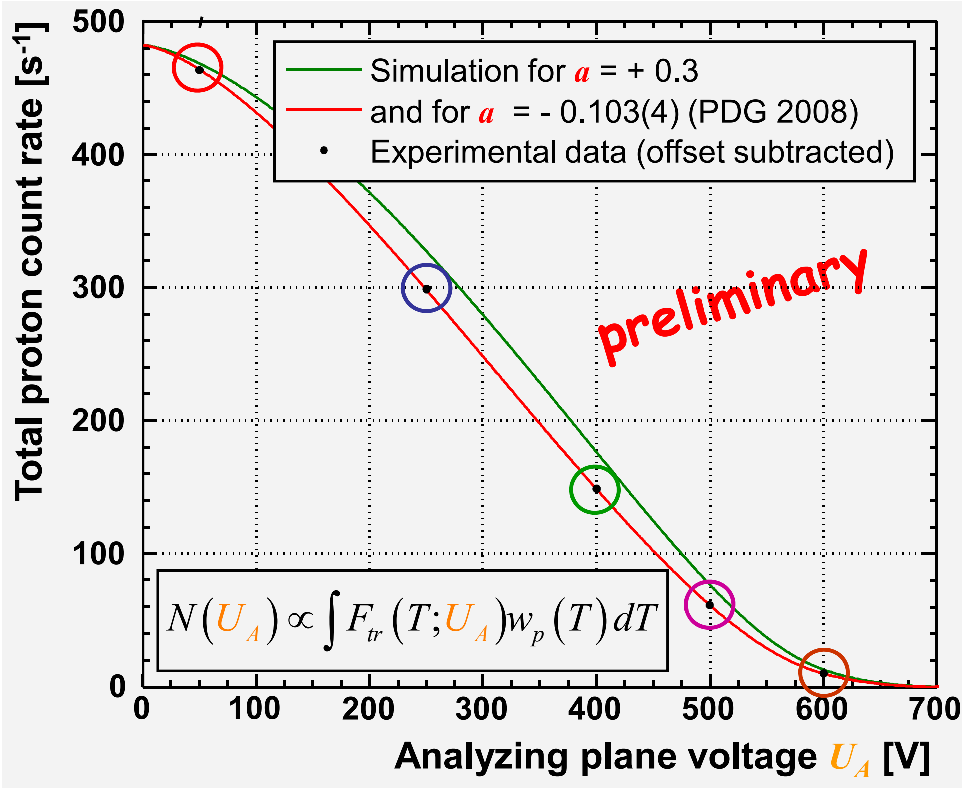
$$F_{tr}(T;U_A) = \begin{cases} 0 & ; \quad T < eU_A \\ 1 - \sqrt{1 - B_0/B_A\left(1 - eU_A/E\right)} & ; \quad \text{otherwise} \\ 1 & ; \quad T > eU_A/\left(1 - B_A/B_0\right) \end{cases}$$

Principle of extraction of *a* and Statistical sensitivity

Pulse height spectrum



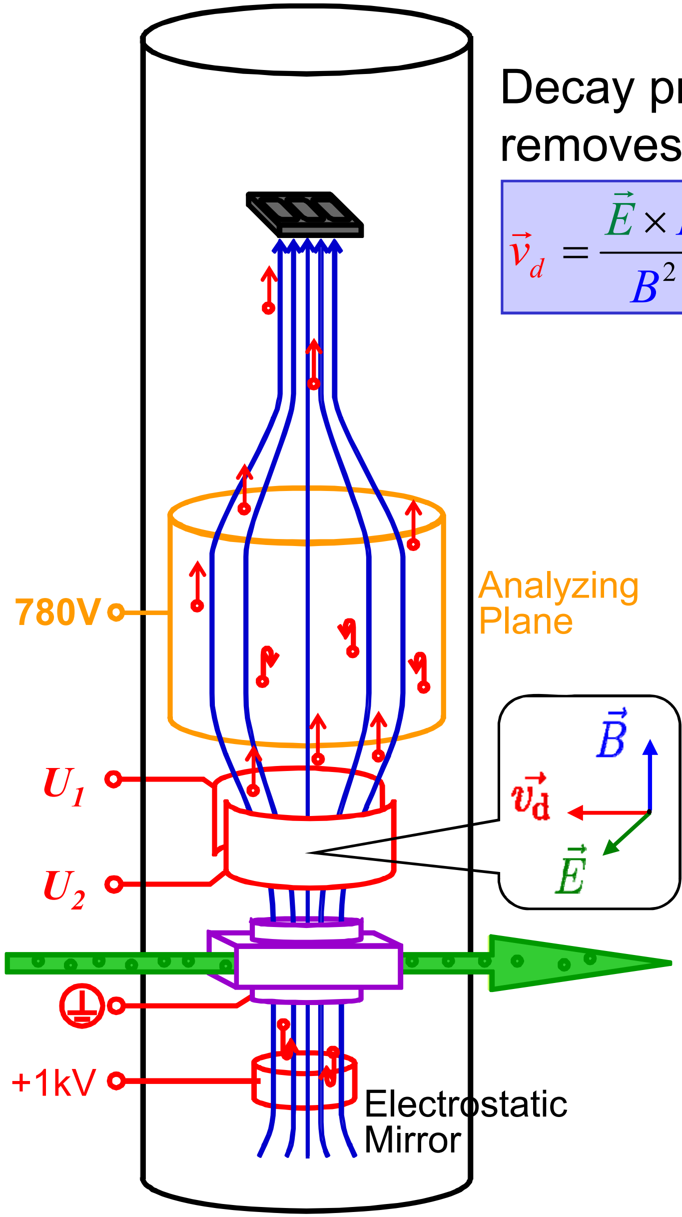
Integrated Proton Spectrum



- About 470 events per second at U_A = 50 V (on one detector pad)
- Statistical sensitivity to *a* about 2 % per 24 hours measurement time

M. Simson et al., Proceedings of the IWPPSN, Nucl. Instr. and Meth. A, accepted, arXiv:0811.3851
G. Konrad et al., Proceedings of the PANIC08, submitted to Nucl. Phys. A

Systematic effects I: Trap Cleaning

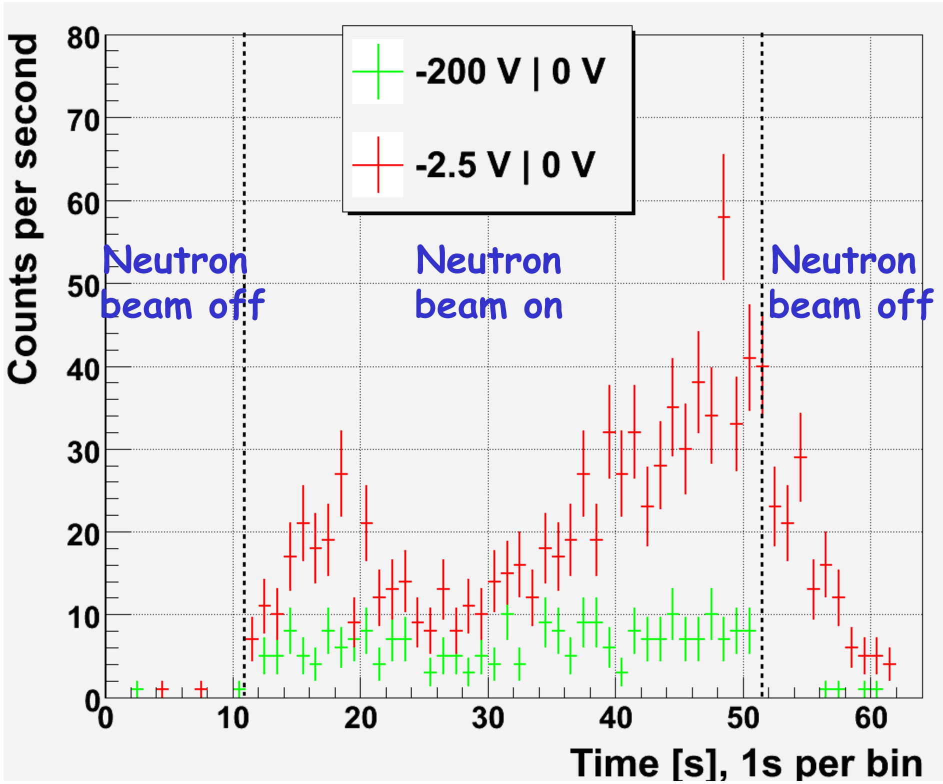


Decay protons can be shifted with an $\vec{E}\times\vec{B}$ electrode, that removes charged particles stored between AP and Mirror

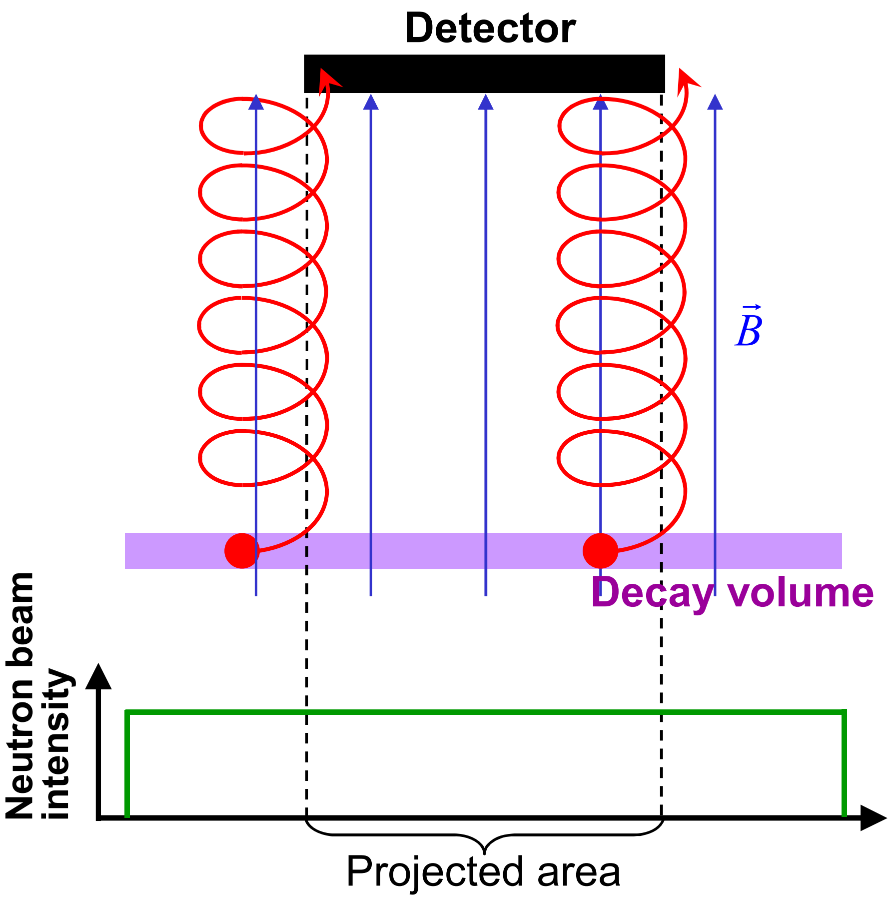
$$\vec{v}_d = \frac{\vec{E}\times\vec{B}}{B^2}$$

