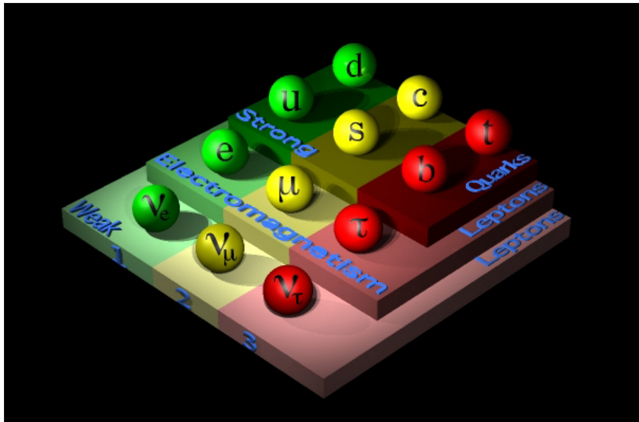
Neutron Beta Decay:
CORRELATION COEFFICIENTS A & B

Hartmut Abele

Solvay Workshop 2014



Standard Model and Neutron Decay

Neutron β-decay

$$n \rightarrow p \; e \; \overline{\nu}_e$$

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

- lifetime $\tau \sim 15$ min
- β-endpoint: $E_{max} = 782$ keV

V-A Theory: Vector coupling: $g_V = G_F V_{ud} f_1(q^2 \rightarrow 0)$

Axial vector coupling: $g_A = G_F V_{ud} \, g_1(q^2 \rightarrow 0)$

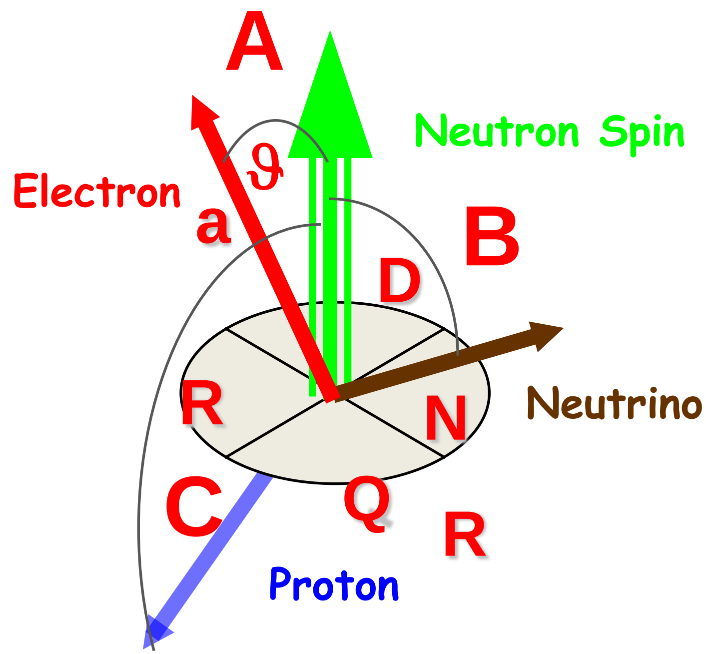
ratio $\lambda = g_A / g_V = -1.276$

- Standard Model: V_{ud}, λ, $e^{i\theta} = -1$

Neutron Alphabet deciphers the SM

Parameters

- Strength: G_F
- Quark mixing: V_{ud}
- Ratio: $\lambda = g_A/g_V$



$$\tau^{-1} = V_{ud}^{\,2} G_F^{\,2} (1 + 3\lambda^2) \frac{f^R m_e^{\,5} c^4}{2\pi^3 \hbar^7}$$

$$d\Gamma \propto \mathcal{N}(E_e)\left\{1 + a\frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + b\frac{\Gamma m_e}{E_e} + \langle\vec{J}\rangle \cdot \left[A\frac{\vec{p}_e}{E_e} + B\frac{\vec{p}_\nu}{E_\nu} + D\frac{\vec{p}_e \times \vec{p}_\nu}{E_e E_\nu}\right] + \vec{\sigma} \cdot \left[N\langle\vec{J}\rangle + G\frac{\vec{p}_e}{E_e} + Q'\hat{p}_e\hat{p}_e \cdot \langle\vec{J}\rangle + R\langle\vec{J}\rangle \times \frac{\vec{p}_e}{E_e}\right]\right\} d\Omega_e d\Omega_\nu dE_e,$$

Observables

- Lifetime τ
- Correlation A
- Correlation B
- Correlation C
- Correlation a
- Correlation D
- Correlation N
- Correlation Q
- Correlation R
- Beta Spectrum
- Proton Spectrum
- Beta Helicity

Neutron Alphabet deciphers the SM

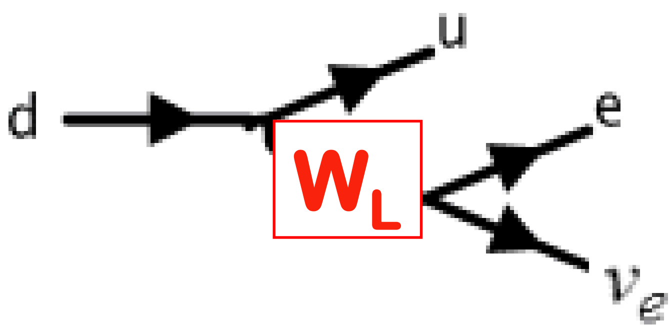
- a,A → $\lambda = g_A / g_V$

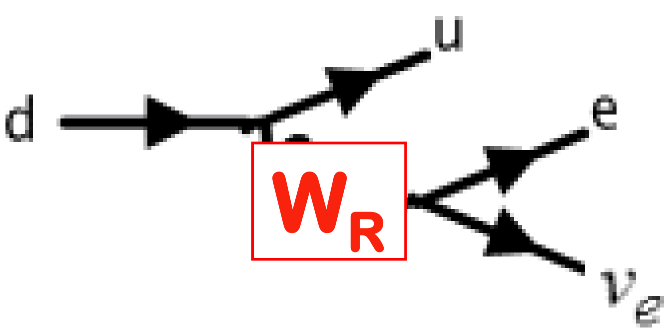
- A + τ → V_{ud} from CKM matrix

$$\tau_n = \frac{2}{\ln 2} \frac{\overline{\mathcal{F}t}}{f^R(1+3\lambda^2)}$$

$$\tau_n = 880.2(^{+1.5}_{-1.6})\ \mathrm{s}.$$

- A + B + τ → Right Handed Currents (RHC)?

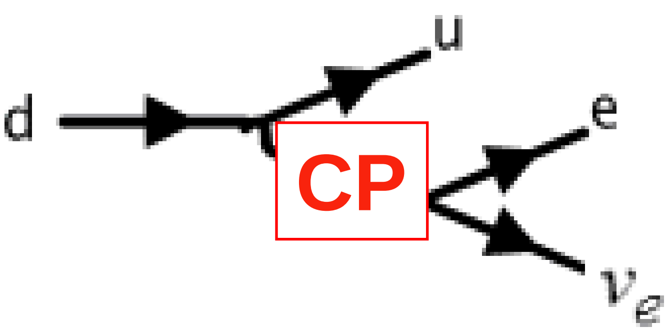




H. Abele, NIM A 611 (2009) 193–197

Neutron Alphabet deciphers the SM

- D, R ? T-odd → CP-violation



$$R = 0.28\,\mathrm{Im}\left(\frac{C_S + C_S'}{C_A}\right) + 0.33\,\mathrm{Im}\left(\frac{C_T + C_T'}{C_A}\right)$$

- Candidate models for scalar couplings (at tree-level):
  - Charged Higgs exchange
  - Slepton exchange (R-parity violating super symmetric models)
  - Vector and scalar leptoquark exchange
- The only candidate model for tree-level tensor contribution (in renormalizable gauge theories) is:
  - Scalar leptoquark exchange

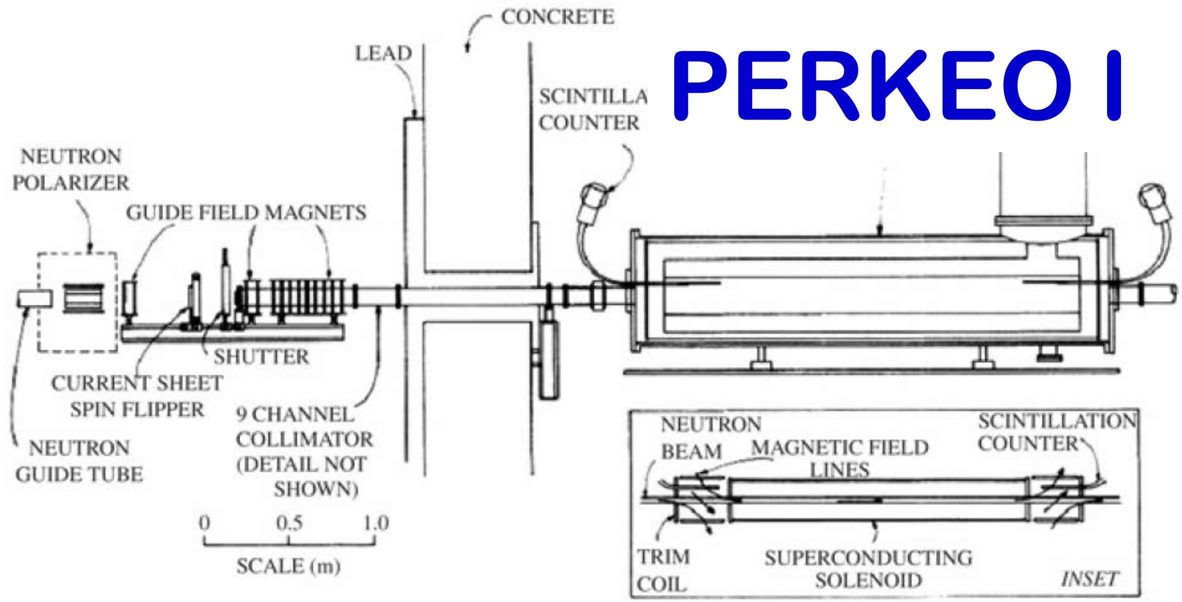
See P. Herczeg, Prog. Part. Nucl. Phys. 46 (2001) 413.

