Workshop on
Precision Measurements at Low Energy

Neutron Decay and Neutron Oscillations

Dirk Dubbers
U. Heidelberg

A short history of unification

'Unification' in physics:
Unified description for previously disparate phenomena

century:	unification of:
17th-18th	"Himmelsmechanik" and earthly mechanics → MECHANICS
19th	Magnetism, electricity, optics, heat radiation → ELECTRODYNAMICS
	Mechanics and thermodynamics → STATISTICAL MECHANICS
20th/1:	Quantum mechanics and electrodynamics → QED
/2:	QED, weak interact., QCD → STANDARD MODEL of Particle-Physics
21st/1:	Particle physics and cosmology,
	Quantum mechanics and relativity: → ???

Standard Model of particle physics …

small input: Symmetries ('principia')

Gauge principle: $\psi'(x) = e^{i\varphi(x)}\psi(x)$
applied to U(1)×SU(2)×SU(3),
Lorentz invariance: $x' = L\cdot x$,
CPT, T, … invariance, …

rich output: Interactions:

		basis for:
→ equations of motion	Maxwell,	technology,
	Schrödinger,	chemistry,
	Dirac, …	molec. biology, …

→ existence of photons, gluons, $W^{\pm}$, Z^0 (carriers of interaction)

→ conservation of charges (sources of interaction)

…is very successful ...

… but is not complete:

Unsolved problems:

3 particle families
9 masses (+3 m_ν?)
4 quark-phases (+4 lepton-phases?) …
gravitation/relativity
baryon-asymmetry of universe
→ mass-energy content of universe …

Is there one 'unified' solution to all remaining problems ?

If so, this unification will probably take place
at extremely high energies.

"Precision measurements at low energy"

Why search then at low energy?

When an unknown process exists
at an unreachable energy scale $M \sim 10^{5\ldots19}$ GeV,
then the propagator is the same,
whether one works at 1 neV or at 10^3 GeV, and is small:
e.g. $1/(p^2+M^2) \rightarrow 1/M^2$

needed is: HIGH PRECISION,
which is highest at LOW ENERGY

Low energy: (mainly) 1st family

	quarks		leptons	
3rd:	b	t	τ	ν_τ
2nd:	s	c	μ	ν_μ
1st :	d	u	e	ν_e

first family is:

- abundant,
- long-lived,
- useful.

Precision tests of Standard Model

To test a theory needs both:

- precise theoretical predictions
- precise experimental results

Both is feasable for electroweak and for gravitational interaction

Neutron gravitational interaction:

- limits on $m_{\text{grav}} - m_{\text{inert}}$
- in neutron self-interference
- neutron quantization in gravitational field → limits on extra dimensions

Neutron electroweak interaction:

- electric properties: limits on neutron charge, neutron EDM, …
- neutron-nuclear weak interaction: → new information on strong interaction
- neutron decay: this talk

Precision reached in neutron work

- in energy: $\delta E = \pm 10^{-23}$ eV $= \pm$ 0.000 000 000 000 000 000 000 01 eV

  reached in neutron oscillations and neutron EDM

- in momentum: $\delta p/p = \pm 10^{-11}$: 1Å/10m

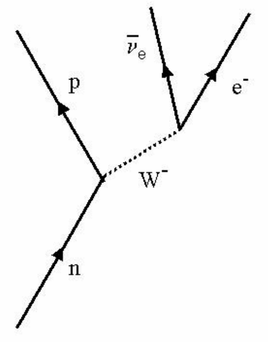
  reached in neutron charge exp't.

- in polarization: $\delta P = \pm 10^{-7}$

  reached in neutron-nuclear PNC interaction

1. Neutron β-decay

	quarks		leptons		
3rd:	b	t	τ	ν_τ	high energy physics
2nd:	s	c	μ	ν_μ	
1st :	$d \rightarrow$	$u +$	$e +$	ν'_e	neutron decay



$n \rightarrow p^+ + e^- + \nu'_e$

neutron lifetime $\tau \approx 15$ min

β-endpoint energy: $E_{max} = 782$ keV

V−A Standard Model:

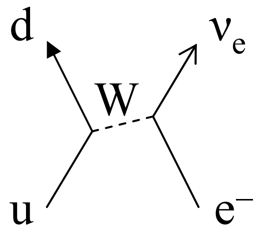
two coupling constants ($E \rightarrow 0$):

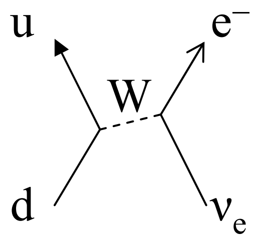
vector c.c. g_V

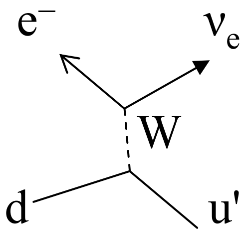
axial-vector c.c. g_A

Neutron decay data are useful

Many processes have the same Feynman diagram as neutron decay:







Primordial element formation $n + e+ \rightarrow p + \nu'_e$ $\sigma_\nu \sim 1/\tau$

(^{2}H, ^{3}He, ^{4}He, ^{7}Li, …) $p + e^- \rightarrow n + \nu_e$ $\sigma_\nu \sim 1/\tau$

$n \rightarrow p + e^- + \nu'_e$ 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.