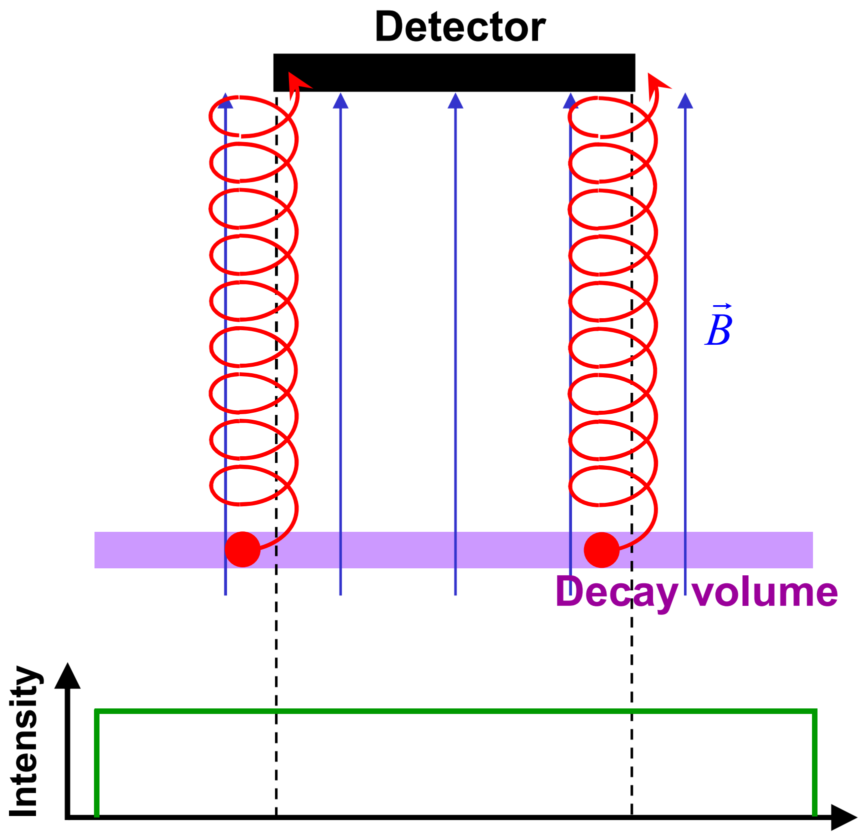
Background measured @ U_A = 780V

for two different settings of the $\vec{E}\times\vec{B}$ electrode



Systematic effects II: Edge effect

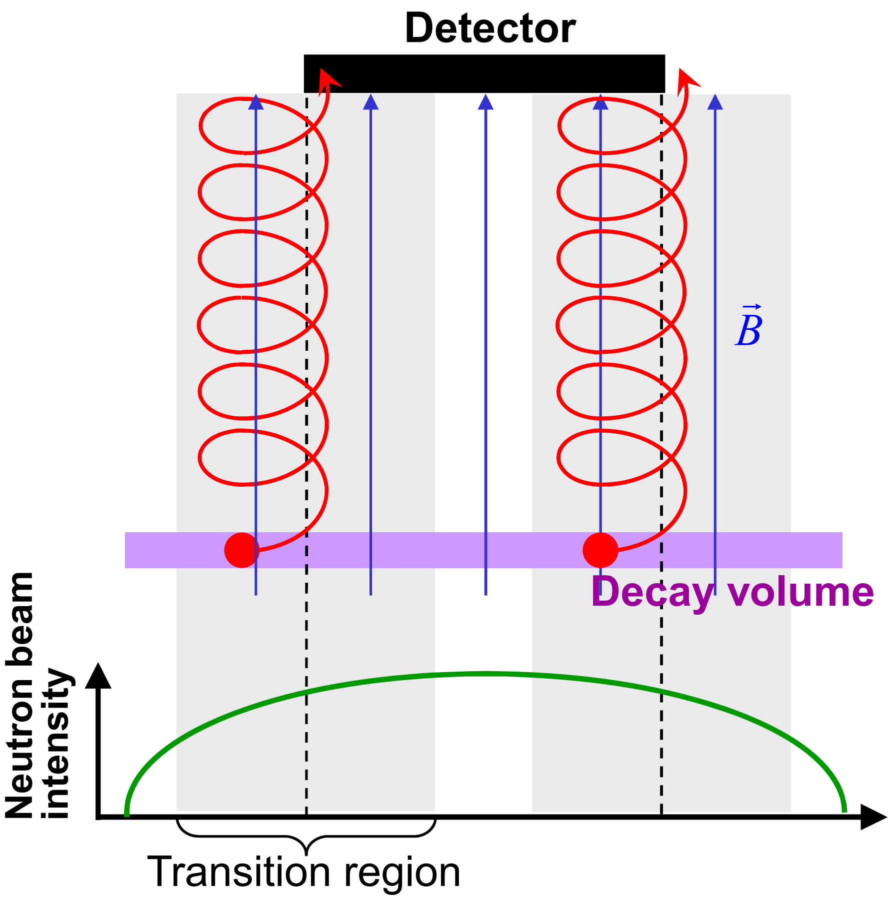


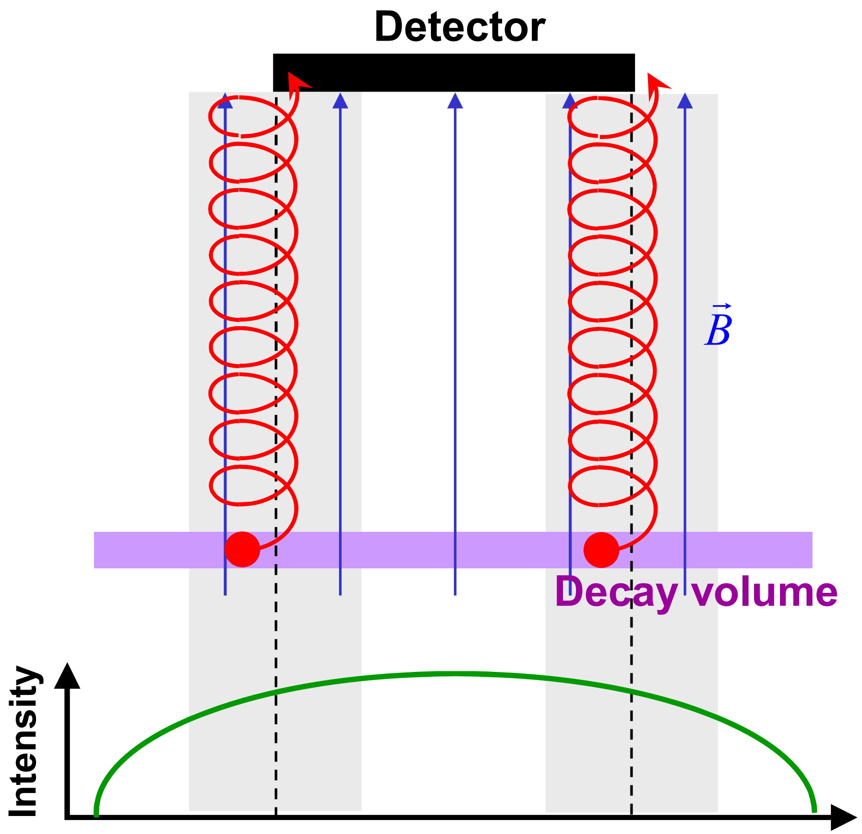


- Protons produced outside the directly projected volume can hit the detector
- and protons produced within the projected area might miss the detector

This two effects cancel if the beam profile is flat, independent of the proton gyration radius

Systematic effects II: Edge effect





… But if the profile is non-flat the probabilities for the two cases become different, and dependent on the proton gyration radius

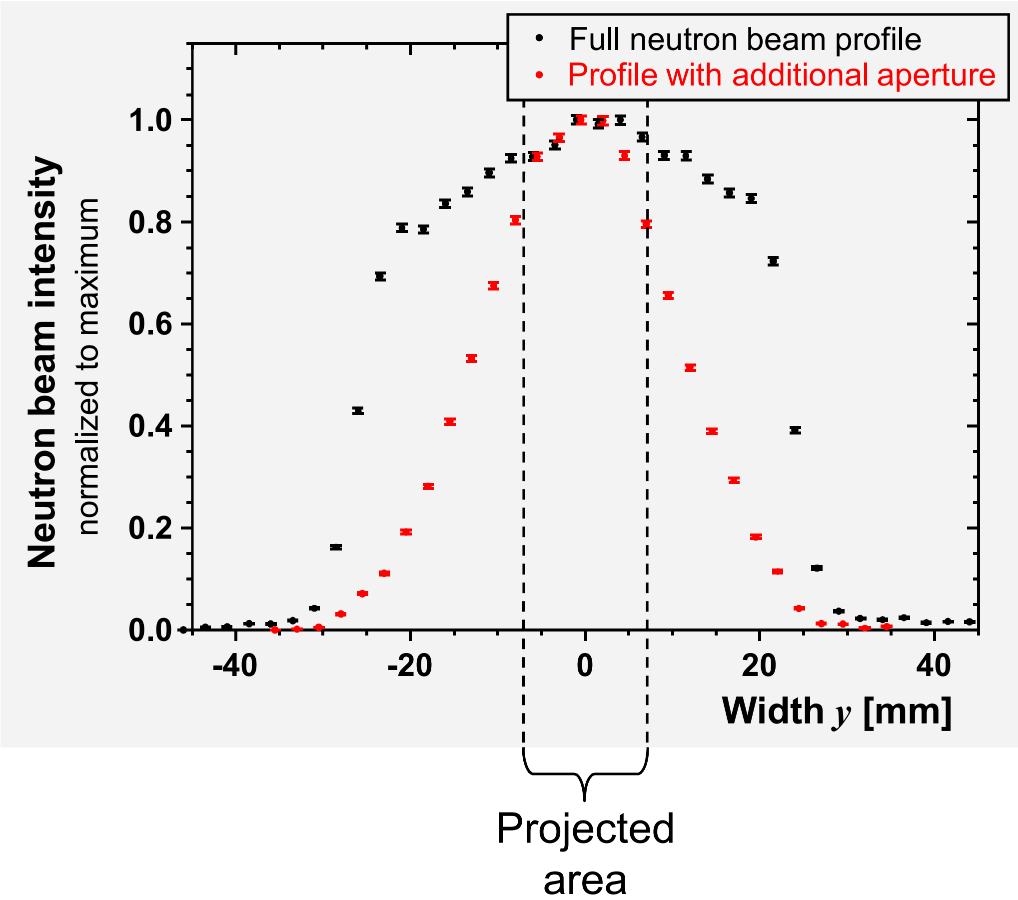
The gyration radius depends on the initial angle and energy of the proton