Courtesy of K. Bodek

Characteristics of Experiments Using Magnetic Fields

(Dubbers 1980s)

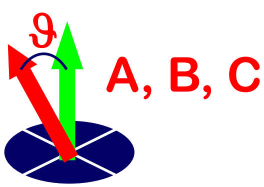
PERKEO I



Transport: The field guides the charged particles from the decay volume to the detectors

Solid angle: The detector's solid angle of acceptance is $2 \times 2\pi$ or can be adjusted individually by a variation of the magnetic field strength

$< \cos\vartheta >$: Neutron spin's direction points either parallel or antiparallel to the magnetic field lines. Therefore, the assignment of the electron momentum to a hemisphere either parallel or antiparallel to the neutron spin is exact. $< \cos\vartheta > = \frac{1}{2}$.



High backscattering suppression: Electron backscattering effects are effectively suppressed.

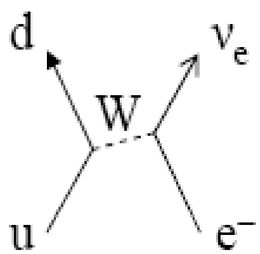
High signal / low background

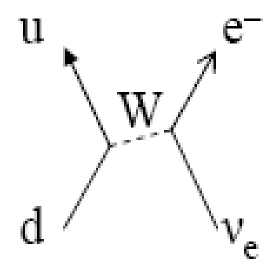
Method: P. Bopp et al., NIM A 267 (1988) 436.

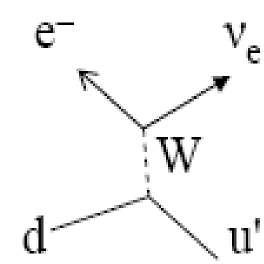
Why ratio $\lambda = g_A / g_V$ from Neutrons?

- Processes with the same Feynman-Diagram

Primordial element formation	$n + e^+ \rightarrow p + \nu'_e$	$\sigma_\nu \sim 1/\tau$
(^2H, ^3He, ^4He, ^7Li, …)	$p + e^- \rightarrow n + \nu_e$	$\sigma_\nu \sim 1/\tau$
	$n \rightarrow p + e^- + \nu'_e$	τ
Solar cycle	$p + p \rightarrow {}^2H + e^+ + \nu_e$	
	$p + p + e^- \rightarrow {}^2H + \nu_e$ etc.	$\sim (g_A/g_V)^5$
Neutron star formation	$p + e^- \rightarrow n + \nu_e$	
Pion decay	$\pi^- \rightarrow \pi^0 + e^- + \nu'_e$	
Neutrino detectors	$\nu'_e + p \rightarrow e^+ + n$	
Neutrino forward scattering	$\nu_e + n \rightarrow e^- + p$ etc.	
W and Z production	$u' + d \rightarrow W^- \rightarrow e^- + \nu'_e$ etc.	







Courtesy of D. Dubbers

Spectrometer Perkeo II

up:

$$A_{exp} = \frac{N^{\Uparrow} - N^{\Downarrow}}{N^{\Uparrow} + N^{\Downarrow}}$$

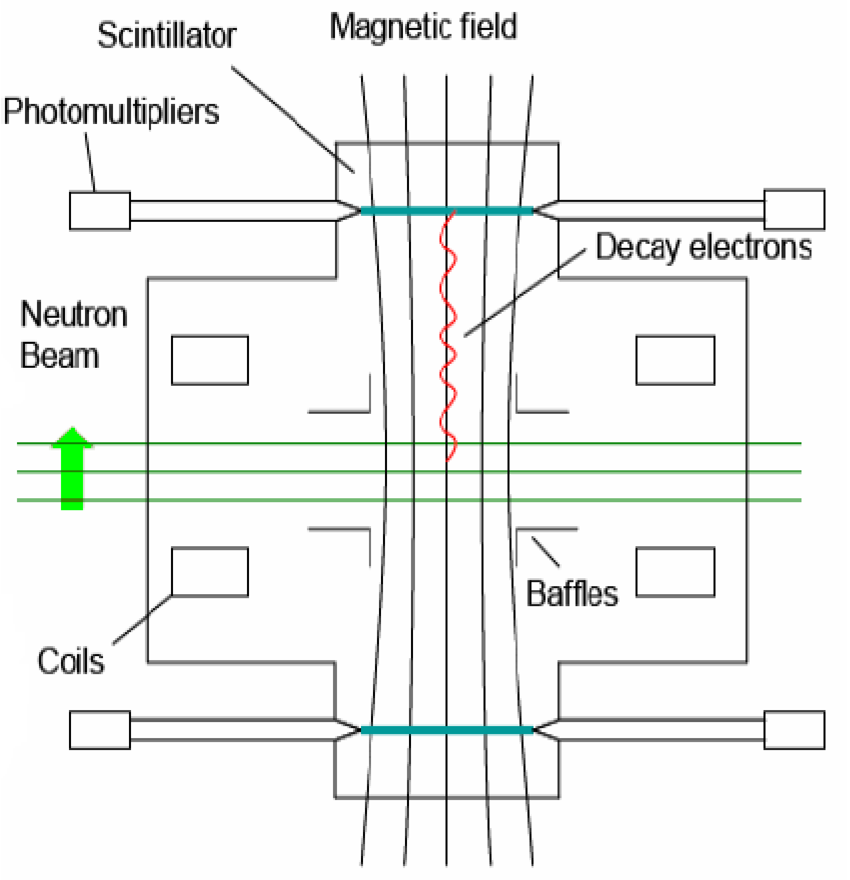
down:

$$A_{exp} = \frac{N^{\Uparrow} - N^{\Downarrow}}{N^{\Uparrow} + N^{\Downarrow}}$$

precise electron spectroscopy

Principle:

- **2x2π- Detection**
- **two hemispheres**
- **backscattering suppression**
- **low background**
- **strong beam PF1:**
  - **count rate→systematic**



$$A_{exp} = A\frac{v}{c}Pf \quad A = -2\frac{\lambda(\lambda+1)}{1+3\lambda^2}$$

$\lambda = g_A/g_V$

Method see also: H. Abele et al., 17 keV Neutrino PLB 316 26 1993

a bit history:

λ from neutron β-decay

- -1.1900(200), PDG (1960)
- -1.2500(200), PDG (1975)
- -1.2610(40), PDG (1990)
- -1.2594(38), Gatchina (1997)
- -1.2660(40), M, ILL (1997)
- **-1.2740(30), PERKEO II (1997)**
- -1.2686(47), Gatchina, ILL (2001)
- **-1.2739(19), PERKEO II (2002)**
- −1.27590(+409)(−445), UCNA (2011)
- -1.2756(30), UCNA (2013)
- **-1.2748^{+13}_{-14} PERKEO II (2013)**

Error Budget A

TABLE I. Summary of corrections and uncertainties relative to the beta asymmetry A_0, $\Delta A_0/A_0$.

Type	Correction (10^{-3})	Uncertainty (10^{-3})
Neutron polarization	3.0	1.0
Spin flip efficiency	0.0	1.0
Background	1.0	1.0
Detector response	0.0	2.5
Edge effect[a]	(−1.6)	0.5
Electron backscattering (detectors)	0.25	0.04
Electron backscattering (baffles)	0.0	+0.6, −0.0
Magnetic mirror effect	0.6	0.2
Dead time[b]	(−1.2)	0.1
Radiative correction	−1.1	0.5
Systematics (total)	0.95	+3.6, −2.7
Statistics		3.8

[a]Included in the fit function.
[b]Measured by the data acquisition system and accounted for in the data set.

a bit history:

λ from neutron β-decay

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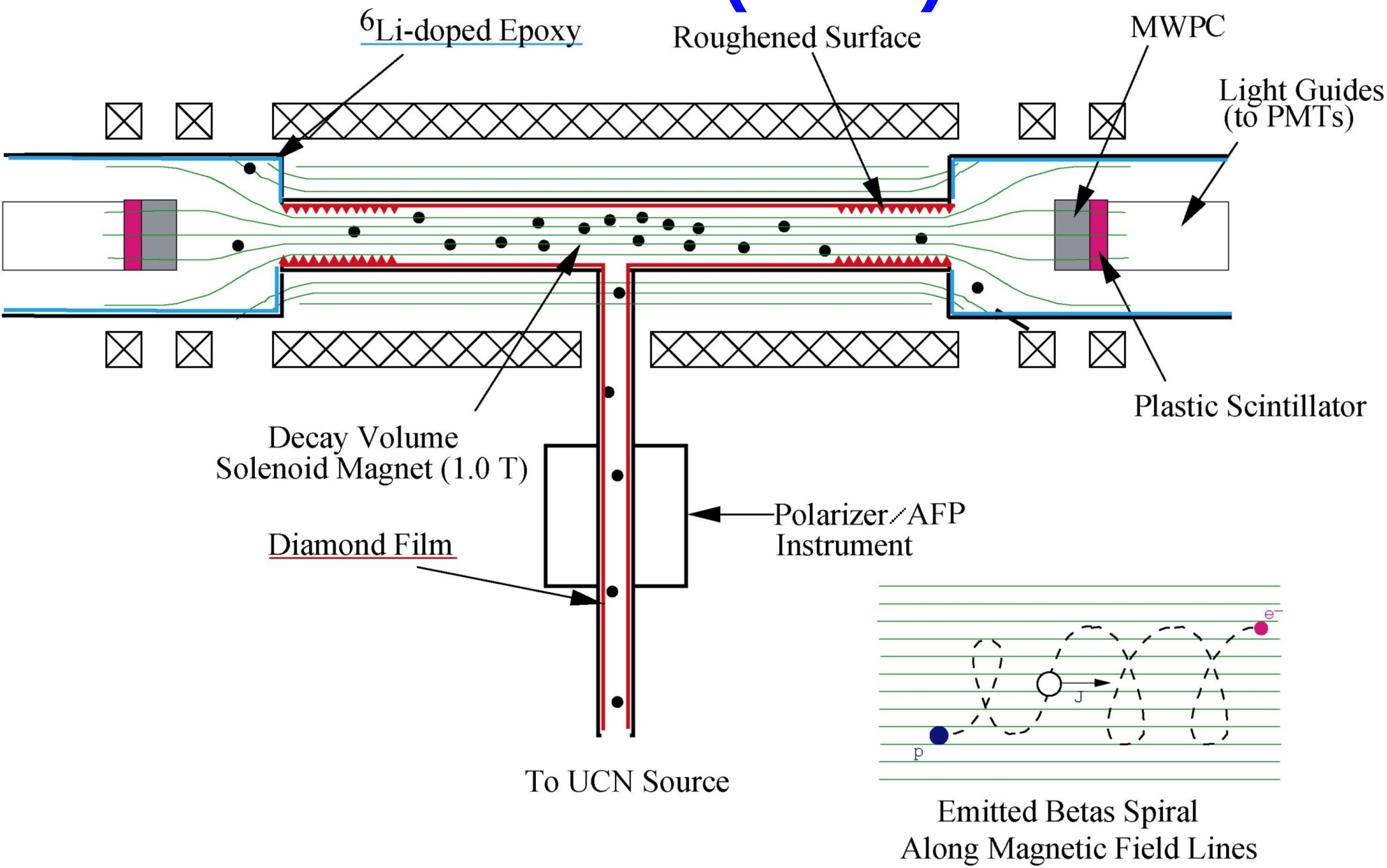
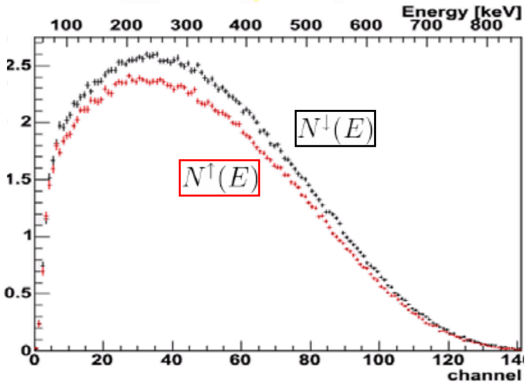
UCNA (2013)