… precision data of weak interaction parameters

today only from neutron decay ('moving target')

Only few n-decay parameters in Standard Model …

n-decay rate: $\tau^{-1} = \text{const}\,(|g_V|^2 + 3|g_A|^2)$

$$= \text{const}\; G_F^{\,2}\, |V_{ud}|^2\, (1+3|\lambda|^2)$$

with: $|g_V|^2 = G_F^{\,2}|V_{ud}|^2$ Fermi c.c. G_F from μ-decay.

At most 3 parameters needed: V_{ud}, λ, φ:

- CKM matrix element V_{ud},
- ratio of c.c. $\lambda = g_A/g_V = |\lambda|e^{i\varphi}$
- relative phase φ
  (T-symmetry: $\varphi = 180^0$)

… but many n-decay observables:

PDG 2006:

decay rate $\tau^{-1} = \text{const}\,|V_{\text{ud}}|^2(1+3\lambda^2),\ \tau = 885.7(8)\,\text{s}$ (talk S. Paul) — (re-)measured by:

e $-\,\bar{\nu}_{\text{e}}$ − correl.: $a = \dfrac{1-\lambda^2}{1+3\lambda^2} = -0.103(4)$ (talk N. Severijns) — *a*SPECT

β − asymmetry: $A = -2\dfrac{\lambda(\lambda+1)}{1+3\lambda^2} = -0.1173(13)$ sensitive to λ, rhc phase ς

$\bar{\nu}_{\text{e}}$ − asymmetry: $B = 2\dfrac{\lambda(\lambda-1)}{1+3\lambda^2} = 0.981(4)$ sensitive to mass of W_{R} — PERKEO

p − asymmetry: $C = 0.2748\dfrac{4\lambda}{1+3\lambda^2} = -0.238(11)$

triple correlations: $D = -2\dfrac{\lambda\sin\varphi}{1+3\lambda^2} = -4(6)\cdot 10^{-4}$ T - viol. — TRINE

$R = \ldots,$ etc. T - viol. (talk N. Severijns)

problem is overdetermined:

many tests of Standard Model possible

Therefore many derived quantities …

Standard model parameters:

axial to vector coupling c.c.	$\lambda = g_A / g_V$ from β-asymmetry A (or a)
CKM- matrix element $\lvert V_{ud} \rvert$ from:	$\lvert V_{ud} \rvert^2 = \dfrac{(4908.7 \pm 1.9)\,\mathrm{sec}}{\tau \cdot (1+3\lambda^2)}$
unitarity test of CKM-matrix	$\Delta = V_{ud}{}^2 + V_{us}{}^2 + V_{ub}{}^2 - 1 = 0$?
phase between g_A and g_V:	$\varphi = 180.06(7)^0$
i.e.	$e^{i\varphi} = -1$ (T-symmetric V−A)
weak magnetism, …	

further derived quantities:

all ν-p, ... weak cross-sections	$\sigma_{\nu p}/E_\nu = 0.67 \cdot 10^{-38}\ \mathrm{cm}^2/\mathrm{GeV}$
number of ν-families	$N_\nu = 2.5 \pm 0.6$
baryonic matter in universe	$\rho/\rho_{crit} = (3.3 \pm 0.7)\ \%$

… more derived quantities

beyond Standard model:

mass of right-handed boson	$m(\mathrm{W_R}) > 300\ \mathrm{GeV/c^2}$ (90% c.l.)
left-right mixing angle	$-0.20 < \zeta < 0.07$ (90% c.l.)
scalar weak interaction amplitudes	g_S
tensor weak interaction amplitudes	g_T
Fiertz interference amplitude	b
second class amplitudes	

neutrino helicity < 1? (semileptonic decays)

… and others

Aim: measure all these parameters to the highest precision possible !

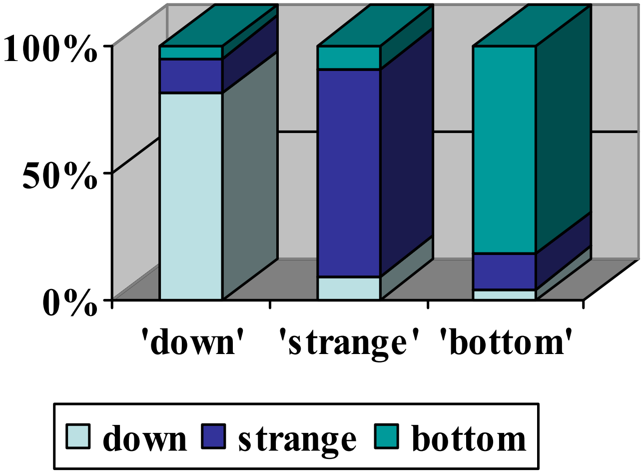
CKM quark mixing

μ-decay: $\sim G_F^2$

n-decay: $\sim 0.95 \cdot G_F^2 = \cos^2\theta_C \cdot G_F^2$ (ΔS=0), strangeness S