⇒ The beam profile has to be sufficiently flat or well known

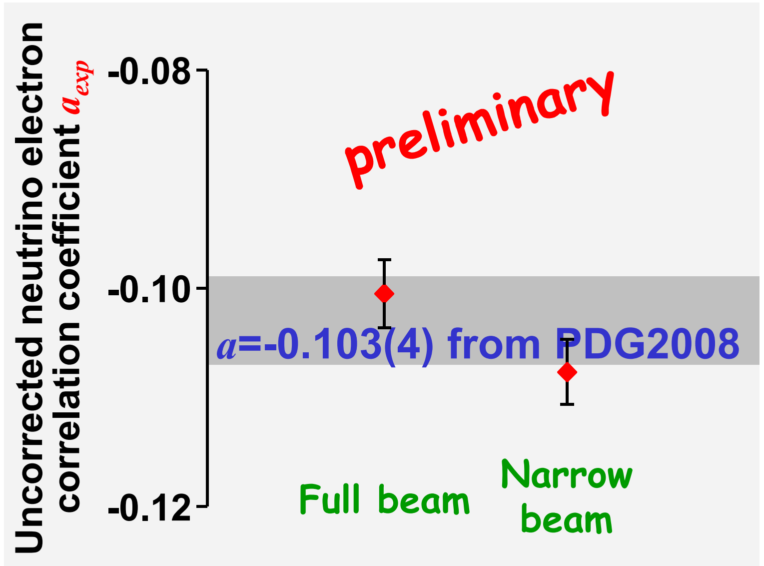
Systematic effects II: Edge effect

Neutron beam profile

at the exit flange of the spectrometer
for two different apertures



The Correlation coefficient a

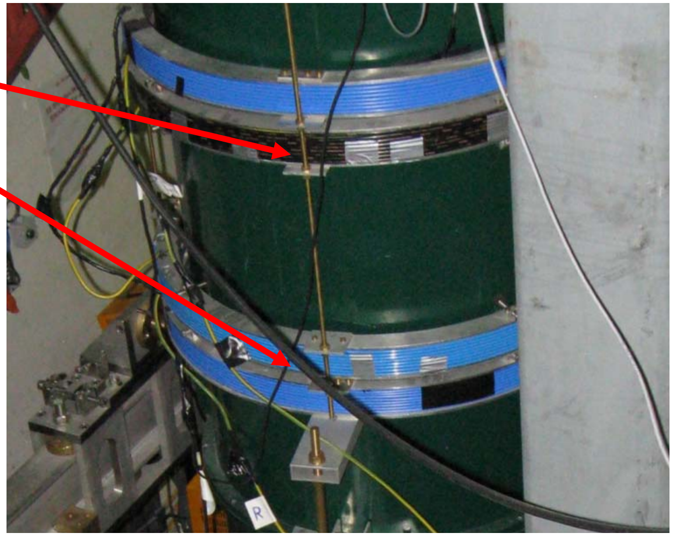


Each data point corresponds to about 14 hours of measurement time

… Monte Carlo simulations are currectly on the way

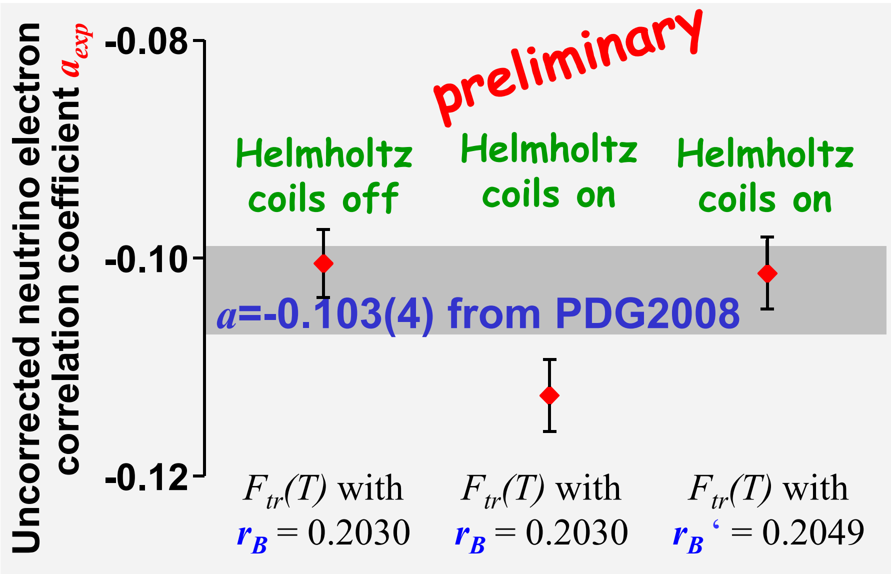
Systematic effects III: The Magnetic field ratio

External Helmholtz coils allow us to change magnetic field ratio $r_B = B_A / B_0$



For 0 A: r_B = 0.2030; For 50 A: r_B' = 0.2049

$$F_{tr}(T;U_A) = \begin{cases} 0 & ; \quad T < eU_A \\ 1 - \sqrt{1 - B_0/B_A (1 - eU_A/E)} & ; \quad \text{otherwise} \\ 1 & ; \quad T > eU_A / (1 - B_A/B_0) \end{cases}$$



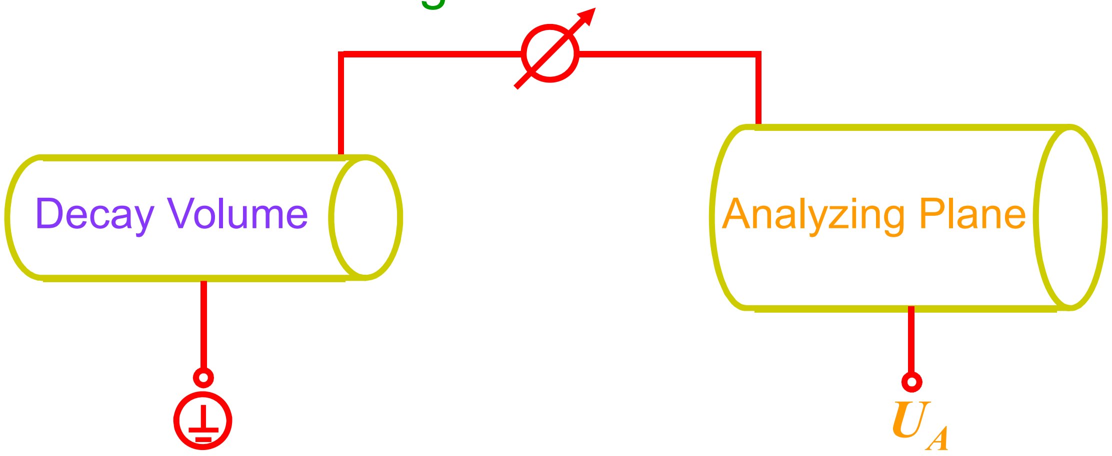
Correlation coefficient a_{exp} changes with the magnetic field ratio r_B, as described by a slightly different transmission function $F_{tr}(T;U_A)$

Each data point corresponds to about 14 hours of measurement time

Improvements and Outlook

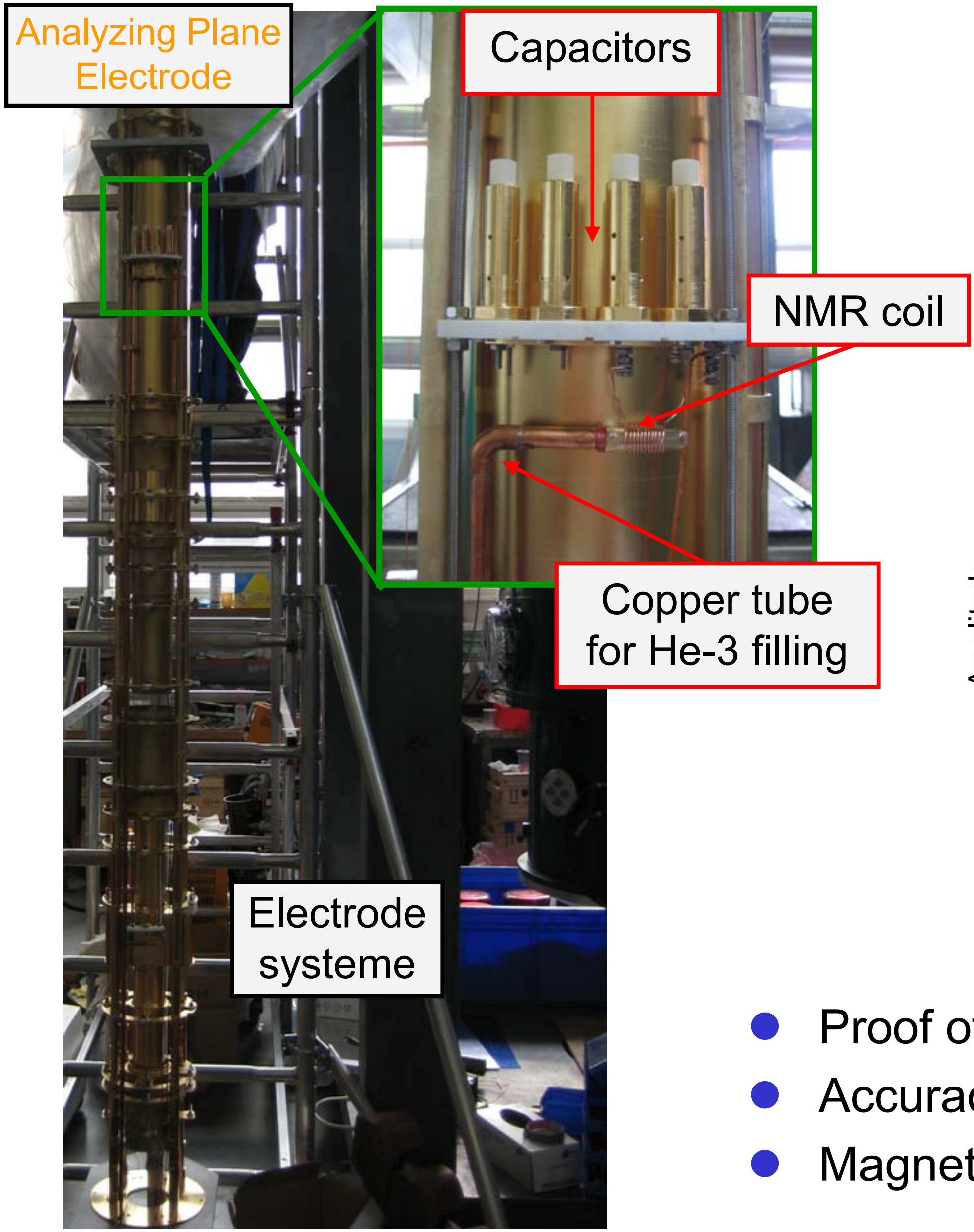
… But a $\Delta a/a$ ~ 0.3% measurement requires $\begin{cases} \Delta U \approx 10mV \\ \Delta\left(B_A/B_0\right) \approx 10^{-4} \end{cases}$

