The neutrino electron correlation coefficient a

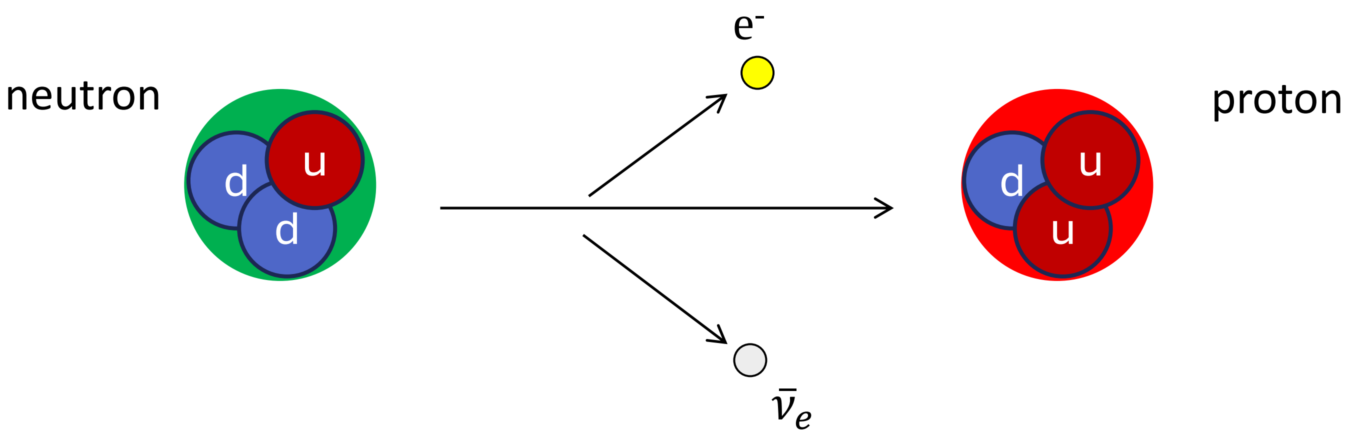
Stefan Baessler

baessler@virginia.edu

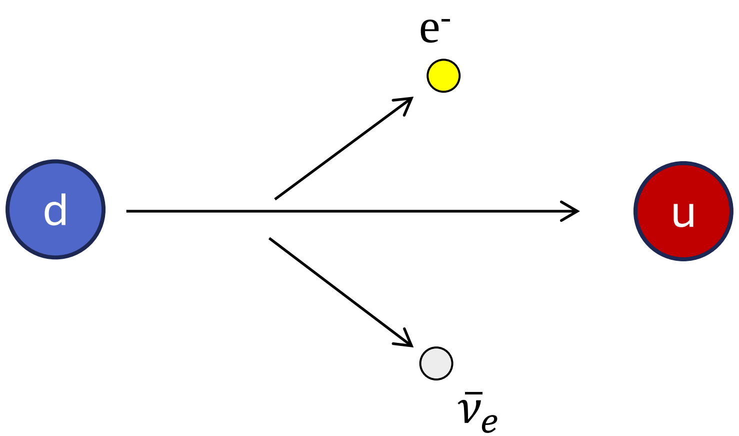
Inst. Nucl. Part. Phys.

Neutron beta decay and the Cabbibo-Kobayashi-Maskawa (CKM) matrix

Neutron beta decay cartoonish:



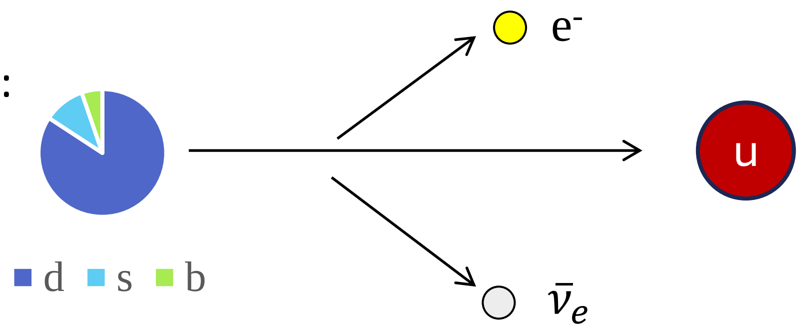
This is elementary particle physics, and we are seeing a quark transition:



Neutron beta decay and the CKM matrix, cont.

Quark composition as seen by weak interaction: d’ quark (an eigenstate of weak interaction) is a linear combination of d, s, and b quark

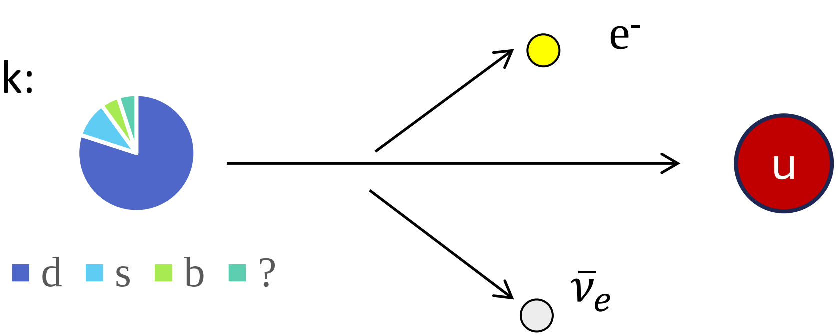
d’-quark:



- Nicola Cabbibo, 1963: First proposal of this idea, explains slightly diminished decay rates
- Makoto Kobayashi, Toshihide Maskawa, 1973: Extension to three quark generation, Noble Price

However, modern measurements seem to indicate that we are missing something:

d’-quark:

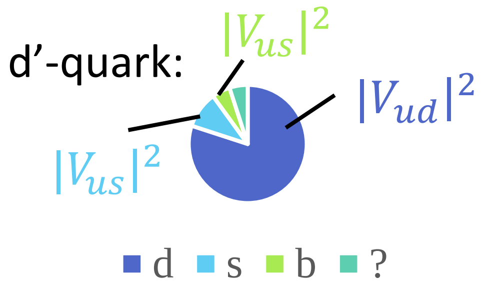


Motivation to study neutron beta decay

Beyond-standard model physics searches in neutron and nuclear beta decay:

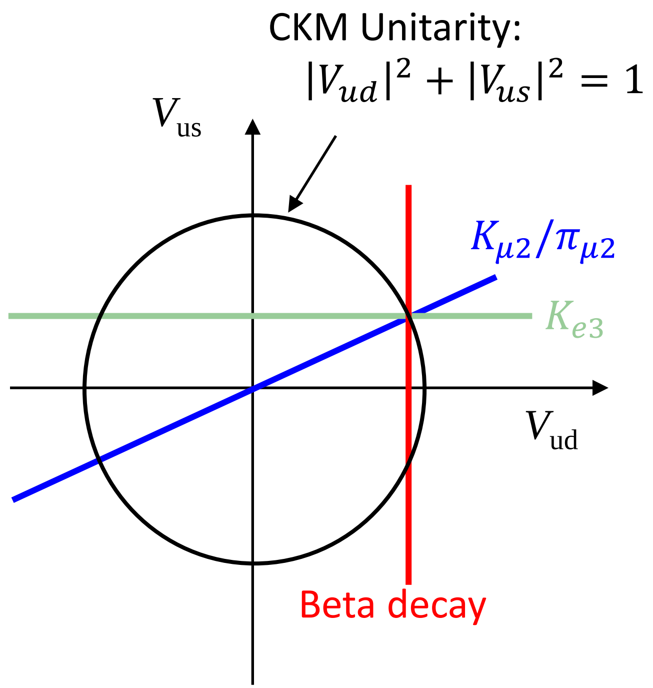
1. Is the Cabbibo Kobayashi Maskawa (CKM) matrix unitary?

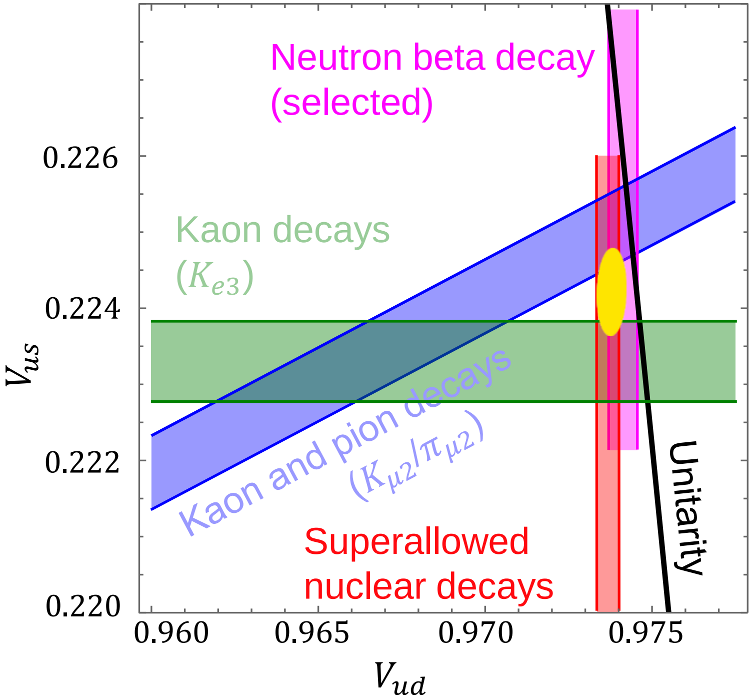
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \cdot \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$



Various unitarity tests possible; most precisely in the first row:

