An attempt to define the "ultimate" determination of correlation coefficients in neutron beta decay

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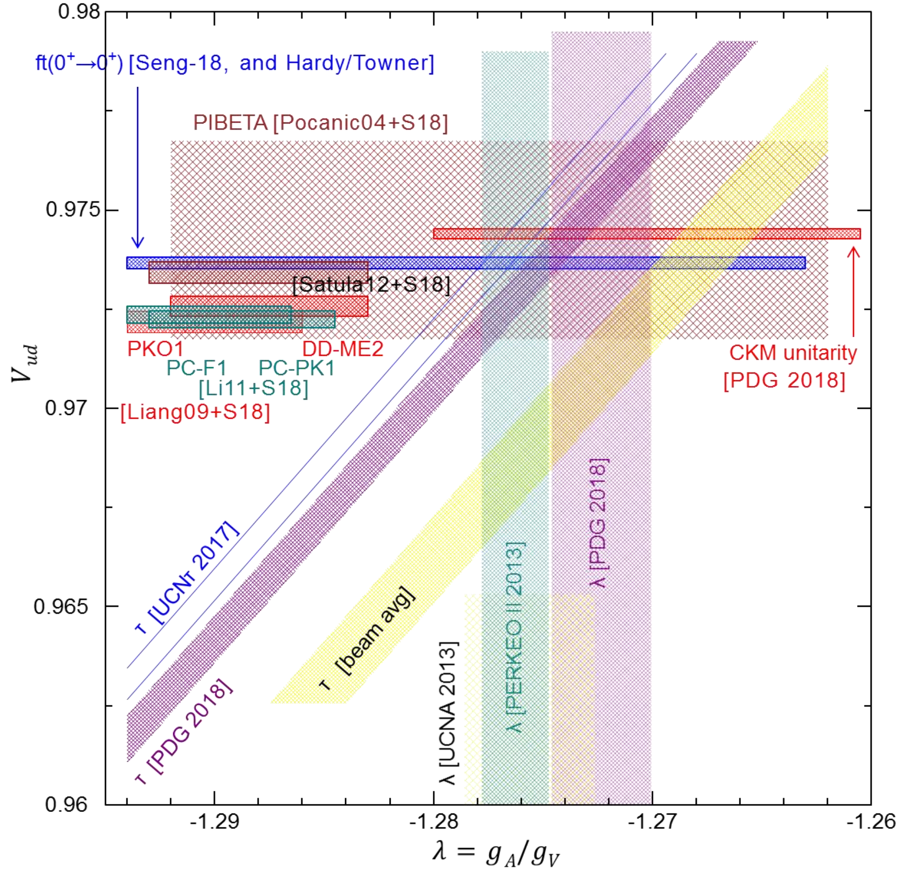
Motivation for precise determination of neutron beta decay correlations



CKM unitarity seems to be violated by about 4σ!

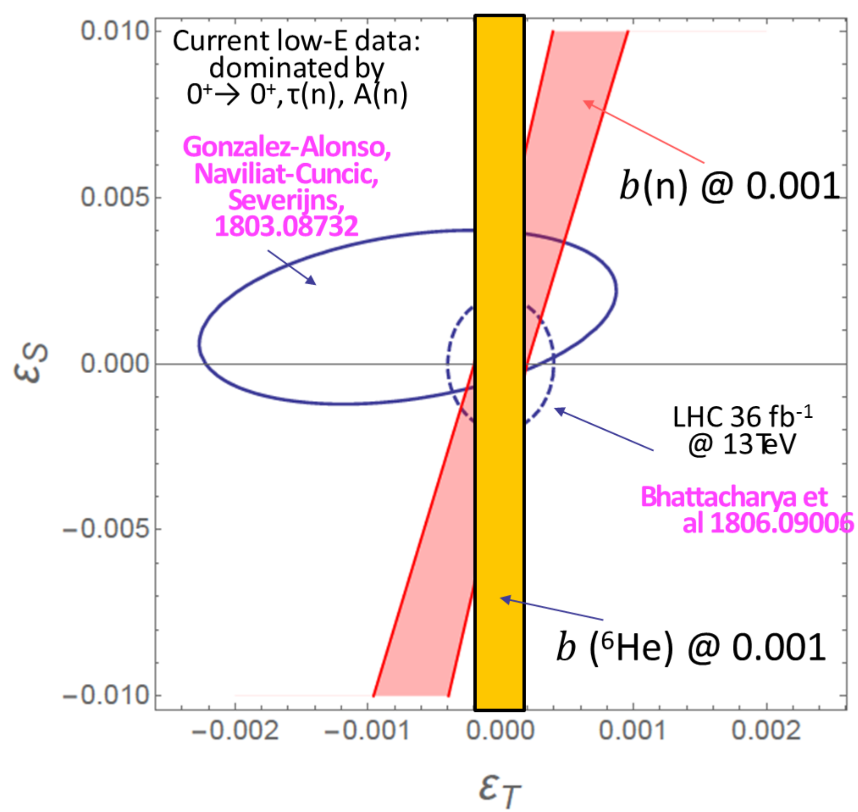
Neutrons reach precision of ft($0^+ \rightarrow 0^+$) if

$\Delta\lambda/\lambda \sim 9 \cdot 10^{-5}$ or $\Delta\lambda \sim 1.1 \cdot 10^{-4}$

$\Delta\tau_n \sim 0.13$ s

Seng-18 moved goal posts!

FUTURE



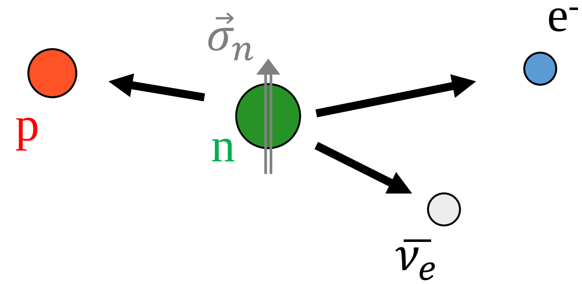
Search for BSM physics, may show as S,T interactions (fermions with "wrong" helicity) at low energies. Competitive if

$\Delta b(n) \sim 10^{-3}$ or $\Delta b_\nu(n) \sim 10^{-3}$

Correlation coefficients in neutron beta decay

Observables in neutron beta decay, as a function of generally possible coupling constants (assuming only Lorentz-Invariance):

J.D. Jackson et al., PR 106, 517 (1957), C.F. v.Weizsäcker, Z. f. Phys. 102,572 (1936), M. Fierz, Z. f. Phys. 105, 553 (1937)



$$d\Gamma \propto \rho(E_e) \cdot (1 + 3|\lambda|^2) \cdot \left\{1 + a\frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + b\frac{m_e}{E_e} + \vec{\sigma}_n \cdot \left(A\frac{\vec{p}_e}{E_e} + B\frac{\vec{p}_\nu}{E_\nu} + D\frac{\vec{p}_e \times \vec{p}_\nu}{E_e E_\nu}\right)\right\} + \vec{\sigma}_e \cdot \ldots$$

Neutrino-Electron-Correlation

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

Fierz interference term $b = 0$

Beta−Asymmetry

$$A = -2\frac{|\lambda|^2 + \mathrm{Re}\,\lambda}{1 + 3|\lambda|^2}$$

Neutrino-Asymmetry B, includes $b_\nu = 0$

Neutron lifetime $\tau_n^{-1} = \frac{2\pi}{\hbar} G_F^2 V_{ud}^2 \left(1+3|\lambda|^2\right) \int \rho(E_e)$

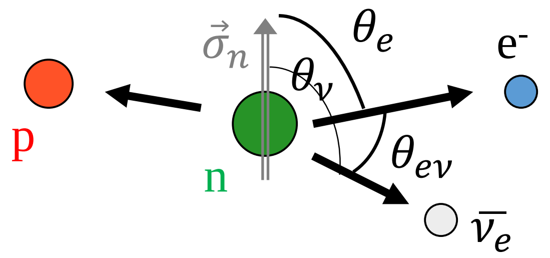
For coefficients involving electron helicity, see K. Bodek's talk later today.