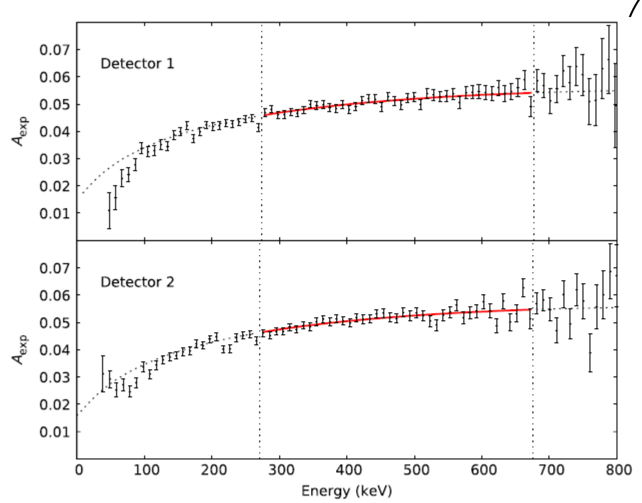


λ = -1.2756(30), UCNA (2013)

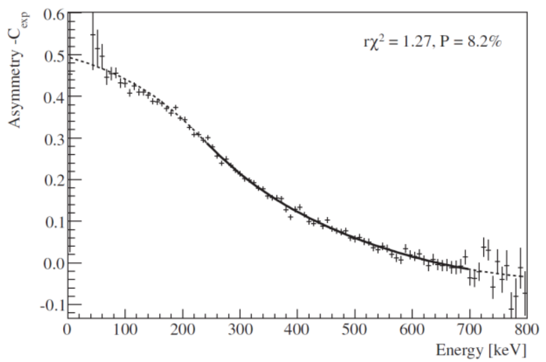
Recent Results: PERKEO Collaboration

Electron Asymmetry A:





Neutrino Asymmetry B



Proton Asymmetry C:

first precision measurement $C = x_C(A + B)$

A = -0.1197(6)

PERKEO II combined:

$A_{PII} = -0.1193(5)$

$\lambda_{PII} = -1.2748(13)$

error: 1×10^{-3}

PRL 110, 172502 (2013)

B = 0.9802(50)

Schumann et a.

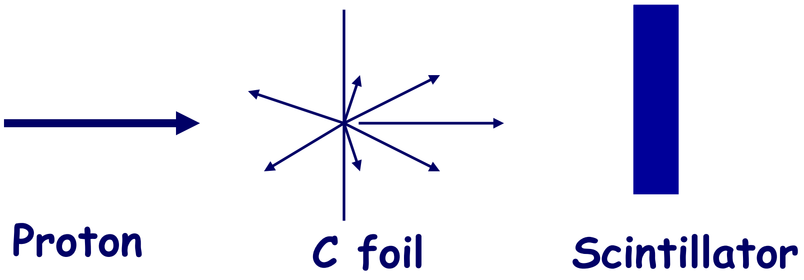
PRL 99, 191803 (2007)

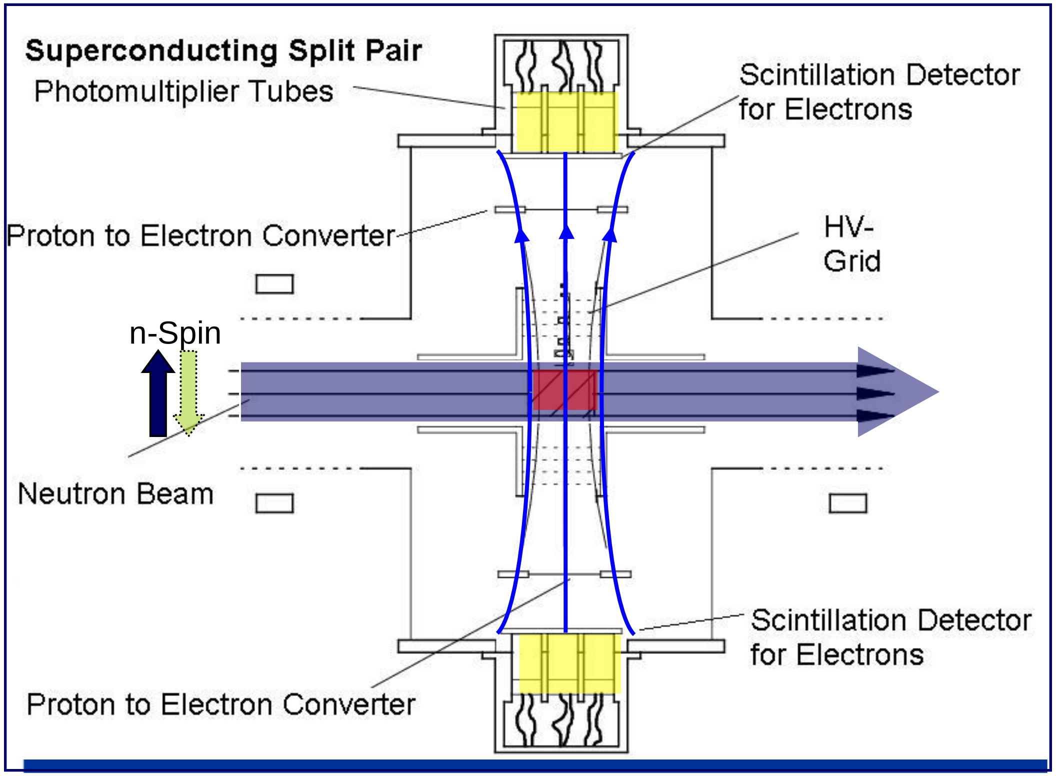
$C = -0.2377(36)$

Schumann et al.,

PRL 100, 151801 (2008)

Coefficient *B,C*
Proton detector





Proton detection:
- Measure electron energy
- Wait for proton
- Convert proton into electron signal

H. Abele, NIM A 611 (2009) 193–197

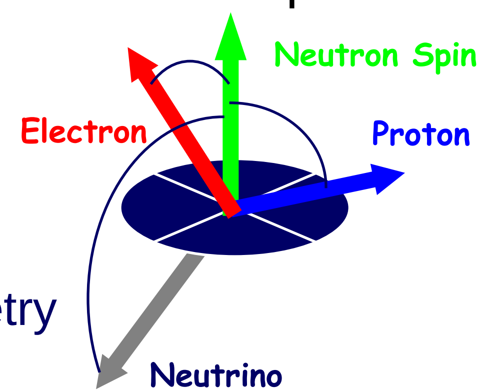
M. Schumann: The Neutrino-Asymmetry B

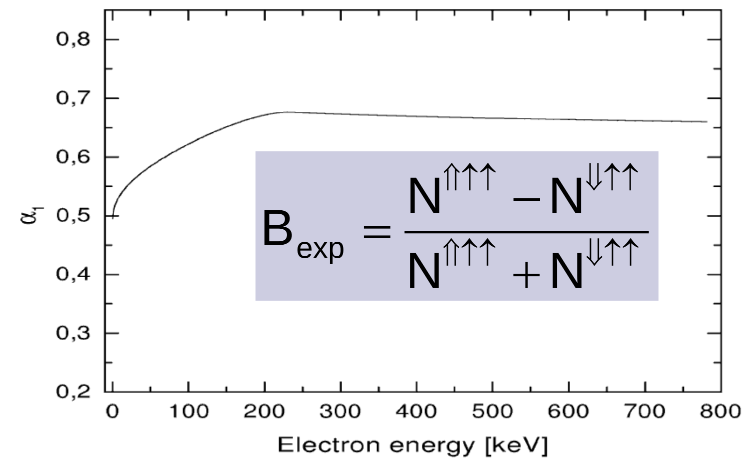
Systematically clean method: Integration over two hemispheres