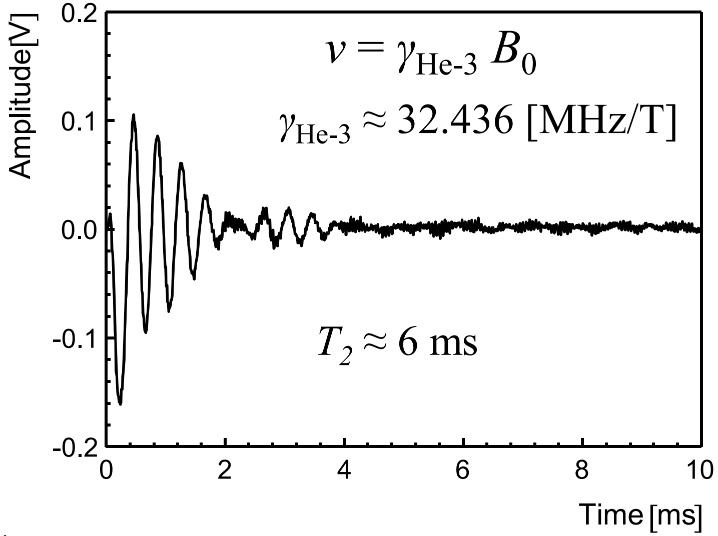
- Electric potential measurements: accurate voltage measurement with multimeter, but: Surface charges

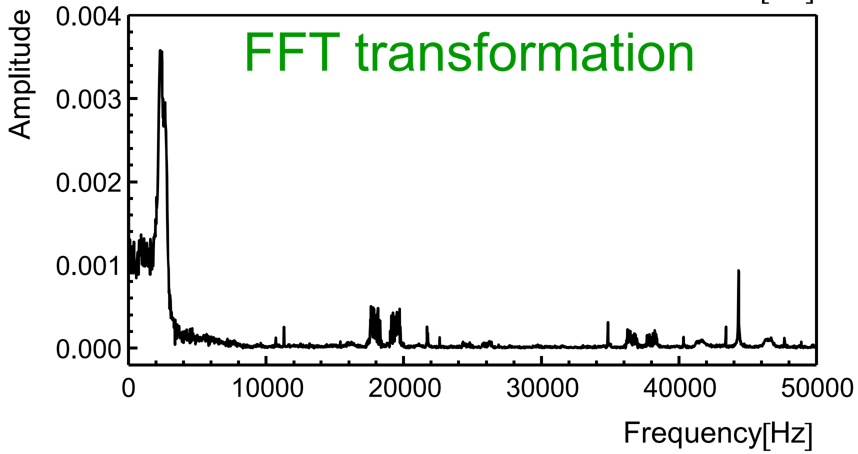


  - Investigations of the work function of the electrodes (Kelvin probe)
- Online monitoring of the magnetic field ratio
  - NMR system with polarized ^{3}He
- Calibration source

Online monitoring of the magnetic field ratio







- Proof of principle
- Accuracy better than 10^{-4}
- Magnetic field ratio $r_B = B_A / B_0$ stable in time

Summary

- *a*SPECT extracts *a* from the measured integrated proton spectrum in free neutron decay
- Statistical accuracy about 2 % per 24 hours measurement time
- Studied several systematic effects
- Total accuracy expected to be well below the present literature value of 5 %
- Data analysis is currently on the way

- A statistical accuracy of $\Delta a / a$ ~ 0.3% can be obtained within one further beam time at ILL

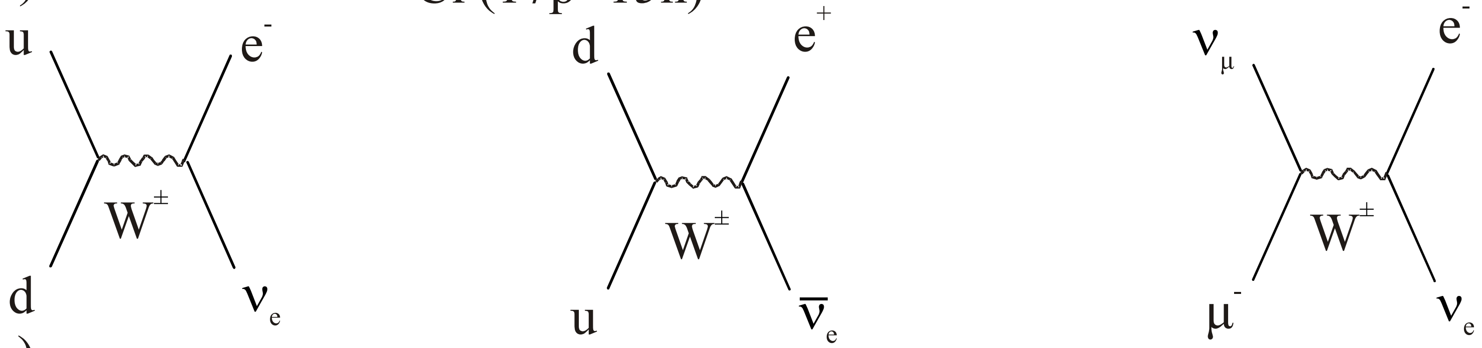
Backup

Why investigate Neutron Beta Decay?

A decaying neutron is an easy system.

p = (udu)

^{32}Cl (17p+15n)



n = (ddu)

^{32}Ar (18p+14n)

neutron (β^-) decay

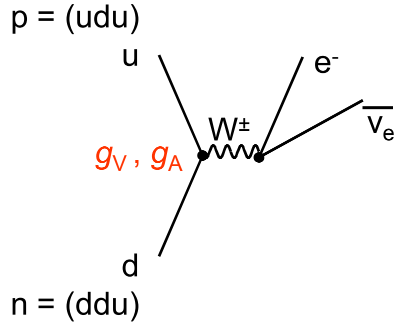
^{32}Ar (β^+) decay

muon decay

Universality: If we neglect phase space, nuclear structure, and spin states, all decays are equal

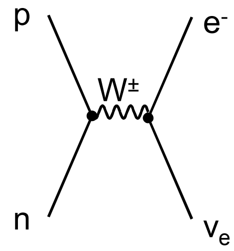
Coupling Constants of the Weak Interaction

Coupling Constants in Neutron Decay

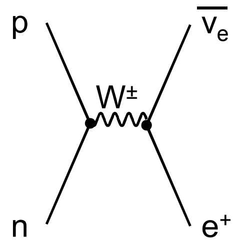


$n \rightarrow p + e^- + \overline{\nu}_e$

Primordial Nucleosynthesis



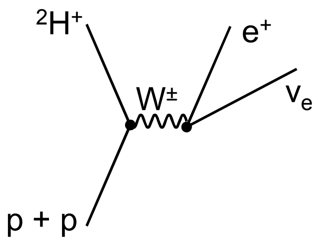
$n + \nu_e \leftrightarrow p + e^-$



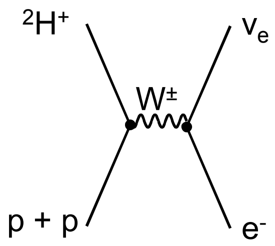
$n + e^+ \leftrightarrow p + \overline{\nu}_e$

Start of Big Bang Nucleosynthesis, Primordial ^{4}He abundance

Solar cycle



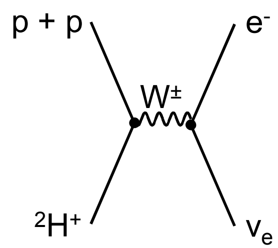
$p + p \rightarrow {}^2H^+ + e^+ + \nu_e$



$p + e^- + p \rightarrow {}^2H^+ + \nu_e$

Start of Solar Cycle, determines amount of Solar Neutrinos

Neutrino Detection (SNO, CC)



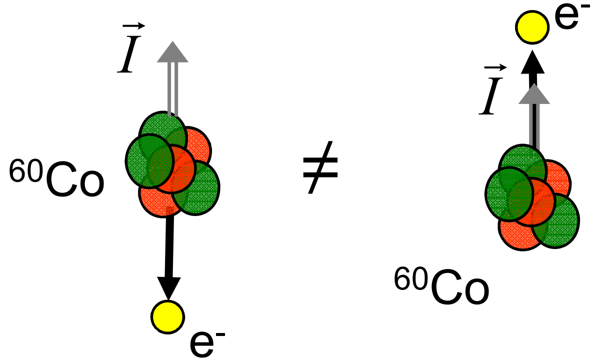
$\nu_e + {}^2H^+ \rightarrow p + p + e^-$

Efficiency of Neutrino Detectors

The Beta Decay Hamiltonian

Task:

Construction of Parity-Violating Hamiltonian, which couples leptons and hadrons



$$H_{\text{weak,elementary}} = G_{\text{F}} \left\langle u \left| \underbrace{\gamma^{\mu} - \gamma^{\mu}\gamma^{5}}_{V-A} \right| d' \right\rangle \left\langle e^{-} \left| \gamma_{\mu} - \gamma_{\mu}\gamma_{5} \right| \nu_{e} \right\rangle$$

Properties: Helicity of (relativistic) fermions is -1, of antifermions is 1

Complication: Nucleons aren‘t elementary particles:

$$H_{\text{weak}} = G_{\text{F}} V_{\text{ud}} \left\langle p \left| \gamma^{\mu} - \lambda \gamma^{\mu}\gamma^{5} \right| n \right\rangle \left\langle e^{-} \left| \gamma_{\mu} - \gamma_{\mu}\gamma_{5} \right| \nu_{e} \right\rangle$$