(Equations in SM, where $\lambda = g_A/g_V$)

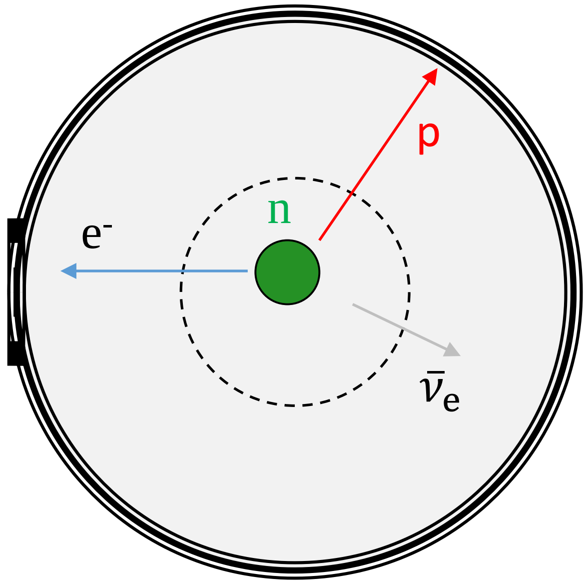
The optimum experiment concerning statistics

Goals:

1. $\Delta\lambda \sim 1.1 \cdot 10^{-4}$ translates to $\Delta A \sim 4 \cdot 10^{-5}$ or $\Delta a \sim 4 \cdot 10^{-5}$.
2. $\Delta b \sim 10^{-3}$ or $\Delta b_\nu \sim 10^{-3}$



Optimum experiment is capable to detect complete kinematics: $\vec{p}_p + \vec{p}_e + \vec{p}_\nu = 0$



Surface: position-sensitive electron+proton detectors (E/P detectors), 4π coverage

Fit variable	Complete kinematics
a from unpolarized decays in SM	$2.34/\sqrt{N}$
λ from unpolarized decays in SM	$7.74/\sqrt{N}$
A from polarized decays in SM	$1.89/\sqrt{N}$
λ from polarized decays in SM	$4.7/\sqrt{N}$
b from unpolarized decays	$7.53/\sqrt{N}$
b from polarized decays	$7.53/\sqrt{N}$
b_ν from polarized decays	$9.96/\sqrt{N}$

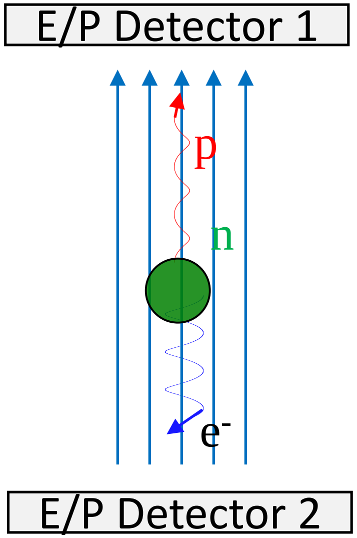
The optimum experiment concerning statistics - interpretation

Fit variable	Complete kinematics	Abs. uncertainty, using $N = 10^{10}$ decays
a from unpolarized decays in SM	$2.34/\sqrt{N}$	$2.34 \cdot 10^{-5}$
λ from unpolarized decays in SM	$7.74/\sqrt{N}$	$7.74 \cdot 10^{-5}$
A from polarized decays in SM	$1.89/\sqrt{N}$	$1.89 \cdot 10^{-5}$
λ from polarized decays in SM	$4.7/\sqrt{N}$	$4.7 \cdot 10^{-5}$
b from unpolarized decays	$7.53/\sqrt{N}$	$7.53 \cdot 10^{-5}$
b from polarized decays	$7.53/\sqrt{N}$	$7.53 \cdot 10^{-5}$
b_ν from polarized decays	$9.96/\sqrt{N}$	$9.96 \cdot 10^{-5}$

b, b_ν not statistically limited

- For a typical experiment, $N = 10^9 .. 10^{10}$ neutrons are decaying in the fiducial volume (e.g. for Nab @ SNS: $N = 6 \cdot 10^9$, in 2 years). Usually, experiments need to compromise some of the optimum sensitivity for systematics. If this was not so, both physics goals achievable with these experiments
- This is true even for experiments with polarized neutrons, where the achievable densities are at least a factor of 2 lower (but may be a factor of 10) lower.
- Numbers given for correlation coefficients a, A, b, and b_ν are computed as if those are independent. This is to make contact with other experiment studies; for an experiment that detects the full kinematics, the analysis should be done in terms of coupling constants, as more than one correlation coefficient is measured at the same time.
- Statistical sensitivity for b and b_ν is so good that it seems irrelevant for experiment design

Statistical uncertainty in a setup with a strong magnetic field



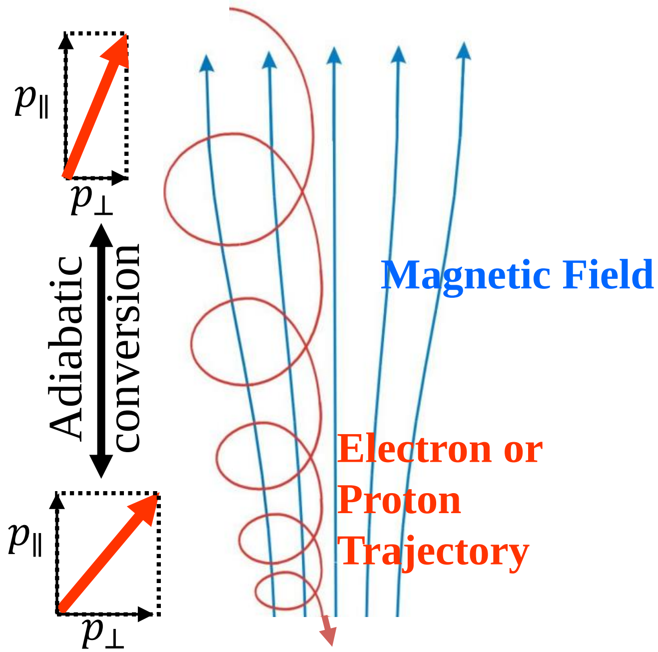
A detector as shown is not used often (see K. Bodek's talk later today). Nearly all experiment proposals require a strong magnetic field that connects neutron decay volume and detector(s), **for systematic reasons and to limit detector surface**. In such a magnetic field, electrons and protons gyrate along field lines. The original angles of electron and protons to magnetic field and polarization are no longer observable beyond the information if they hit first upper or lower detector, that is, if they gyrated along or opposite to field lines.

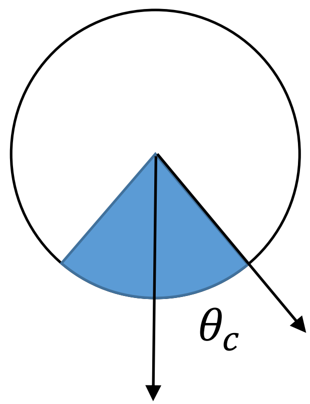
Fit	Complete kinematics	Magnet spectrometer (2 detectors)
a from unpolarized decays in SM	$2.34/\sqrt{N}$	$2.33/\sqrt{N}$
λ from unpolarized decays in SM	$7.74/\sqrt{N}$	$7.74/\sqrt{N}$
A from polarized decays in SM	$1.89/\sqrt{N}$	$2.56/\sqrt{N}$
λ from polarized decays in SM	$4.7/\sqrt{N}$	$5.54/\sqrt{N}$
b from unpolarized decays	$7.53/\sqrt{N}$	$7.54/\sqrt{N}$
b from polarized decays	$7.53/\sqrt{N}$	$7.53/\sqrt{N}$
b_ν from polarized decays	$9.96/\sqrt{N}$	$16.3/\sqrt{N}$

We see: Loss of (most) angular resolution does not result in much loss of sensitivity; our goals are still achievable with a similar amount of neutron decays.

Magnetic filter

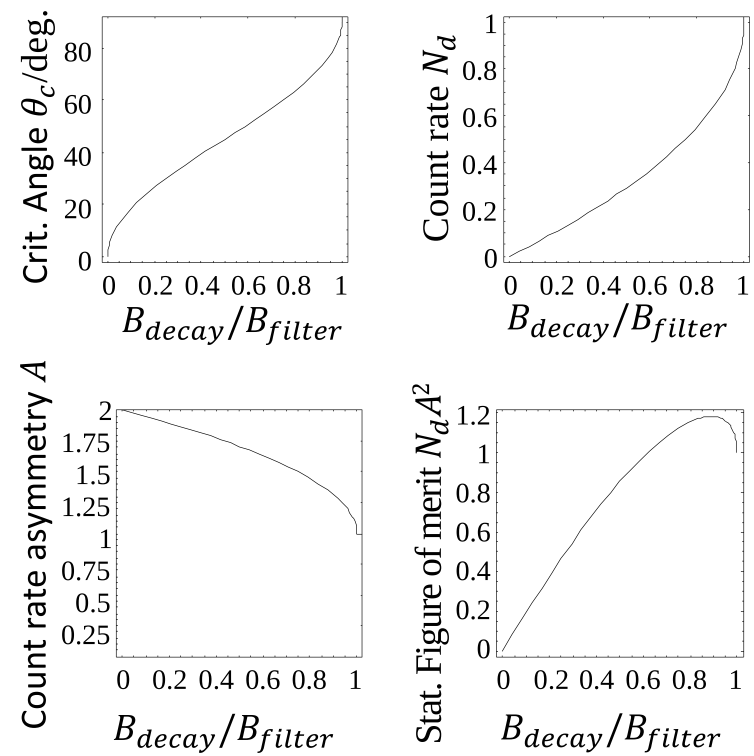
- In a magnetic field that is changing adiabatically, electron and proton movement preserves their respective orbital angular momentum. The angle of the momentum to the field changes. Particles can get reflected on a high magnetic field (magnetic mirror).
- A magnetic filter may increase sensitivity through use of magnetic filter (see also A. Serebrov, Nucl. Inst. Meth. 505, 344 (2005)), although **main purpose is systematics**.