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



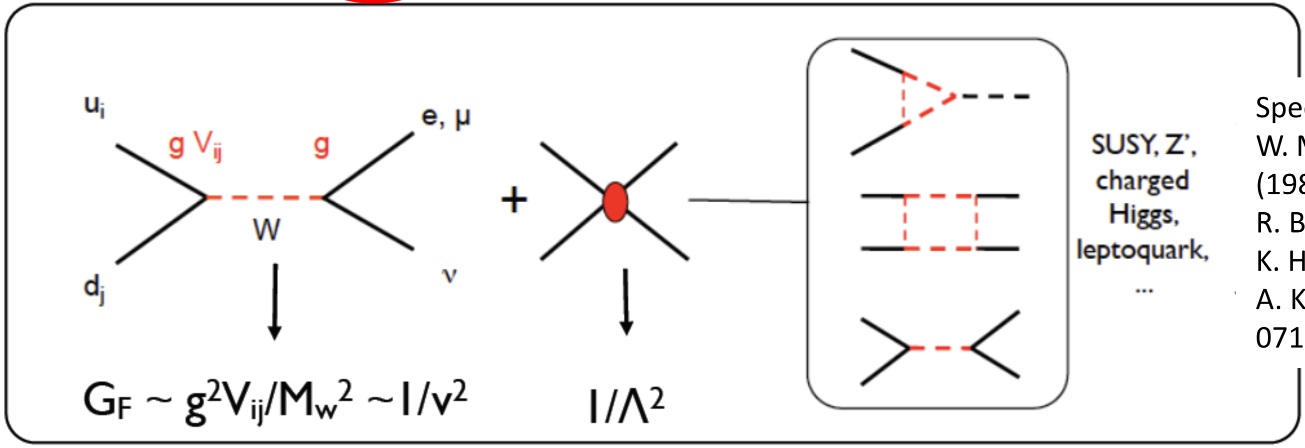


From: 2023 Nuclear Physics Long Range Plan for Nuclear Science

Motivation to study neutron beta decay, cont.

Present status:

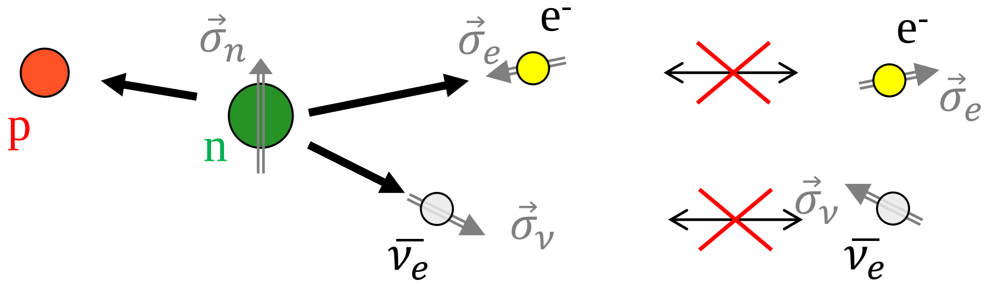
$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9983(6)(4) \text{ (experiment, PDG2024)}$$



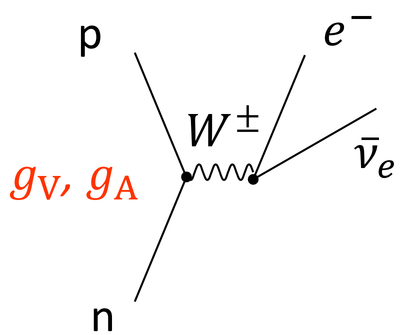
Specific models: E.g.
W. Marciano, A. Sirlin, PRD 35, 1672 (1987).
R. Barbieri et al., PLB 156, 348 (1985)
K. Hagiwara et al., PRL 75, 3605 (1995)
A. Kurylov, M. Ramsey-Musolf, PRL 88, 071804 (2000)

Energy scale of new physics: $\Lambda \geq 11$ TeV V. Cirigliano et al., NPB 830, 95 (2010)

2. V-A structure of weak interaction: Scalar- and tensor (S,T) interactions, which could be mediated by non-standard intermediate bosons, causes beta decays with one of the leptons having the opposite helicity.



Observables in neutron beta decay



Coupling constants in weak interaction:

Vector coupling: $g_V = V_{ud} \cdot G_F$

Axialvector coupling: $g_A = V_{ud} \cdot G_F \cdot \lambda$

$$\lambda = \frac{g_A}{g_V}$$

Fermi constant G_F is precisely known from muon lifetime

Observables in neutron beta decay, as a function of coupling constants:

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

Nonzero b or b_ν indicates S,T

$B_0 \neq B_0(\lambda)$ indicates V+A

$$\frac{d^3\Gamma}{dE_e d\Omega_e d\Omega_\nu} \propto \rho(E_e)\left[1 + a\frac{p_e}{E_e}\cos(\vec{p}_\nu, \vec{p}_e) + b\frac{m_e}{E_e} + A_0\frac{p_e}{E_e}\cos(\vec{\sigma}_n, \vec{p}_e) + \left(B_0 + b_\nu\frac{m_e}{E_e}\right)\cos(\vec{\sigma}_n, \vec{p}_\nu)\right]$$

$a_0 = a_0(\lambda)$

$A_0 = A_0(\lambda)$

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)

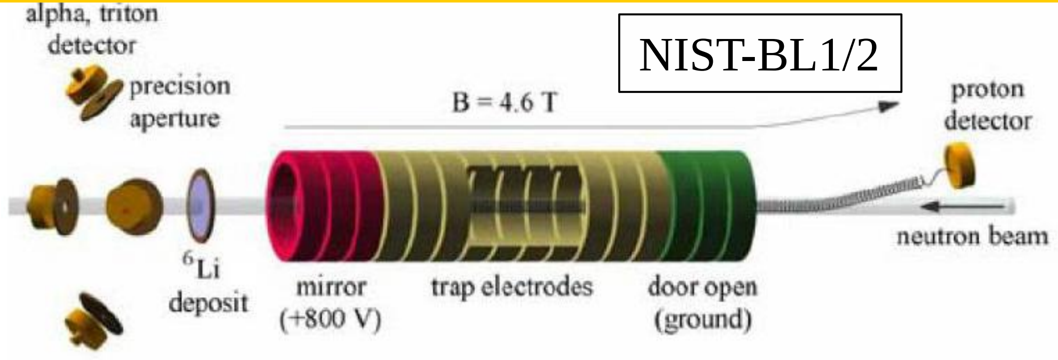
Takeaway: Need to combine neutron lifetime with either beta asymmetry A or neutrino electron correlation a to determine V_{ud}.

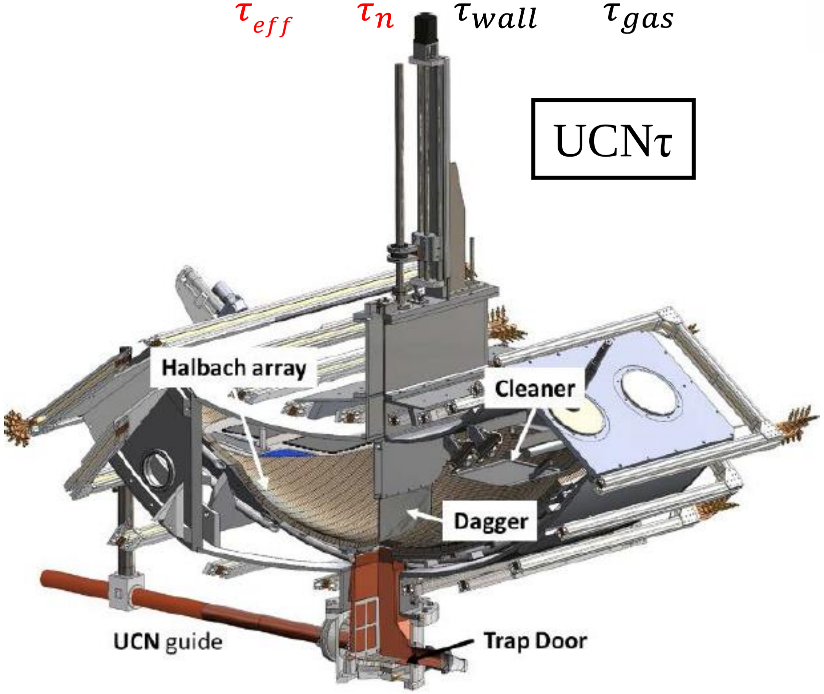
Neutron beta decay lifetime

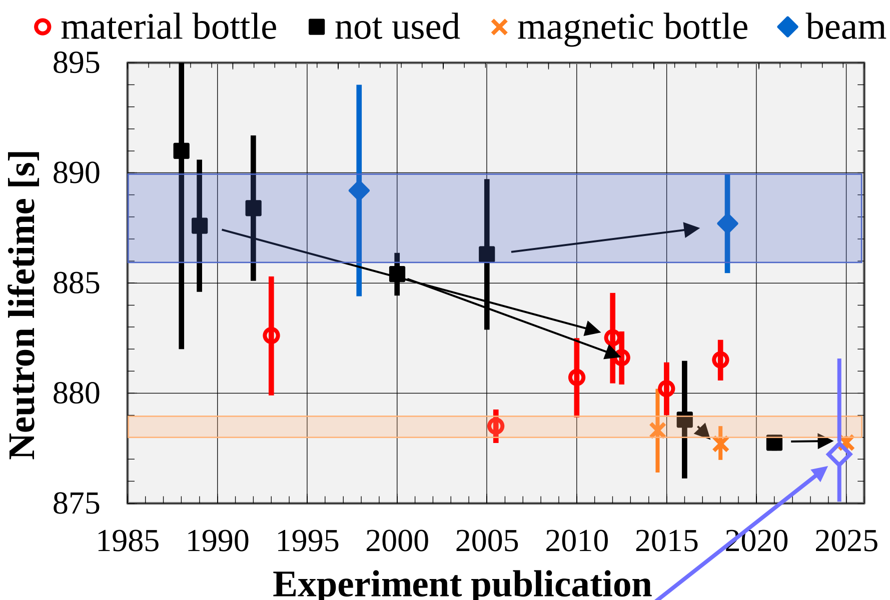
Beam: Decay rate: $\frac{dN}{dt} = \frac{N}{\tau_n}$

