The recent measurement of the neutrino electron correlation coefficient a in free neutron beta decay with the aSPECT spectrometer

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N.B.: I thank W. Heil, U. Schmidt, C. Schmidt, and G. Konrad for slides.

The problem

Neutron beta decay can inform unitarity test of Cabbibo-Kobayashi-Maskawa-Matrix.

… and speaking on a Friday of a dedicated conference, I am skipping a few pages of introduction here.

V_{ud} from neutron beta decay:

$$|V_{ud}|^2 = \frac{5099.33\text{ s}}{\tau_n(1+3\lambda^2)(1+\Delta_R)}$$

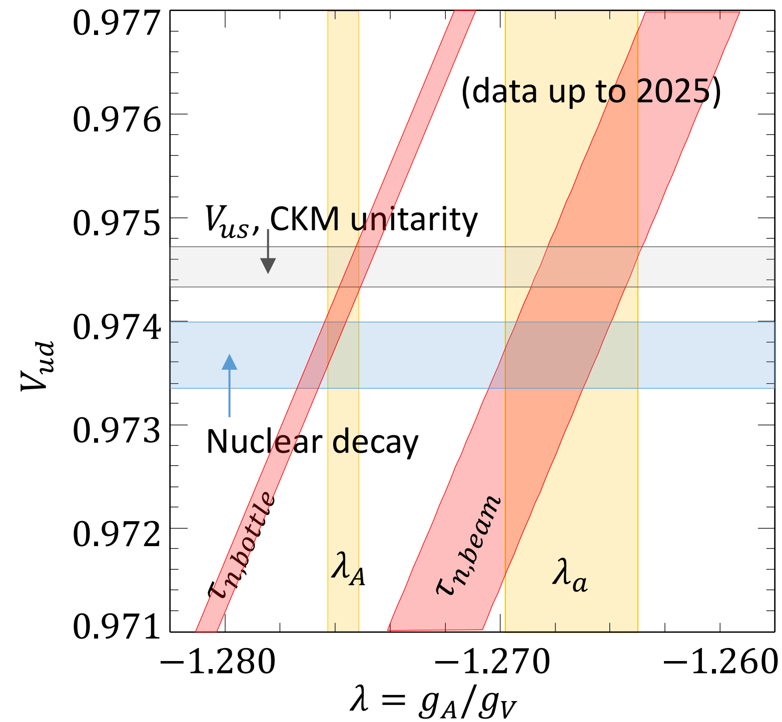
Chen-Yu Liu discussed the neutron lifetime:

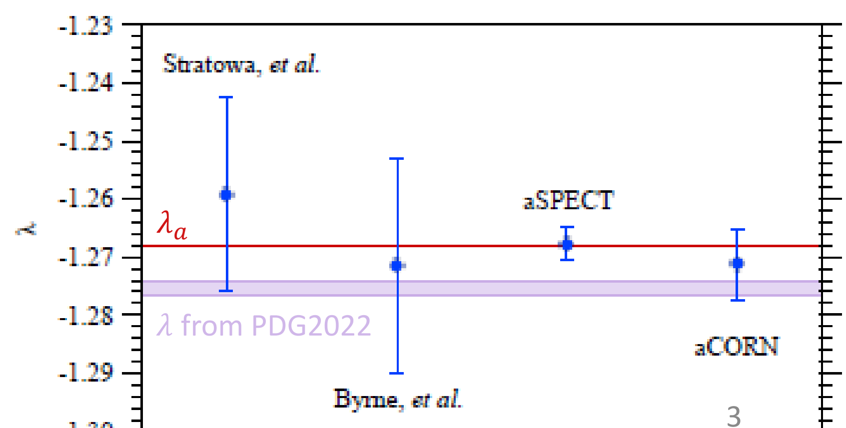
- Thanks to her an collaborators recent work, we know it quite well.
- The bottle vs. beam discussion is unresolved.

This talk is about the λ value from *a*SPECT.

- Dominant uncertainty in V_{ud} determination
- Discrepancy between measurements, albeit "only" at the 3 sigma level.

K. Kleinknecht: "One needs to discuss the results one has, not the ones one wants to have…"

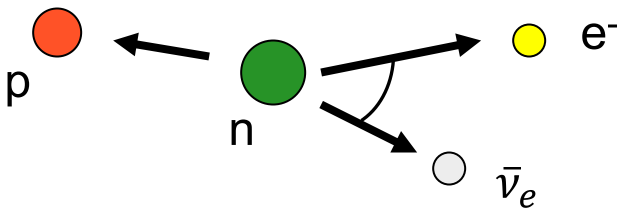




F.E. Wietfeldt, PRC 110, 015502 (2024)

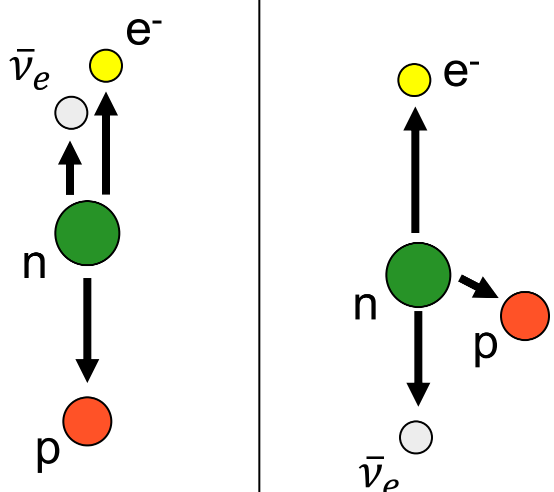
The Neutrino Electron Correlation and the Proton Spectrum in Neutron Decay

The correlation coefficient *a*



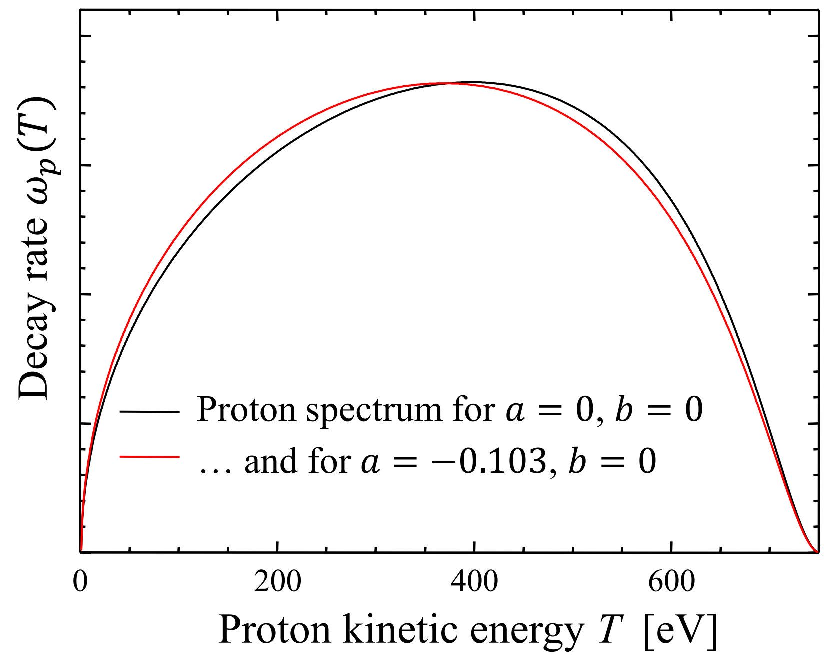
$$d\Gamma \propto \rho(E_e)\left(1 + a\,\frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + b\,\frac{m_e}{E_e}\right)$$