If $B_{filter} > B_{decay}$, detector behind filter detects only particles with angle to field θ less than crit. angle θ_c with $\sin\theta_c = \sqrt{\frac{B_{decay}}{B_{filter}}}$

For asymmetry $d\Gamma \propto (1 + A\cos\theta)$ and one detector behind filter:

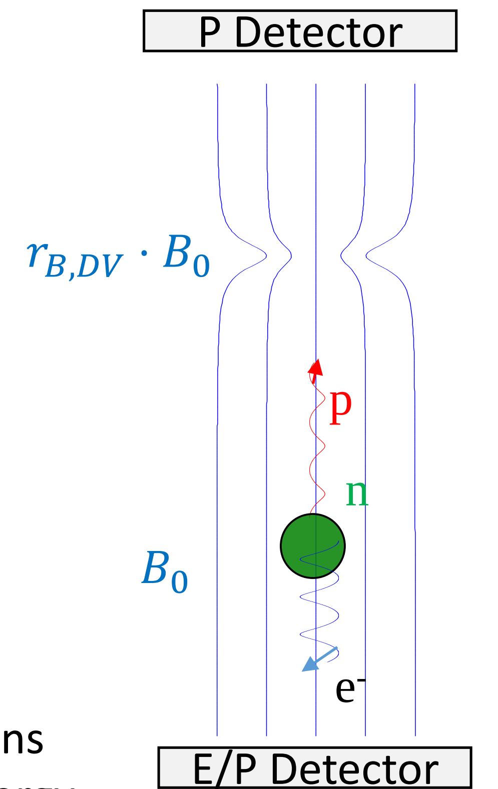


from D. Dubbers et al., Nucl. Instr. Meth. A 596, 238 (2008)

Statistical uncertainty in a setup with a strong magnetic field and magnetic filter

Motivated by the success in the planning of PERC, I investigated in various scenarios if the filter helps the sensitivity, too.

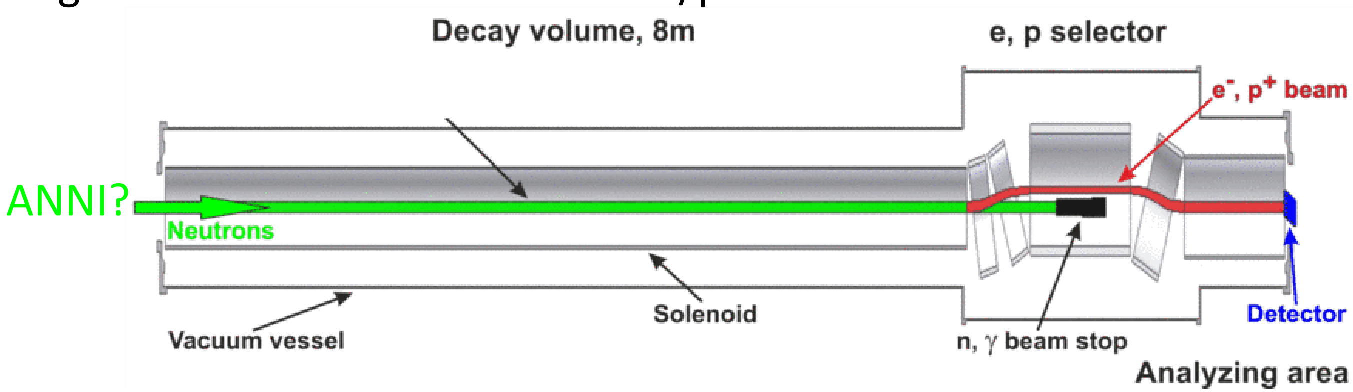
Fit	no filter, only upward proton detected	same, $r_{B,DV} = 0.8$	same, $r_{B,DV} = 0.5$
a in SM, unpolarized	$3.3/\sqrt{N}$	$4.44/\sqrt{N}$	$6.11/\sqrt{N}$
λ in SM, unpolarized	$10.95/\sqrt{N}$	$14.8/\sqrt{N}$	$20.34/\sqrt{N}$
A in SM, polarized	$3.62/\sqrt{N}$	$4.33/\sqrt{N}$	$5.27/\sqrt{N}$
λ in SM, polarized	$7.84/\sqrt{N}$	$8.81/\sqrt{N}$	$10.3/\sqrt{N}$
b, unpolarized	$10.7/\sqrt{N}$	$14.3/\sqrt{N}$	$19.7/\sqrt{N}$
b, polarized	$10.7/\sqrt{N}$	$14.3/\sqrt{N}$	$19.7/\sqrt{N}$
b_ν, polarized	$23.0/\sqrt{N}$	$25.0/\sqrt{N}$	$28.5/\sqrt{N}$



I am still assuming perfect detectors. Both detectors detect electrons and their energy. Only the upper one detects protons and their energy.
N is the number of decays, not the number of detected events N_d.
The sensitivity for λ is getting worse, to the extent that there is no room for additional losses due to experimental realities.
No preference for unpolarized or unpolarized neutrons, as the latter have a higher density.
The magnetic filter has advantages for the systematic uncertainty, which I will discuss with general systematic issues in the second half of my talk.

Potential neutron decay sources stronger than in use in the past

1. Cold neutrons
   a) Longitudinal extraction of electrons/protons



Shown is PERC (see B. Märkisch’s talk later today), developed for TU München, planned to come to ESS at ANNI (see T. Soldner’s talk, on Monday)

- Very large count rate improvement, as instrument looks into neutron decays in a long guide section. No issue with PERC being far from statistically optimized.
- Can be used as instrument, as beam configuration and detector is changeable.

   b) Transverse extraction

ANNI does not provide a larger average cold neutron flux than other sources. Nevertheless, the time structure could help to measure neutron beam polarization, and to determine non-prompt background (see T. Soldner’s talk).

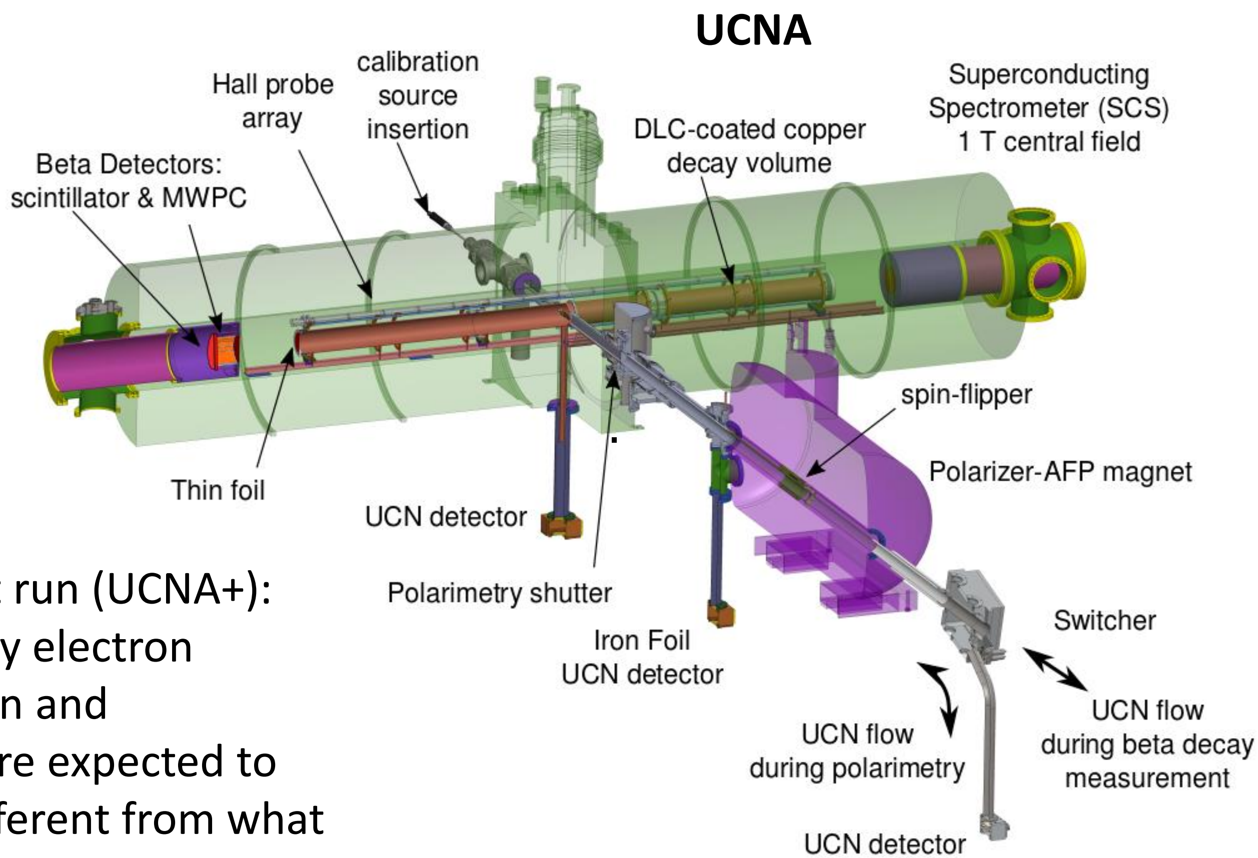
Potential neutron decay sources stronger than in use in the past

2. Ultra cold neutrons

- Recent upgrades of UCN source at LANL allow for count rates that allows for $\Delta A/A \sim 10^{-3}$ in a calendar year.