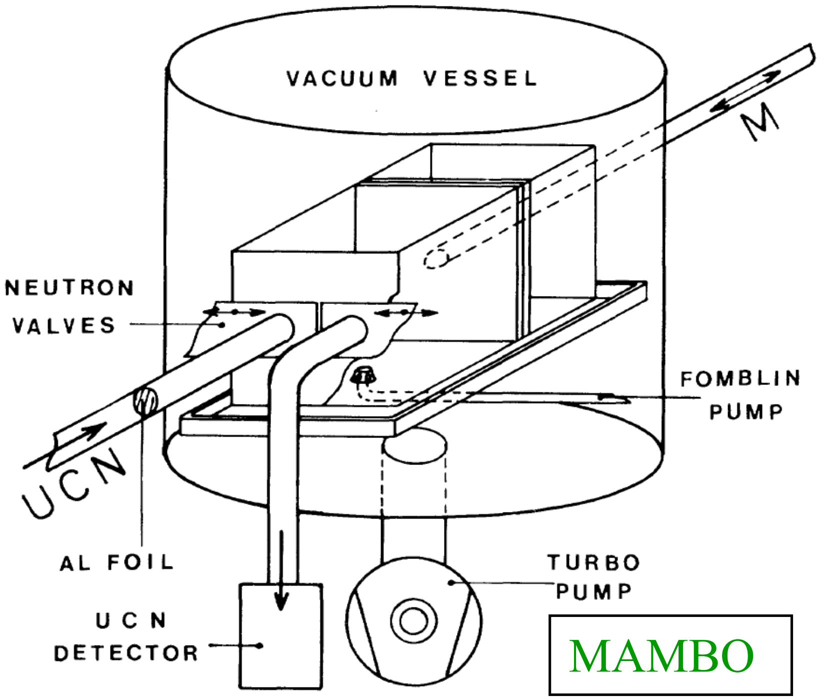
Coupling constants are unknown. Fermi-Transitions: $g_{\text{V}} = G_{\text{F}} \cdot V_{\text{ud}}$

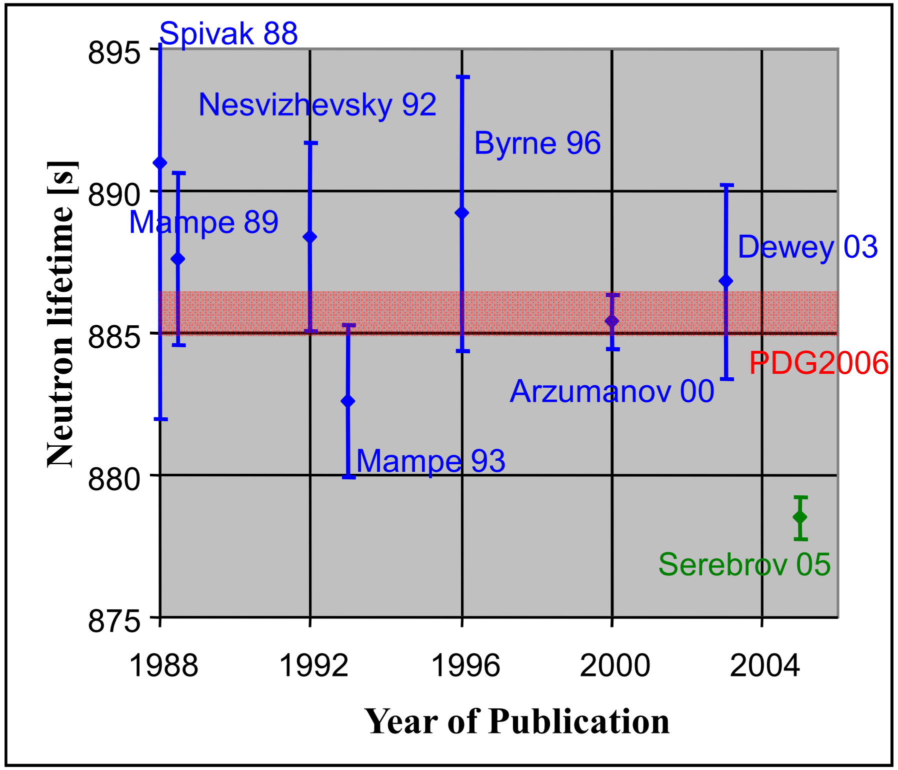
Gamow-Teller-Transitions: $g_{\text{A}} = G_{\text{F}} \cdot V_{\text{ud}} \cdot \lambda$

Neutron Lifetime Measurements

Decrease of Neutron Counts N with storage time t: $N(t) = N(0)\exp\{-t/\tau_{eff}\}$

$1/\tau_{eff} = 1/\tau_{\beta} + 1/\tau_{wall\ losses}$





Many new attempts planned, mostly with magnetic bottles

The Unitarity of the CKM Matrix

Cabibbo-Kobayashi-Maskawa-Matrix

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{td} & V_{tb} \end{pmatrix} \cdot \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Unitarity Condition

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$$

$|V_{ud}|$:

- Superallowed Fermi Decays
- Neutron Decay

  $$n \rightarrow p + e^- + \nu_e$$

- Pion Decay

$|V_{us}|$:

- Kaon (Ke3) Decays

  $$K \rightarrow e + \pi + \nu_e$$

- Kaon (Kμ2) Decays

  $$K \rightarrow \mu + \nu_\mu$$

- Hyperons

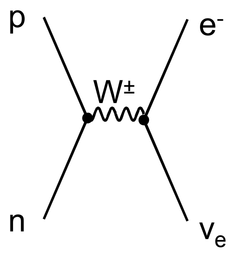
$|V_{ub}|$:

- B/D mesons

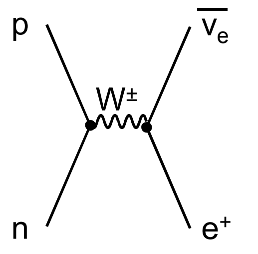
Primordial Nucleosynthesis

Before Phase Transition:

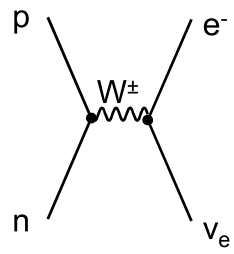
Equilibrium



$n + \nu_e \leftrightarrow p + e^-$



$n + e^+ \leftrightarrow p + \bar{\nu}_e$



$n \leftrightarrow p + e^- + \bar{\nu}_e$

After Phase Transition (about 1 min after Big Bang):

$n + p \rightarrow d + \gamma$ $\quad$ $d + d \rightarrow {}^3He + n \rightarrow t + p$ $\quad$ $d + {}^3He \rightarrow {}^4He + p$ $\quad$ …..

Then the Primordial Nucleosynthesis stops, since there are no stable nuclei with A = 5, 8 and since the free neutrons die out.

Lower $\tau_n \Rightarrow$ more $n \leftrightarrow p$ reactions $\Rightarrow$ Phase Transition later $\Rightarrow$ less ${}^4He$

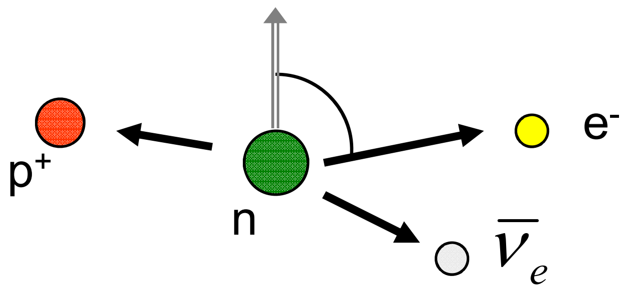
"After about three minutes, the cosmic hydrogen to helium ratio was fixed….

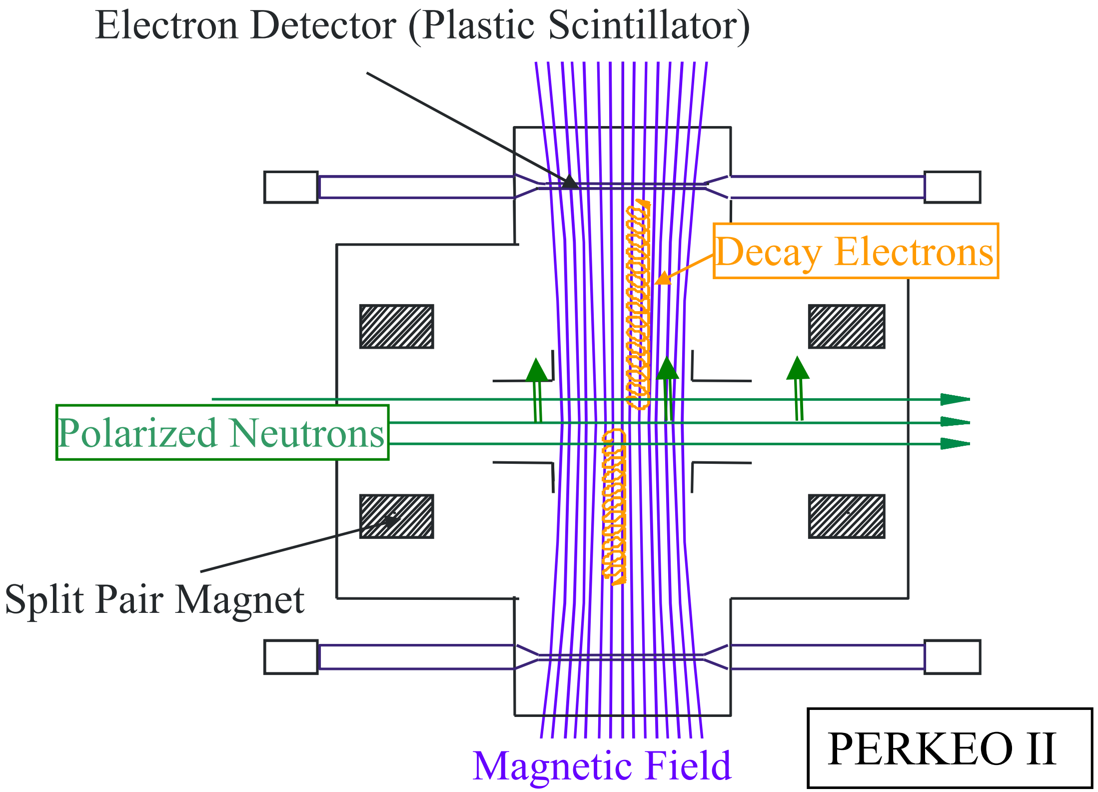
...Nothing of interest has happened since"