Bottle: Neutron counts : $N = N_0 e^{-\frac{t}{\tau_{eff}}}$

$$\text{with } \frac{1}{\tau_{eff}} = \frac{1}{\tau_n} + \frac{1}{\tau_{wall}} + \frac{1}{\tau_{gas}}$$



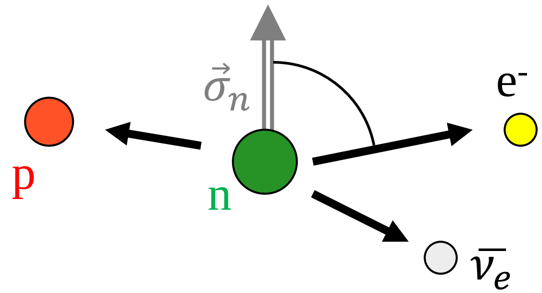




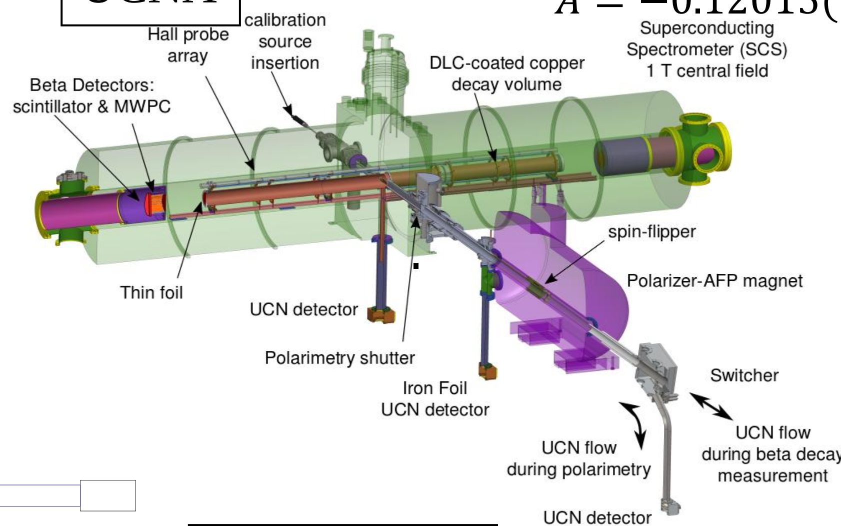
Discrepancy between beam and bottle may be real (decay into dark particle, not otherwise detected, or an experiment error. Previous analysis uses only last data point. Many new experiments:

- Magnetic bottles (UCNτ+, LANL; τSPECT, PSI; PENELOPE, TU München/TRIUMF)
- Beam Lifetime: BL2 and BL3, NIST; JPARC (Prelim. result from JPARC: Y. Fuwa et al., arXiv:2412.19519)
- UCNProBe, LANL: UCN trap in which both decay rate and neutron count decay are observed.

The Beta Asymmetry A_0 in neutron beta decay



UCNA



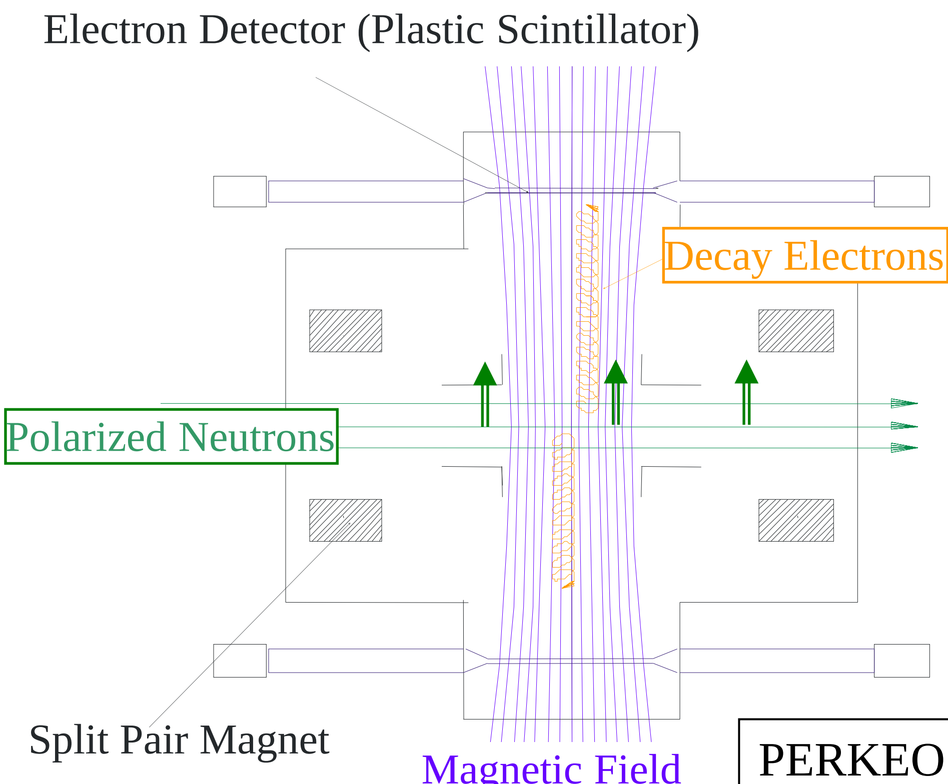
Final result of UCNA:

$$A = -0.12015(34)_{stat}\,(63)_{sys}$$

M. Brown et al., PRC **97**, 035505 (2018)

$$b = 0.066(41)_{stat}\,(24)_{sys}$$

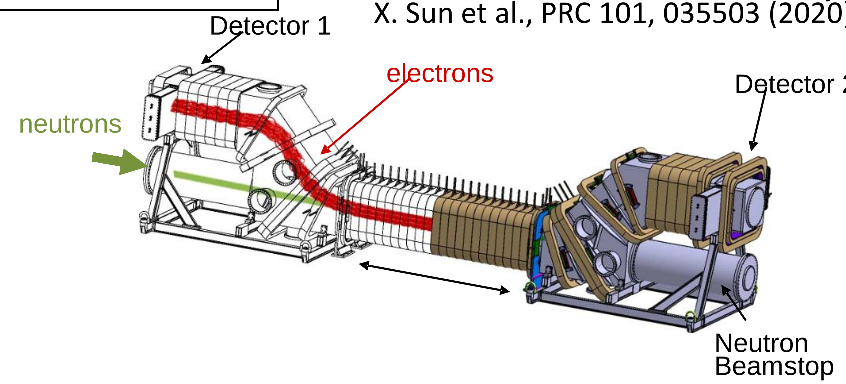
X. Sun et al., PRC 101, 035503 (2020)



PERKEO II

$$A = -0.11972(+53/-65)$$ D. Mund et al., PRL 110, 172502 (2013)

PERKEO III



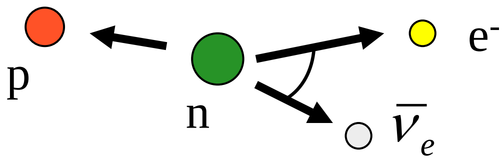
$$A = -0.11985(17)_{stat}\,(12)_{sys}$$

B. Märkisch et al., PRL. 122, 242501 (2019)

$$b = 0.017(20)_{stat}\,(3)_{sys}$$

H. Saul et al., PRL 125, 112501 (2020)

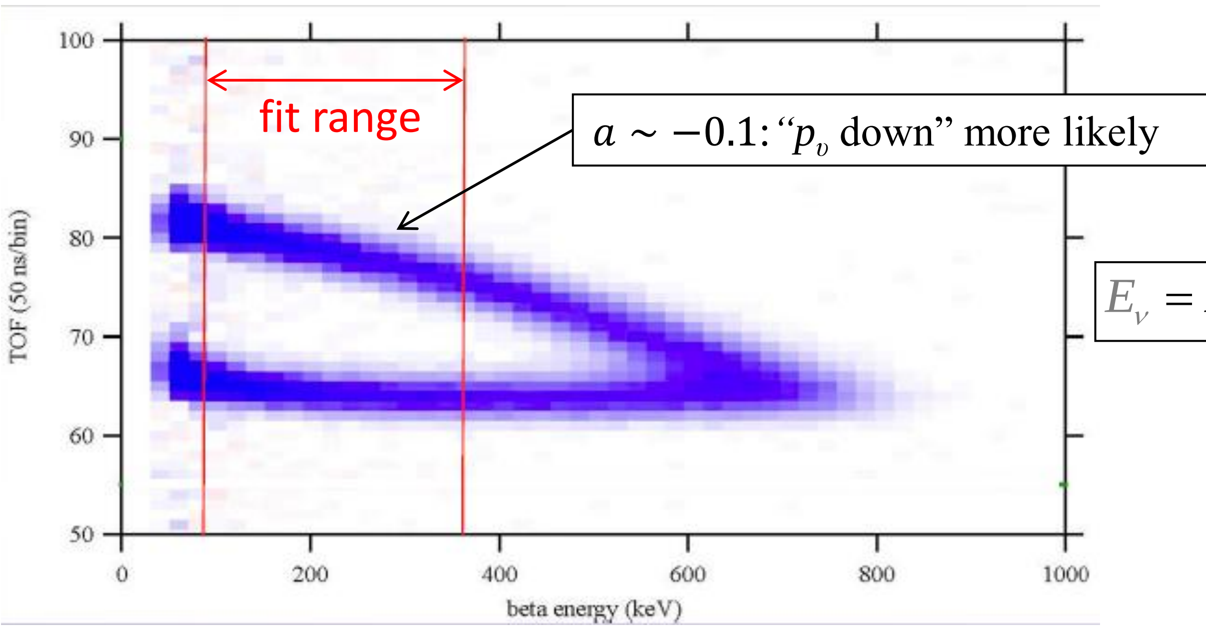
The neutrino electron correlation coefficient: aCORN@NIST