Experiment geometry makes optimum use of neutron decays (before cuts).

- Estimates for potential next run (UCNA+): $\Delta A/A \sim 6 \cdot 10^{-4}$, limited by electron detector effects. Polarization and Background uncertainties are expected to become lower, and very different from what one would see with cold neutrons.
- Going beyond would need (at least) a stronger UCN source (no fundamental limit).



Final result of UCNA:

$$A_0 = -0.12054(44)_{stat}\,(68)_{sys}$$

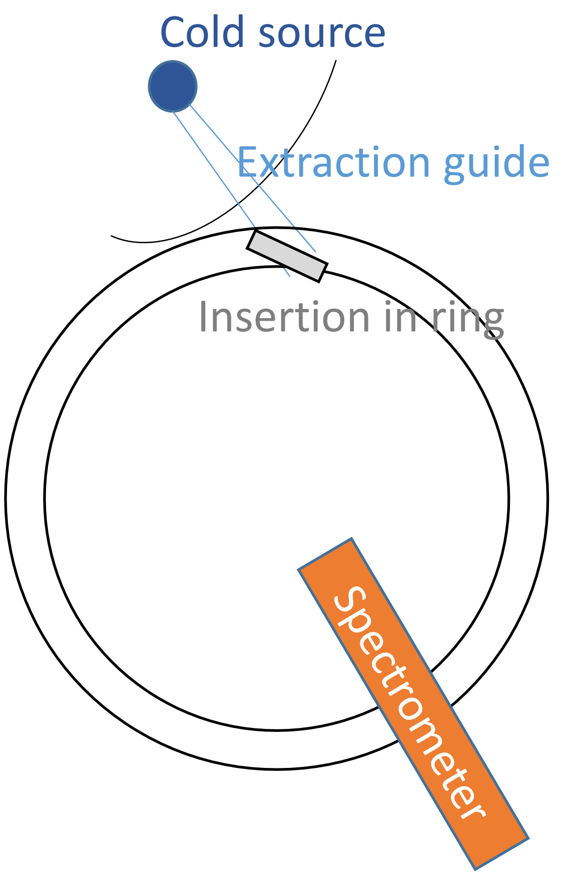
M. Brown et al., PRC **97,** 035505 (2017)

Potential neutron decay sources stronger than in use nowadays: PF1B, Mephisto, (FNPB)

3. Very cold neutrons (Here, $v_{mean}(\mathrm{VCN}) \sim v_{mean}(\mathrm{CN})/10$). V. Nesvishevsky's proposal to do nnbar in a storage ring with VCN may be useful for beta decay, too:

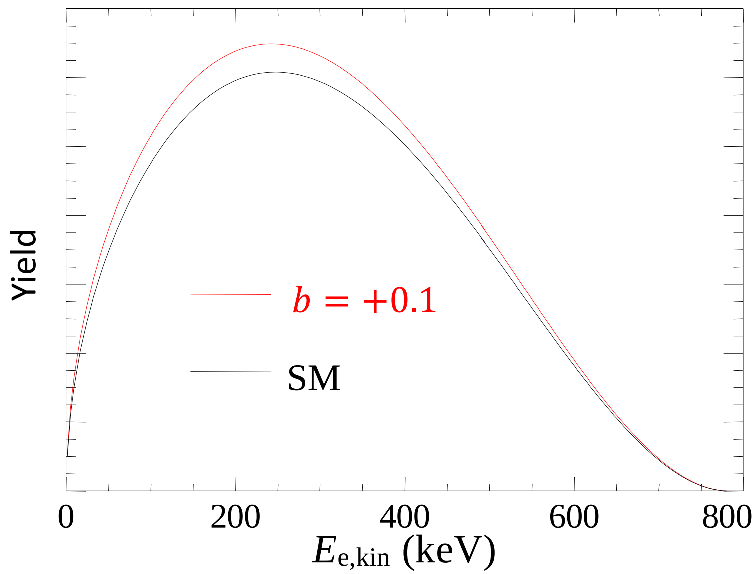
- Concept is shown in the picture. Estimate of neutron density in ring: 10 times higher with VCN than with CN:
  - Phase space density in moderator scales with v_{mean}^3
  - Intensity of extracted neutron beam scales with v_{mean}
  - Extraction efficiency in guide scales with v_{mean}^{-2}
  - Decay density scales with v_{mean}^{-1}
  - Higher efficiency of potential SD_2 moderator: Factor 10
  - Insertion mechanism could make use of pulse structure, which may give another factor of 10

  Required advancement in neutronics (efficiencies, limits on depolarization) is more than incremental (as it is for ANNI).
- Experiments probably similar to the one for cold neutrons with transverse extraction.
- Beta decay spectrometer could coexist with nnbar, although it is unclear if both could be operational at the same time (magnetic field, beta decay spectrometer requires opening in ring, which could lead to unacceptable neutron losses for nnbar).

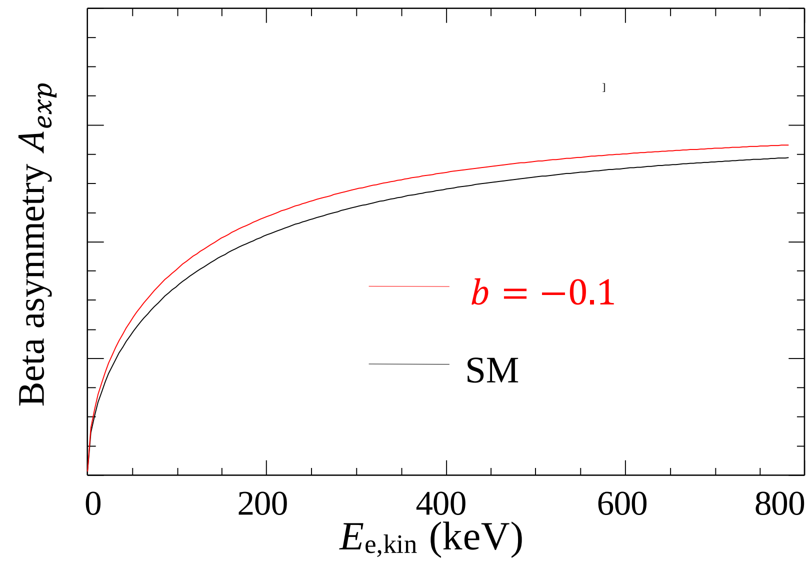


Generic systematics of a measurement of a electron spectrum or its asymmetry

Beta spectrum:

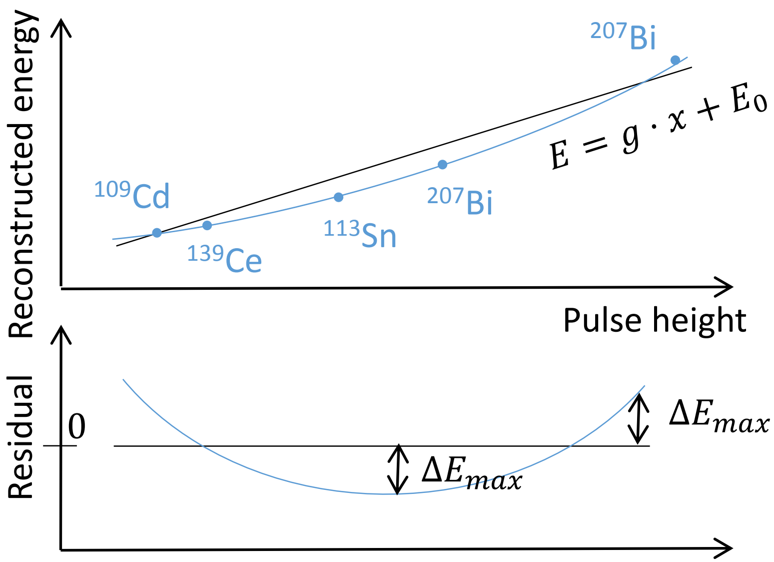


Beta asymmetry ($A_{exp} = \frac{N_e^{\uparrow}(E_{e,kin}) - N_e^{\downarrow}(E_{e,kin})}{N_e^{\uparrow}(E_{e,kin}) + N_e^{\downarrow}(E_{e,kin})}$):