C.F. v. Weizsäcker, Z. f. Phys. 102,572 (1936), M. Fierz, Z. f. Phys. 104, 553 (1937), J.D. Jackson et al., PR 106, 517 (1957)

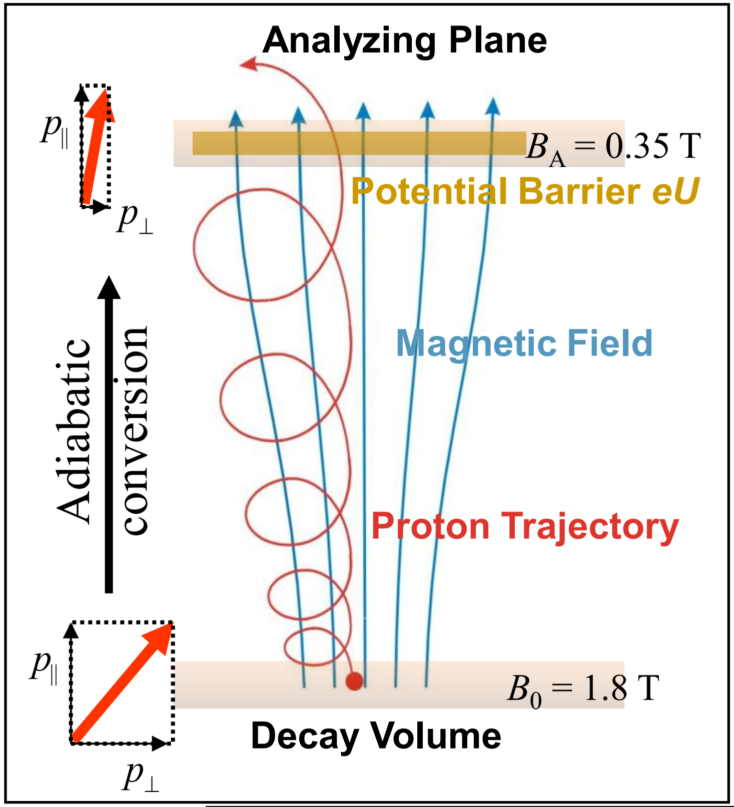


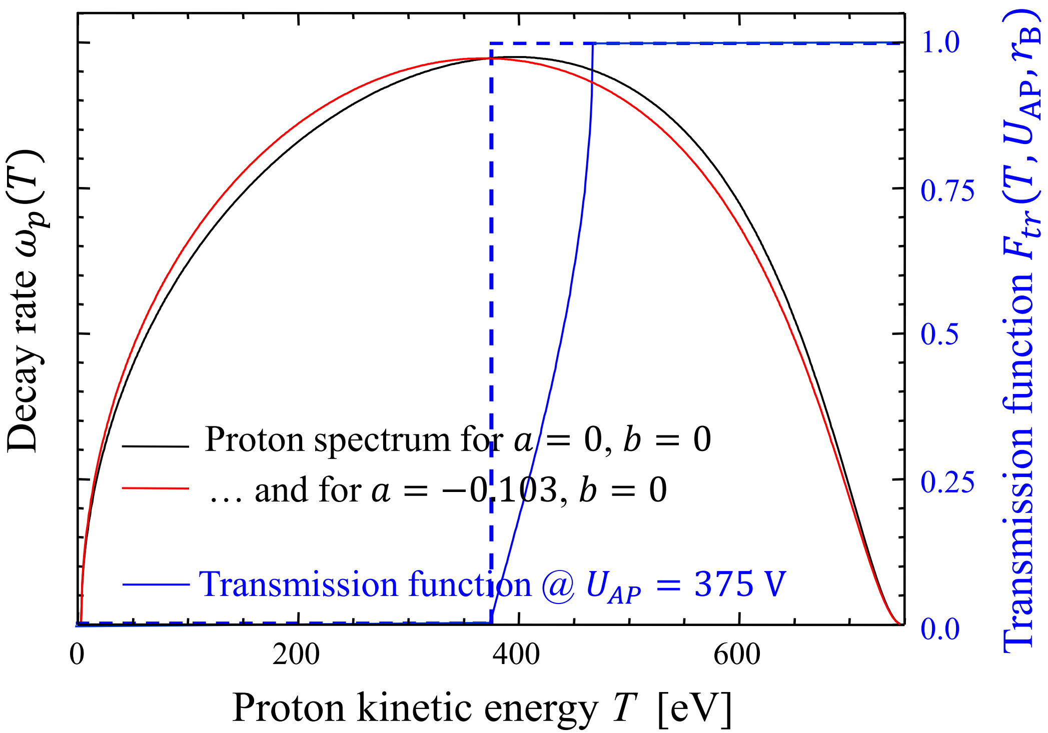
Proton kinetic energy is big	Proton kinetic energy is small
Preferred for $a > 0$	Preferred for $a < 0$

Sensitivity of the proton spectrum to *a* and *b*:



Principle of a Retardation Spectrometer

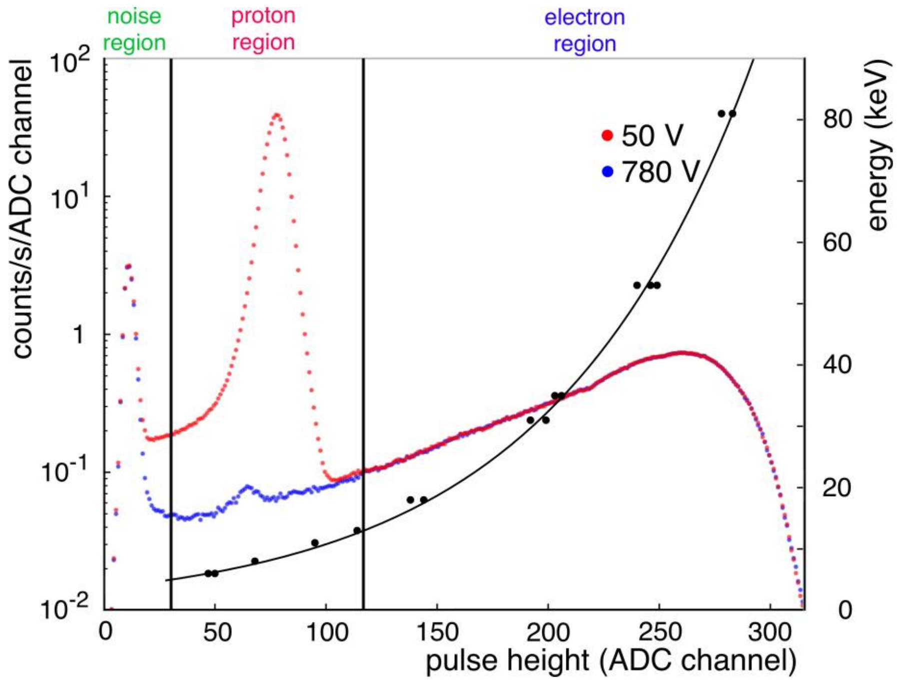


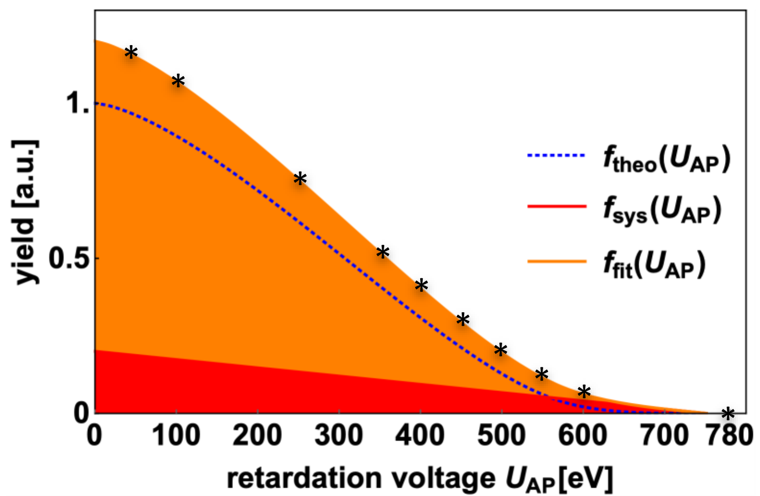


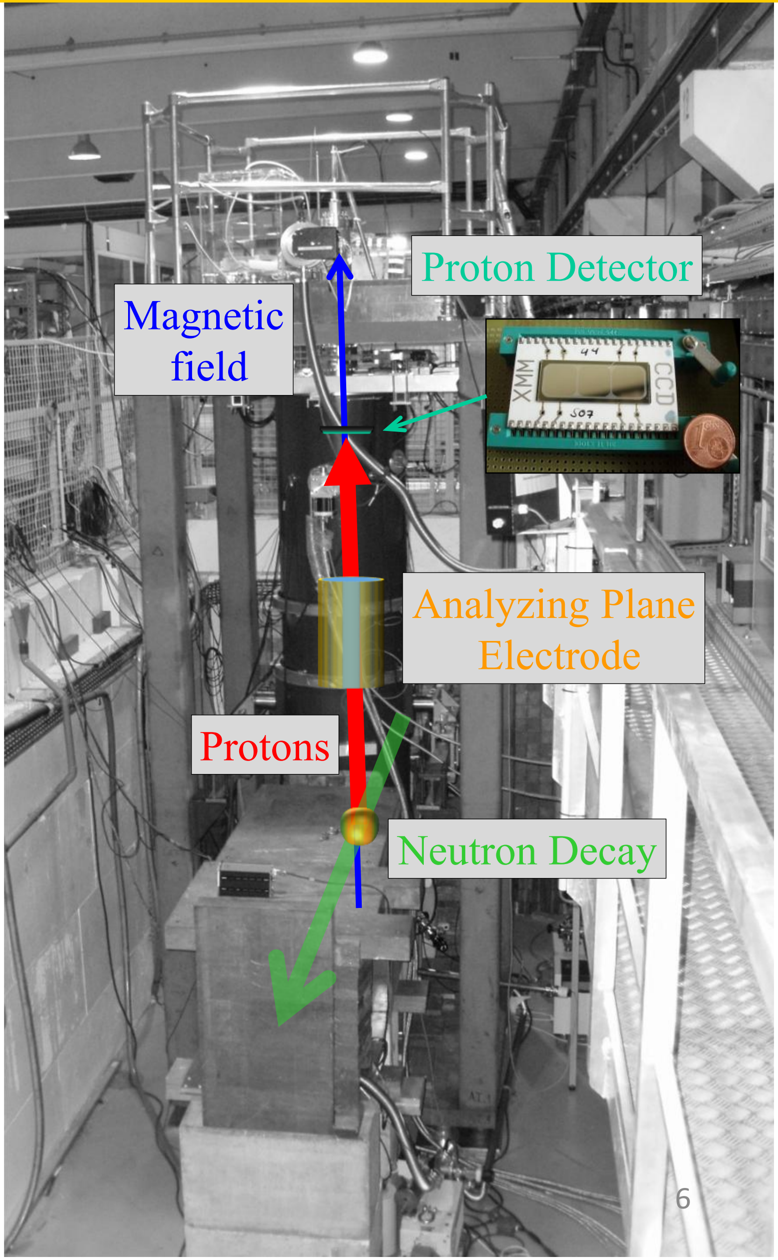
Transmission function $F_{tr}(T, U_{AP}, r_B = B_A/B_0)$ in the adiabatic limit:

$$F_{tr}(T, U_{AP}, r_B) = \begin{cases} 0 & T < eU_{AP} \\ 1 - \sqrt{1 - r_B^{-1}\left(1 - \frac{eU_{AP}}{T}\right)} & \text{otherwise} \\ 1 & T > eU_{AP}/(1 - r_B) \end{cases}$$

Principle of *a*SPECT spectrometer







Global fit (also called grand χ^2)

$$f_{fit}(U_{AP}) = f_{theo}(U_{AP}) + \sum f^j_{sys}(U_{AP})$$

$$\propto \int w_p(T,a) F_{tr}(T, U_{AP}, r_B)\, dT$$

$$\sum f^j_{sys}(U_{AP}, r_B, a, N_0, \{fpar_j\})$$

U. Schmidt, U. Heidelberg

This is the usual fit to the model function after inclusion of systematic corrections

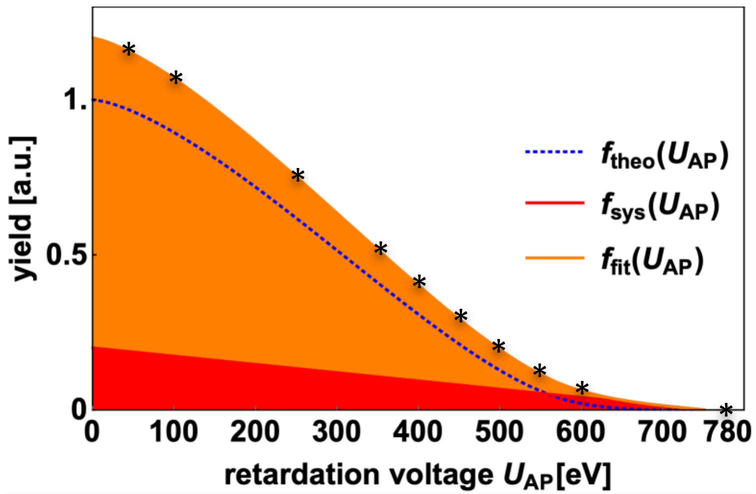
Minimization of global χ^2:

$$\chi^2_{global} = \sum_{configs,pads} \left(\sum_i^n \frac{\left(y_{exp,i} - f_{fit}(U_{AP}, r_B, a, N_0, \{fpar_j\})\right)^2}{\left(\Delta y_{exp,i}\right)^2} + \sum_j \sum_k^{n_j} \frac{\left(y^j_{sys,k} - g^j_{sys}(U_{AP}, T, r_B, \{gpar_j\})\right)^2}{\left(\Delta y^j_{sys,k}\right)^2} \right)$$

These are fits to the results of auxiliary measurements and simulations, e.g. to the measurements of $r_B = B_A/B_0$