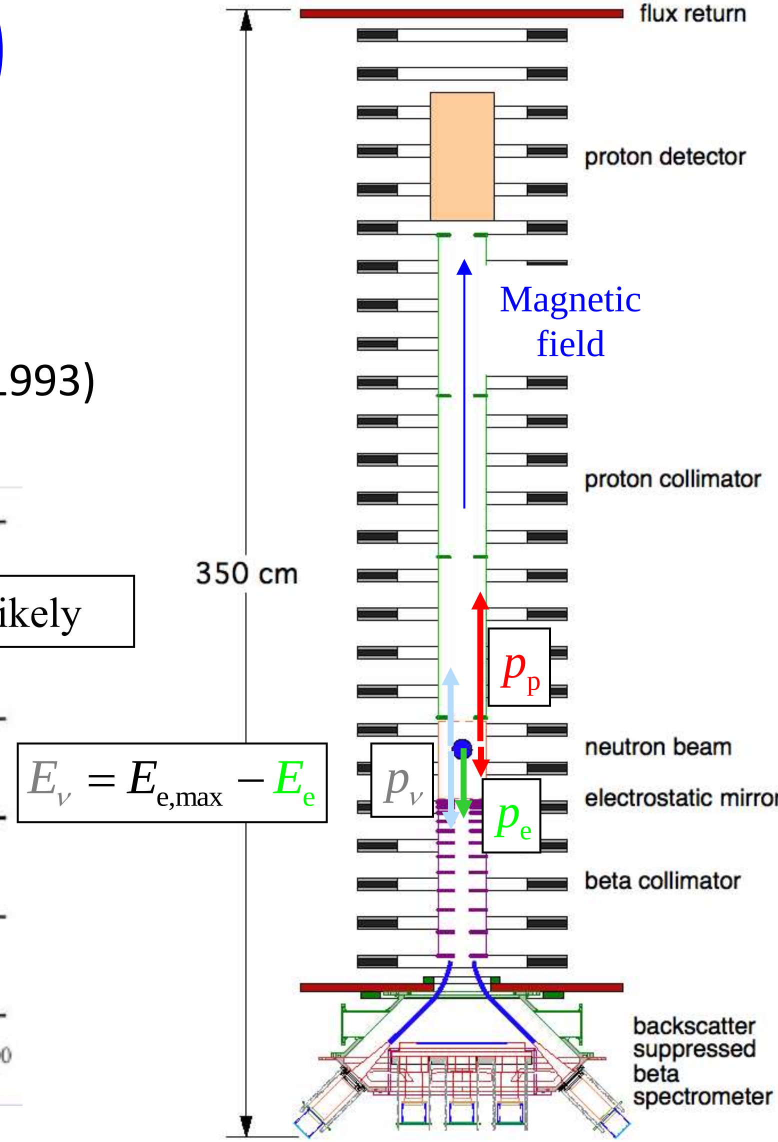


$$d\Gamma \propto \left(1 + a\frac{p_e}{E_e}\cos\theta_{e\nu}\right)$$

How to access angle between electron and neutrino w/o detecting neutrino?

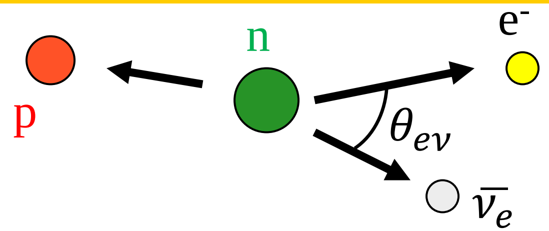
One idea: B. Yerozolimskii, S. Balashov, Y. Mostovoi (~1993)
Experiment done at NIST, led by F. Wietfeldt (Tulane)





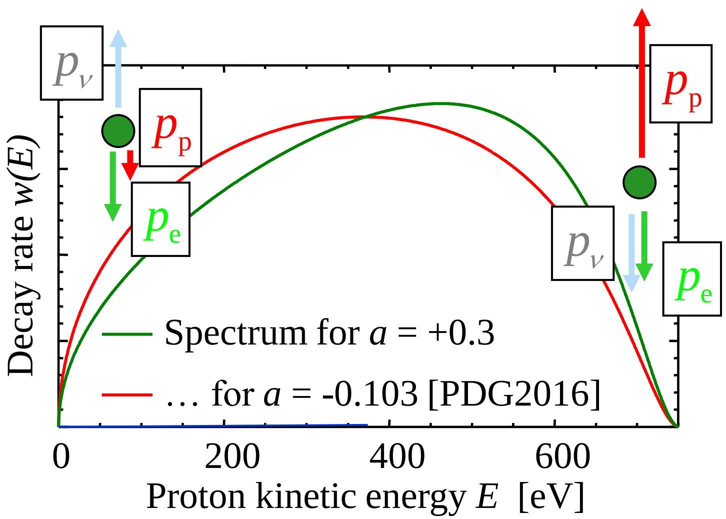
Result: $a = -0.1053(18)$ F.E. Wietfeldt et al., PRC 110, 015502 (2024)

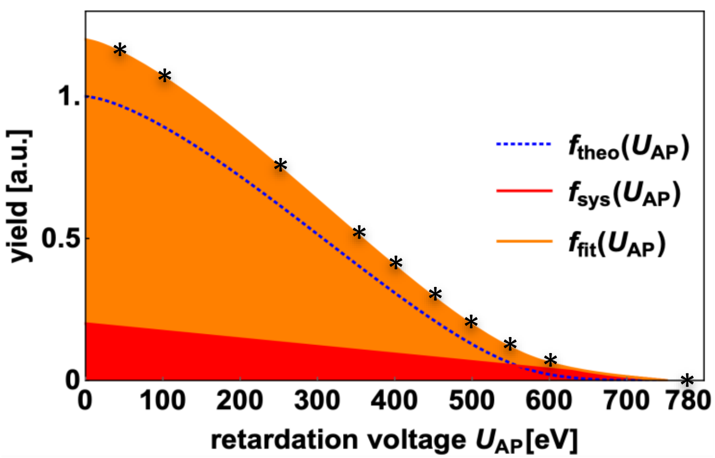
aSPECT @ ILL Grenoble (lead institution: JGU Mainz)