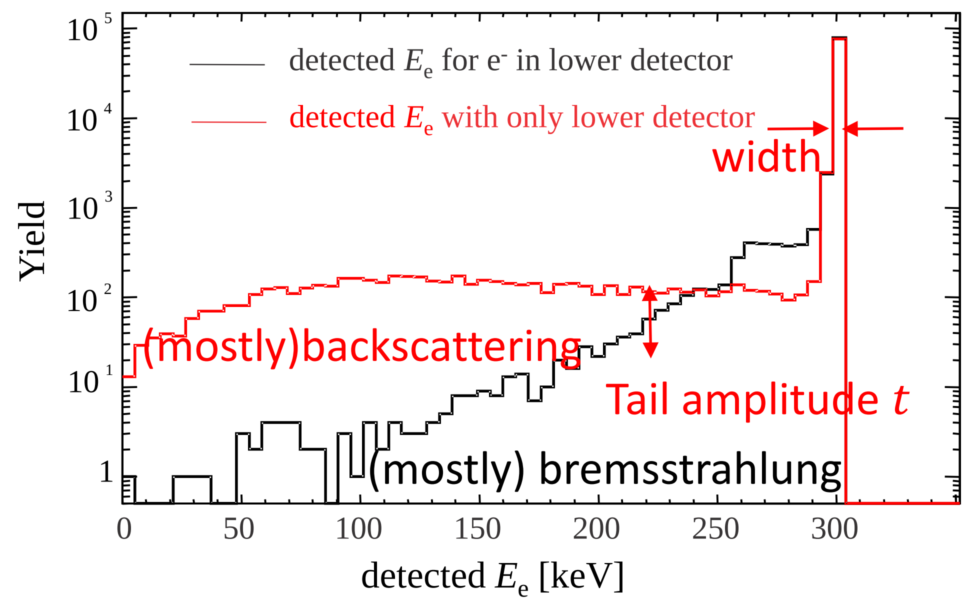


Generic systematics of a measurement of a electron spectrum or its asymmetry

1. Detector effects



Detector response in Si detector for incoming E_e = 300 keV,
(Max. impact angle of electrons is 12°, due to magnetic filter)



Specification	for $\Delta b = 5 \cdot 10^{-4}$ from beta spectrum	for $\Delta b = 5 \cdot 10^{-4}$ from beta asymmetry	for $\Delta A = 3 \cdot 10^{-5}$(SM) from beta asymmetry
gain factor ($\Delta g/g$)	fit parameter	0.0008	0.0018
Offset E_0	0.03 keV	0.05 keV	0.2 keV
Nonlinearity (ΔE_{max})	0.03 keV	0.1 keV	0.3 keV
peak width	3 keV	8 keV	10 keV
tail amplitude (Δt of peak)	0.100%	0.900%	2.40%

(numbers for Si detector) from H. Li

Generic systematics of a measurement of a electron spectrum or its asymmetry

2. Neutron beam polarization: Relevant for beta asymmetry A. Nowadays believed to be under control much better than 10^{-3} (see A. Pethoukov, T. Soldner et al. for cold neutrons, and A. Young et al for ultracold neutrons)

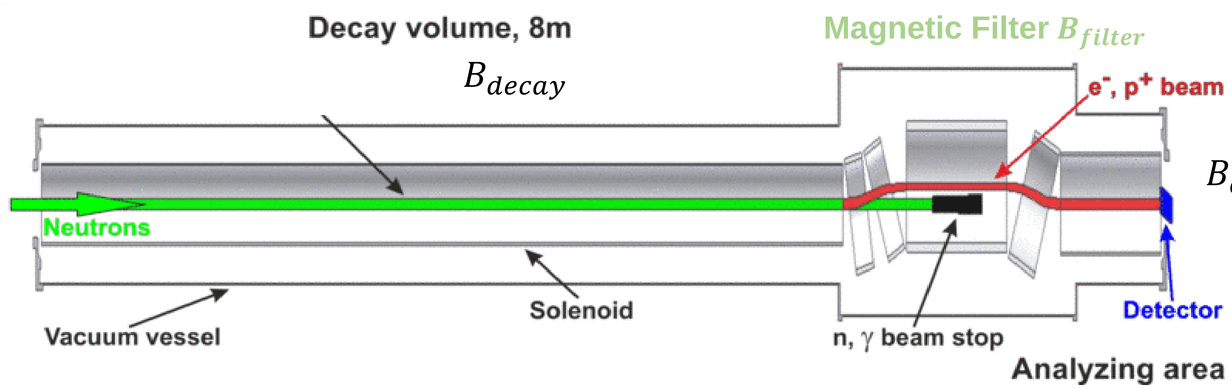
3. Definition of solid angle: One advantage of the strong magnetic field is that the solid angle of the detectors is well defined (2π without magnetic filter, with filter given by magnetic field ratio $r_{B,DV}$, corrections due to inhomogeneity of field (magnetic mirror effect) under control).

4. Background: Can be managed by requiring coincidence with protons (Nab), but even if not, this is believed to be under control in PERKEO III, PERC, UCNA due to pulse structure of beam.

Way to go beyond: Detector is not responsible for electron energy measurement:

- $R \times B$ spectrometer (NOMOS (G. Konrad et al.), Goal is in the order of $\Delta b \sim 10^{-3}$, maybe part of B. Maerkisch's talk later today)
- Cyclotron Radiation Emission Spectroscopy (See B. Vandevender's talk later today)

The PERC facility @ FRM II (at least, at first ...)

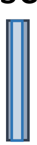


Active volume in a 8 m long neutron-guide, $B_{decay} \leq 1.5$ T:
(statistics, phase space density (S/B !), smaller detectors)

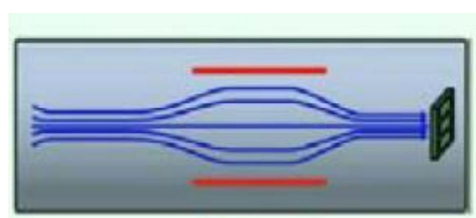
Magnetic Filter, $B_{filter} \leq 6$ T (can select $B_{filter}/B_{decay} = 2 \ldots 12$): phase space selection, systematics
(choice of solid angle, backscatter suppression)
⋮

Source for specialized spectrometers

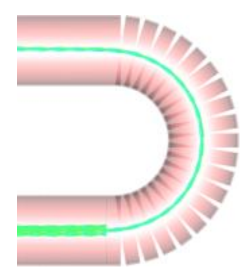
Electron or proton detector (Plastic scintillator, silicon)
(+ backscatter detector?)



MAC-E filter
(as in "aSPECT" – see later)



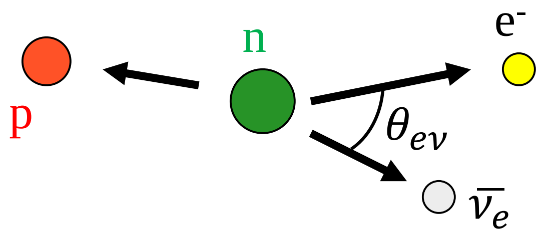
R×B spectrometer for e^- or p (NOMOS)

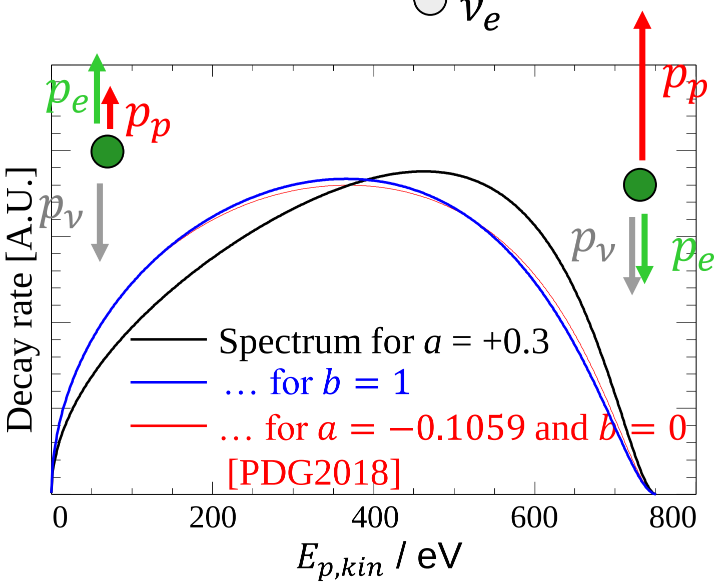


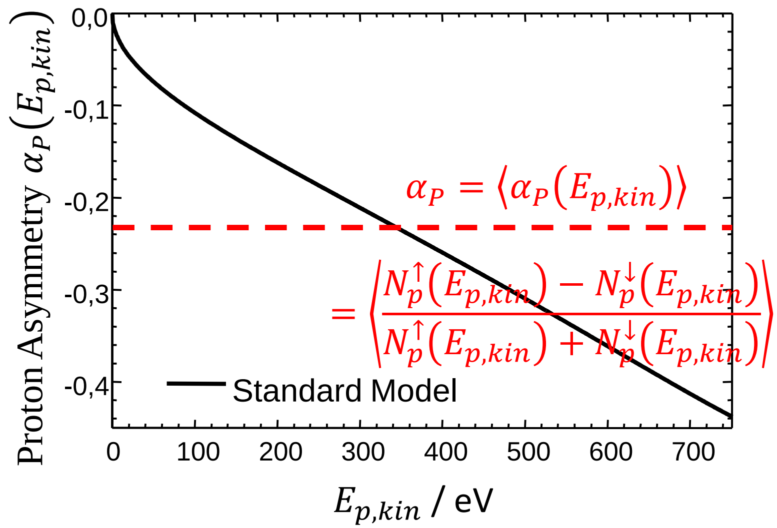
Transverse displacement of beam $\propto p$