- Electron and Proton in same hemisphere

$\rightarrow$ low dependence on energy calibration and energy resolution

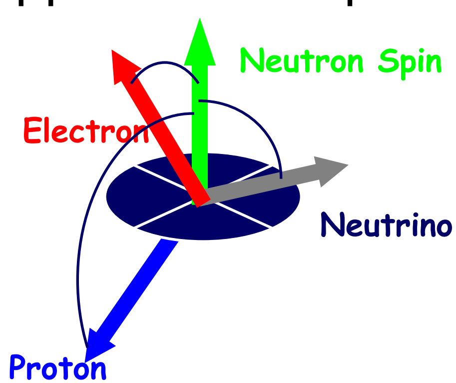
$\rightarrow$ higher sensitivity due to larger exp. asymmetry

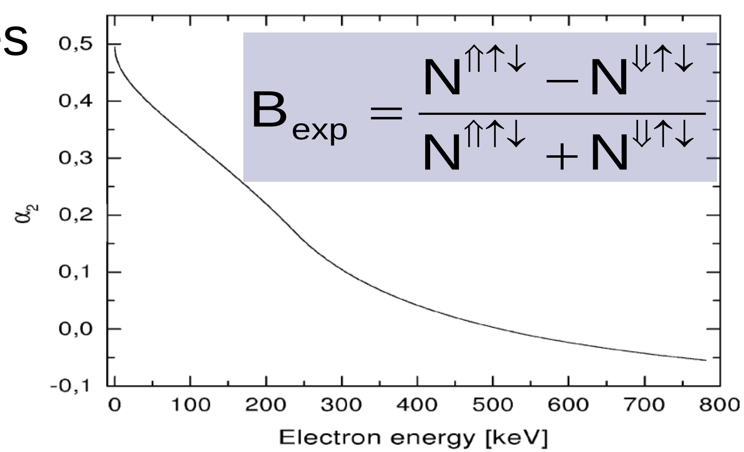




Electron and Proton in opposite hemispheres

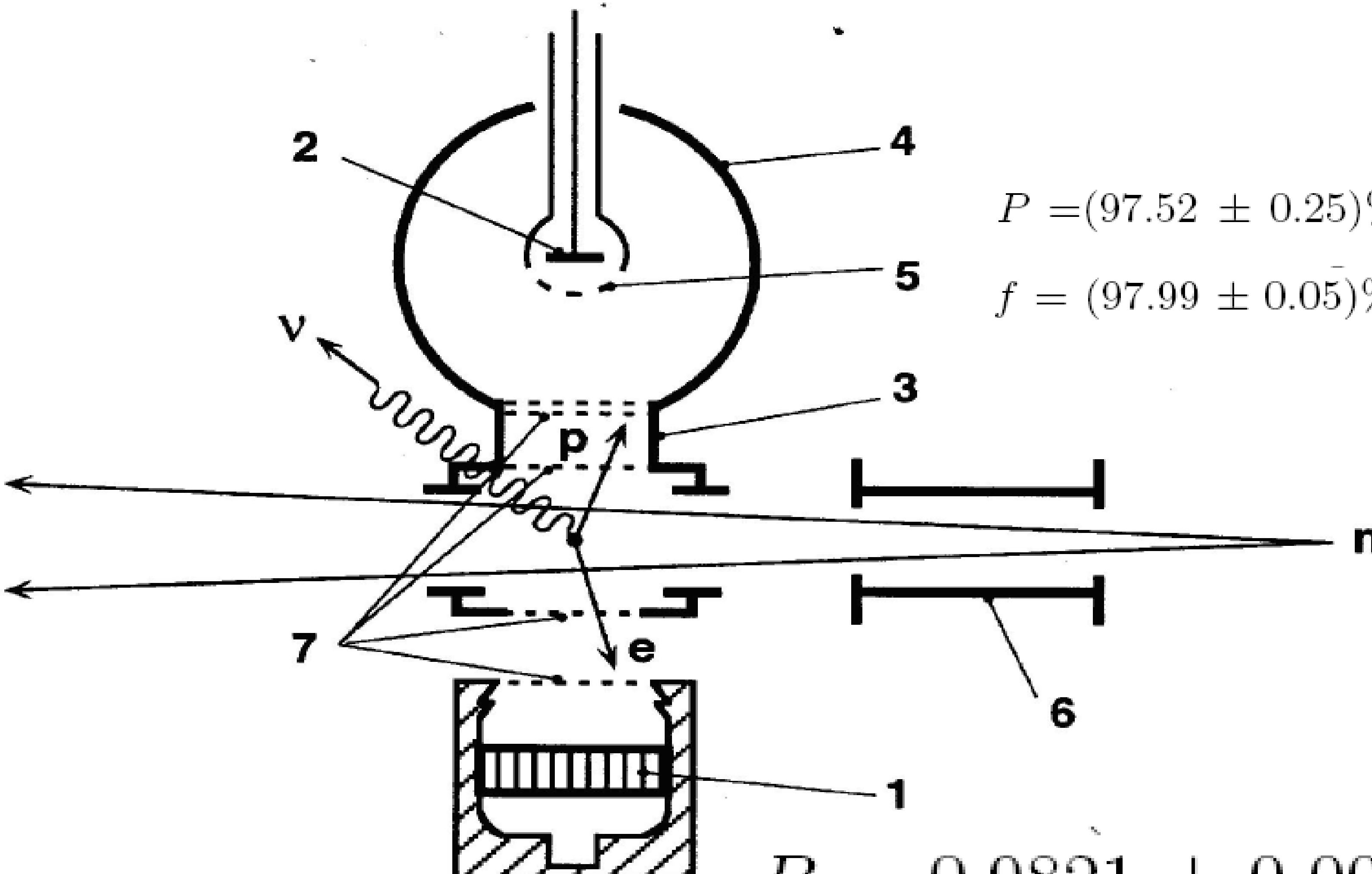
$\rightarrow$ more statistics since this case occurs for ~78% of the events





M. Schumann,M. Kreuz, M. Deissenroth,F. Glück,J. Krempel, B. Märkisch,D Mund, A. Petoukhov, T. Soldner, H. Abele, **PRL 100, 151801 (2008)**

Coefficient B, Serebrov et al.

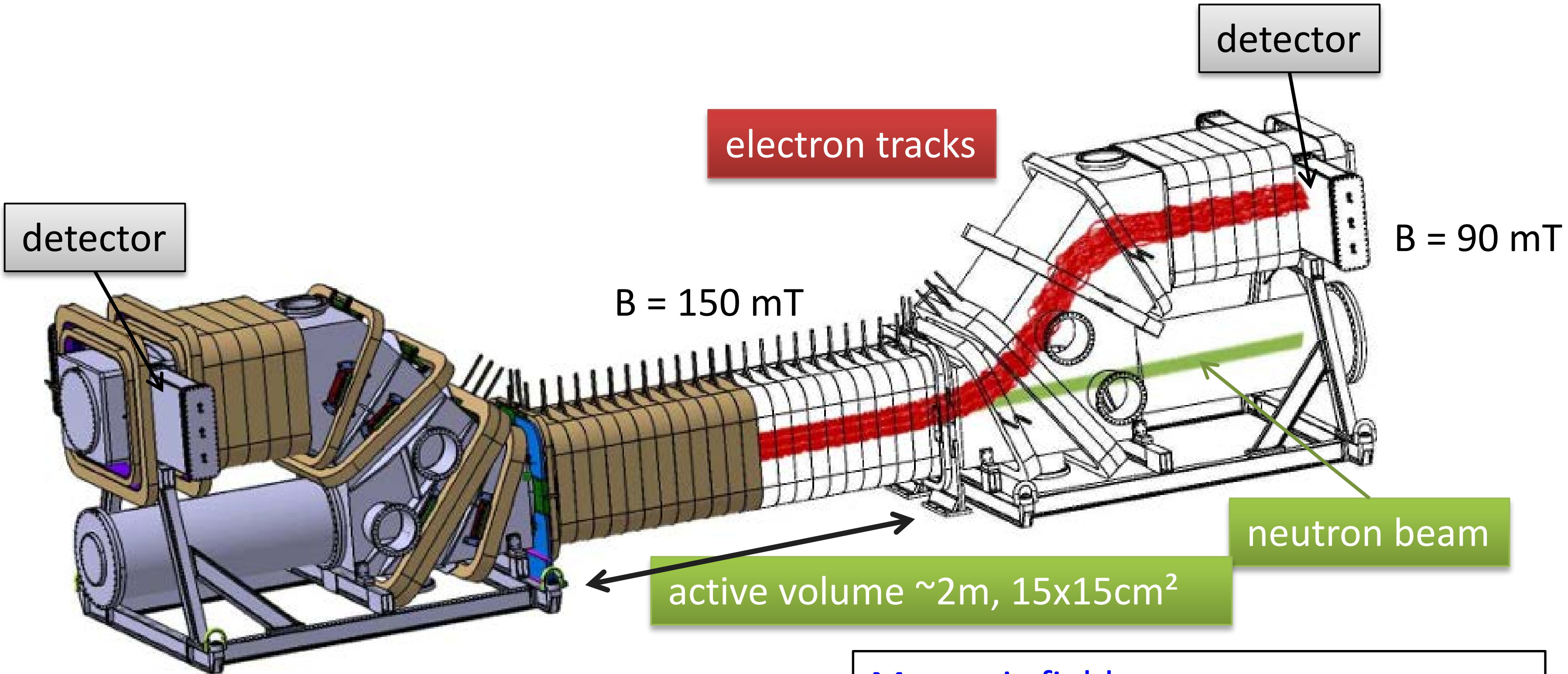


$$P = (97.52 \pm 0.25)\%$$

$$f = (97.99 \pm 0.05)\%$$

$$B = 0.9821 \pm 0.004.$$

B. Maerkisch et al.: Spectrometer PERKEO III



54 water-cooled copper coils
Total Weight: 8 t
Total Length: 8 m
Electric: 300 kW, 540 A

B. Maerkisch et al., NIM 611 (2009) 216–218

Magnetic field :

- alignment of n–spin
- guide e^-, p onto detectors
  $\Rightarrow$ 2 x 2 π detector
- separation into hemispheres

Error Budget

Uni HD Maerkisch et al., ILL: Soldner et al. TU Wien: Wang et al.