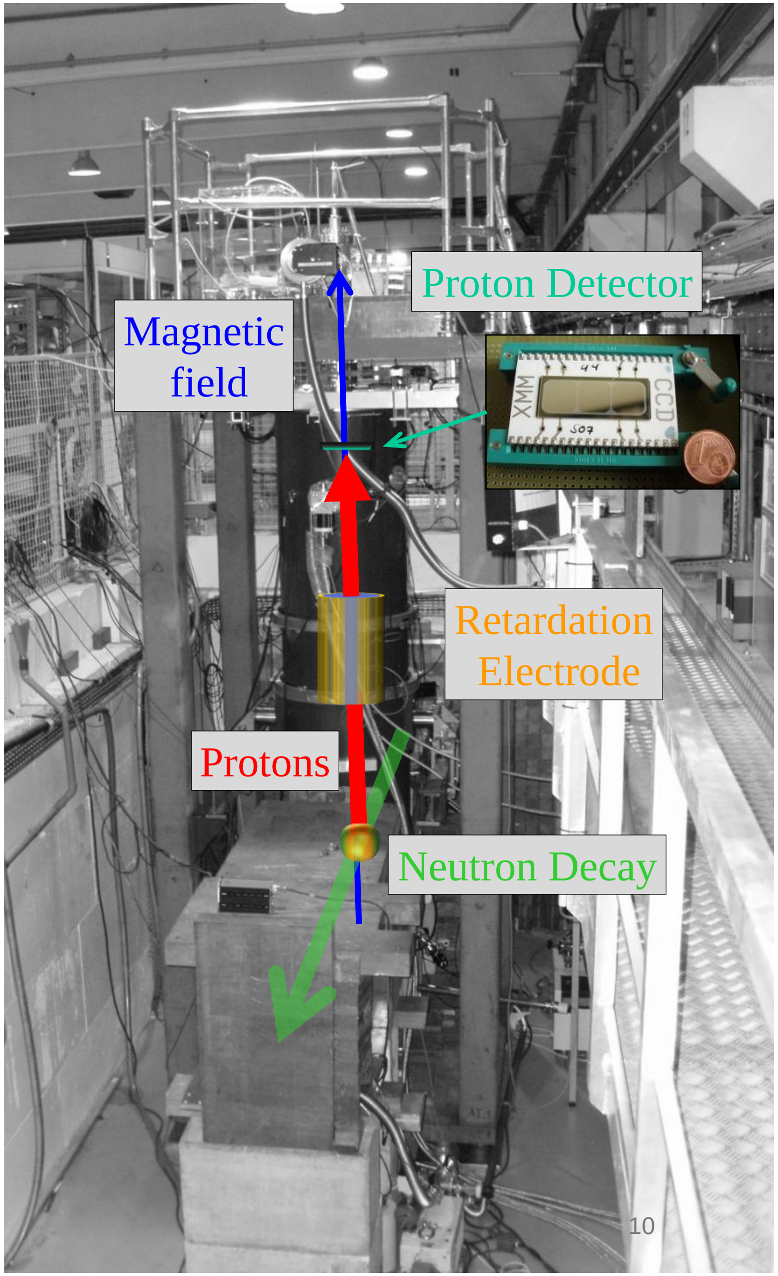


$$d\Gamma \propto \left(1 + a\frac{p_e}{E_e}\cos\theta_{e\nu}\right)$$

Second idea to access $\Theta_{e\nu}$: Proton spectrum







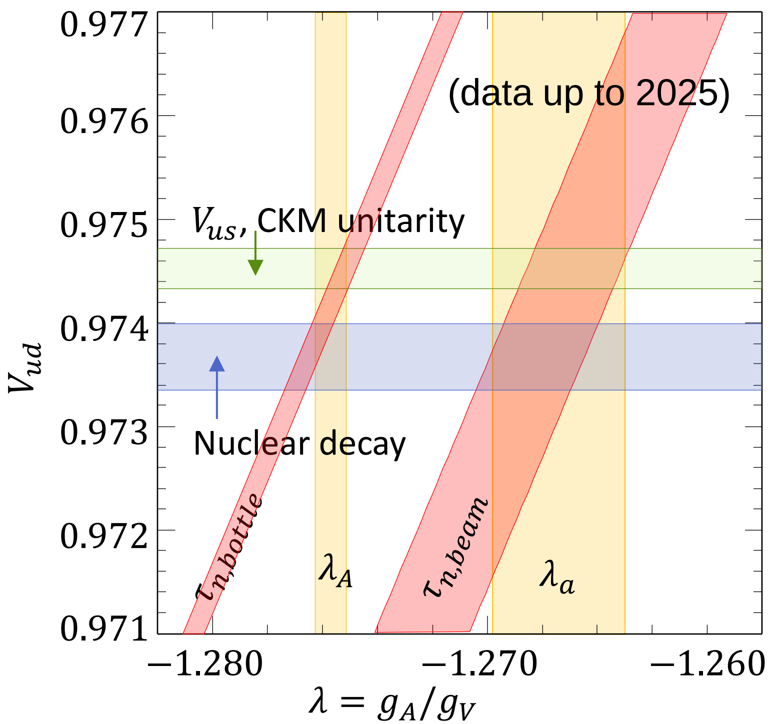
aSPECT result

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	$1.25\ (\nu = 263)$	$3.7 \cdot 10^{-3}$

Final aSPECT result: M. Beck et al., PRL 132, 102501 (2024)

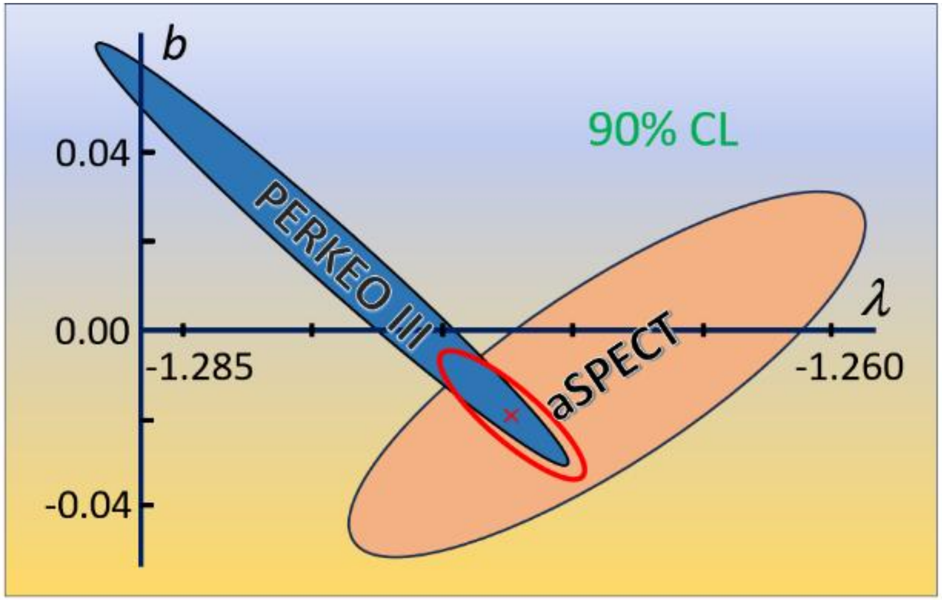


2nd result: This result constitutes the present best determination of the Fierz term in neutron beta decay. The Fierz term found is consistent with the SM prediction ($b = 0$).

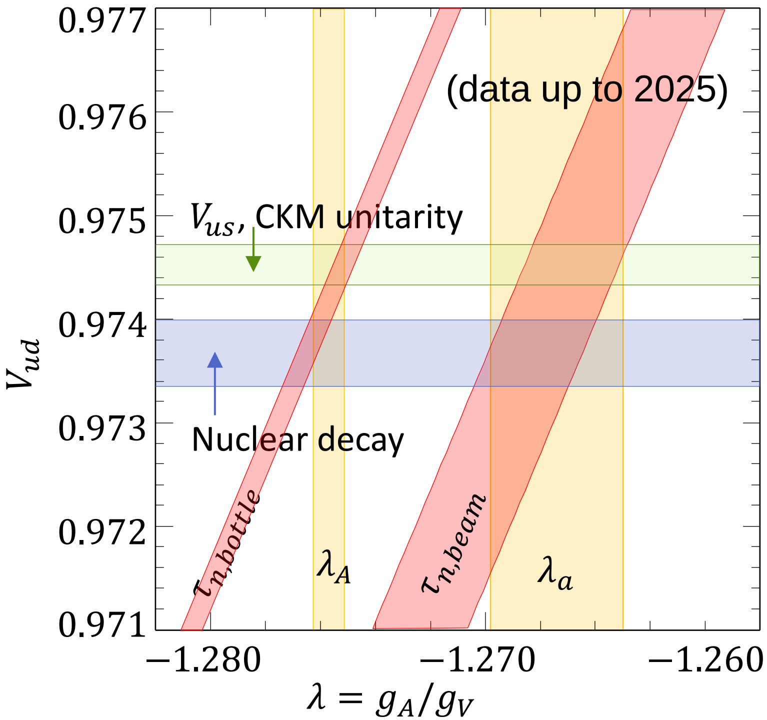
aSPECT result, cont.

Note: The SM requires $\lambda_a = \lambda_A$. The discrepancy is only between two experiments (PERKEO III and aSPECT) and needs resolution.

One possibility is that both experiments are correct, and neutron beta decay has discovered a non-zero Fierz term of $b(\text{combined}) = -0.0184(65)$. On the other hand, this is hard to reconcile with limits radiative pion decay or HEP.

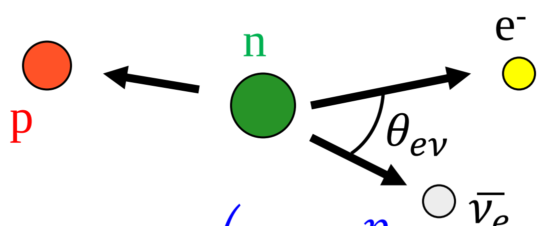


W. Heil (Mainz)



Final aSPECT result: M. Beck et al., PRL 132, 102501 (2024)

The Nab experiment

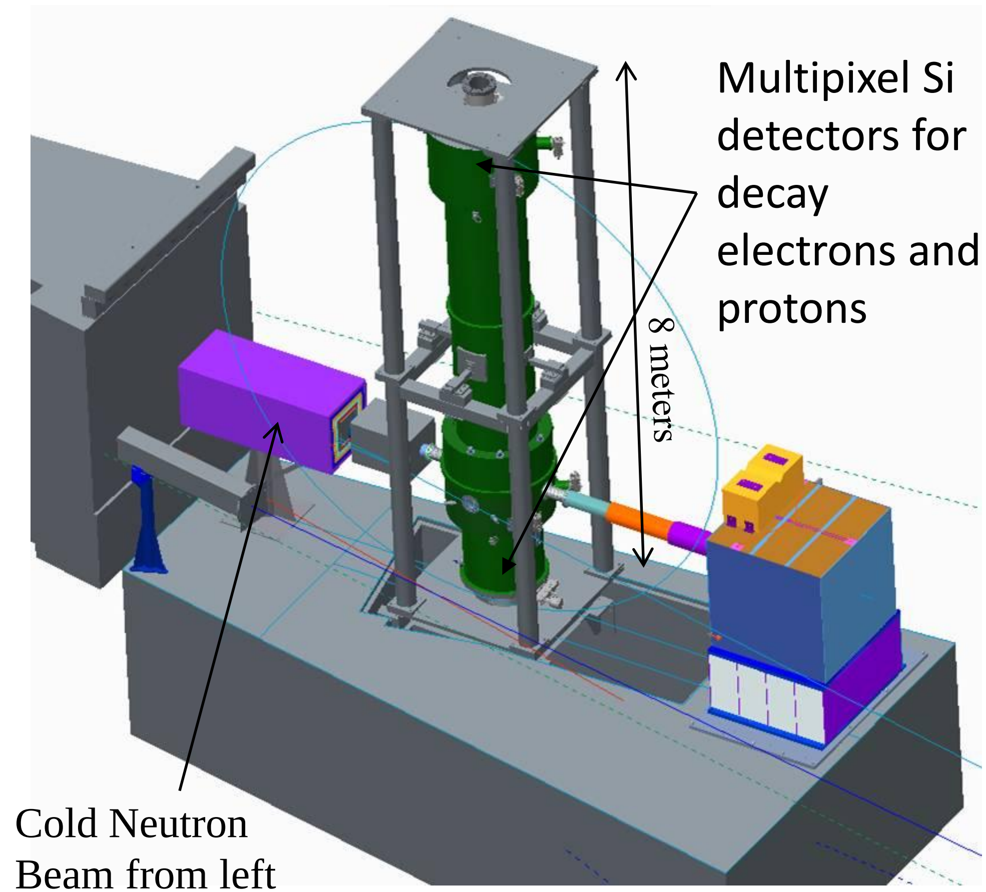


$$d\Gamma \propto \varrho(E_e)\left(1 + a\frac{p_e}{E_e}\cos\theta_{e\nu} + b\frac{m_e}{E_e}\right)$$

Third idea to access $\Theta_{e\nu}$: Measurement of a from measurement of proton and electron energy.