B. Märkisch (TU München), D. Dubbers, U. Schmidt (U Heidelberg), H. Abele, G. Konrad (TU Wien), T. Soldner (ILL) et al.

Generic systematics of a measurement of a proton spectrum or its asymmetry

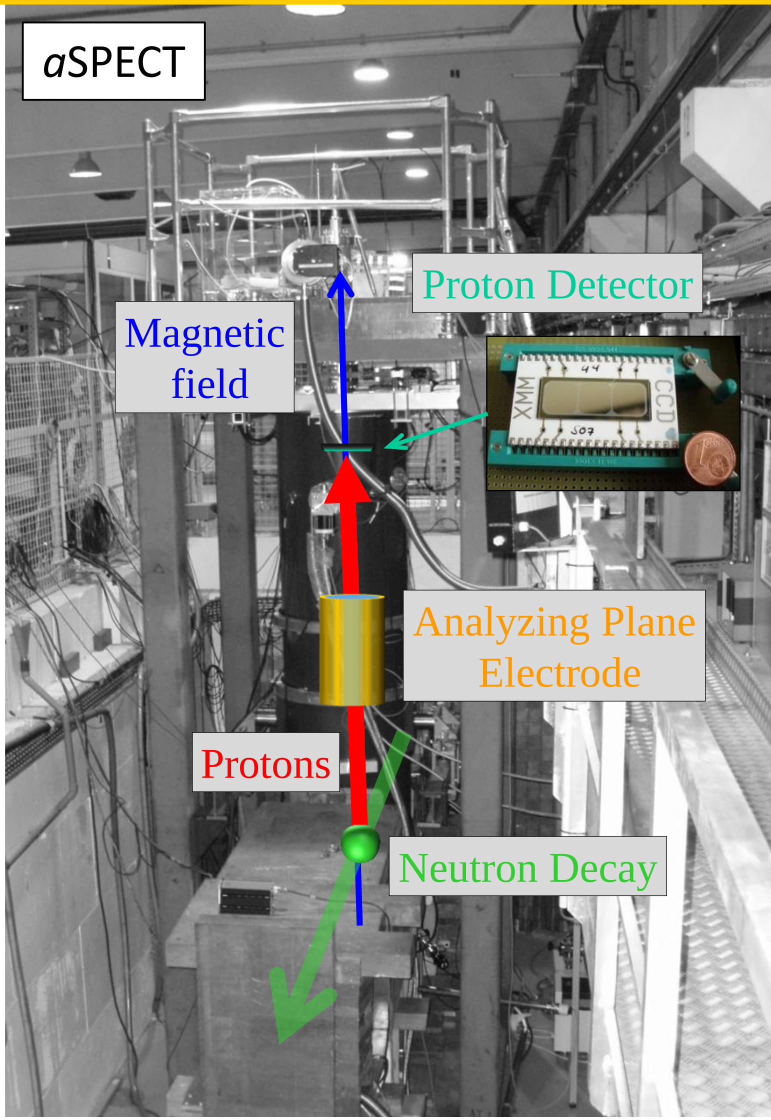






The proton asymmetry allows to determine A and B

Proton spectrometer



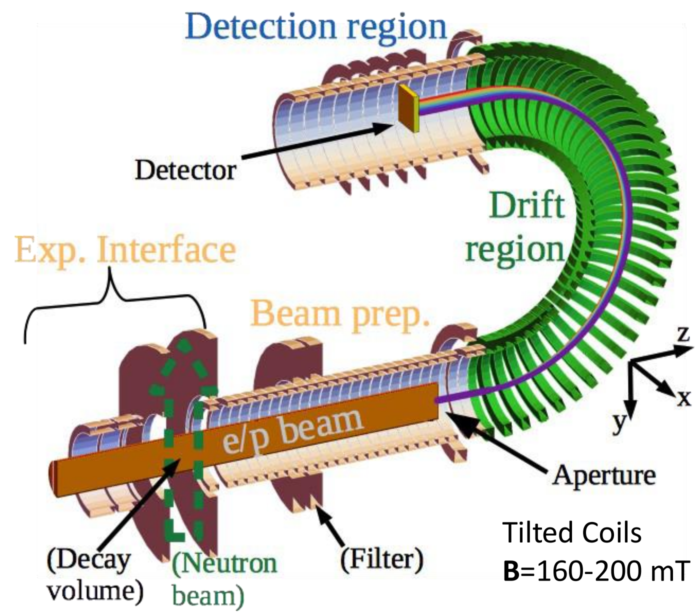
Preliminary result (PPNS Grenoble, 2018): $a = -0.10603(91)$

W. Heil, M. Beck, C. Schmidt (U Mainz) et al.

NoMoS (**N**eutron Decay Pr**o**ducts **Mo**mentum **S**pectrometer) (electron and protons)

$$\vec{v}_d \propto \frac{R \times B_3}{qR^2 B_3^2}$$

$$D(p,\theta) = \int_T v_d \mathrm{d}t = \frac{p}{qB_3} \cdot \alpha \cdot \frac{1}{2}\left(\cos\theta + \frac{1}{\cos\theta}\right)$$

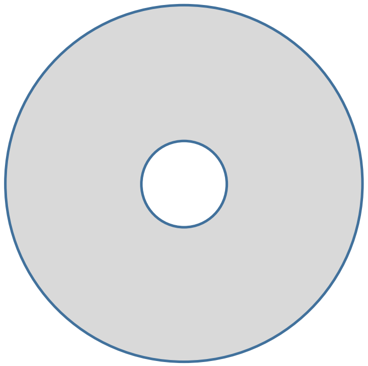


R×B Magnet is planned to be available at the end of 2020. Nomos is planned to be used to determine a and b to 0.1% level.

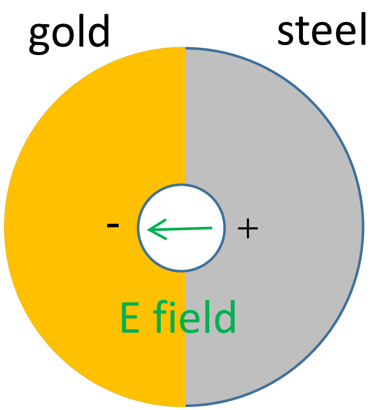
G. Konrad, D. Moser et al. (SMI Wien)

Electrostatic potentials in decay volume: What is the issue?

Most undergraduate textbooks teach: No electric field in empty hole inside conductor…

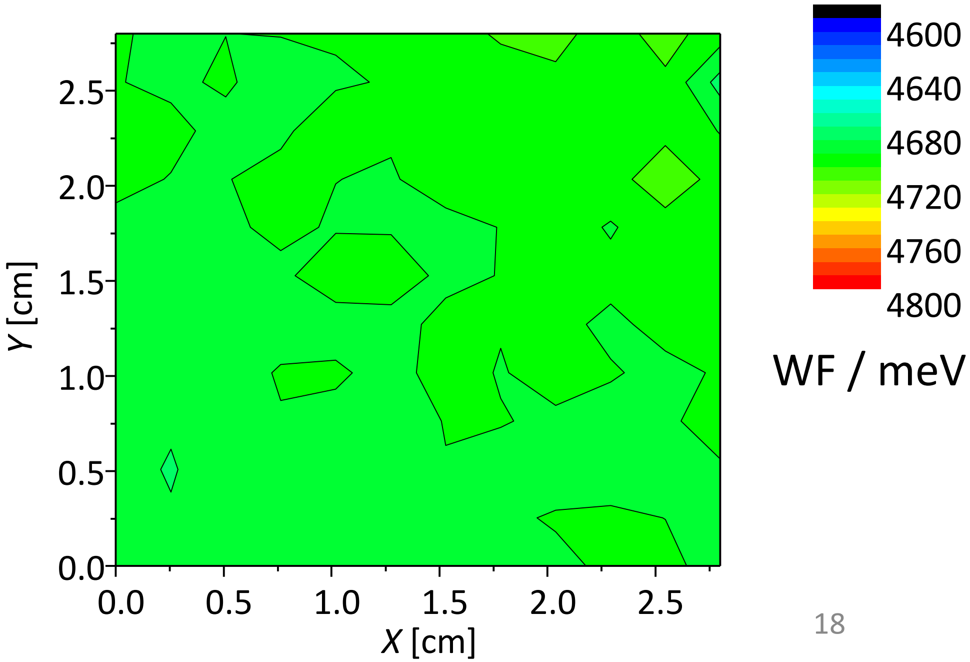


…and I have no objection if the conductor is homogenous. However, if not (and at some level, it is never):



Variation of surface potential
… between different metals: ~Volts
… on naïve gold surface: ~ 100 mV
… really good surfaces: ~ 10 mV

This is caused by variations of the work function (WF).