Systematic effects

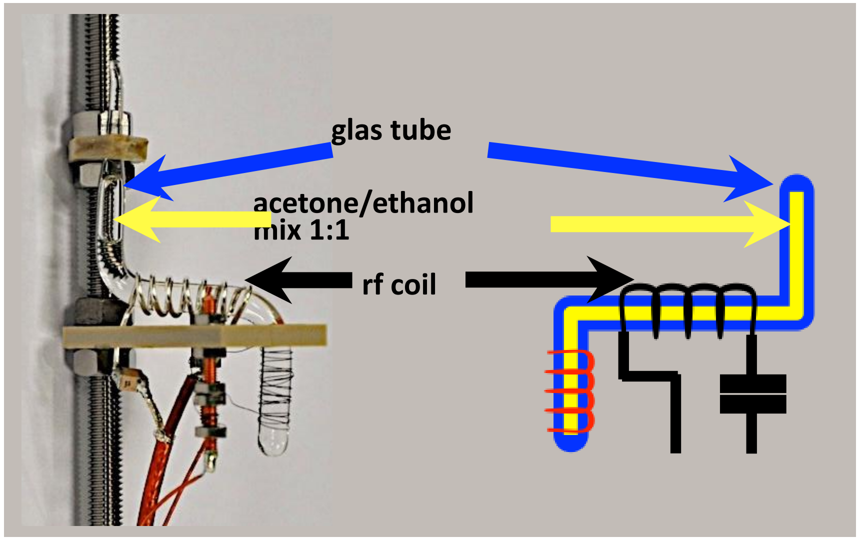
A. Temporal stability and normalization
B. Magnetic field ratio <r_B>
C. Retardation voltage <U_{AP}>*)
D. Background
E. Edge effect
F. Backscattering and below-threshold losses*)
G. Dead time and pile-up
H. Proton traps in the DV region



$$f_{fit}(U_{AP}) = f_{theo}(U_{AP}) + f_{sys}(U_{AP})$$

*) Systematic effects that were improved on in 2024 analysis

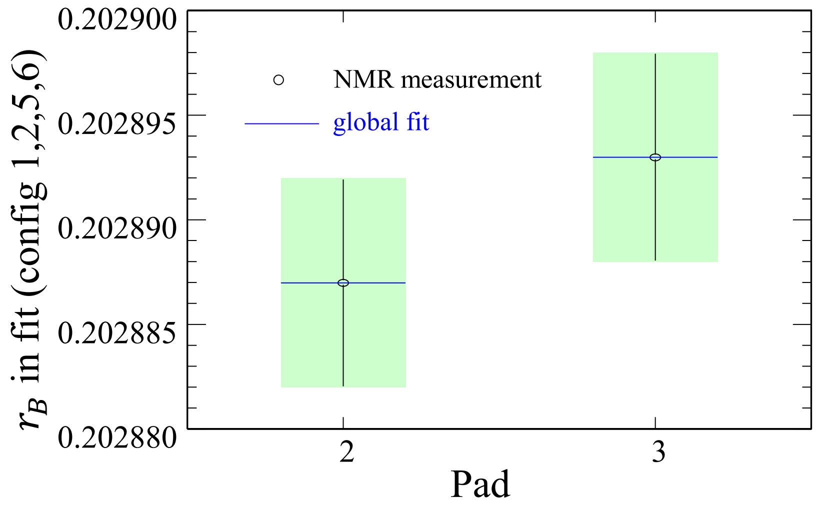
Magnetic field ratio $r_B = B_A/B_0$



Two probes mounted at electrode system:

- high field probe (92 MHz / 2.2 T)
- low field probe (18 MHz / 0.44 T)

For fit: $\Delta r_B/r_B \sim 2.4 \cdot 10^{-5}$



NMR measurement

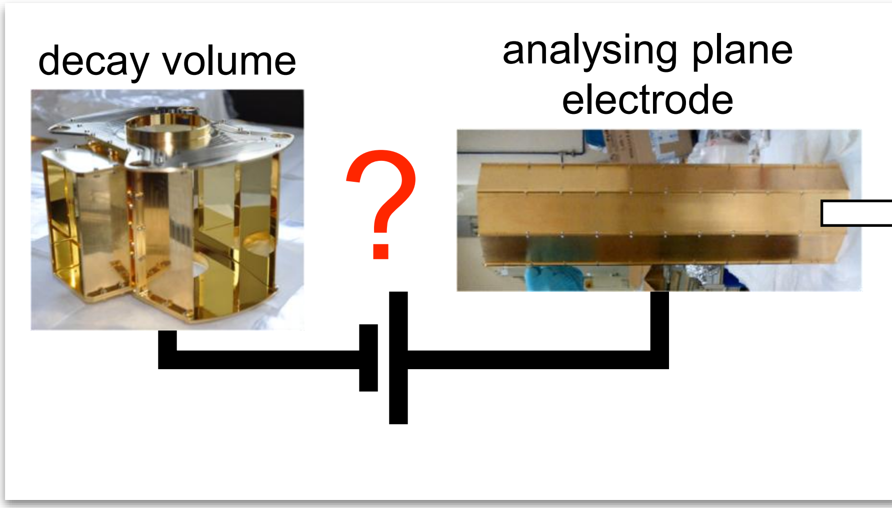
- statistical $\Delta B/B < 10^{-6}$
- with systematics $\Delta B/B \sim 10^{-5}$

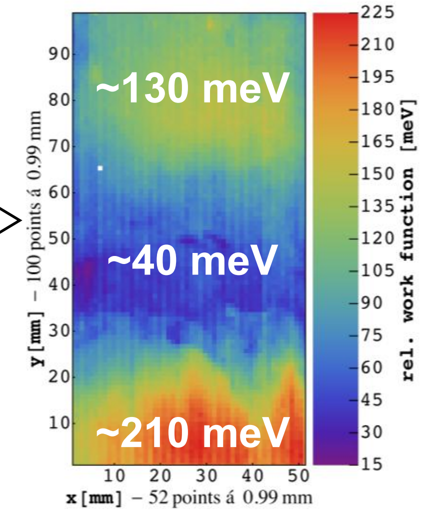
Systematic investigations

- Long-term stability
- Reproducibility
- Hysteresis of superconducting magnet
- Hysteresis of air-coils
- Influence of stainless steel detector cup
- Magnetic field drift due to energy dissipation

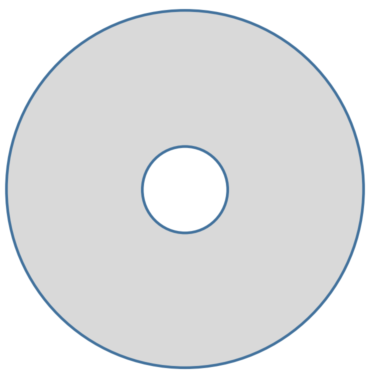
Retardation potential U_{AP}

Sensitivity:
$\Delta U_{AP} = 10$ mV
results in
$\Delta a/a \sim 10^{-3}$

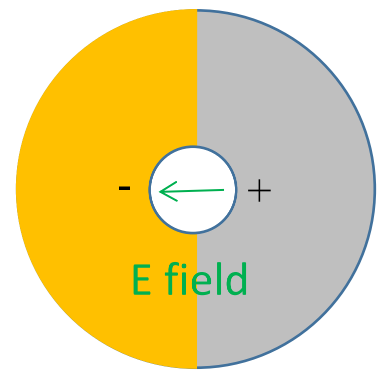




Most undergraduate textbooks teach: No electric field in empty hole inside conductor…



...and I have no objection if the conductor is homogeneous.