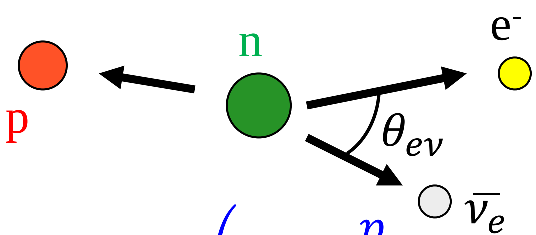
Measurement of electron energy spectrum gives the Fierz term b.

Nab @ Fundamental Neutron Physics Beamline (FNPB) @Spallation Neutron Source (SNS) @Oak Ridge National Lab



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)
Si Detector: L.J. Broussard et al., Nucl. Inst. Meth. A 849, 83 (2017) and Hyperfine Int. 240,1 (2019)
Simulated Spectrometer Performance: J. Fry et al., EPJ WOC 219, 04002 (2019)

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

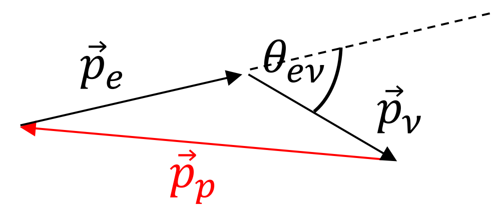


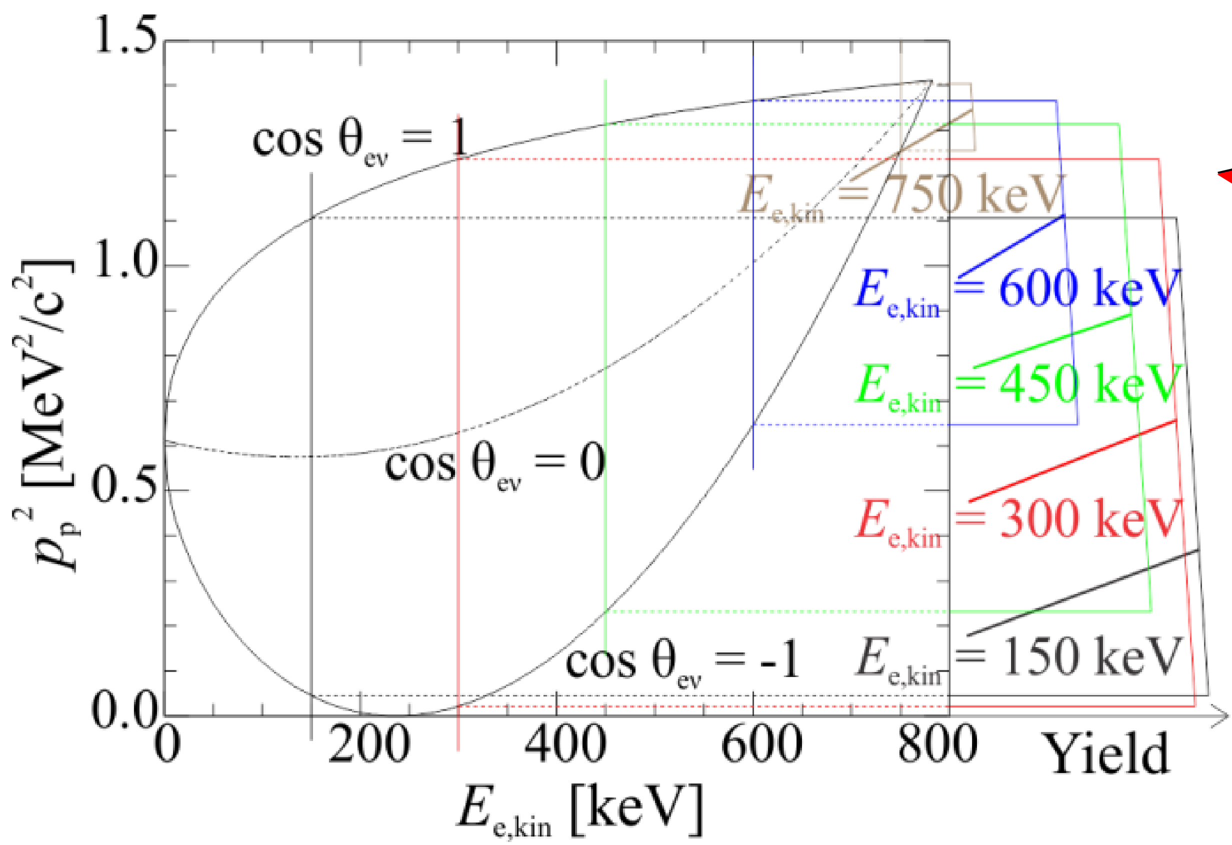
$$d\Gamma \propto \varrho(E_e)\left(1 + a\frac{p_e}{E_e}\cos\theta_{e\nu} + b\frac{m_e}{E_e}\right)$$

- 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)



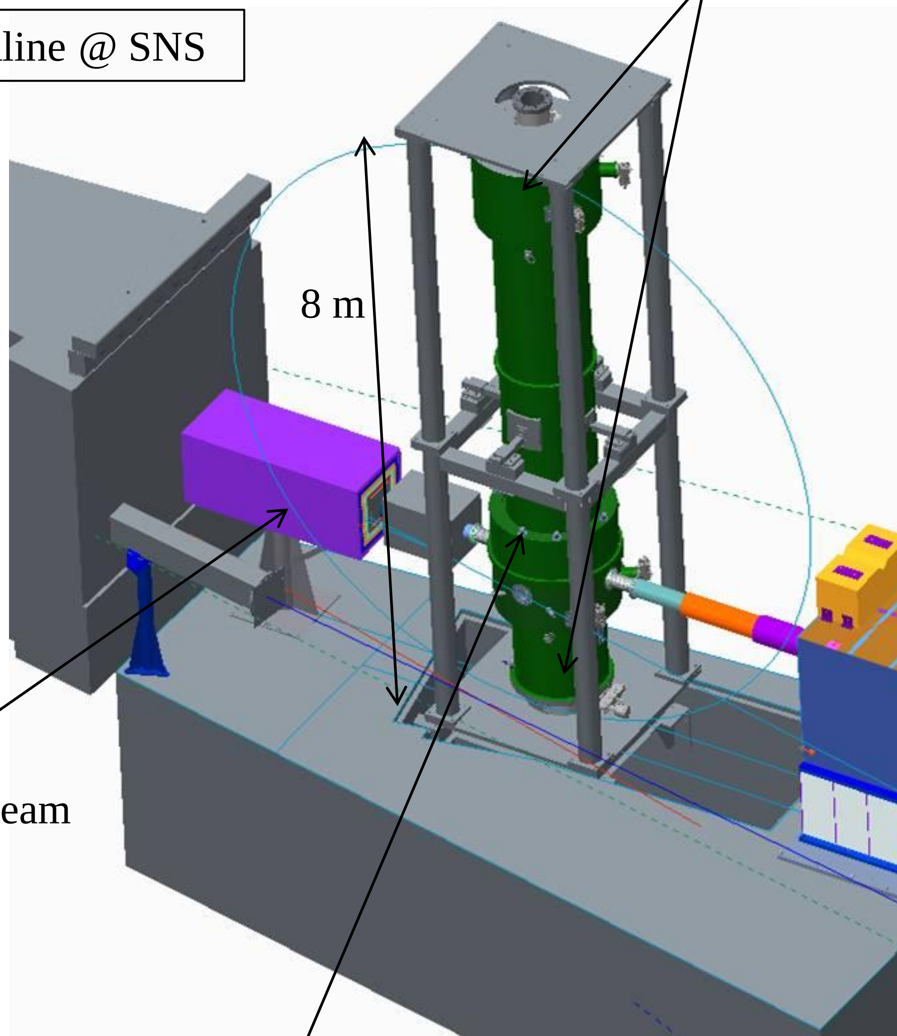


- Edges of trapeziums: spectrometer response for p_p^2 from proton TOF.
- Slope of trapeziums is proportional to a.