Steven Weinberg

Lecture, Harvard University, 1975

The Beta Asymmetry



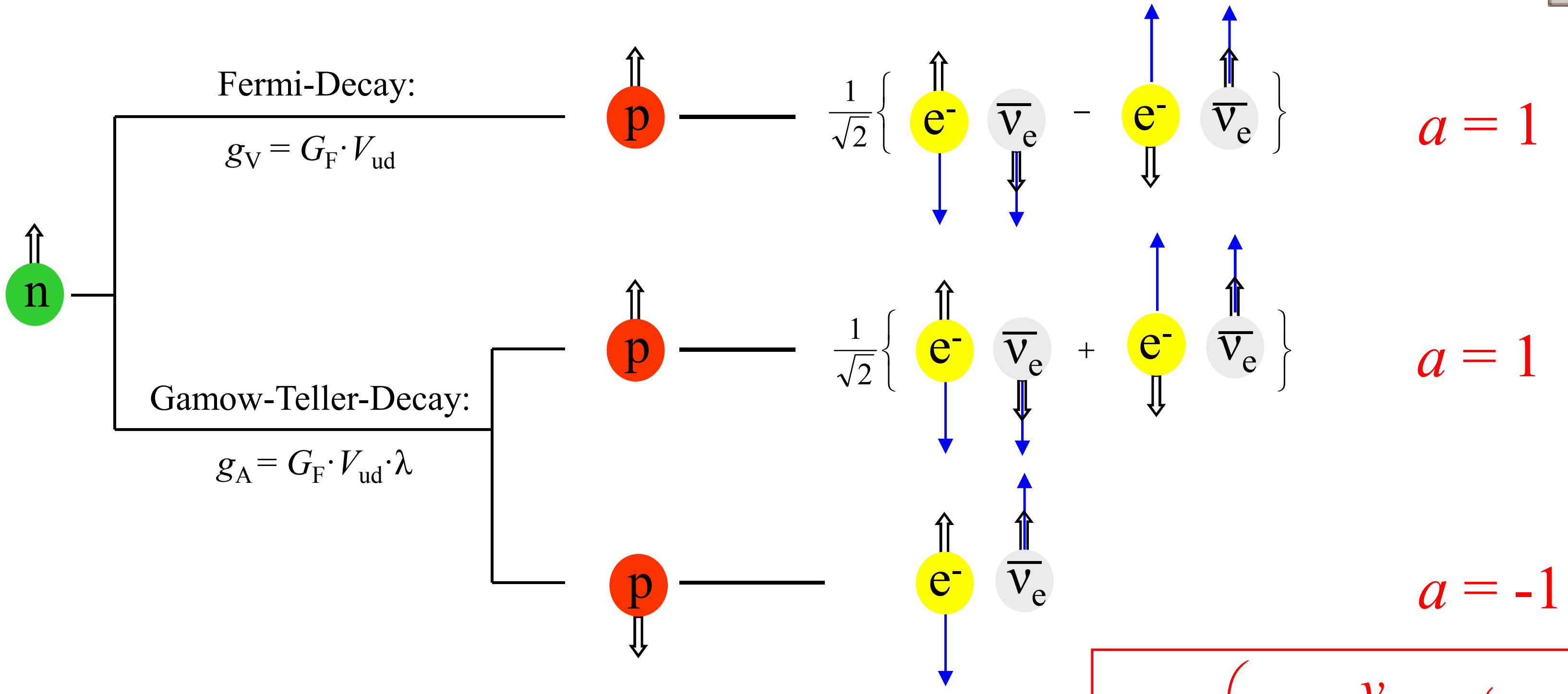


$$dw \propto \left(1 + A\frac{v}{c}\cos\left(p_e, \sigma_n\right)\right)$$

$$A \propto \frac{N_{up} - N_{down}}{N_{up} + N_{down}}$$

Beam time	Result	Publication
1995	A = -0.1189(12)	H. Abele, S. B. et al., Phys. Lett. B 407, 212 (1997)
1997	A = -0.1189(7)	H. Abele, S. B. et al., PRL 88, 211801 (2002)
2004	A = -0.1198(5)	(preliminary)
1995 – 2004 combined	A = -0.11933(34) (preliminary)	H. Abele, Prog. Part. Nucl. Phys. 60, 1 (2008)

Determination of the Coupling Constants



$$dw \propto \left(1 + a\frac{v}{c}\cos\left(p_e, p_{\bar{\upsilon}_e}\right)\right)$$

Two unknown parameters, g_A and g_V, need to be determined in 2 experiments

1. Neutron-Lifetime: $\tau_n^{-1} \propto \left(g_V^2 + 3g_A^2\right)$ $\tau_n \approx 885$ s

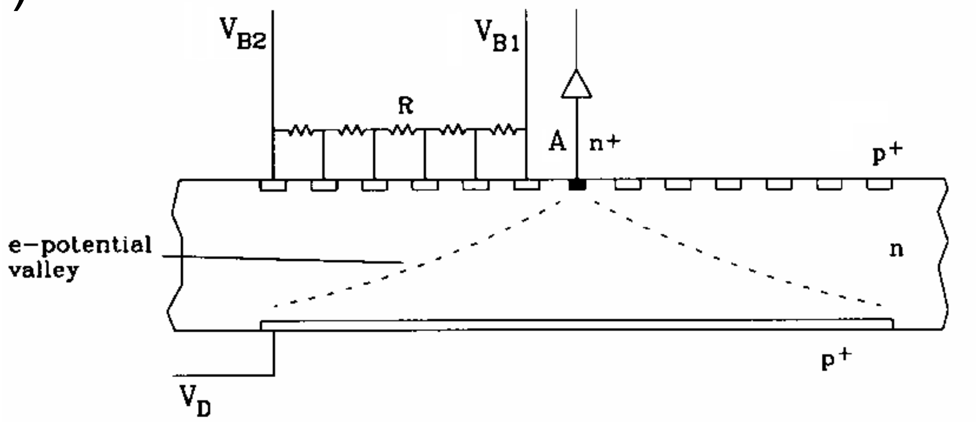
2b. Neutrino-Electron-Correlation *a*: $a = \frac{1-\lambda^2}{1+3\lambda^2} \sim -0.1$ $\lambda = \frac{g_A}{g_V}$

The proton detector

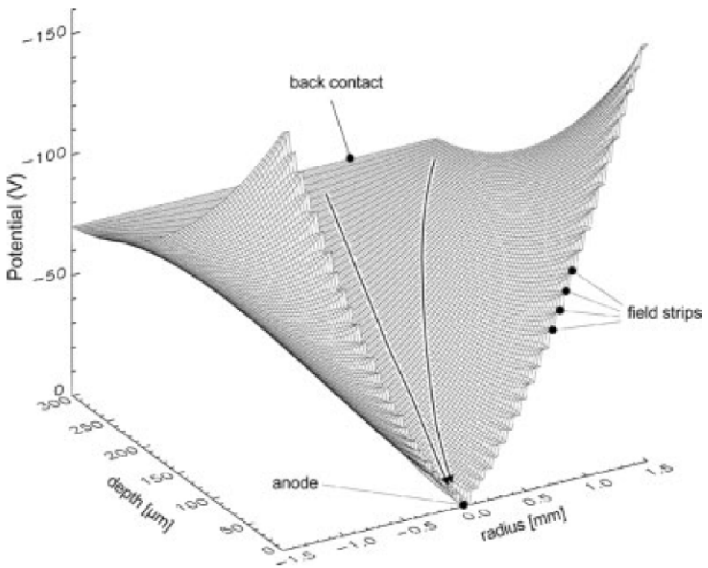
Type: Silicon Drift Detector (SDD)

Principle:

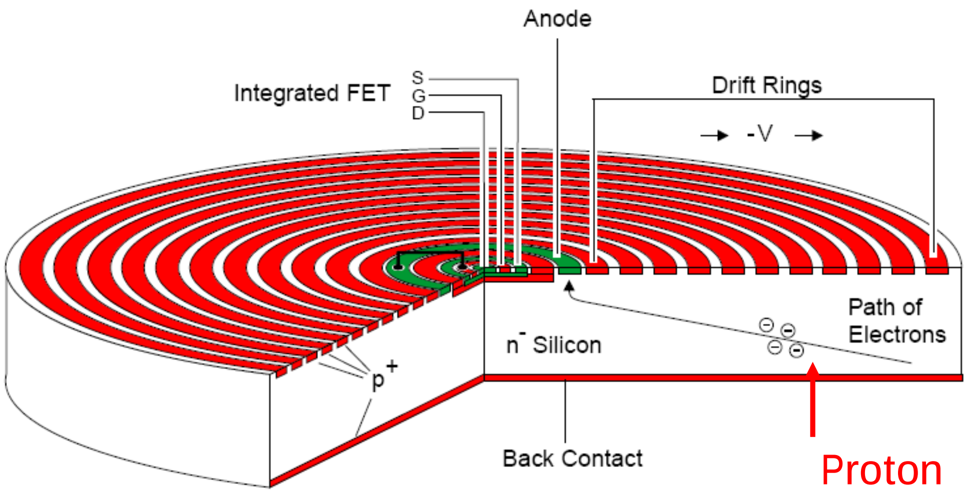
- p-doped backside, p-doped rings
- ⇒ Potential Valley
- e^- drift to a small anode in the middle