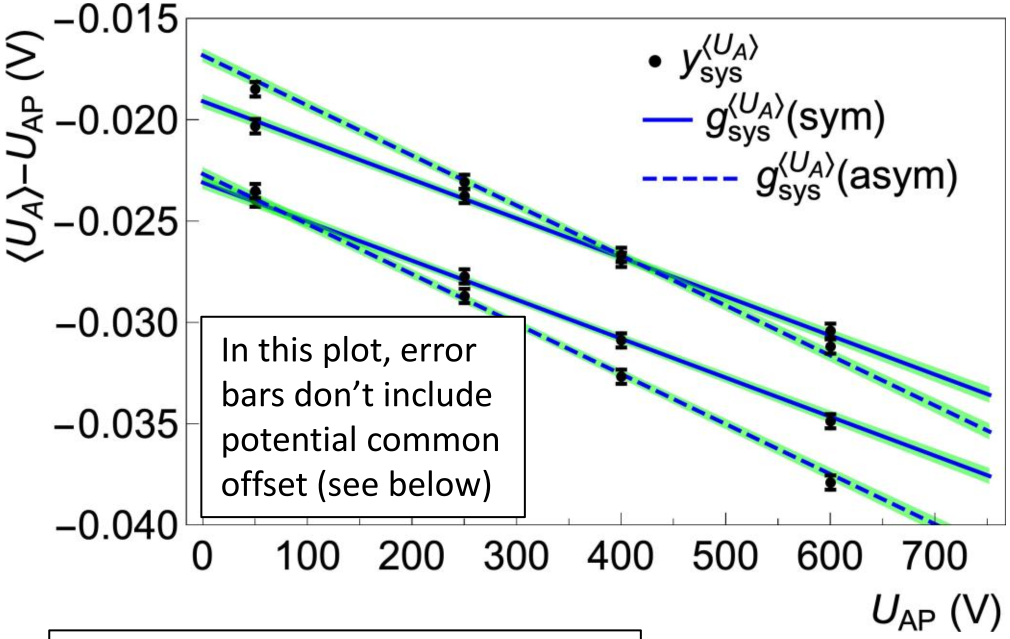


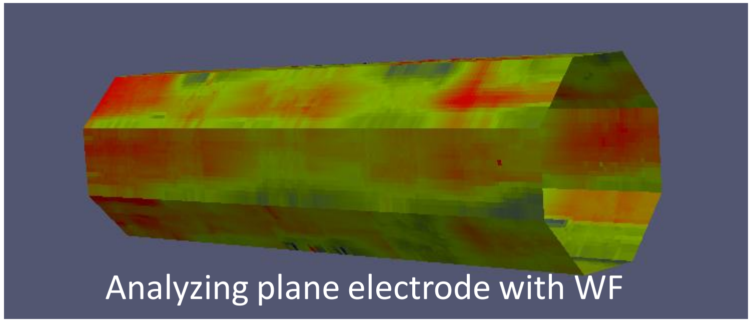
However, if not:

No conductor is perfectly uniform. Impurities, crystal orientation, unwanted adsorbates on surface matter if sub-volt accuracy is desired.

Retardation potential U_{AP} (2)

Shift of the effective retardation voltage from particle tracking simulations:





Beamtime with aSPECT 2013

Electrodes at ~ 120 K and 10^{-9} mbar

Measurements of work function too difficult in situ. Instead, cut up electrodes electrodes in pieces were studied at ambient conditions, and HV, until 2017

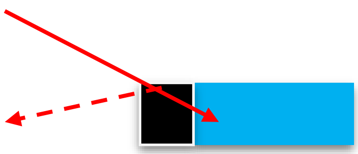
Additional uncertainties from multimeter (< 13 mV, included for 2024 analysis) and workfunction offsets:

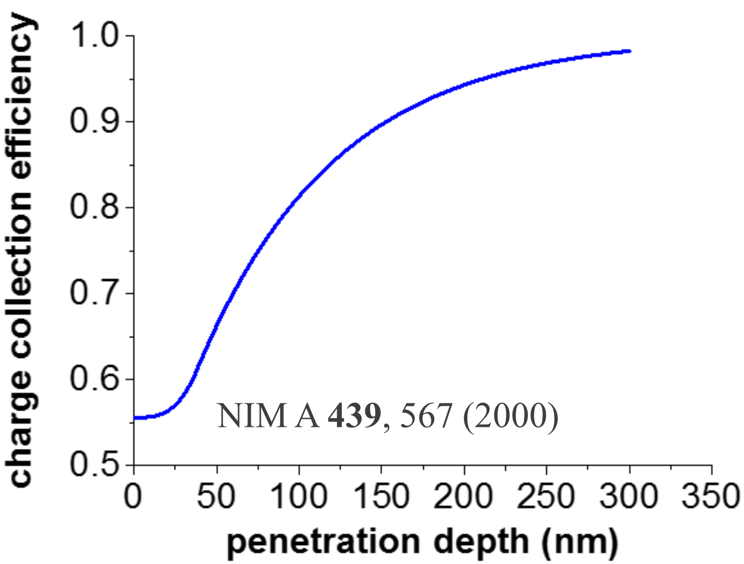
- Aging effects: < 20 mV
- Temperature effects: < 10 mV
- Air-Vacuum difference: < 11 mV

Proton detection efficiency (updated 2024)

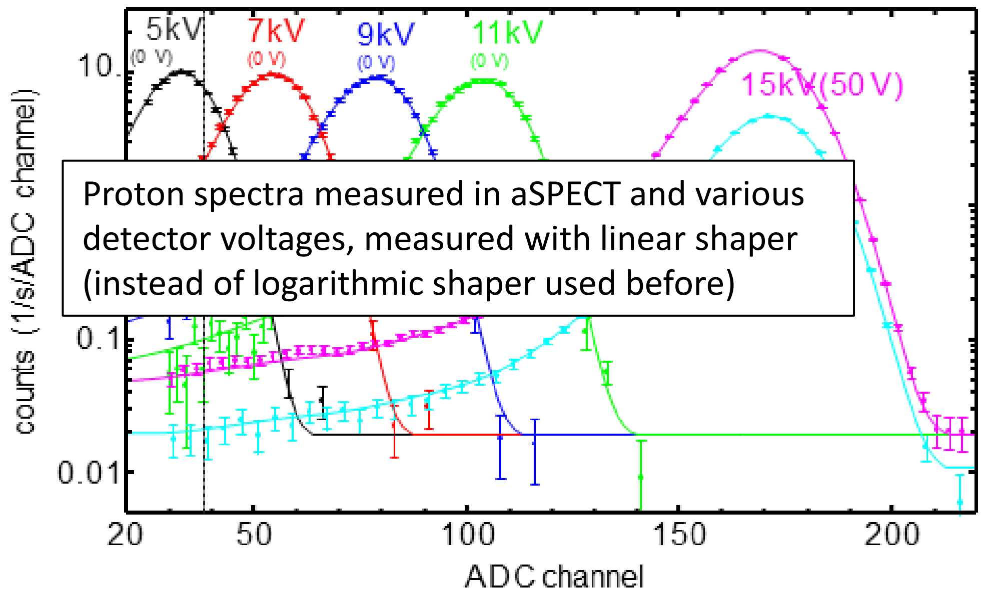
Silicon drift detector (SDD)