K-decay: $\sim 0.05 \cdot G_F^2 = \sin^2\theta_C \cdot G_F^2$ (ΔS=1), Cabbibo angle θ_C

three generation Standard Model:
under the weak interaction,
quarks are not the usual quarks, but:



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

↑weak eigenstates ↑mass eigenstates

quark mixing is pure rotation in flavor space ('zero-sum game'),
Cabbibo-Kabojashi-Maskawa quark mixing matrix is unitary

$|V_{ud}|$ from neutron decay

from $\tau^{-1} = \mathrm{const}\ G_F^2\ |V_{ud}|^2\ (1+3|\lambda|^2)$:

$$|V_{ud}|^2 = \frac{(4908 \pm 4)\,\mathrm{sec}}{\tau \cdot (1+3\lambda^2)}$$

i.e. two measurements needed: τ and λ

History of neutron lifetime

PDG:

- neutrons 'in-beam': 1960: $\tau = (1010 \pm 30)$ s
  1982: $\tau = (925 \pm 11)$ s
- stored UCN: 1989: $\tau = (888 \pm 3)$ s

PDG since 2002: $\tau = (885.7 \pm 0.8)$ s

2005: $\tau = (878.5 \pm 0.8)$ s ?

History of $\lambda = g_A/g_V$

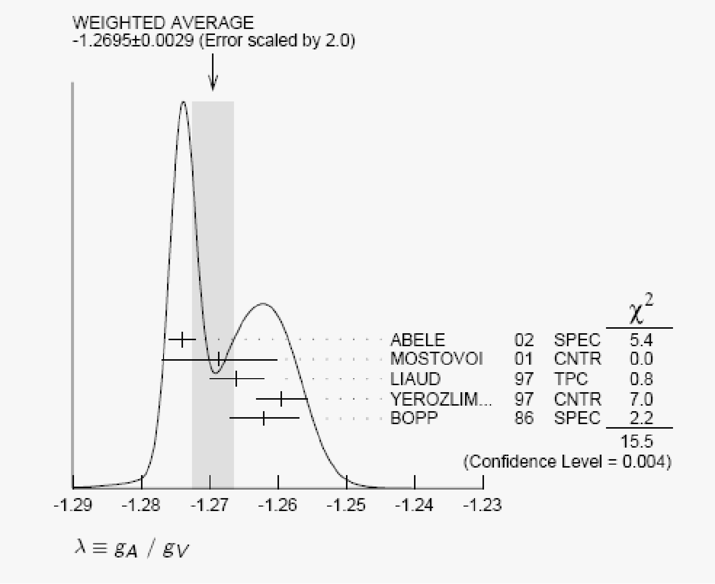
PDG: from β-asymmetry *A* in neutron-decay:

1960: $\lambda = -1.19(2)$

1975: $\lambda = -1.25(2)$

1994: $\lambda = -1.261(4)$ syst. corrections: >15%

PDG since 2002: $\lambda = -1.270(3)$ syst. corrections: $5\cdot 10^{-3}$



Is the unitarity of the CKM matrix violated in neutron β-decay?

H. Abele et al., PRL 88, 211801 (2002)

CKM-Unitarity of first row:

$$|V_{ud}|^2 + |V_{us}|^2 + \underset{\uparrow 0.0000}{|V_{ub}|^2} = 1 - \Delta$$

$$\approx \cos^2\theta_C + \sin^2\theta_C$$

Standard Model: unitarity, i.e. $\Delta = 0$

Using the world average of neutron lifetime: $\tau = 885.7(7)$ s,

almost all error came from $\lambda = g_A/g_V$.

λ from new measurement of β-asymmetry: $A = -\dfrac{2\lambda(\lambda+1)}{1+3\lambda^2} \cong -0.1189(7)$

Deviation from unitarity (Perkeo)

from: $A = -0.1189(7)$

→ $\lambda = g_A/g_V = -1.2739(9)$

→ $|V_{ud}| = 0.9713(13)$ neutron

in detail: $= 0.9717\ (4)_\tau\ (12)_\lambda\ (4)_{\mathrm{rad.corr.}}$

↑ culprit?

with : $|V_{us}| = 0.2196(23)$ Kaon

$|V_{ub}| = 0.0036(9)$ B-meson (PDG 2002)

$\Delta = |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 - 1$:

$\Delta = 0.0084 \pm 0.0028$

3σ deviation from zero (PERKEO 2002)

Similar results from other β-decays:

H. Abele, E. Barberio, D.Dubbers, F. Glück, J.C. Hardy,
W.J. Marciano, A. Serebrov, N. Severijns, Eur. Phys. J. C33, 1 (2004)

$\|V_{ud}\| = 0.9717 \pm 0.0013$	neutron
$\|V_{ud}\| = 0.9738 \pm 0.0004$	$0^+ \rightarrow 0^+$ nuclei
$\|V_{ud}\| = 0.9728 \pm 0.0030$	pion