Source	Correction $\Delta A/A$ (10^{-4})	Uncertainty $\Delta A/A$ (10^{-4})
Neutron beam		
Polarisation	separate analysis	< 10
Spin flip efficiency		
Background		
Undetected		1
Time variation	-1	1
Electrons		
Magnetic mirror effect	separate analysis	4
Lost backscatter energy		1,4
Detector		
Deadtime *	-5	2
Non-linearity		4
Non-uniformity		3
Stability *		2
Calibration		0,5
Theory		
Radiative corr. *	-1,1	2
Total Systematics		12,4
Statistics		13,9
Total		18,6

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

Result:

$$\frac{\Delta A}{A} = 1.9\cdot 10^{-3}$$

$$\frac{\Delta\lambda}{\lambda} = 4.8\cdot 10^{-4}$$

Factor 4 improvement over PDG 2013 average

Close to Publication

- aCORN @ NIST
- aSPECT @ Mz, ILL, TUW
- PERKEO III @ UHD, ILL, TUW: *A (B,C not so close)*

New Instruments

- Nab, PERC

R. Feynman

- Nature has always looked like a horrible mess, but as we go along we see patterns and put theories together; a certain clarity comes and things get simpler (Feynman).

Standard Model of Particle Physics

D. Dubbers 2007

- Input: Principia:
  - Gauge principle U(1) x SU(2) x SU(3)
  - Lorentz invariance : x‘ = Lx
  - CPT, ...Invariance
- Output:
  - Interactions
  - Equation of motion — Maxwell, Schrödinger, Dirac
  - Existence of — Photons, Gluons, $W^{\pm}$, Z^0 (carriers of interaction)
  - Charge conservation — (Source of interaction)
- Conclusion: SM very successful
  - e.g. as basis for technology, chemistry, biology, mol.biologie

Weak Magnetism form factor f_2

Neutron Decay Transition Matrix:

$$T_{fi} = \frac{G_F}{\sqrt{2}} V_{ud} \cdot \langle p \,|\, \gamma_\mu (1-\gamma_5) \,|\, n \rangle \cdot (\bar{\nu} \gamma^\mu (1-\gamma_5) e)$$

$$V_\mu = \langle p \,|\, [\, f_1(k^2)\gamma_\mu + \frac{f_2(k^2)}{2m_p} \sigma_{\mu\nu} k^\nu + i f_3(k^2) k_\mu \,] \,|\, n \rangle$$

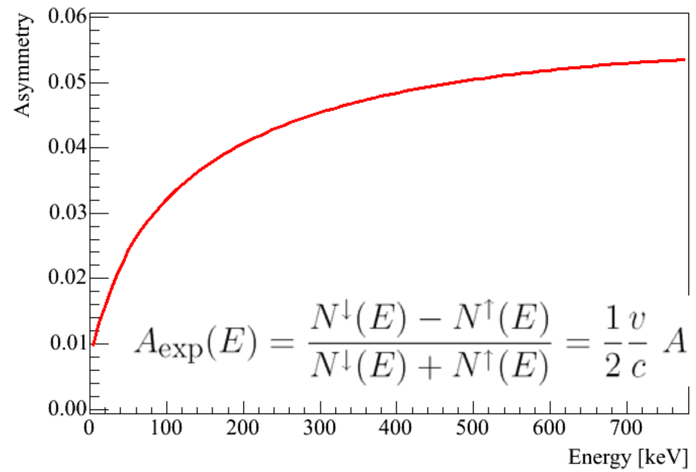
f_2 Weak Magnetism Form Factor (SM prediction)

Electron Asymmetry:

$$A_0 = -2 \frac{\lambda^2 + \lambda}{1 + 3\lambda^2}$$

$$A(E) = A_0 (1 + c + a_{\mathrm{wm}}(\lambda, f_2)\; E)$$

2 % additional E–dependence of A



$$A_{\mathrm{exp}}(E) = \frac{N^{\downarrow}(E) - N^{\uparrow}(E)}{N^{\downarrow}(E) + N^{\uparrow}(E)} = \frac{1}{2} \frac{v}{c} \; A \; P \; F$$

Beyond SM

- **A search for**
  - right-handed admixtures to the left-handed feature of the Standard model. They are forbidden in the Standard-Model, but, as a natural consequence of symmetry breaking in the early universe, they should be found in neutron-decay. Signatures are a W_R mass with mixing angle z.
  - scalar and tensor admixtures g_S and g_T to the electroweak interaction. g_S and g_T are also forbidden in the Standard model but supersymmetry contributions to correlation coefficients or the Fierz interference term b can approach the 10^{-3} level.
- **A precision measurement of**
  - the weak-magnetism form factor f_2 prediction of electroweak theory. Such an experiment would be one of the rare occasions, where a strong test of the underlying structure itself of the Standard model becomes available.
- **Supersymmetry search in the LHC era:**
  - one could expect small deviations in the low-energy tests, such as deviations from CKM unitarity, but no effect at the LHC, especially if the supersymmetry spectrum is below one TeV, but the spectrum is compressed, or if some of the superpartners are light and others are heavy (a variant on the "split-SUSY" scenario)

DFG/FWF Priority Programme 1491 : Precision experiments in particle- and astrophysics with cold and ultracold neutrons,

- Participating Institutions:
  - IST Braunschweig
  - Univ. Heidelberg
  - ILL
  - Univ. Jena
  - Univ. Mainz
  - Exzellenzcluster ‚Universe' München
  - Techn. Univ. München *
  - PTB Berlin
  - Vienna University of Technology *

- Priority Areas
  - CP-symmetry violation and particle physics in the early universe.
  - The structure and nature of weak interaction and possible extensions of the Standard Model.
  - Tests of gravitation with quantum objects
  - Charge quantization and the electric neutrality of the neutron.

- New Infrastructure (UCN-Source, cold Neutrons)

\- *** Coordinators first round (S. Paul, H.A.)**

Priority Programme 1491

- Research Area A: *CP-symmetry violation and particle physics in the early universe*
  - **Neutron EDM** $\Delta E = 10^{-23}$ eV
- Research Area B: *The structure and nature of weak interaction and possible extensions of the Standard Model*
  - **Neutron β-decay** V – A Theory
- Research Area C: *Test of gravitation with quantum interference*
  - **Neutron bound gravitational quantum states**
- Research Area D: *Charge quantization and the electric neutrality of the neutron*
  - **Neutron charge**
- Research Area E: *New measuring techniques*
  - ***Particle detection***
  - ***Magnetometry***
  - ***Neutron optics***

Priority area B (first 3 years round):
Novel experiments on neutron beta-decay

- Experiment PERC
  - PERC, a clean, bright and versatile source of neutron decay products (Maerkisch)
  - Proton spectroscopy (Heil, Zimmer)
  - Electron spectroscopy (Abele)
  - Neutron polarisation + analysis with 10^{-4} accuracy (Soldner)
  - design of the beam line for PERC (Soldner, Jericha)
  - Development of a non-depolarising neutron guide needed for PERC (Schmidt)
- Measurement of the neutron lifetime
  - O. Zimmer et al.
- Measurement of n -> H
  - S. Paul et al.

SM tests on 10^{-4} level

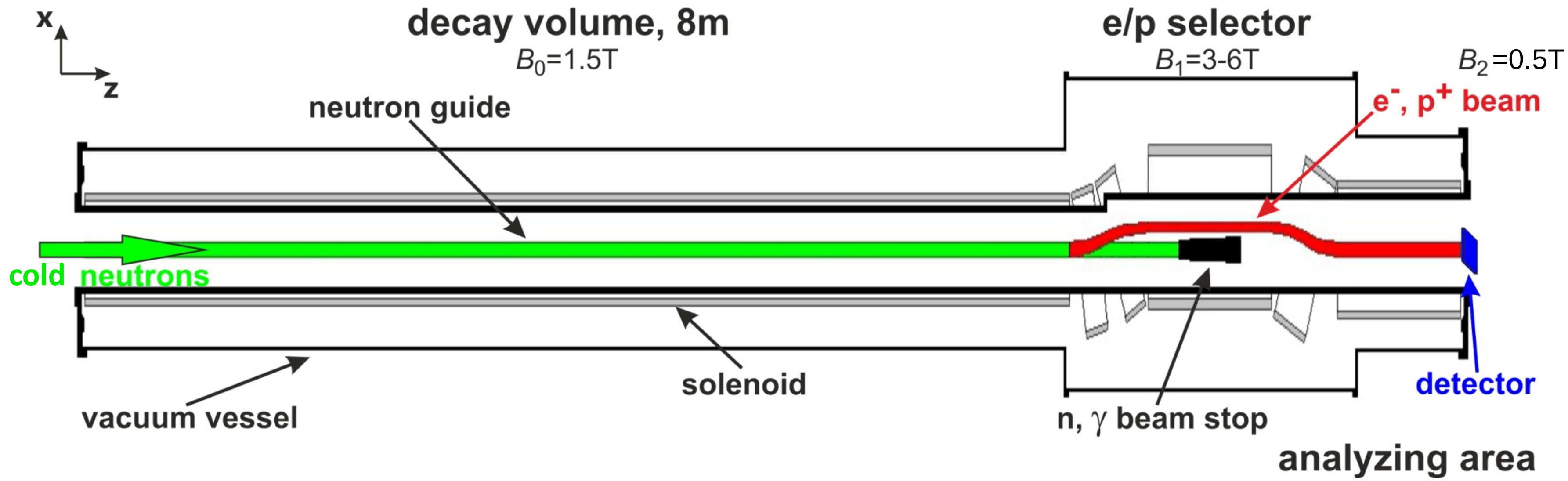
Theory

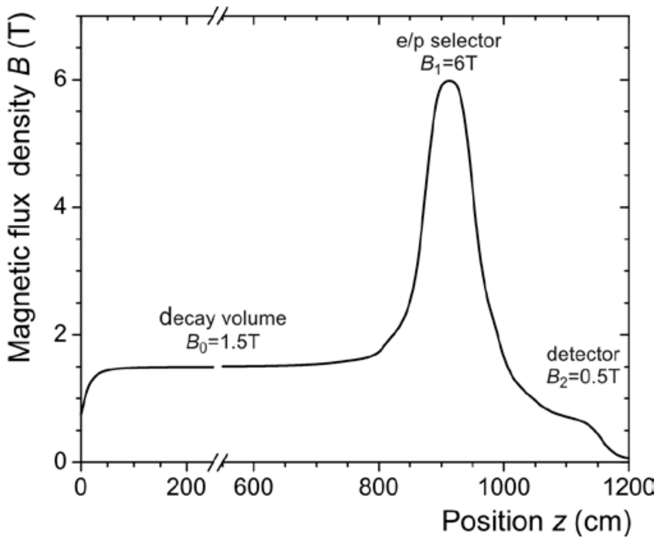
- **Recalculation of corrections induced by the "weak magnetism", the proton recoil and the radiative corrections.**
- A. Ivanov, M. Pitschmann, and N. Troitskaya, Phys.Rev. D88, 073002 (2013), 1212.0332.