Protons with E_p, ϑ_p

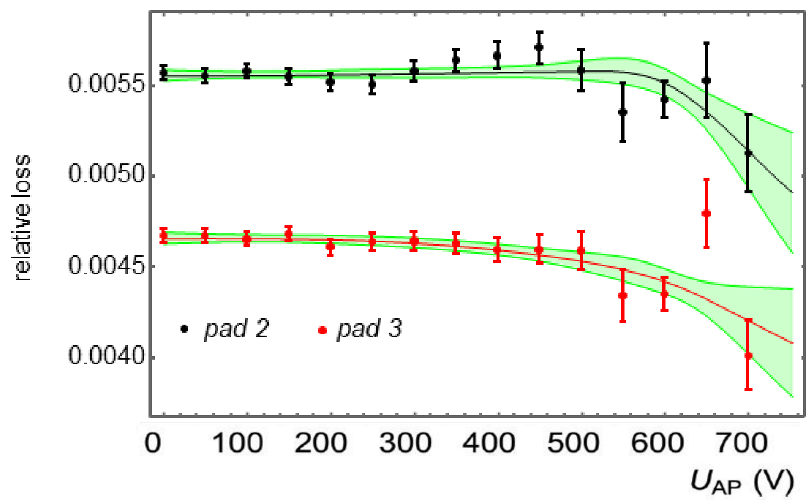




Charge collection efficiency in active layer of similar detector (Simulation with SRIM)

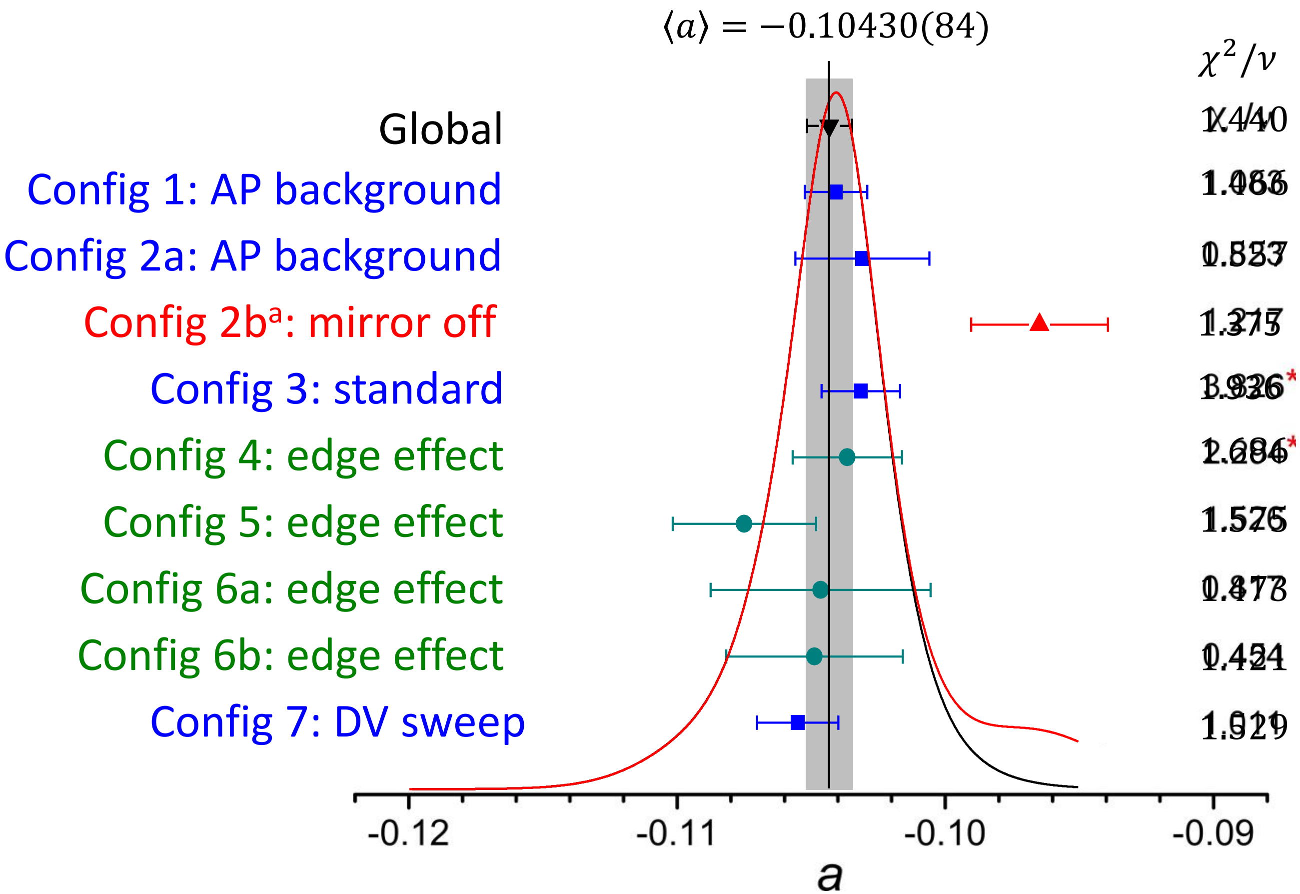


Proton spectra measured in aSPECT and various detector voltages, measured with linear shaper (instead of logarithmic shaper used before)



(2024: modeling includes channeling and neutralization)

Global fit results (2020)



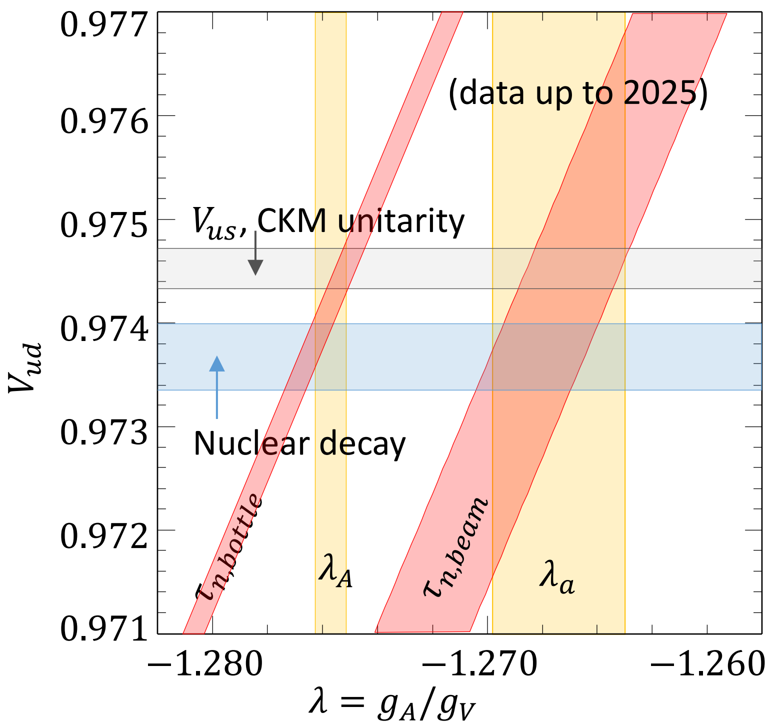
[a] Config 2b is not used in fit, as corrections from proton backscattering from bottom flange or eventual unwanted neutron beam polarization are undetermined.