Generic systematics of a measurement of a proton spectrum or its asymmetry

Protons need to be accelerated in an electric field before detection. Proton detection and eventual proton energy measurement is usually separated. Major systematics are:

1. **Unwanted electrostatic potential variations:** The electrostatic potential (or: its difference to other places) can be controlled to about 10 mV. This corresponds to
   - An uncertainty of $\Delta a \sim 10^{-3}$ in a measurement of the proton spectrum (aSPECT, PERC/NOMOS)
   - An uncertainty of $\Delta B \sim 10^{-2}(!)$ from a proton asymmetry measurement. For $\Delta B \sim 10^{-3}$, the voltage has to be known to 0.1 mV. The situation is much more favorable is is much better if a magnetic or electrostatic filter is used, $\Delta \mathrm{B} \sim 10^{-3}$ is possible with a 10 mV uncertainty in the voltage.

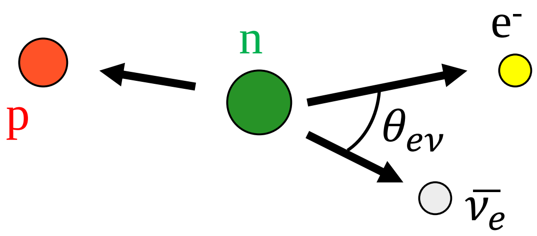
   A common mitigation strategy in surface physics is to have the electrodes far away from the volume of interest, for better averaging of work function fluctuation.
2. **Doppler effect:** Relevant for longitudinal extraction of protons from a cold neutron beam. Energy shift for a decay proton from 4 Å neutron is 2.8 eV. In PERC, average wavelength of neutron beam pulse has to be known to 1% (and: pulse structure helps).
3. **Residual gas pressure:** Proton scattering and charge exchange usually require a residual gas pressure of less than 10^{-8} mbar.
4. **Neutron beam polarization:** Relevant for B, believed to be under control much better than 10^{-3} (see A. Pethoukov, T. Soldner et al. for cold neutrons, and A. Young et al for ultracold neutrons)

See F. Glück et al., Eur. Phys. J. A 23, 135 (2005), G. Konrad et al., J. Phys.: Conf. Ser. 340, 012048 (2012)

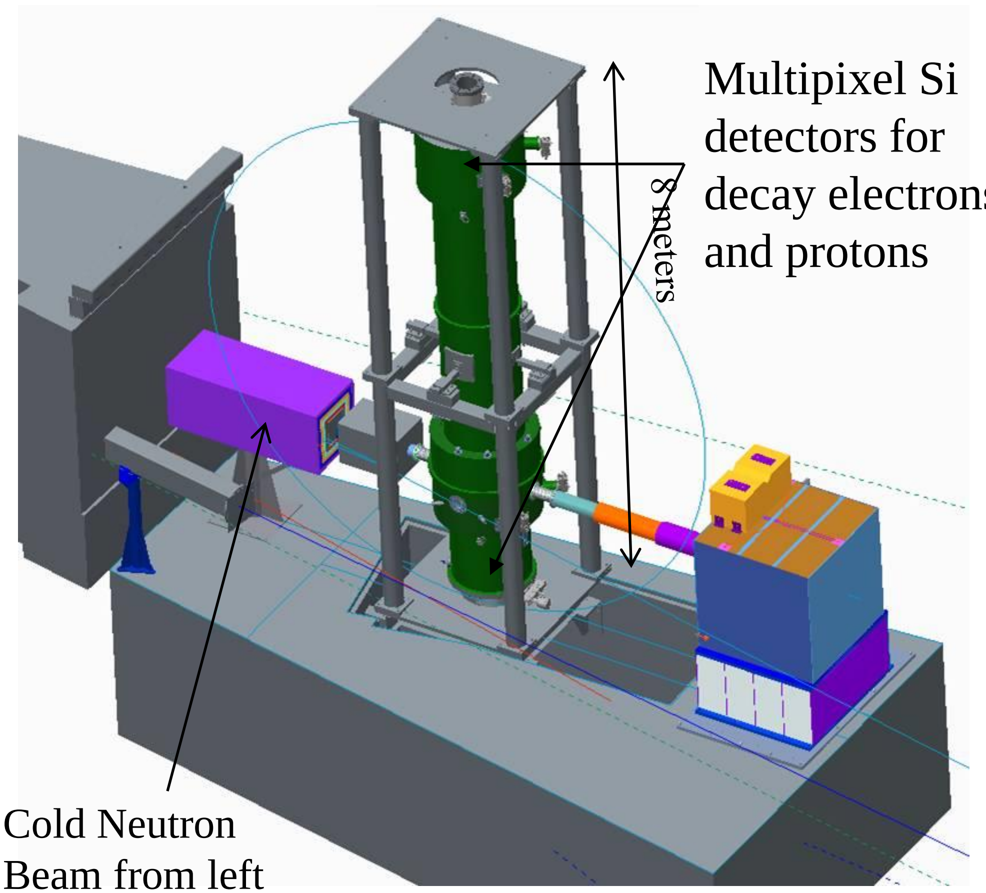
The neutrino electron correlation coefficient a

Measurement of electron energy spectrum gives the Fierz term b.

Measurement of a from measurement of proton and electron energy.

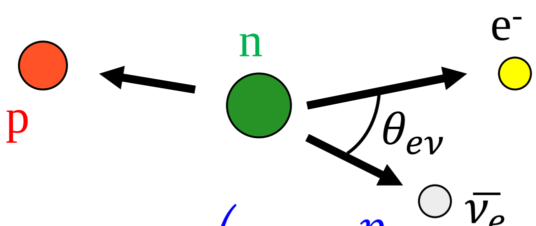


Nab @ Fundamental Neutron Physics Beamline (FNPB) @ Spallation Neutron Source (SNS)



General Idea: J.D. Bowman, Journ. Res. NIST 110, 40 (2005)
Original configuration: D. Počanić et al., NIM A 611, 211 (2009)
Asymmetric configuration: S. Baeßler et al., J. Phys. G 41, 114003 (2014)