Experiment PERC

- **High statistic measurements:**
- **Today: High Average Flux: $\Phi = 2 \times 10^{10}$ $cm^{-2}s^{-1}$**
- **Decay rate of 1 MHz / metre**
- **Thesis C. Klauser (2013) Polarizer $\Delta P/P = 10^{-4}$, Spin Flipper $\Delta f/f = 10^{-4}$**

Proton Electron Radiation Channel: B. Maerkisch





Versatile: A, B, C, a, b, κ, …

Sensitivity:
- improved by up to 2 orders of magnitude
- high phase space density

Systematics:
- 10^{-4} (for e^-)
- precise cuts in $d\Omega_e$: $$\frac{\sin\theta}{\sin\theta_0} = \sqrt{\frac{B}{B_0}}$$

Requirements:
- no local field minima
- adiabaticity criterion
- B_1 homogeneity 10^{-4} in e/p beam

D. Dubbers *et al.*, NIM A **596** (2008) 238 and arXiv:0709.4440
G. Konrad *et al.* (for the PERC collaboration), J. Phys.: Conf. Ser. **340** (2012) 012048

SOURCE OF ERROR	COMMENT	SIZE OF CORRECT.	SIZE OF ERROR:
non-uniform n-beam	for $\Delta\Phi/\Phi$ = 10 % over 1 cm width	$2.5\cdot10^{-4}$	$5\cdot10^{-5}$
other edge effects on e/p-window	for worst case at max. energy	$4\cdot10^{-4}$	$1\cdot10^{-4}$
magn. mirror effect, contin's n-beam		$1.4\cdot10^{-2}$	$2\cdot10^{-4}$
magn. mirror effect, pulsed n-beam	for $\Delta B/B$ = 10 % over 8 m length	$5\cdot10^{-5}$	$<10^{-5}$
non-adiabatic e/p-transport		$5\cdot10^{-5}$	$5\cdot10^{-5}$
background from n-guide	}is separately measurable	$2\cdot10^{-3}$	$1\cdot10^{-4}$
background from n-beam stop		$2\cdot10^{-4}$	$1\cdot10^{-5}$
backscattering off e/p-window		$2\cdot10^{-5}$	$1\cdot10^{-5}$
backscattering off e/p-beam dump		$5\cdot10^{-5}$	$1\cdot10^{-5}$
backscatt. off plastic scintillator	}for worst case	$2\cdot10^{-3}$	$4\cdot10^{-4}$
~ same with active e/p-beam dump		–	$1\cdot10^{-4}$
neutron polarisation	present status	$3\cdot10^{-4}$	$1\cdot10^{-4}$

Dubbers, Baessler, Märkisch, Schumann, Soldner, Zimmer, H.A., arXiv 2007

Reserva

Neutron Beta–Decays and New Physics

- Ref.[1]: A. N. Ivanov, M. Pitschmann, and N. I. Troitskaya, PRD **88**, 073002 (2013)
- Ref.[2]: A. N. Ivanov, R. Höllwieser, N. I. Troitskaya, and M. Wellenzohn, PRD **88**, 065026 (2013)
- Ref.[3]: A. N. Ivanov, M. Pitschmann, N. I. Troitskaya, and Ya. A. Berdnikov, PRC **89**, 055502 (2014)

- The theoretical analysis of lifetime, energy spectra and angular distributions of the neutron beta–decay ($n \to p + e^- + \bar{\nu}_e$) and the bound beta–decay ($n \to \mathrm{H} + \bar{\nu}_e$) was carried out within the standard quantum field theory at the rest frame of the neutron and in the non–relativistic approximation for the proton by taking into account the radiative corrections to order α, the proton recoil corrections and the “weak magnetism” to order $1/M$, where $M = (m_n + m_p)/2$ is the average mass (see Ref.[1,2,3]).

Neutron Beta–Decays and New Physics

- We showed that the account for the contributions of the proton–photon correlations in the radiative corrections to the neutron beta–decay does not contradict the description of the radiative corrections to the lifetime of the neutron and the proton recoil spectrum in terms of the standard radiative corrections but makes the proton recoil asymmetry C symmetric with respect to a change $A_0 \leftrightarrow B_0$ (see Ref.[2]).
- We showed that the Standard Model (SM) describes well the lifetime of the neutron $\tau_n = 880.1(1.1)\,\mathrm{s}$ (the theoretical value is $\tau_n = 879.6(1.1)\,\mathrm{s}$) for the axial coupling constant $\lambda = -1.2750(9)$ and the CKM matrix element V_{ud}, obtained from the $0^+ \to 0^+$ transitions and the unitarity condition, respectively (see Ref.[1]).

Neutron Beta–Decays and New Physics

- Above the theoretical background, calculated in the SM, we investigated the contributions of new physics in terms of the Herczeg coupling constants. We showed that after renormalisation of the axial coupling λ constant and V_{ud} the contributions of new physics to linear order perturbation theory can be expressed in terms of the scalar and tensor weak lepton–baryon interactions, which can be measured from the asymmetries of the energy spectra and angular distributions of the neutron beta decay (see Refs.[1,2]).
- For the bound beta–decay we showed that angular distribution of the production of hydrogen in the ground hyperfine state with $F = 0$ can be used for the measurements of the contributions of new physics by measuring the left–handed polarisation state of the electron antineutrino (see Ref.[3]).

A REVIEW GOES HERE – Check our WWW List of Reviews

MASS LIMITS for W' (Heavy Charged Vector Boson Other Than W) in Hadron Collider Experiments

Couplings of W' to quarks and leptons are taken to be identical with those of W. The following limits are obtained from $p\overline{p}$ or $pp \rightarrow W' X$ with W' decaying to the mode indicated in the comments. New decay channels (*e.g.*, $W' \rightarrow WZ$) are assumed to be suppressed. The most recent preliminary results can be found in the "W'-boson searches" review above.

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
>1680	95	AAD	13D	ATLS	$W' \rightarrow q\overline{q}$
>1920	95	CHATRCHYAN	13A	CMS	$W' \rightarrow q\overline{q}$
>1510	95	[1] CHATRCHYAN	13E	CMS	$W' \rightarrow tb$
>1130	95	[2] AAD	12AV	ATLS	$W' \rightarrow tb$
> 760	95	[3] AAD	12BB	ATLS	$W' \rightarrow WZ$
>2550	95	AAD	12CR	ATLS	$W' \rightarrow e\nu, \mu\nu$
>2630	95	[4] CHATRCHYAN	12AB	CMS	$W' \rightarrow e\nu, \mu\nu$
>1143	95	[3] CHATRCHYAN	12AF	CMS	$W' \rightarrow WZ$

• • • We do not use the following data for averages, fits, limits, etc. • • •

W_R (Right-Handed W Boson) MASS LIMITS

Assuming a light right-handed neutrino, except for BEALL 82, LANGACKER 89B, and COLANGELO 91. $g_R = g_L$ assumed. [Limits in the section MASS LIMITS for W' below are also valid for W_R if $m_{\nu_R} \ll m_{W_R}$.] Some limits assume manifest left-right symmetry, *i.e.*, the equality of left- and right Cabibbo-Kobayashi-Maskawa matrices. For a comprehensive review, see LANGACKER 89B. Limits on the W_L-W_R mixing angle ζ are found in the next section. Values in brackets are from cosmological and astrophysical considerations and assume a light right-handed neutrino.

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
$>$ 592	90	[1] BUENO	11	TWST	μ decay
$>$ 715	90	[2] CZAKON	99	RVUE	Electroweak
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$>$ 245	90	[3] WAUTERS	10	CNTR	^{60}Co β decay
$>$ 180	90	[4] MELCONIAN	07	CNTR	^{37}K β^+ decay
$>$ 290.7	90	[5] SCHUMANN	07	CNTR	Polarized neutron decay
[$>$ 3300]	95	[6] CYBURT	05	COSM	Nucleosynthesis; light ν_R
$>$ 310	90	[7] THOMAS	01	CNTR	β^+ decay
$>$ 137	95	[8] ACKERSTAFF	99D	OPAL	τ decay
$>$1400	68	[9] BARENBOIM	98	RVUE	Electroweak, Z-Z' mixing
$>$ 549	68	[10] BARENBOIM	97	RVUE	μ decay
$>$ 220	95	[11] STAHL	97	RVUE	τ decay
$>$ 220	90	[12] ALLET	96	CNTR	β^+ decay

Limit on W_L-W_R Mixing Angle ζ

Lighter mass eigenstate $W_1 = W_L \cos\zeta - W_R \sin\zeta$. Light ν_R assumed unless noted. Values in brackets are from cosmological and astrophysical considerations.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
−0.020 to 0.017	90	BUENO	11	TWST	$\mu \rightarrow e \nu \overline{\nu}$
< 0.022	90	MACDONALD	08	TWST	$\mu \rightarrow e \nu \overline{\nu}$
< 0.12	95	[1] ACKERSTAFF	99D	OPAL	τ decay
< 0.013	90	[2] CZAKON	99	RVUE	Electroweak
< 0.0333		[3] BARENBOIM	97	RVUE	μ decay
< 0.04	90	[4] MISHRA	92	CCFR	νN scattering
−0.0006 to 0.0028	90	[5] AQUINO	91	RVUE	
[none 0.00001–0.02]		[6] BARBIERI	89B	ASTR	SN 1987A
< 0.040	90	[7] JODIDIO	86	ELEC	μ decay
−0.056 to 0.040	90	[7] JODIDIO	86	ELEC	μ decay

[1] ACKERSTAFF 99D limit is from τ decay parameters.