aSPECT result

Final result: 1st result: Most precise measurement of a in neutron beta decay

	a	Δa	b	Δb	χ^2_{global}/ν	p-value
aSPECT 2020 (SM)	-0.10430	0.00084	–	–	$1.44\ (\nu = 268)$	$3.1 \cdot 10^{-6}$
Reanalysis 2024, SM	-0.10402	0.00082	–	–	$1.25\ (\nu = 264)$	$4.1 \cdot 10^{-3}$
Reanalysis 2024, BSM	-0.10459	0.00139	-0.0098	0.0193	$1.25\ (\nu = 263)$	$3.7 \cdot 10^{-3}$

Re-analyzed aSPECT result: M. Beck et al., PRL 132, 102501 (2024)
(uncertainties rescaled to reflect low p value)



2nd result: This result constitutes the present best determination of the Fierz term in neutron beta decay. The Fierz term found ($b = -0.0098(193)$) is consistent with the SM prediction ($b = 0$).
Previous work:

UCNA ($b = 0.066(41)(24)$)

PERKEO III ($b = 0.017(20)(3)$)

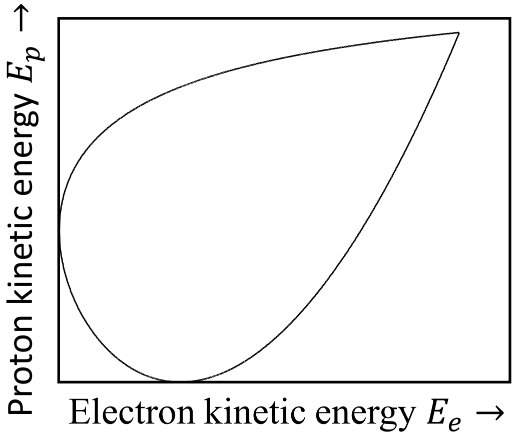
aSPECT Beyond-Standard-Model analysis

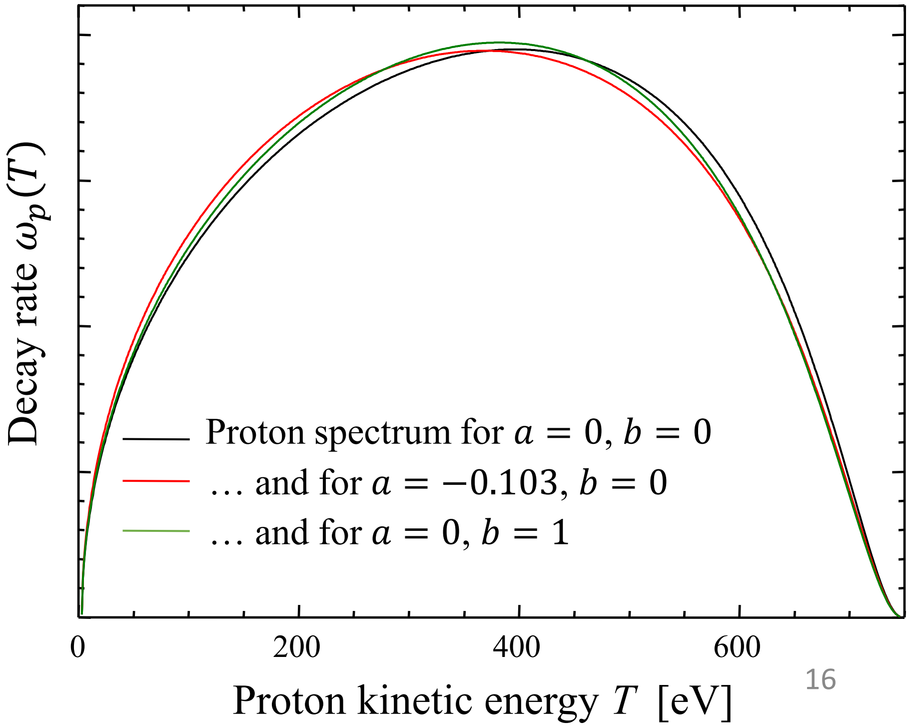
Inspection of effect of positive Fierz term b on (normalized) proton spectrum:

- A spectral shape measurement distinguishes the effect of a and b on the proton spectrum
- However, a positive b looks pretty similar to a more negative value of a (compare red and green curves).
- Unfortunately, we are not able to vary a or b. If we assume a positive value for b and take the experimental data as is, we expect a larger fit value for a to compensate. That is also a larger value for λ.

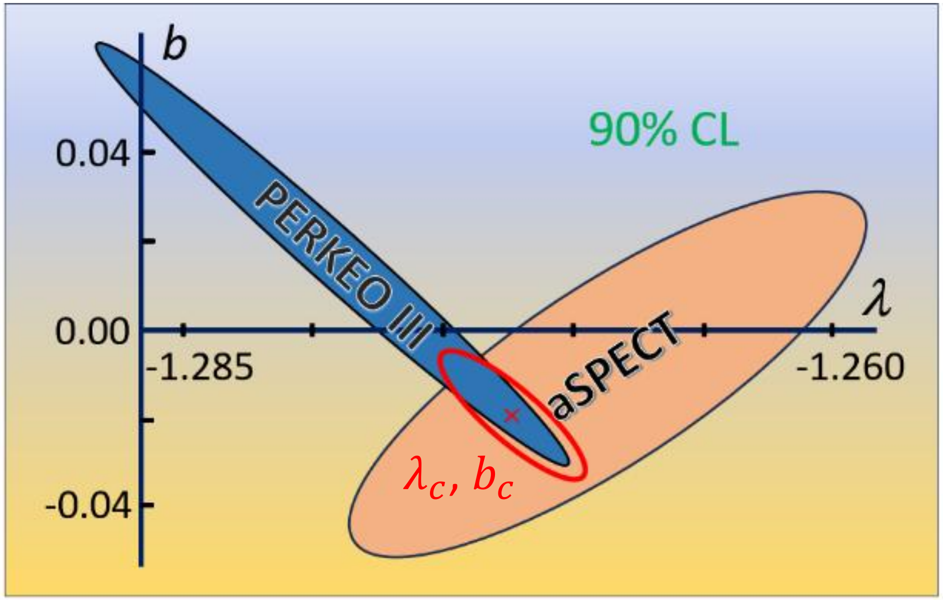
That is: We expect a positive correlation between λ and b.