Idea of the cos $\theta_{e\nu}$ spectrometer Nab @ SNS

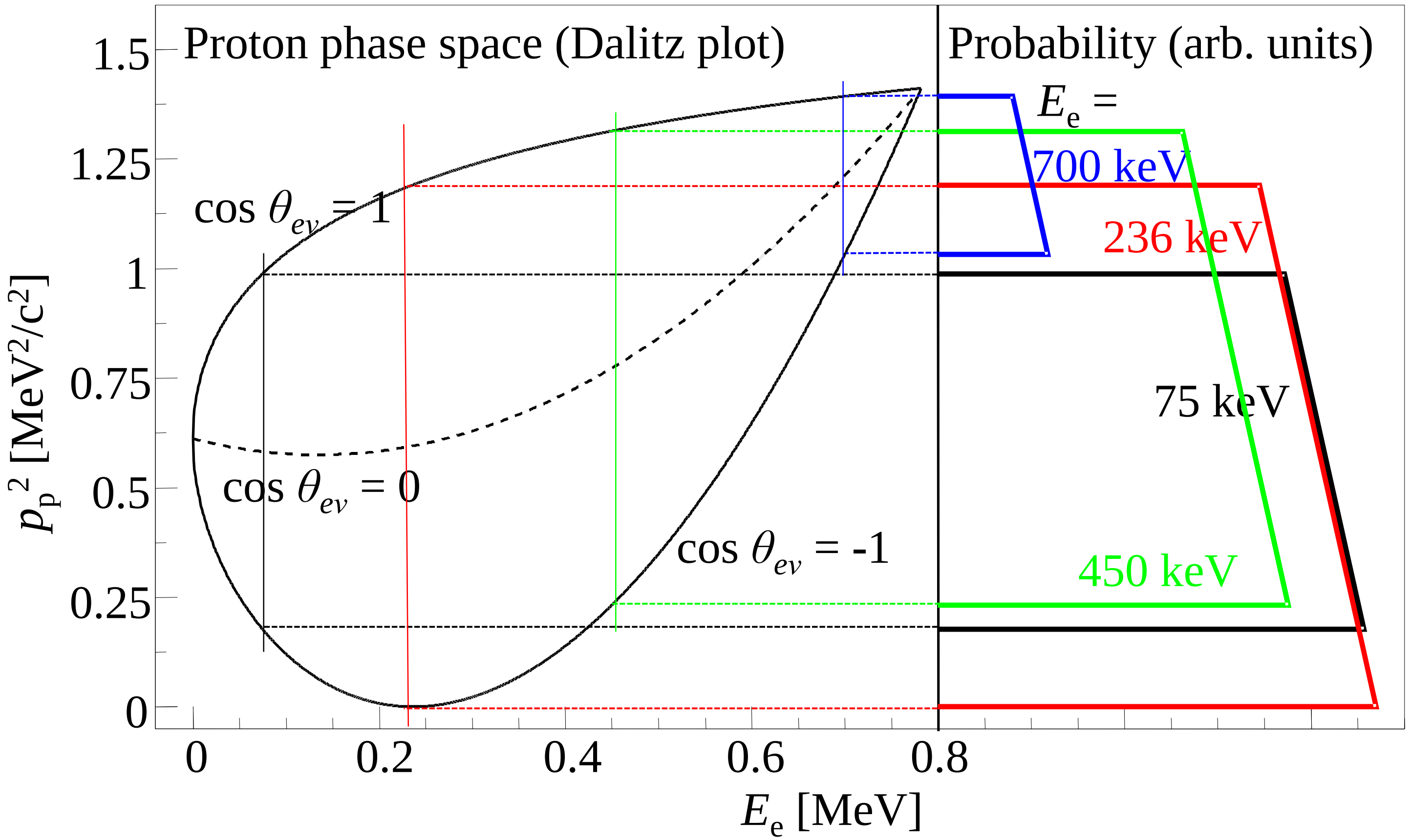


$$d\Gamma \propto \varrho(E_e)\left(1 + a\frac{p_e}{E_e}\cos\theta_{e\nu} + b\frac{m_e}{E_e}\right)$$

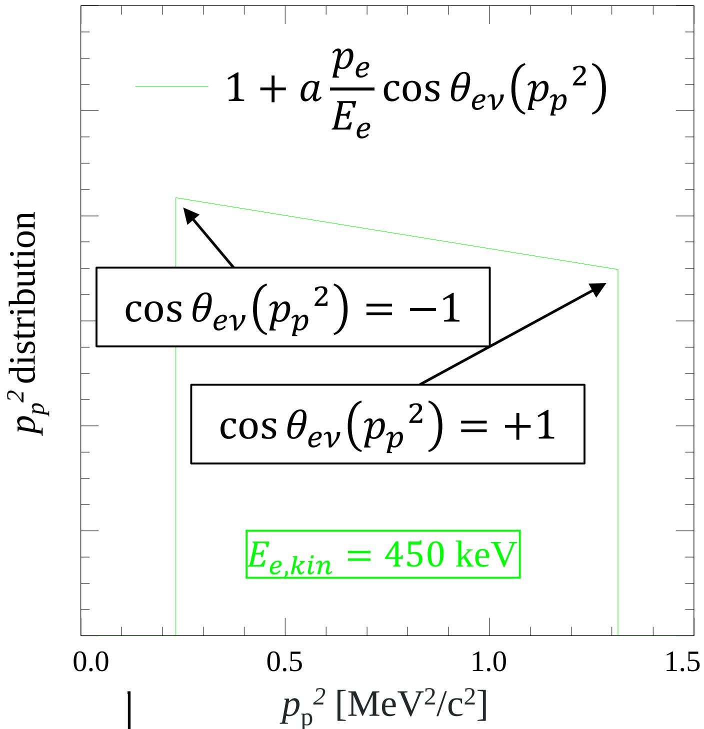
- Energy Conservation in Infinite Nuclear Mass Approximation: $E_\nu = E_{e,max} - E_e$
- Momentum Conservation:

$$p_p^2 = p_e^2 + p_\nu^2 + 2p_e p_\nu \cos\theta_{e\nu}$$

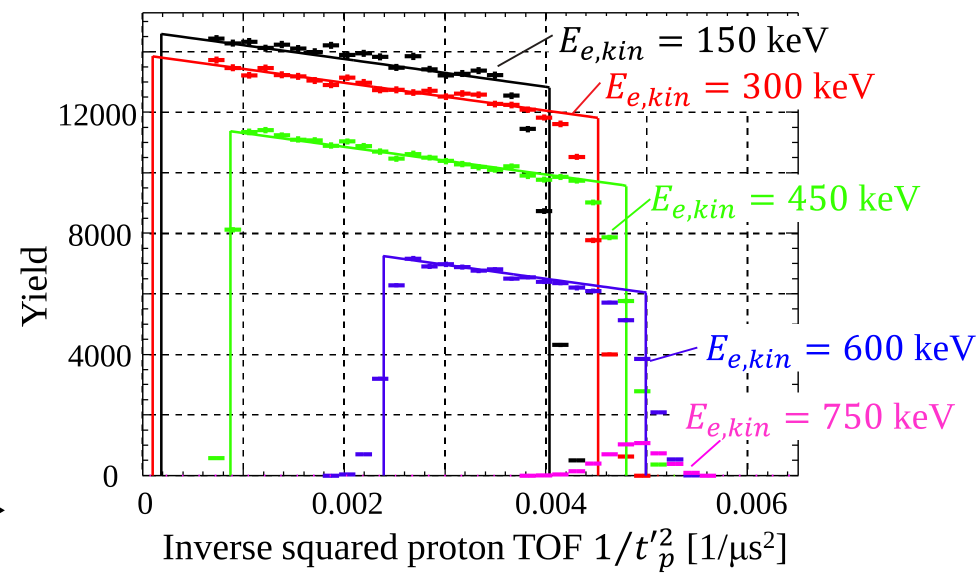
(p_p is inferred from proton time-of-flight)



Nab data analysis



Full GEANT4 spectrometer simulation:



$$t_p = \frac{m_p \cdot \text{spectrometer length}}{p_p - \text{component along } \vec{B}}$$

Data analysis: Use edge to determine or verify the spectrometer TOF response function.

Then, use central part to determine slope and correlation coefficient a. Need agreement for all.

Nab goal for SNS run and outlook

Experimental parameter	Systematic uncertainty $\Delta a/a$
Magnetic field	**$6\cdot10^{-4}$**
Electrical potential inhomogeneity:	**$5.5\cdot10^{-4}$**
Neutron Beam:	
… position	$1.7\cdot10^{-4}$
… profile (including edge effect)	$2.5\cdot10^{-4}$
… Doppler effect	small
… Unwanted beam polarization	can be small
Adiabaticity of proton motion	$1\cdot10^{-4}$
Detector effects:	
… Electron energy calibration	$2\cdot10^{-4}$
… Shape of electron energy response	**$4.4\cdot10^{-4}$**
… Proton trigger efficiency	$3.4\cdot10^{-4}$
… TOF shift due to detector/electronics	$3\cdot10^{-4}$
Residual gas	$3.8\cdot10^{-4}$
Background / Accidental coincidences	small
Sum	**$1.2\cdot10^{-3}$**

Statistical uncertainty in idealized configuration:

$$\Delta a \propto 2.4/\sqrt{N_d};\ \Delta\lambda \propto 8/\sqrt{N_d}$$

(close to theoretical optimum)

Realistic spectrometer:

$$\Delta a \propto 4.6/\sqrt{N_d};\ \Delta\lambda \propto 16/\sqrt{N_d}$$

(close to theoretical optimum)

Goal: $\Delta a/a = 10^{-3}$; $\Delta\lambda \propto 3\cdot10^{-4}$

What's next:

- Could move to NIST or ESS for larger decay density
- Leading systematics are reducible by a factor of two at least
- Advantages of ESS: Pulsed beam (as for aSPECT), although the issue with the trapped particle background has not been shown yet.
- ESS: Needs a deep pit below installation to be able to install Nab.

Summary

- Physics goal (recently adjusted) is to achieve at least $\Delta\lambda \sim 1.1 \cdot 10^{-4}$ (for unitarity) and $\Delta b \sim 10^{-3}$ or and $\Delta b_{\nu} \sim 10^{-3}$. Several experiments promise to get close:
  - Electron spectrum and asymmetry may achieve goal with cold pulsed beam and longitudinal source extraction, or with ultracold neutron sources which must become even stronger for that. However, detector effects may give uncertainty larger than goal. This may be overcome with new ideas (Cyclotron radiation electron spectroscopy).
  - Measurements involving protons are hard due to work function inhomogeneity, Doppler effect (for longitudinal extraction) and residual gas. I find other measurement schemes more promising, but they need stronger neutron decay sources to achieve physics goal.
- If something interesting is found, at least two different experiments are needed
- It is also worth to revisit other physics inputs to unitarity (superallowed decays, kaons, pion beta decay).

Thank you for listening.