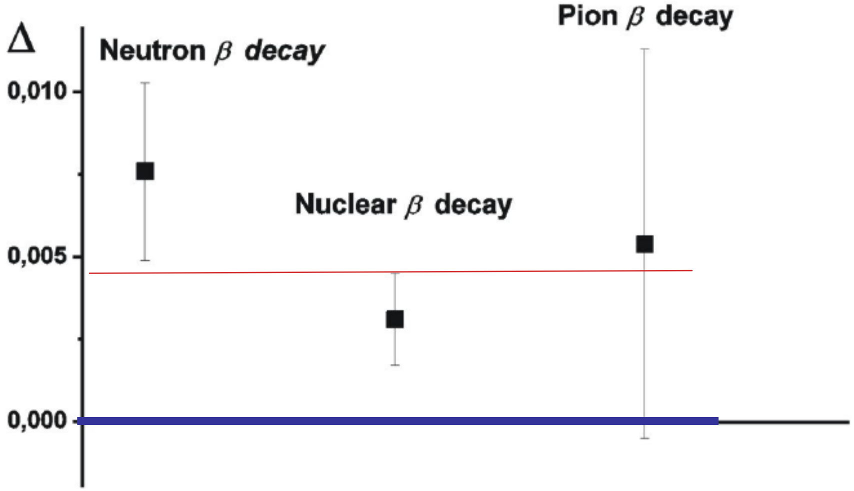
PDG 2004:

combined: $\Delta = 0.0040 \pm 0.0012$ (all V_{ud})

if $\Delta \neq 0$ is due to right-handed currents:

phase $\zeta = 0.0020 \pm 0.0006$

Standard Model →



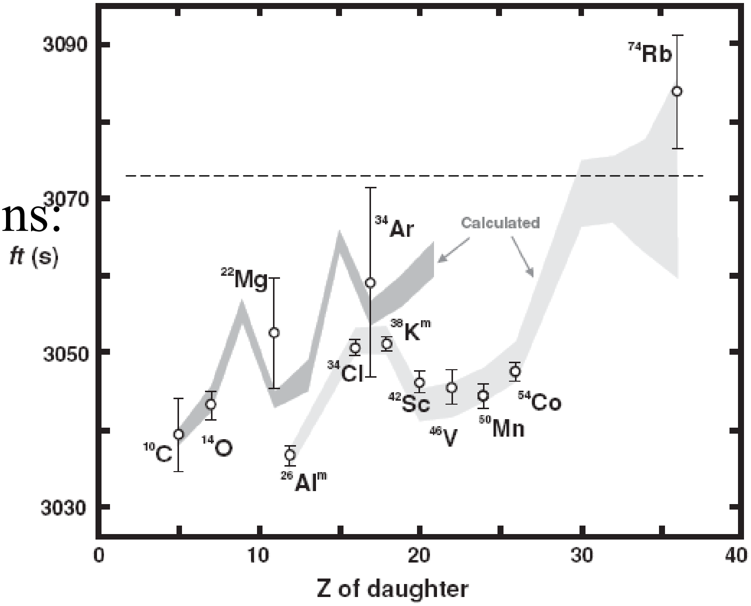
Nuclear super-allowed $0^+ \rightarrow 0^+$ β-transitions

$$ft = \frac{K}{G_F^2 \left|V_{\mathrm{ud}}\right|^2}$$

(plus corrections)
with half life t,
phase space factor f

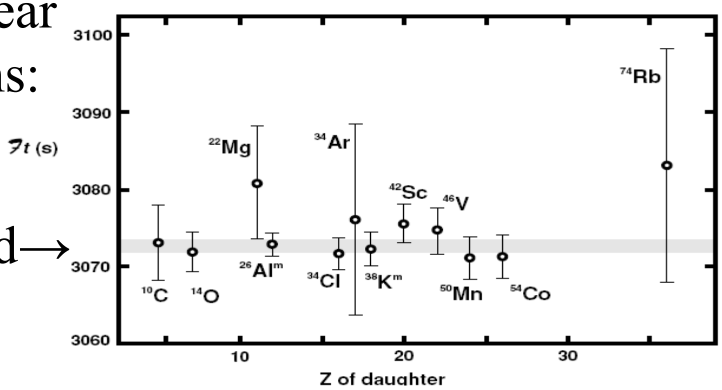
J.C. Hardy, I.S. Towner,
PR C 71, 055501 (2005)

before nuclear corrections:



after nuclear corrections:

1σ band→



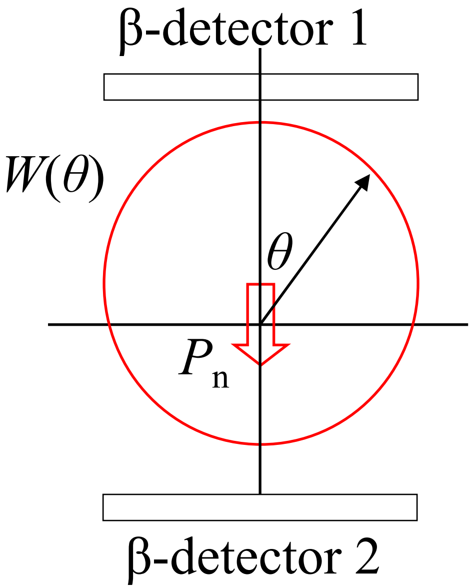
(from > 100 measurements)