[2] CZAKON 99 perform a simultaneous fit to charged and neutral sectors.

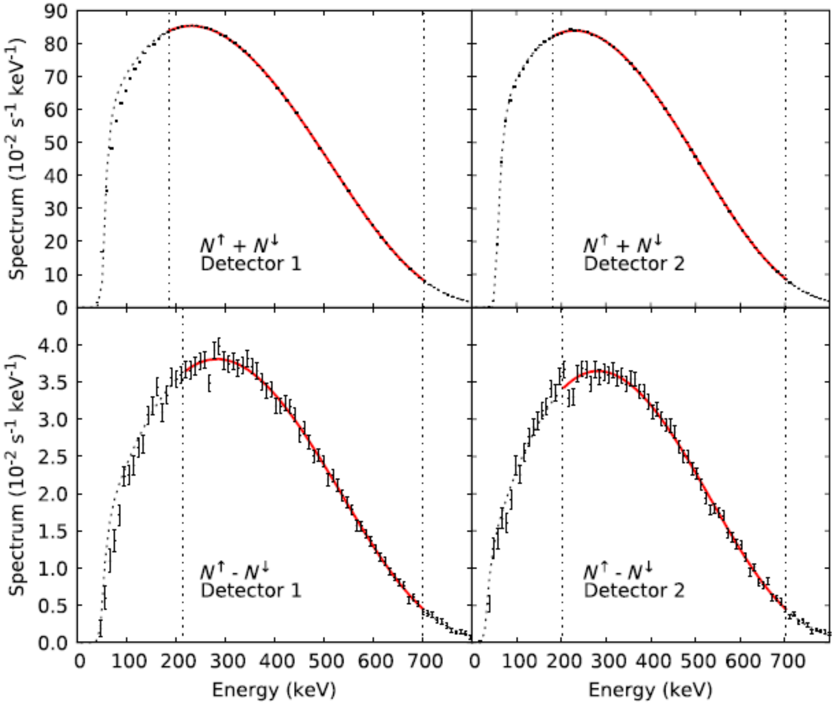
[3] The quoted limit is from μ decay parameters. BARENBOIM 97 also evaluate limit from K_L-K_S mass difference.

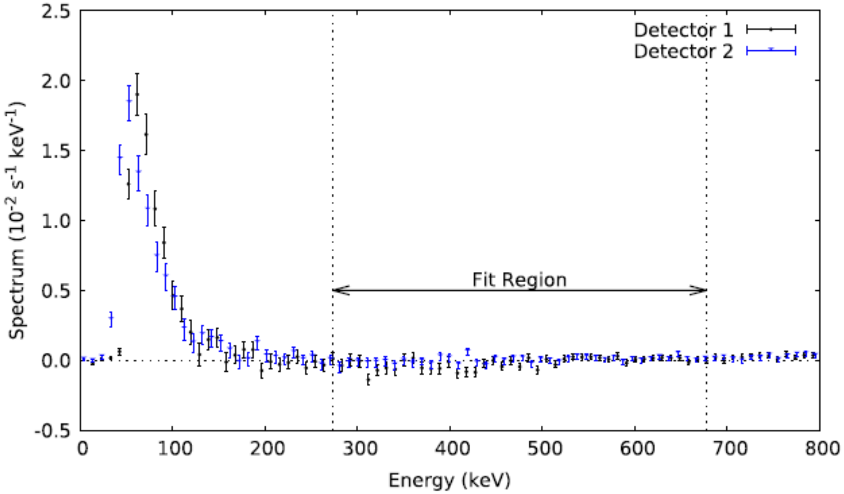
[4] MISHRA 92 limit is from the absence of extra large-x, large-y $\overline{\nu}_\mu N \rightarrow \overline{\nu}_\mu X$ events at Tevatron, assuming left-handed ν and right-handed $\overline{\nu}$ in the neutrino beam. The result gives $\zeta^2(1-2m^2_{W_1}/m^2_{W_2}) < 0.0015$. The limit is independent of ν_R mass.

[5] AQUINO 91 limits obtained from neutron lifetime and asymmetries together with unitarity of the CKM matrix. Manifest left-right asymmetry is assumed.

[6] BARBIERI 89B limit holds for $m_{\nu_R} \leq 10$ MeV.

Coefficient *A*



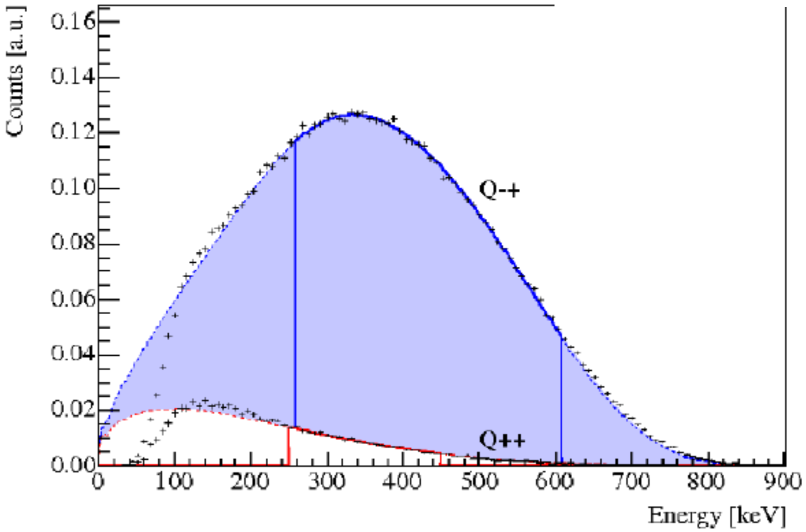


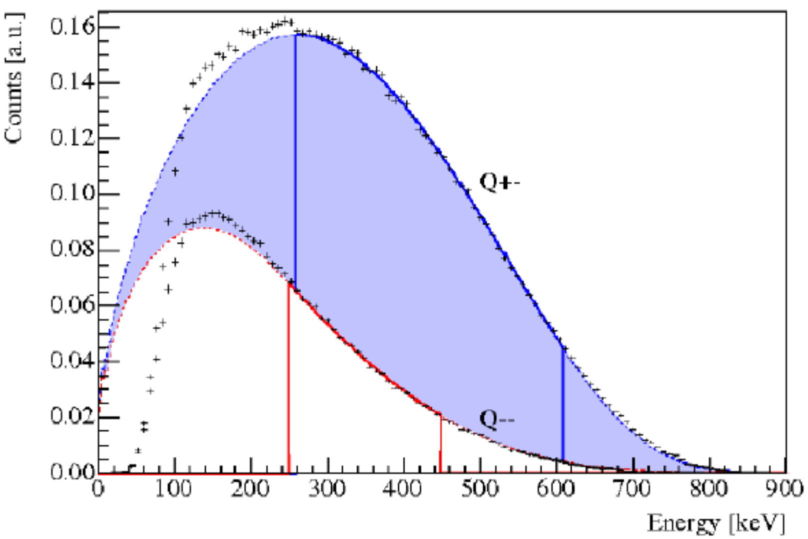
Coefficient C

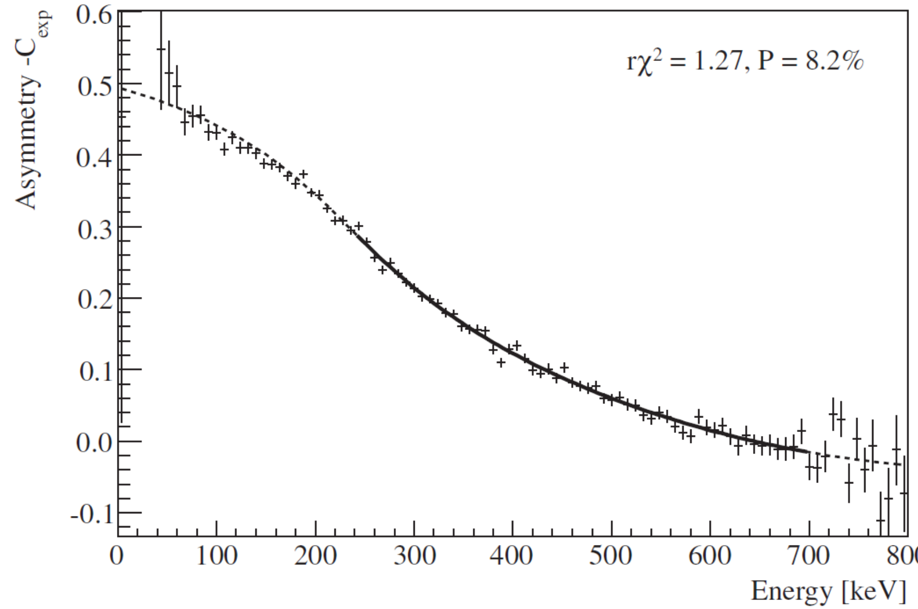
$$C = \frac{\rho^+ - \rho^-}{\rho^+ + \rho^-}$$

$$\rho^+ = \int (Q^{++}(E) + Q^{-+}(E))dE$$

and $$\rho^- = \int (Q^{+-}(E) + Q^{--}(E))dE$$







The expressions to describe the Q spectra are given in [5] with $Q^{ij} = q^{ij}F(E)$ and the Fermi function $F(E)$:

$$q^{++}_{r<1} = \frac{2-r}{2} + \frac{a\beta}{4}\left(\frac{r^2}{2} - 1\right) + \frac{PA\beta}{2}\left(1 - \frac{2r}{3}\right) + \frac{PB}{2}\left(\frac{r^2}{3} - 1\right),$$

$$q^{++}_{r\geq 1} = \frac{1}{2r}\left(1 - \frac{a\beta}{4r} + \frac{PA\beta}{3r} - \frac{2PB}{3}\right),$$

$$q^{--} = q^{++}[P \to -P], \quad q^{+-} = 2 + PA\beta - q^{++},$$

$$q^{-+} = 2 - PA\beta - q^{--}, \quad \text{with } r = \beta\frac{E+m_e}{E_{\max}-E}. \qquad (6)$$

Error budget B

TABLE I. Neutrino asymmetry B: corrections and errors.