Neutron decay phase space (Dalitz plot)





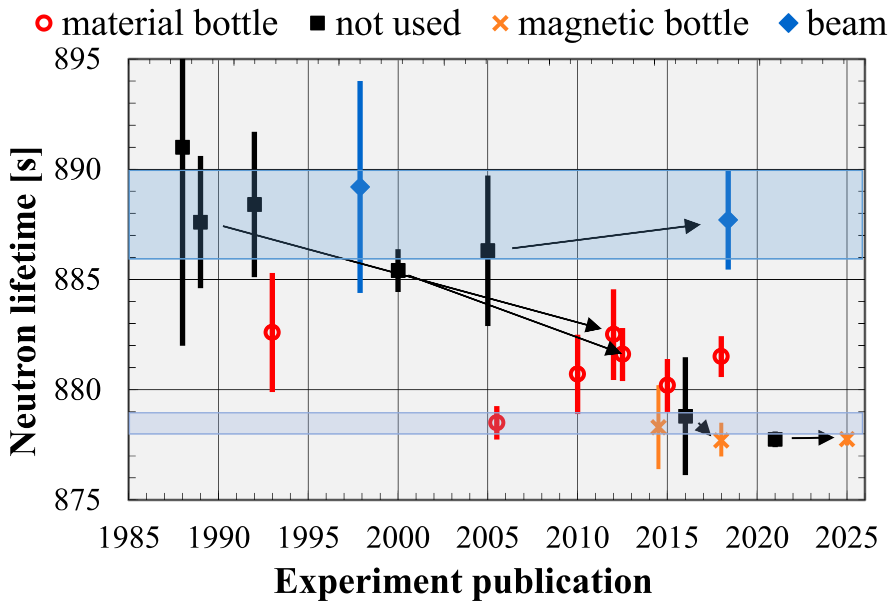
aSPECT result, cont.



W. Heil (Mainz)
Re-analyzed aSPECT result: M. Beck et al., PRL 132, 102501 (2024)

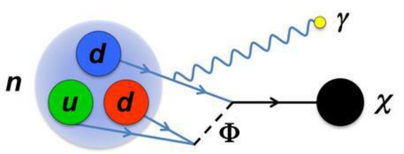
- (Again): aSPECT alone gives a Fierz term consistent with SM.
- Our issue in the SM analysis, $\lambda_a \neq \lambda_A$, could be explained with a non-zero Fierz term of $b_c = -0.0184(65)$. However, as one reviewer has put it: “we are replacing one 3σ problem with another 3σ problem.

Discussion of (λ_c, b_c): Neutron lifetime puzzle



$\tau_c = 894.2(42)$ s;
from $\lambda_c, b_c, V_{\mathrm{ud}}$

NB: this is consistent with Ivanov et al., Nucl. Phys. B 938, 114 (2019)



Could be exciting. There is a series of papers about the possibility that the trap lifetime is really lower than the beam lifetime due to neutron decay into dark particles: Fornal & Grinstein, PRL 120, 191801 (2018)

- $n \to \chi\gamma$ ($m_n > m_\chi > m_p$; $0.8\ \mathrm{MeV} < E_\gamma < 1.7\ \mathrm{MeV}$, BR ~ 1%): undetected in UCNA.
- $n \to \chi\varphi$ (not necessarily detectable)
- $n \to \chi e^+ e^-$ (undetected in PERKEO II and UCNA)

Z. Tang et al, PRL Phys. Rev. Lett. 121, 022505, X. Sun et al., PRC 97, 052501 (2018), M. Klopf et al., PRL 122, 222503 (2019)

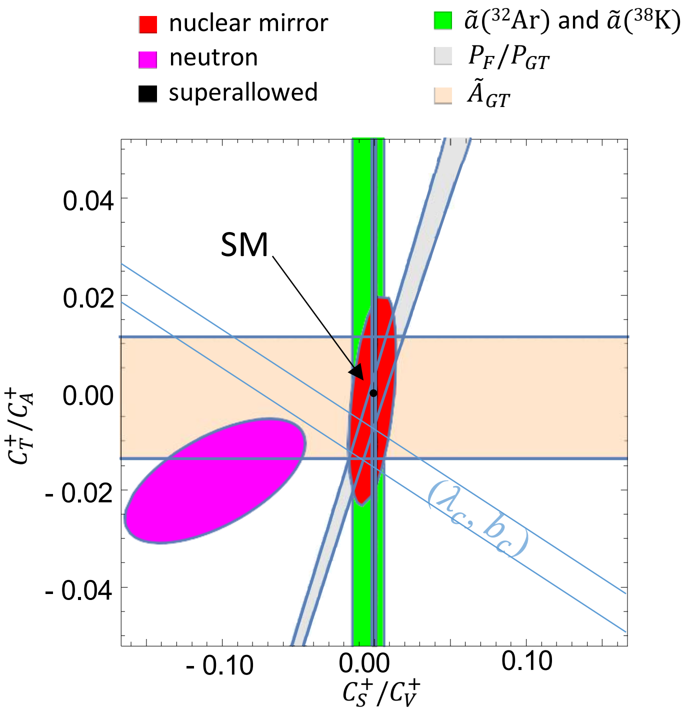
In SM analysis, V_{ud} and λ favor the lower neutron lifetime from bottles, inconsistent with the simpler dark decay explanations. Possible fixes:

- Neutron oscillations into mirror neutrons, may be turned off (or on) with magnetic field

Z. Berezhiani, EPJC 79,484 (2019), A. Serebrov et al., PLB 663, 181 (2008), L.J. Broussard et al., PRL 128, 212503 (2022), …

- In the scenario given by λ_c and b_c, neutron decay into dark particles is viable.

Limits for scalar (S) and tensor (T) interactions



Plot on the left shows searches for beta decay processes where the charged lepton has anormal helicity (S and T interactions with coupling constants C_S^+ and C_T^+, respectively). From A. Falkowski et al, JHEP 04, 126 (2021)

From Falkowski: "We encourage once again experimental groups to analyze the data including the Fierz term b, especially once higher precision is reached." – Point taken. Their neutron ellipse, which is said to be away from SM due to aSPECT and B_n, was drawn before our BSM analysis was available, and needs correction.

We add a band for $b_c \approx 0.34\frac{C_S^+}{C_V^+} + 1.66\frac{C_T^+}{C_A^+}$.

Our (λ_c, b_c) is not excluded by other nuclear decay studies, including the more recent study on Li-8 β Decay. M.T. Burkey, PRL 128, 202502 (2022)

As we have a very tight limit on C_S^+ from superallowed decays, it makes sense to discuss our result as a coupling at the quark level: $\left|\frac{C_T^+}{C_A^+}\right| = 4g_T\left|\frac{\epsilon_T}{g_A}\right|$

- We need the form factor, most precisely from Lattice QCD: $g_T = 0.989(33)$

  R. Gupta et al., PRD 98, 034503 (2018)

- Alternatively, g_T can be tied to data from electron scattering A. Courtoy et al., PRL 115, 162001 (2015)

Our ϵ_T can compared to limits from radiative pion decay M. Bychkov et al., PRL 103, 051802 (2009)

… or to LHC limits for $p + p \rightarrow e^+ + e^- + X$ R. Gupta et al., PRD 98, 034503 (2018)

Both of them favor $b = 0$ at the relevant level of accuracy.

Summary

- The aSPECT collaboration determined the neutrino electron correlation coefficient a:
  $a = -0.10430(84)$ (SM fit), $\lambda = -1.2668(27)$ PRL 132, 102501 (2024)
- The SM result for λ is in tension with the one from PERKEO III by 3.4σ and therefore casts doubt on the current ability to test CKM unitarity with neutrons despite being theoretically advantageous.
- A BSM analysis which allows for a non-zero Fierz term finds $b = -0.0098(193)$
- A combined BSM analysis of aSPECT and PERKEO III which allows for a non-zero Fierz term finds $b_c = -0.0184(65)$, disfavored by other experiments, and a sensation if confirmed.
- The neutron community needs to verify the result. At ORNL, LANL and in Europe, follow-up experiments are being worked on. Nab and pNAB offer the possibility to obtain A and a in the same instrument.

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