β-asymmetry *A* in polarized neutron-decay

angular distribution of electrons (Wu-exp't.):

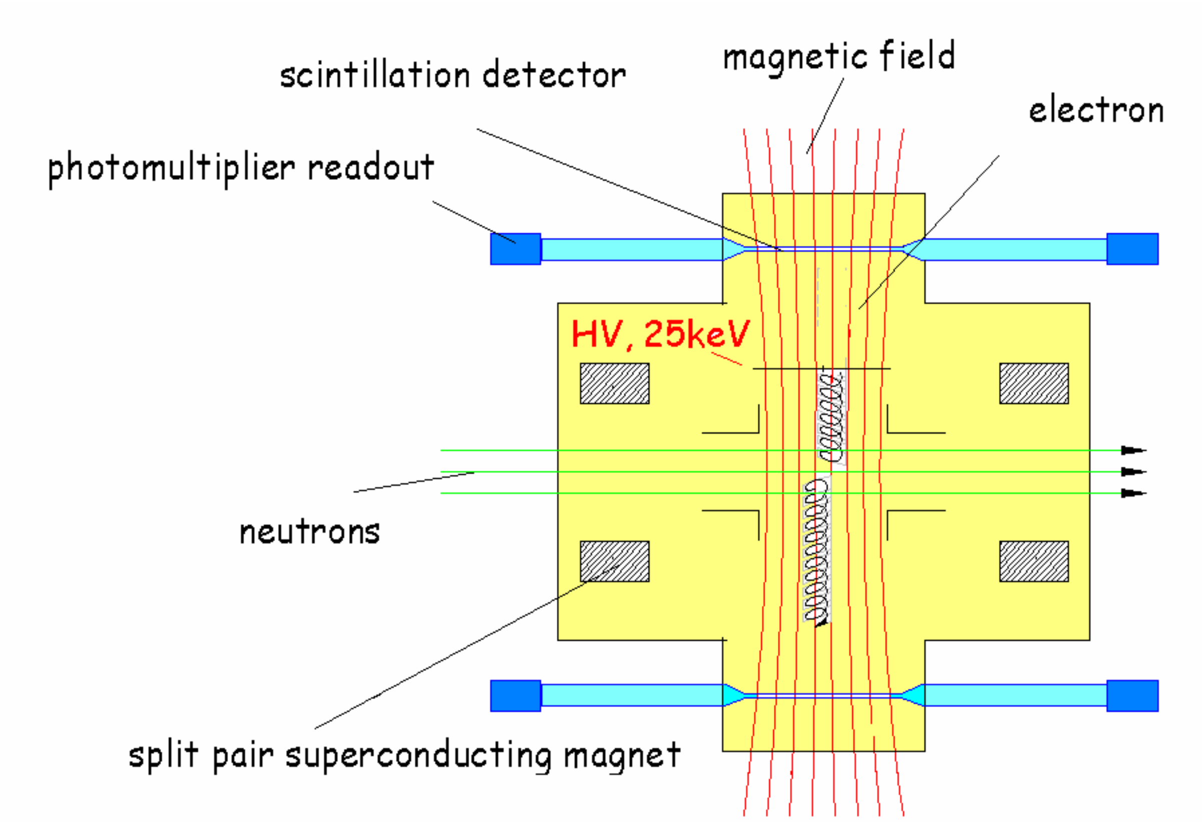
$$W_\beta(\theta) = 1 + \frac{\upsilon_\beta}{c} A P_\mathrm{n} \cos\theta$$

polarized cold neutron beam →



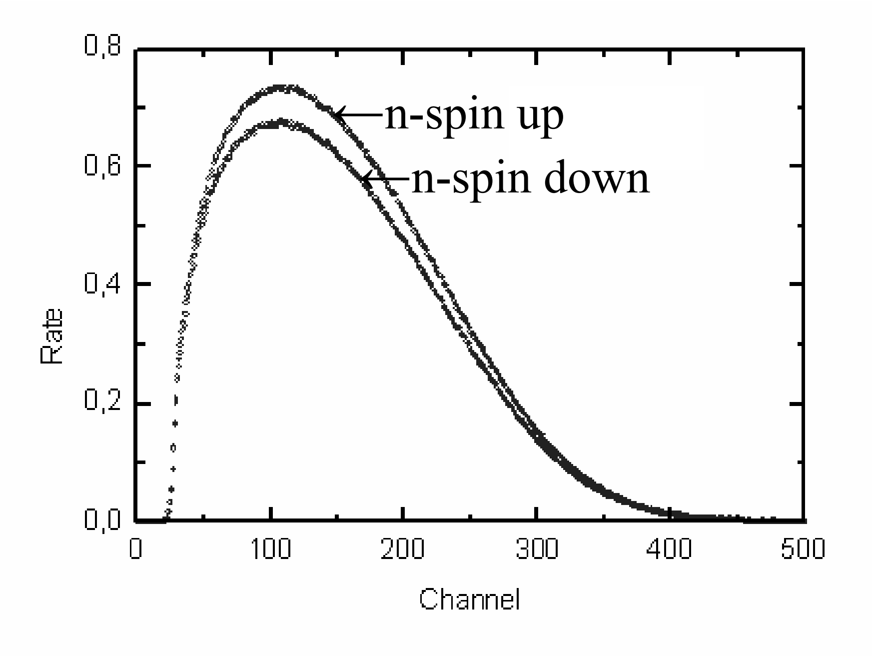
n-flux $\Phi_\mathrm{n} \sim 10^9\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
n-temperature $T_\mathrm{n} \sim 30\mathrm{K}$
n-polarization $P_\mathrm{n} = 0.997(1)$