G. Lutz, *Semiconductor Radiation Detectors*



P. Lechner et. al. , XRS 2004 **33** 256-261



Detector features

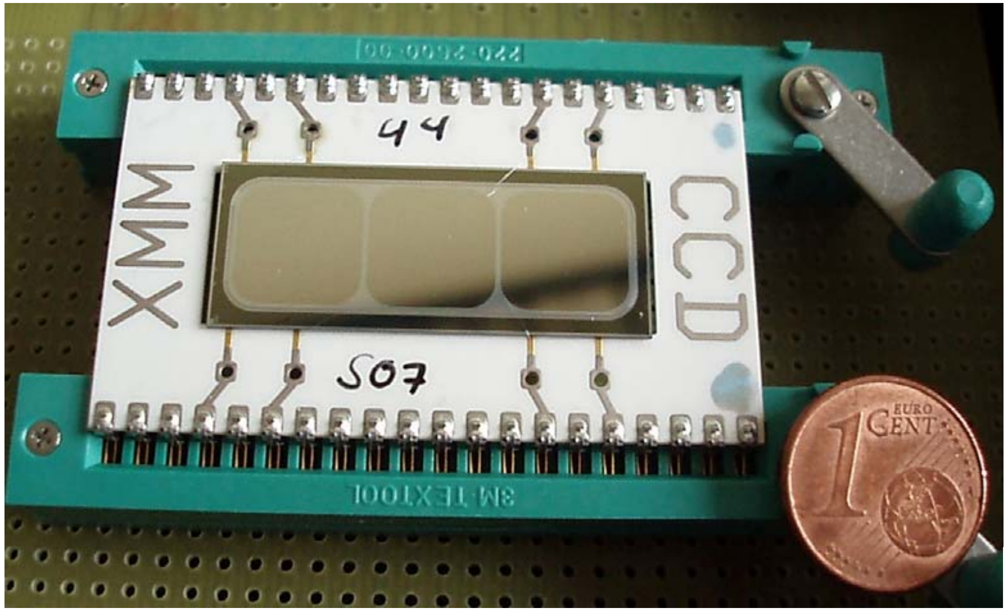
Chip size 14x34 mm²

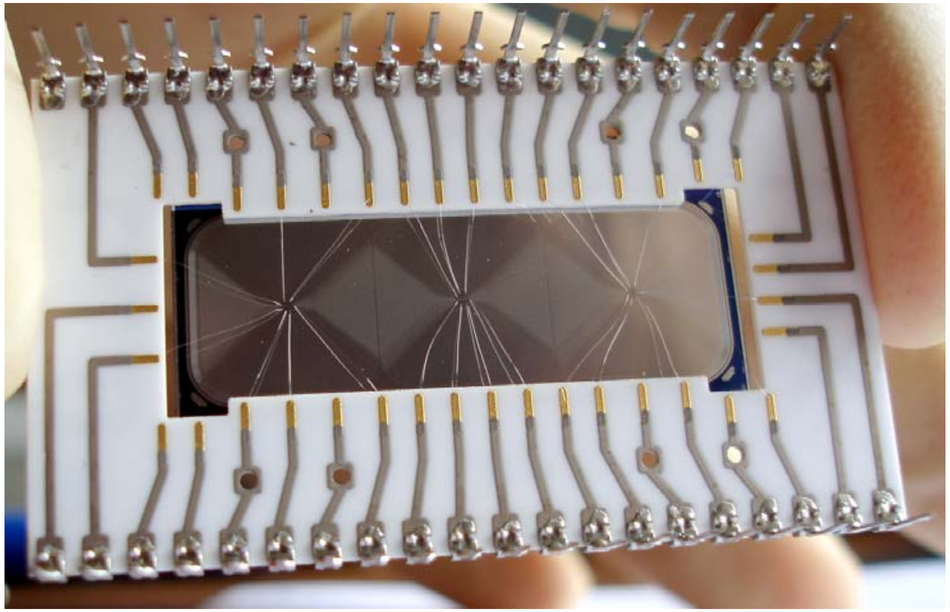
3 Pads of 10x10 mm²

Thickness 450 µm

Entrance window
30 nm aluminium

Suitable for UHV





Integrated temperature diode

First amplifying FET on chip

Preamp based on 3 Amptek A250

Investigations of systematic effects

Background

- Additional neutron shutter
- Different „trap cleaner“ and „beam shifter“ ExB settings

Adiabatic transmission function

- Different magnetic field settings
- Measurement of the magnetic field at the beam position, before and after the beam time
- Different electric field settings

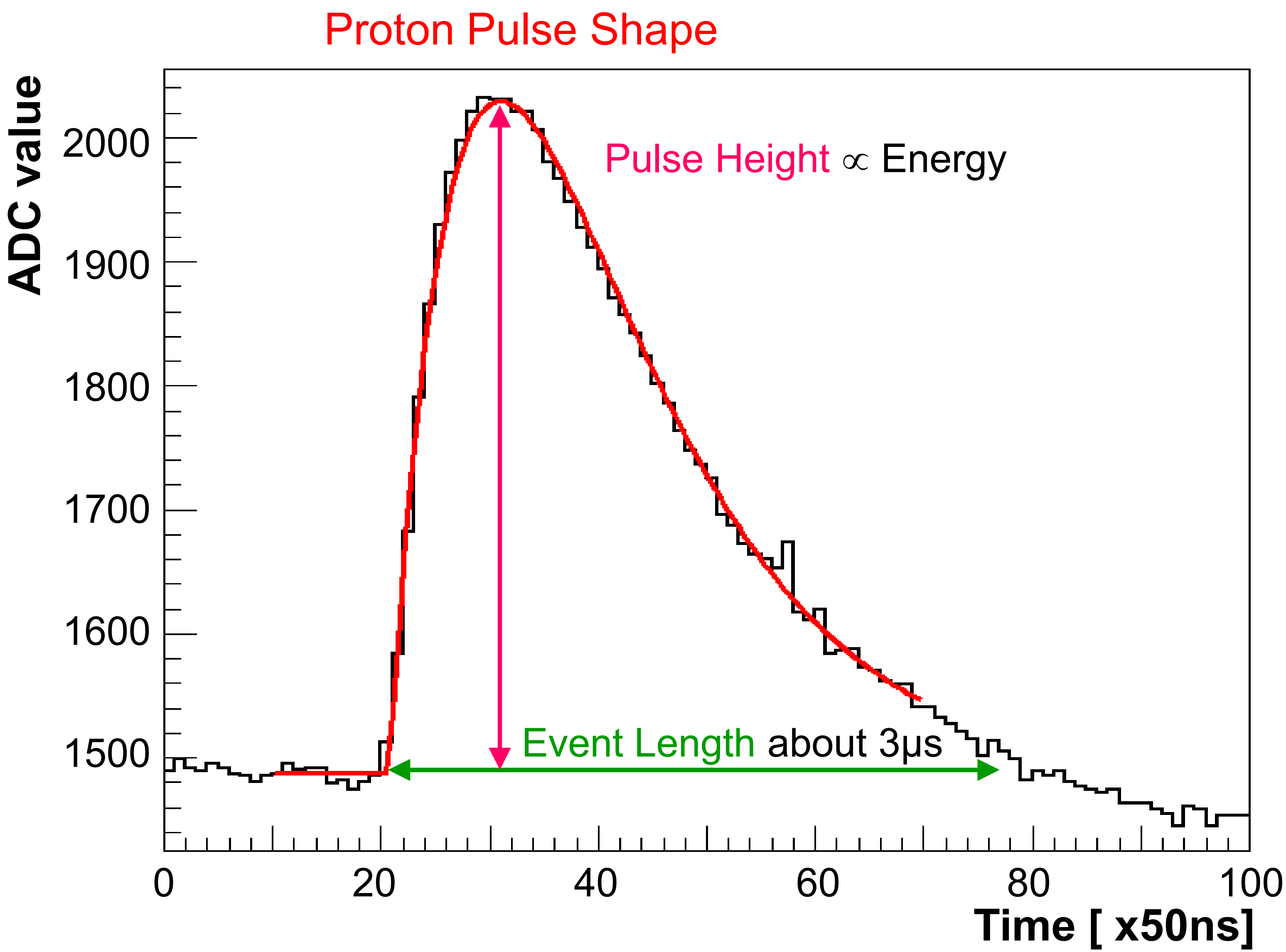
Edge effect

- Different neutron beam profiles
- Monte Carlo simulations are currectly on the way

Detector efficiency

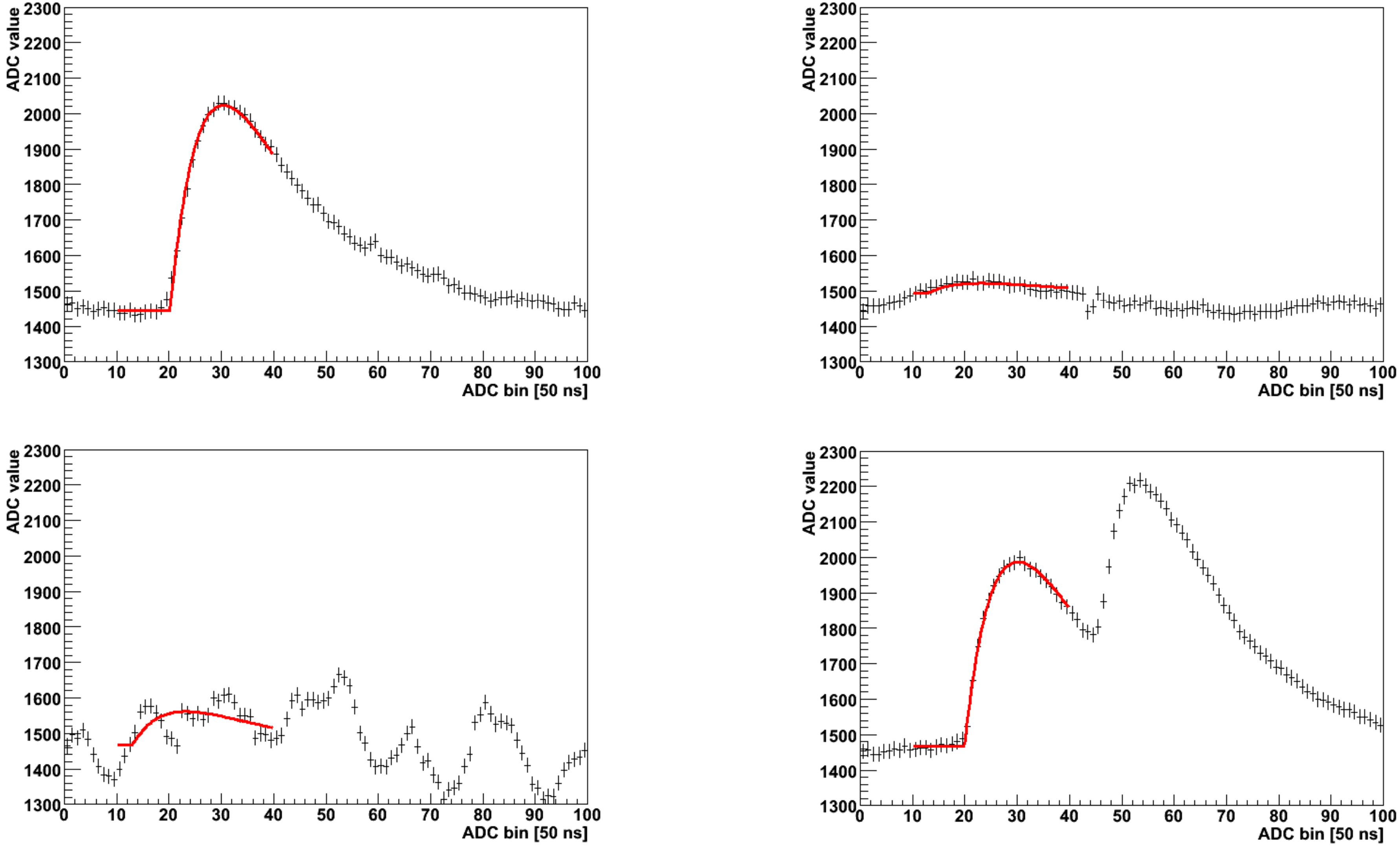
- Different trigger settings
- Different post-acceleration voltages
- Tests at a proton source + SRIM calculations are currently on the way