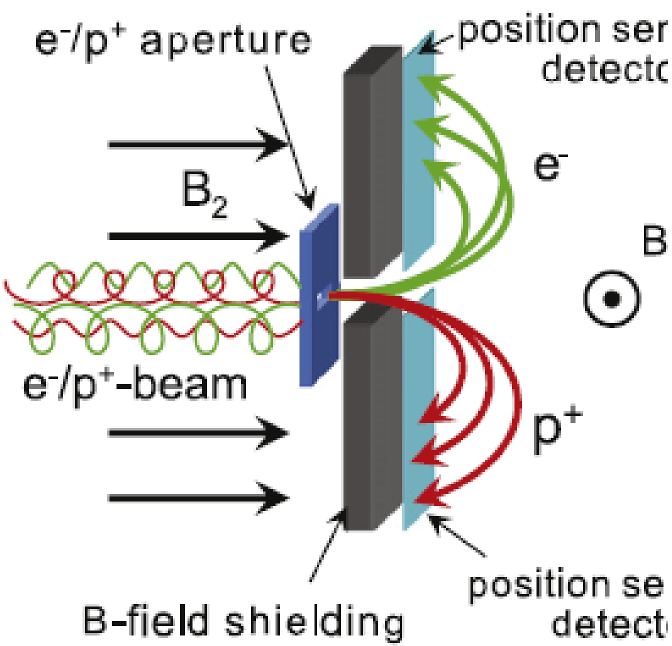
Effect [%]	Detector 1 Corr.	Detector 1 Err.	Detector 2 Corr.	Detector 2 Err.
Polarization	+0.30	0.10	+0.30	0.10
Flip Efficiency		0.10		0.10
Data Set: *Statistics*		1.22		0.36
Proton Window	−0.05	0.03	−0.05	0.03
1 Stop Condition	−0.24	0.06	−0.13	0.03
Background		0.10		0.08
Detector Calibration		0.02		0.02
Spectrometer: *Edge Effect*	−0.16	0.05	−0.16	0.05
Grid Effect	+0.03	0.05	+0.03	0.05
Mirror Effect	+0.44	0.05	+0.44	0.05
Displacement Δ	−0.10	0.32	+0.10	0.32
Correlations A, a		0.07		0.07
Sum	+0.22	1.28	+0.53	0.52

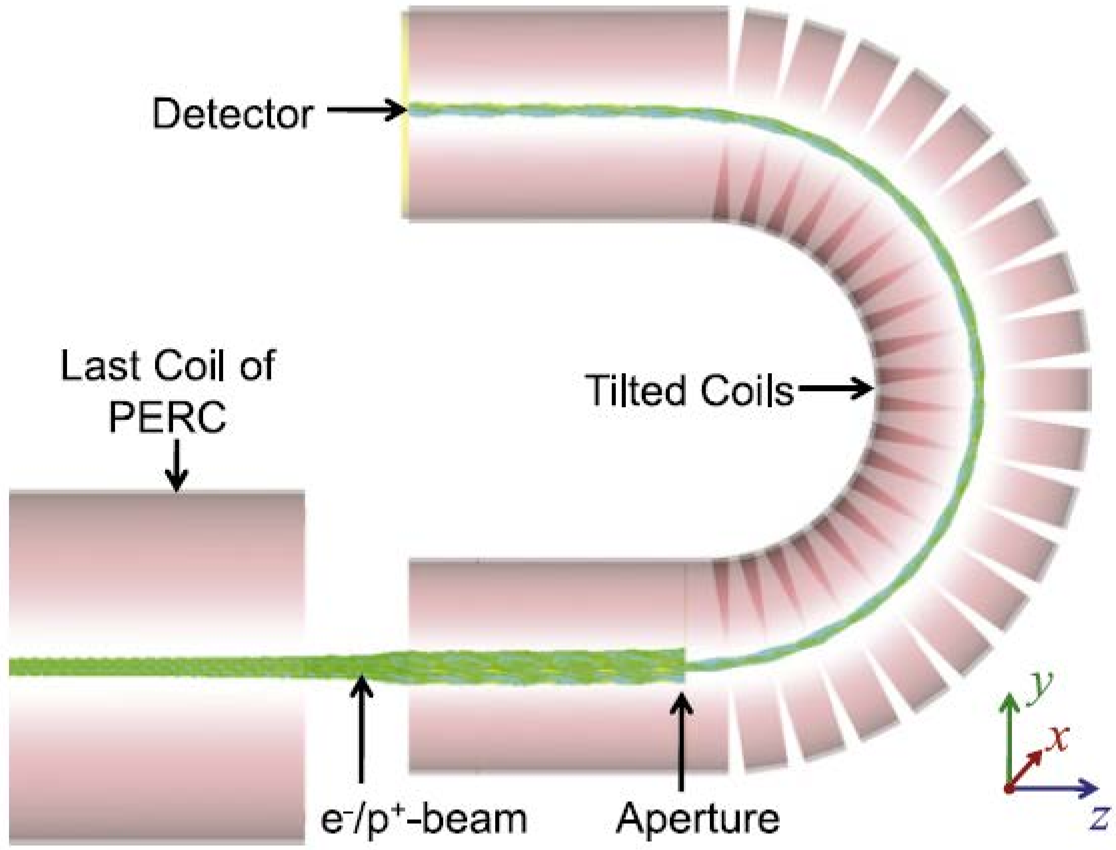
Error Budget C

TABLE I. Corrections and errors of the proton asymmetry parameter *C*. The extrapolation uncertainty contributes to the statistical and the detector calibration errors.

Effect [%]	Correction	Error
Polarization	0.30	0.10
Flip efficiency		0.10
Data set: *Statistics*		0.44
Fit region		0.35
Accidental coincidences	−0.81	0.15
Background		0.18
Detector: *Gain*		0.38
Offset		0.82
Resolution		0.12
Spectrometer: *Mirror effect*	0.01	0.06
Edge effect	0.26	0.05
Grid effect	0.08	0.05
Correlations: *A*, *B*, *a*		0.07
Sum	−0.16	1.11

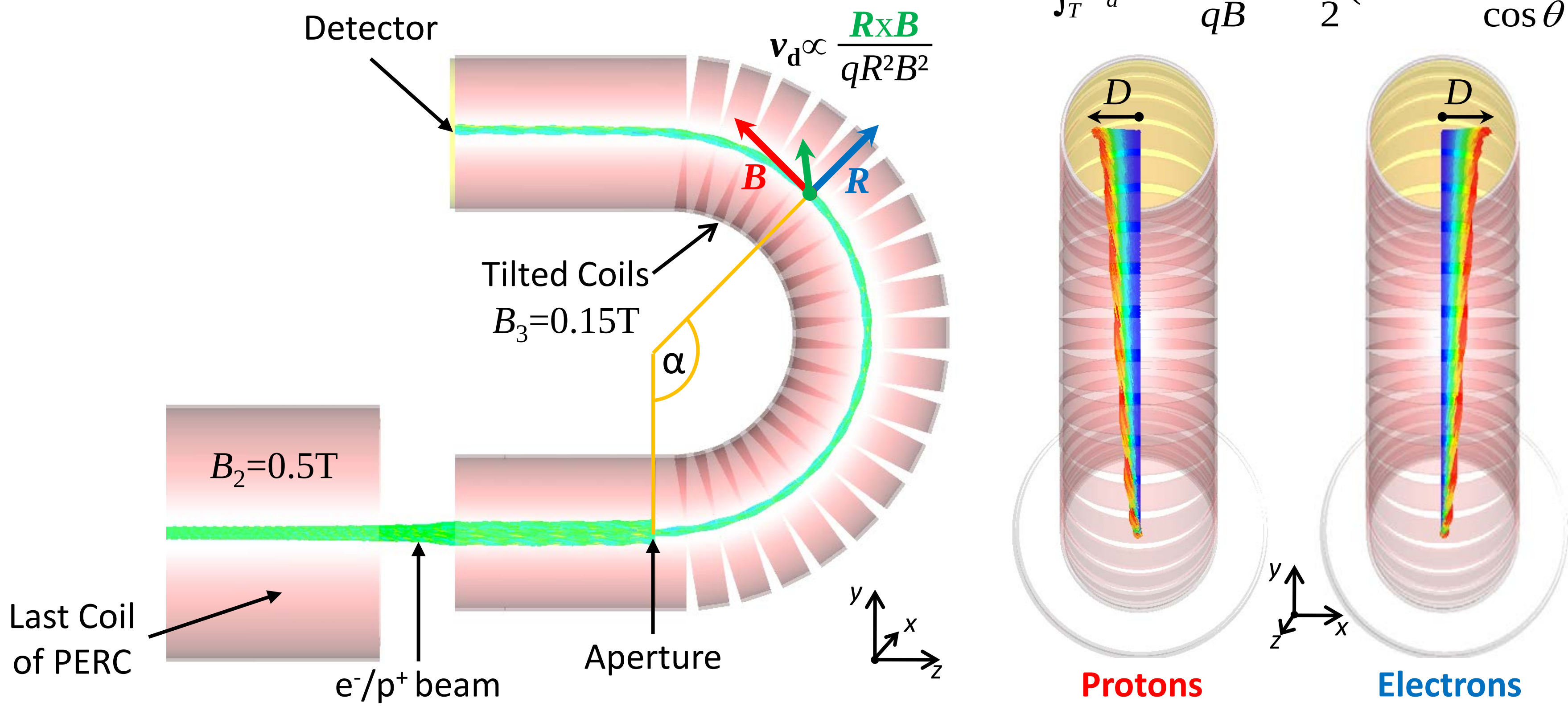
G. Konrad: R x B Spectrometer





R×B Drift Momentum Spectroscopy

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



+ Adiabatic transport of particles
+ Low momentum measurements
+ Large acceptance of θ_0
+ Small corrections for θ_0

– Small drift distances $\mathcal{O}$(cm)

Xiangzun Wang, G. Konrad *et al.*, NIM A (2012), DOI 10.1016/j.nima.2012.10.071