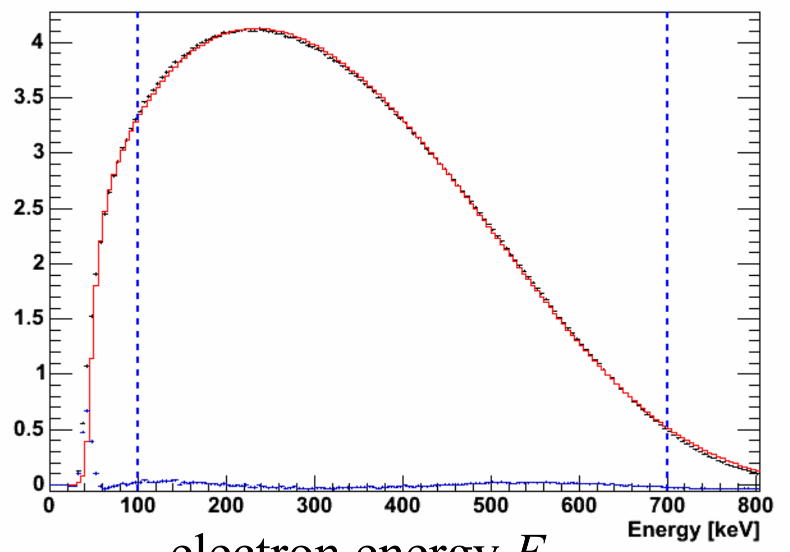
The PERKEO neutron decay spectrometer



measured: β-asymmetry *A*
ν_e'-asymmetry *B*
proton asymmetry *C*

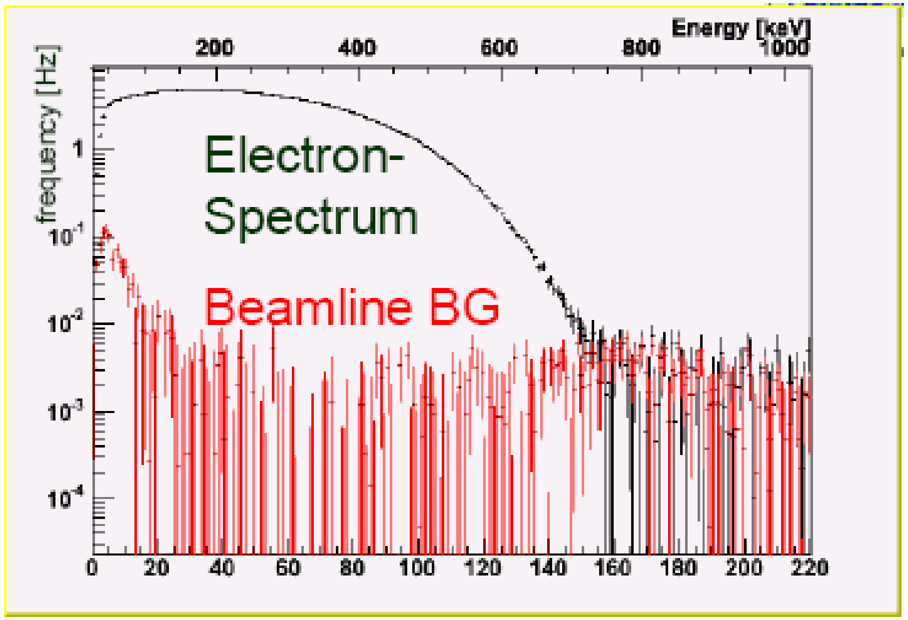
β-energy spectra





electron energy E_β

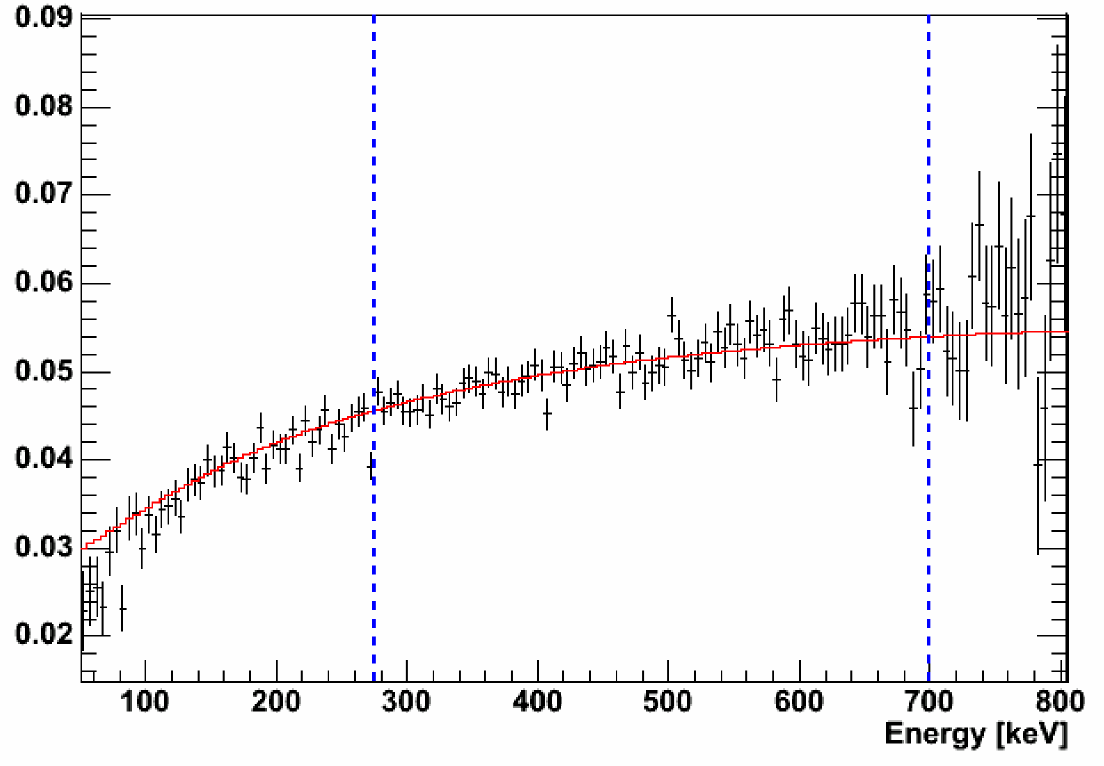
Beam related background



in-beam: 1 of 10^7 neutrons decay in spectrometer;
uncompensated background $< 10^{-3}$

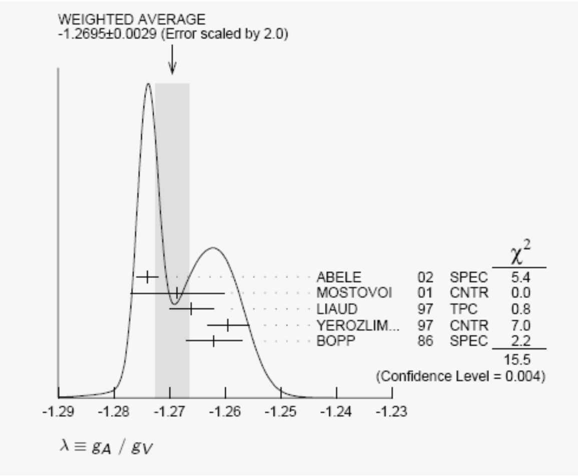
β-asymmetry *A*:

$\frac{1}{2}(v_\beta/c)\, A$



electron energy E_β

New Perkeo results (prelim.)



Abele-group

β-asymmetry:

PDG 2006 (≈2002): $A = -0.1173(13) \rightarrow \lambda = -1.270(3)$

PERKEO 2002: $A = -0.1189(7) \rightarrow \lambda = -1.274(2)$

system. corr.: $5 \cdot 10^{-3}$

PERKEO 2006: $A = -0.1195(4) \rightarrow \lambda = -1.275(1)$ reconfirmed

system. corr.: $1 \cdot 10^{-3}$ thesis Mund 2006 error: statistics domin.

ν-asymmetry:

old world average: $B = 0.981(4)$ dominated by Serebrov et al. (1998)

PERKEO: $B = 0.983(5)$ thesis Schumann 2007

proton-asymmetry $C = -0.238(11)$ thesis Kreuz 2004

$C = -0.239(3)$ thesis Schumann 2007

New neutron lifetime

$\tau = (878.5 \pm 0.8)$ Serebrov et al. (2005)