Typical Proton Event



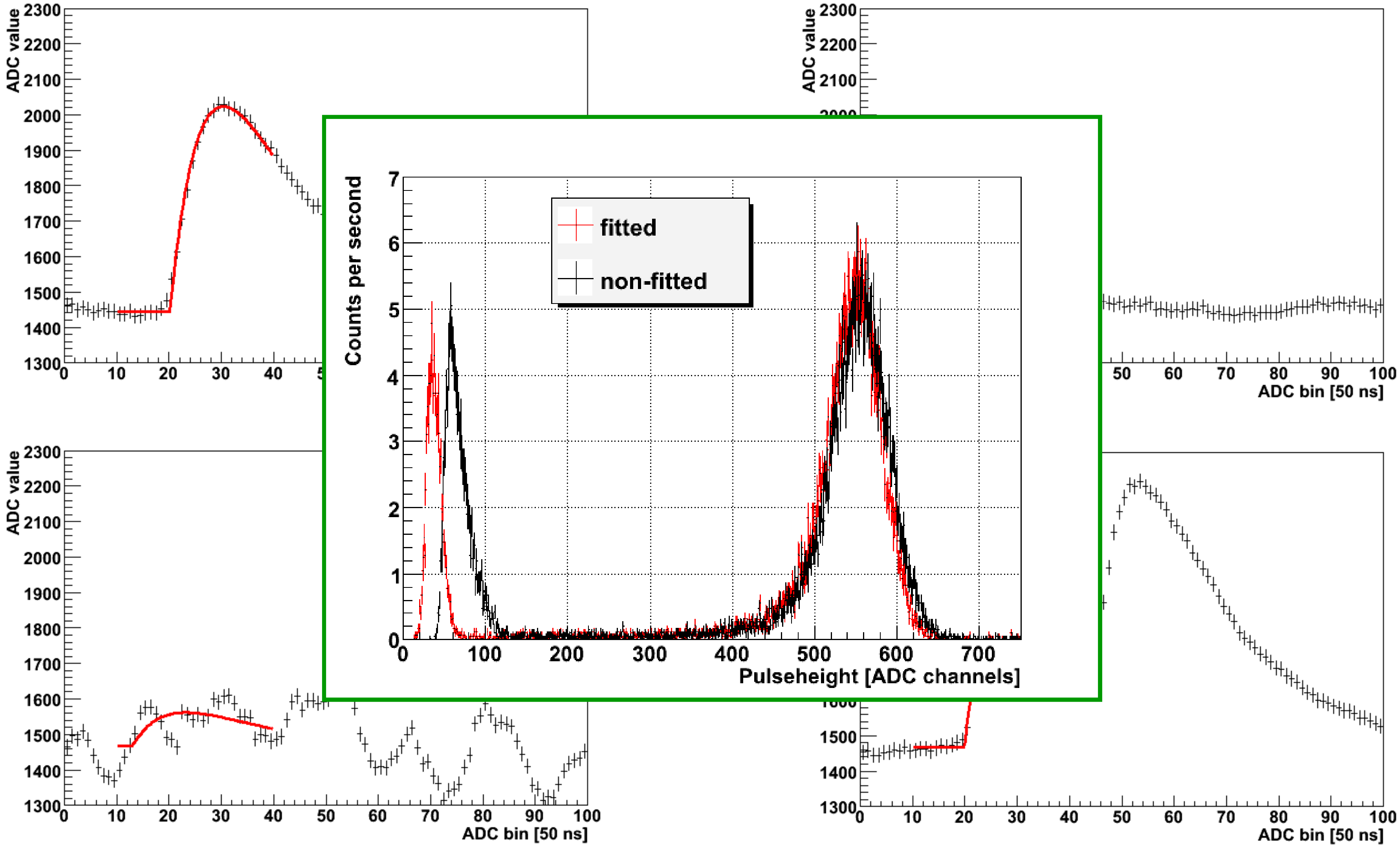
Data analysis

Fit function: $y = y_0 + A\left(1 - e^{\frac{x-x_0}{t_1}}\right)^p e^{\frac{x-x_0}{t_2}}$



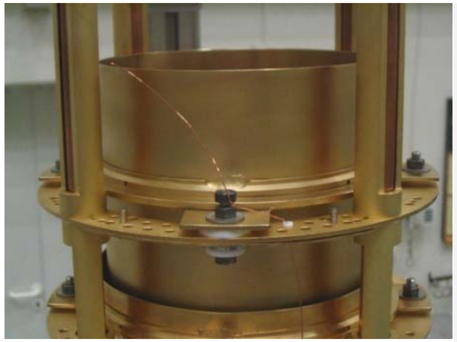
Data analysis

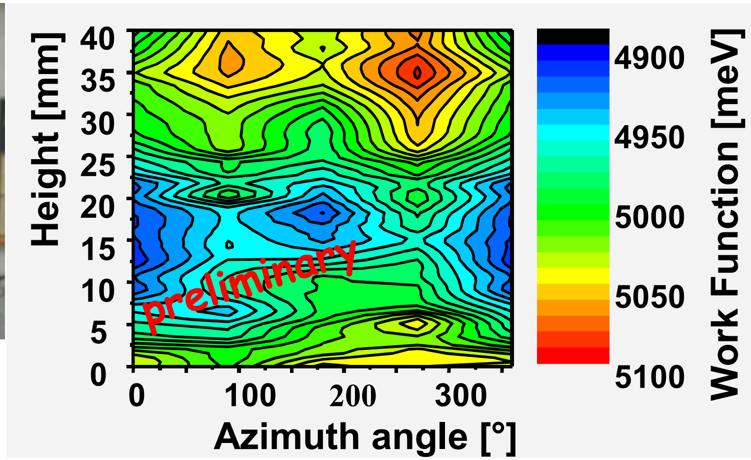
Fit function: $$y = y_0 + A\left(1 - e^{\frac{x-x_0}{t_1}}\right)^p e^{\frac{x-x_0}{t_2}}$$



Further on-going improvements

- Study of surface potential; Kelvin probe





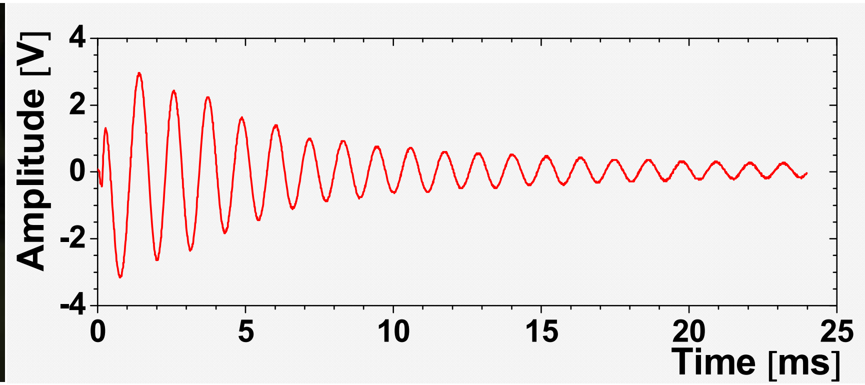
In collaboration with
Prof. I. Baikie,
KP Technologies

Possible solution

Other surface coatings

- evaporated gold?
- chromium?
- colloidal carbon?

- On-line monitoring of the magnetic field ratio; NMR with polarized ^{3}He

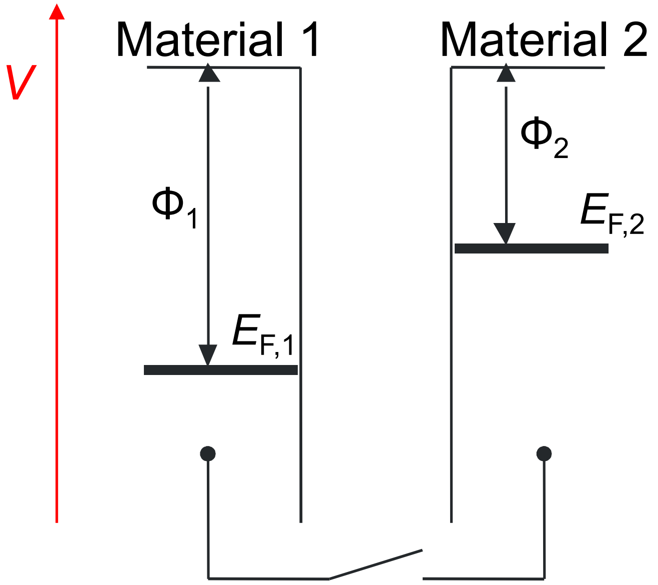


$$\nu = \gamma_{\text{He-3}} B_0$$

$$\gamma_{\text{He-3}} \approx 32.436 \quad [\text{MHz/ T}]$$

- Calibration source; electron impact ionization

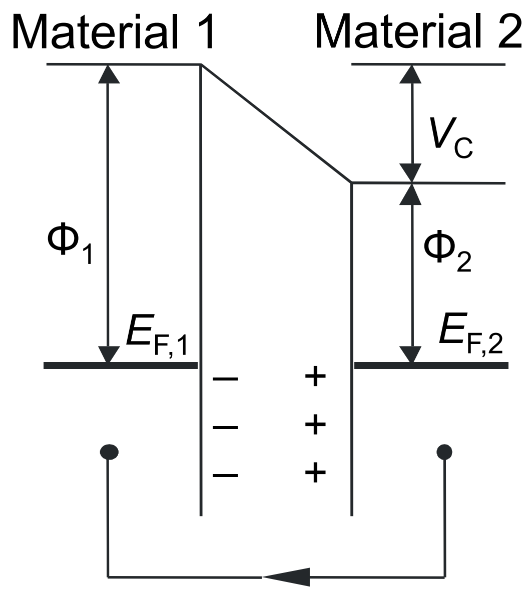
Kelvin Probe



2 Materials with different work functions, isolated

1st material: to be tested

2nd material: tip with known work function

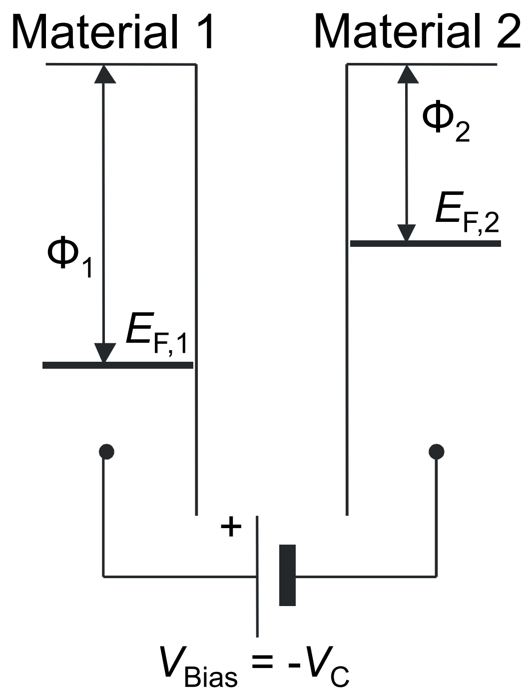


Electrical Connection:

→ Charging, until Fermi levels are equal

→ External electric field

→ If Material 2 is moved: Capacitance changes, Measurable Current



Bias Voltage:

→ Charge disappears, no external electric field

→ No current if Material 2 is moved