2021: Nab installation completed

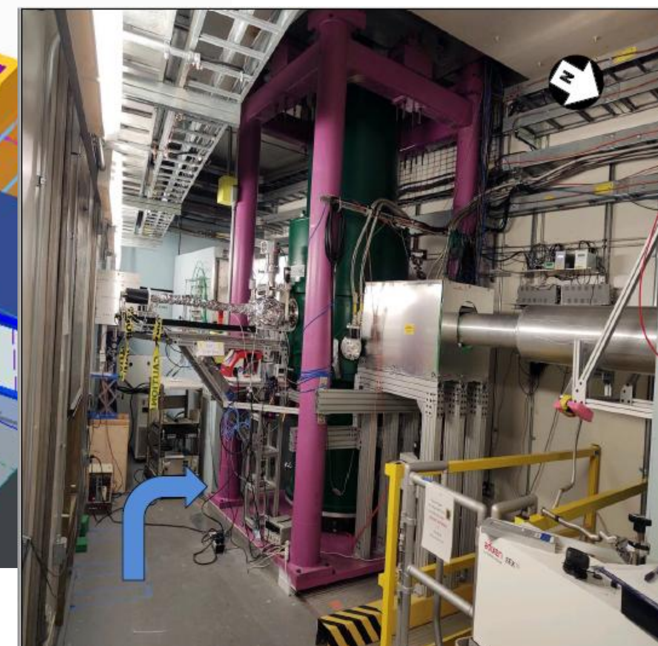
FNPB beamline @ SNS

Si detectors



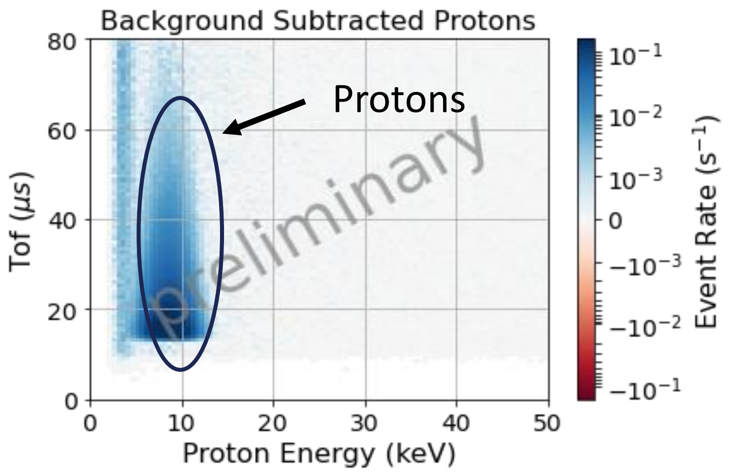
Cold neutron beam

Spectrometer magnet

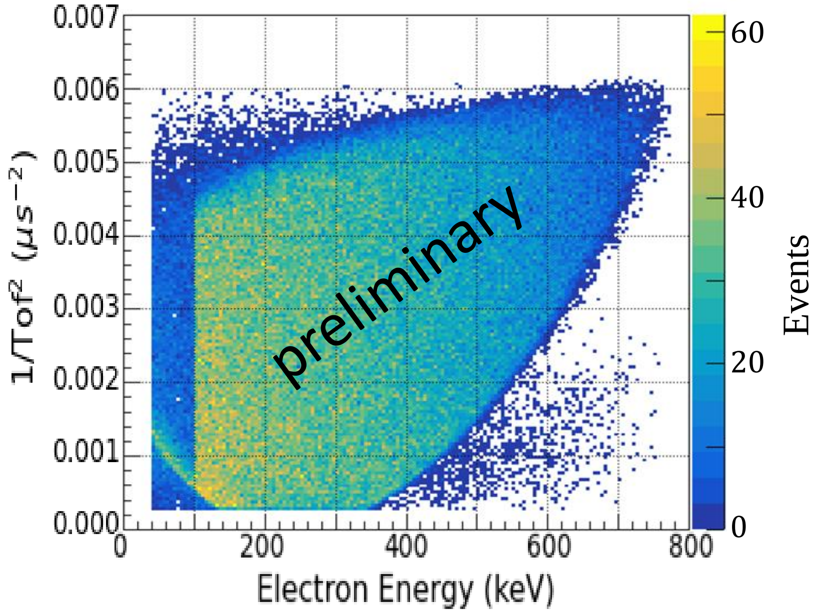


2023: Nab takes commissioning data

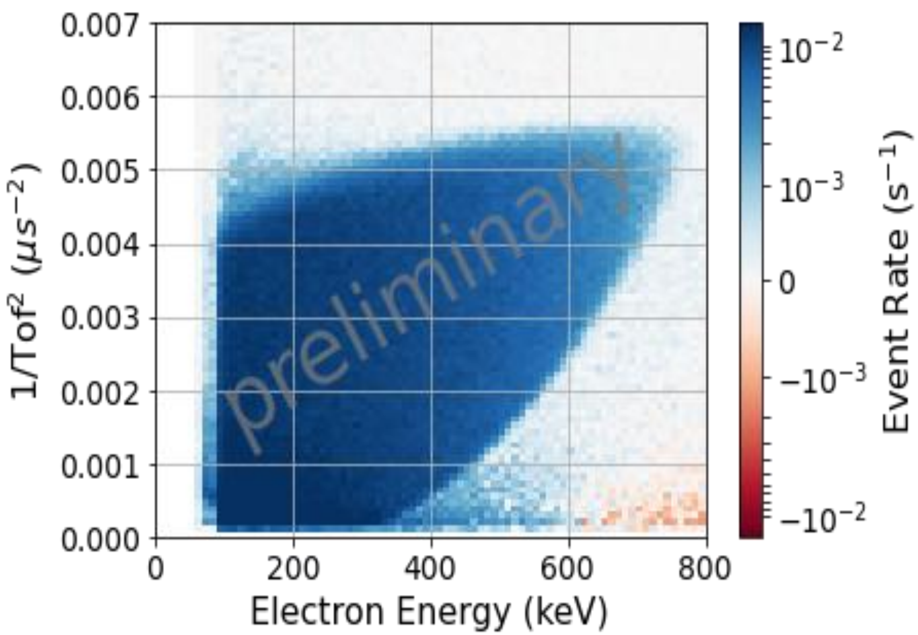
- Commissioning data taken in summer 2023
- Proof-of-principle has been achieved:
  - Right: Arrival time and energy for proton candidate signal after electron candidate signal.
  - Bottom: Event topology from commissioning data.



Simulation



Data

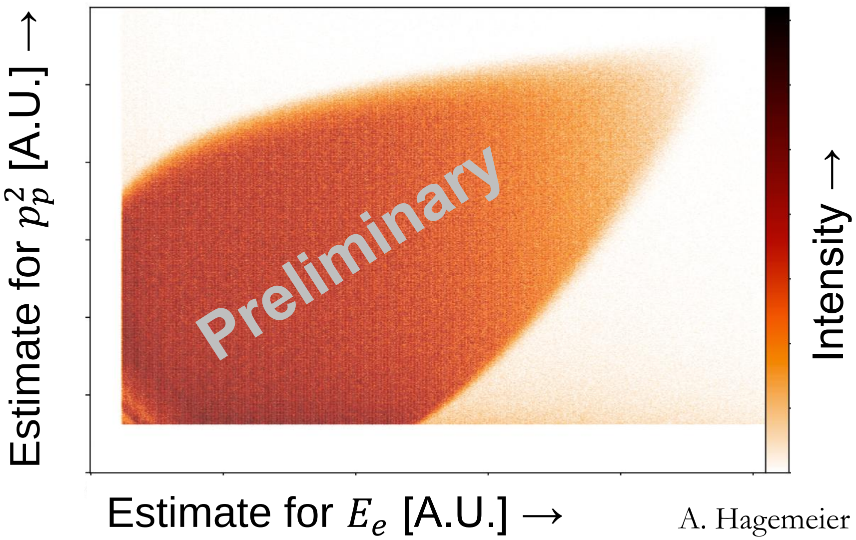


Analysis: Frank Gonzalez et al., ORNL

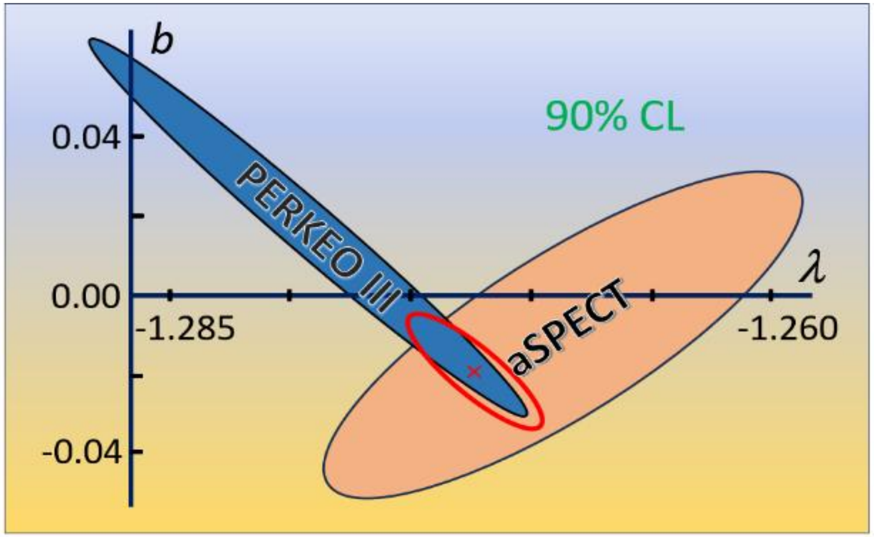
Fall 2024: Nab physics data taking started, cont.

Physics data-taking hast started in fall 2024

- Regularly producing teardrops, much sharper and cleaner edges than previously
- Focus: systematic studies and optimizations for precision data-taking



A. Hagemeier (UVA)



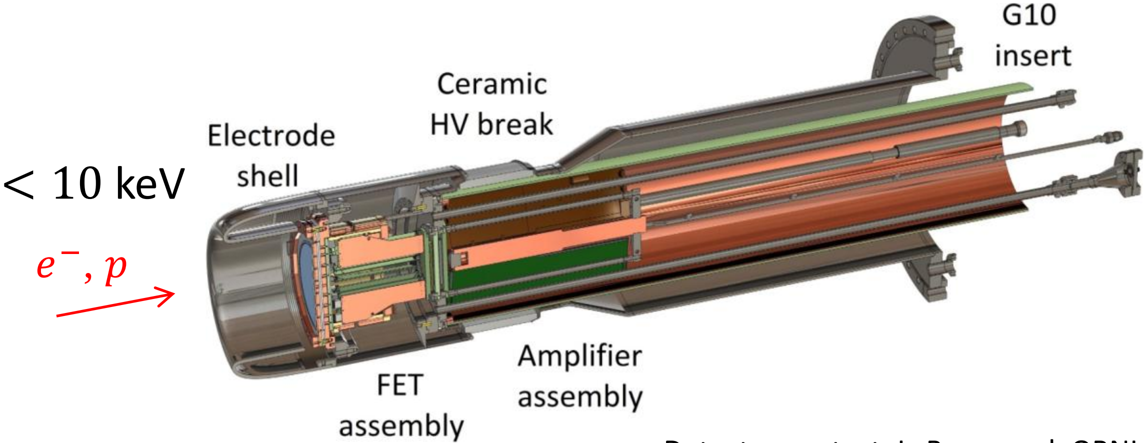
Plot from: W. Heil (Mainz)

2025 Goal: similar or better precision as aSPECT

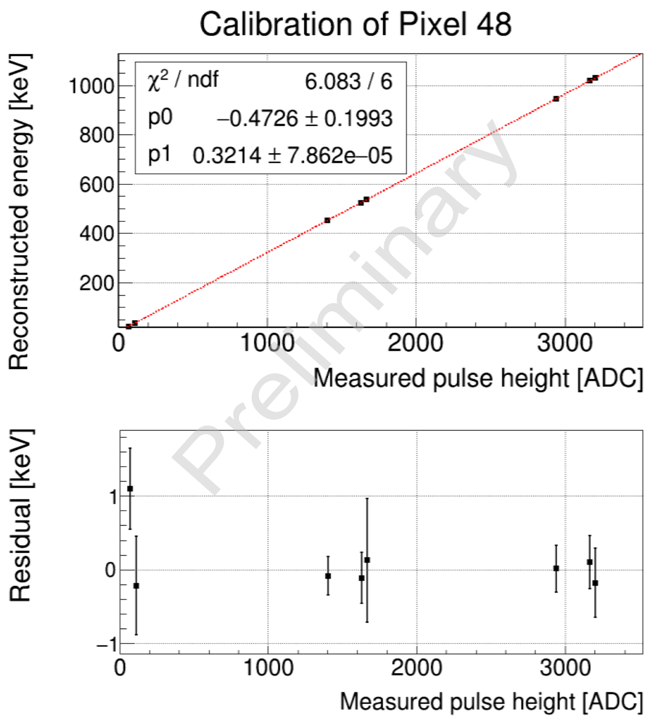
- Inform discrepancy in λ from neutron decay
- Understand systematics for ultimate precision goal ($\Delta a/a = 0.1\%$)

2024/2025: Calibration of Main detector system

- 127 pixel Si detector, 2 mm thick
- Energy resolution about 2.5 keV
- Low (proton) detection threshold < 10 keV
- Detector transit time bias sub-ns



Detector contact: L. Broussard, ORNL



Specification for	Current analysis (based on ^{207}Bi)	$\Delta a = 3 \cdot 10^{-5}$
gain factor (Δg/ g)	$< 0.02\%$	fit par.
Offset E_0 (ΔE_0)	0.2 keV	0.3 keV
nonlinearity (ΔE_{max})	~ 1 keV	1.5 keV ✓
peak width (Δw)	0.25 keV	1 keV ✓
tail amplitude (Δt of peak)		10^{-4}

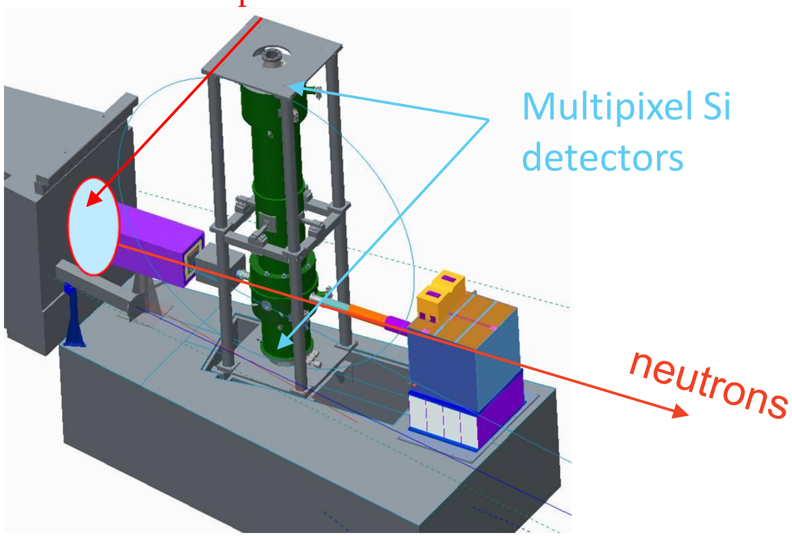
Calibration analysis lead by J.H. Choi, NCSU

pNab experiment is proposed to follow

Purpose of pNab: Measure polarized neutron decay correlations:

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

Addition to existing (Nab) setup:
Neutron beam polarizer



Proposal for an experiment at the FnPB/SNS

pNab: a program of studies of beta decay of polarized free neutrons

R. Alarcon,[a] S. Baeßler,[b,c] L. Barrón Palos,[d] L. Broussard,[c] J.H. Choi,[e] T. Chupp,[f] C. Crawford,[g] G. Dodson,[h] N. Fomin,[i] J. Fry,[j] F. Gonzalez,[c] J. Hamblen,[k] L. Hayen,[l] A. Jezghani,[m] M. Makela,[n] R. Mammei,[o] A. Mendelsohn,[p] P. E. Mueller,[c] S. Penttilä,[c] J. Pioquinto,[b] B. Plaster,[g] D. Počanić,[b] A. Saunders,[c] W. Schreyer,[c] A. R. Young.[e]

(The pNab Collaboration)

[a] Department of Physics, Arizona State University, Tempe, AZ 85287–1504, USA
[b] Department of Physics, University of Virginia, Charlottesville, VA 22904–4714, USA
[c] Physics Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA
[d] Universidad Nacional Autónoma de México, Mexico City, D.F., Mexico
[e] Department of Physics, North Carolina State University, Raleigh, NC 27695-8202, USA
[f] University of Michigan, Ann Arbor, MI 48109, USA
[g] Department of Physics and Astronomy, University of Kentucky, Lexington, KY 40506, USA
[h] Massachusetts Institute of Technology, Cambridge, MA 02139, USA
[i] Department of Physics and Astronomy, University of Tennessee, Knoxville, TN 37996, USA
[j] Department of Physics, Geosciences, and Astronomy, Eastern Kentucky Univ., Richmond, KY 40475, USA
[k] Department of Chemistry and Physics, Univ. of Tennessee-Chattanooga, Chattanooga, TN 37403, USA
[l] Laboratoire de Physique Corpusculaire, Caen, France
[m] Partnership for an Advanced Computing Environment, Georgia Institute of Technology, Atlanta, GA 30332, USA
[n] Los Alamos National Laboratory, Los Alamos, NM 87545, USA
[o] Department of Physics, University of Winnipeg, Winnipeg, Manitoba R3B2E9, Canada
[p] Department of Physics, University of Manitoba, Winnipeg, Manitoba, R3T 2N2, Canada

1 July 2024

Abstract: The Nab and pNab collaborations are undertaking a program of studies

pNab proposal

The pNab collaboration proposes improvements for the four main uncertainties in past beta asymmetry experiments:

1. Neutron beam polarization: $(\Delta A/A)_{\mathrm{pol}} = 5\cdot 10^{-4}$
2. Electron energy response: $(\Delta A/A)_{\mathrm{det}} = 5\cdot 10^{-4}$
3. Background suppression through e/p coincidence: $(\Delta A/A)_{\mathrm{bg}}$ small
4. Solid angle coverage (mirror effect): $(\Delta A/A)_{\mathrm{sa}}$ small

Total uncertainty with statistics: $(\Delta A/A)_{\mathrm{tot}} < 10^{-3}$ (improvement of present limit by a factor of two)

Summary and Outlook

- Currently, our understanding of quark mixing in weak interactions is questionable. unitarity of the CKM matrix is violated by about $2 - 3\sigma$. This test is based on V_{ud} from superallowed nuclear decays and Kaon decays. Selected neutrons decay experiments contribute. Inputs to this test are under scrutiny.
- Neutron (or pion) beta decay should replace nuclear beta decay if experiments gain accuracy, due to absence of nuclear-structure dependent theoretical corrections. There is steady, albeit slow progress.
- An analysis based on "best" experiments in neutron beta decay achieves that goal already, but discrepancies between results from different methods need to be understood.
- 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 radiative pion decay or HEP, and a sensation if confirmed.

Outlook:

- Nab and pNab allow to obtain A and a in the same instrument, with a precision that improves the CKM unitarity test.
- Nab has started to take physics data
- Nab will also provide a value for the Fierz term b that tests the $b(\text{combined})$ solution.

Acknowledgements

aSPECT collaboration:

M. Beck, F. Ayala Guardia[*+] , M. Borg[*+] , W. Heil, J. Kahlenberg[*], R. Muñoz Horta[*+], C. Schmidt[+], and A. Wunderle[+]
Johannes Gutenberg-Universität Mainz, Germany
S. Baeßler
Department of Physics, University of Virginia, Charlottesville, USA, and Oak Ridge National Lab, Oak Ridge, USA
F. Glück[*]
Karlsruhe Institute of Technology, Germany
M. Klopf[*], and G. Konrad
Atominstitut, Technische Universität Vienna, Austria
R. Maisonobe[+], M. Simson[+], T. Soldner, R. Virot, and O. Zimmer
Institut Laue-Langevin, Grenoble, France
U. Schmidt[*]
Ruprecht-Karls-Universität Heidelberg, Germany

[*] not on picture [+]Ph.D. Student with aSPECT as main project

Nab collaborating institutions:

Oak Ridge National Laboratory
Los Alamos National Laboratory
University of Virginia
The University of Tennessee Knoxville
Arizona State University
NC State University
Massachusetts Institute of Technology
University of Kentucky
University of Michigan
Eastern Kentucky University
The University of Tennessee Chattanooga
University of Manitoba
Georgia Tech
Montclair State University
The University of Winnipeg

University of South Carolina,
Universität Karlsruhe (TH),
Universidad Nacional Autónoma de México,
Western Kentucky University

Main project funding:

NSF
U.S. Department of Energy Office of Science
Oak Ridge National Laboratory
University of Virginia