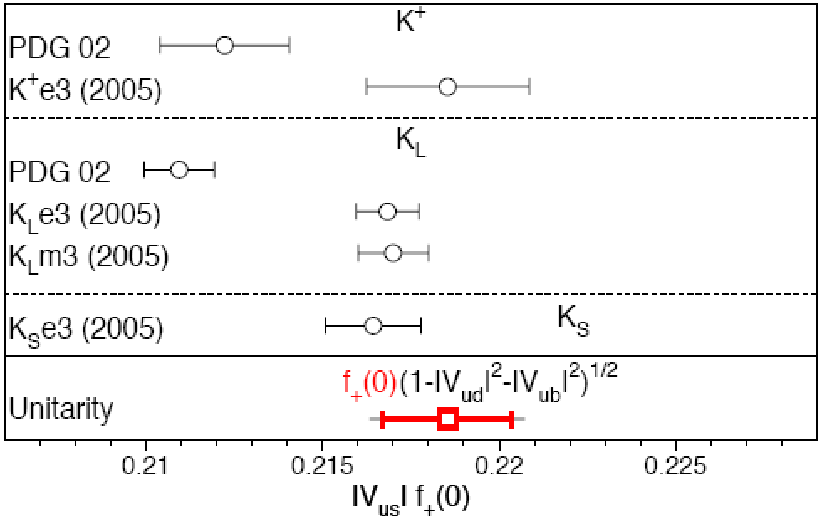
reestablishes unitarity when using old V_{us}

and fits better to cosmology (confirms n_B/n_γ from CMB)

New V_{us} value

= by-product of ε'/ε-analysis:

2002↓ ↓2005



B.R. $K_L \rightarrow \pi\, e\, \nu, \pi\, \mu\, \nu$

New CKM element V_{us} reestablishes unitarity when using old τ_n:

PDG 2006, all measurements: $\Delta = 0.0008\ (5)_{ud}\ (9)_{us}$

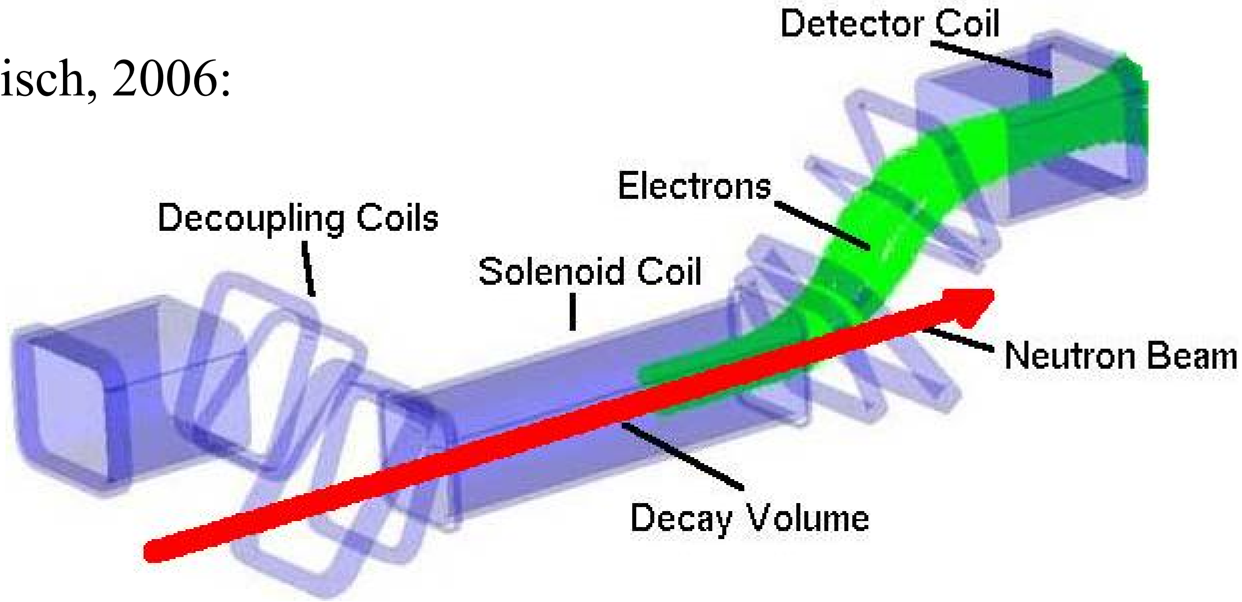
Serebrov, neutron: short τ, high λ: $\Delta = -0.0038\ (28)$

- still clarification needed.

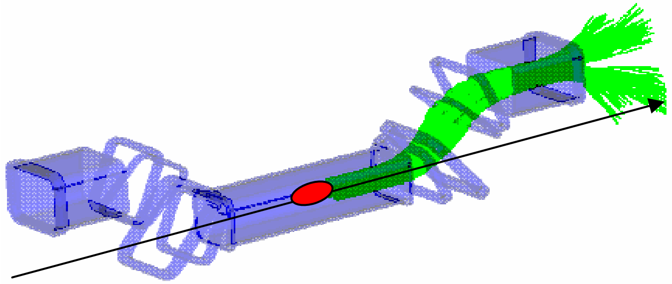
Other strategy: assume unitarity to hold → strong-interaction physics

New Perkeo instrument

thesis B. Märkisch, 2006:



later:



PERKEO 3
November 2006
ILL, GRENOBLE

count rate:

25 000 n-decays/sec.

= 100 × PERKEO 2

First measurement:

weak magnetism in n-decay

$\sim \mu_n - \mu_p$

(~ 1% effect in β-asymmetry)

far future:

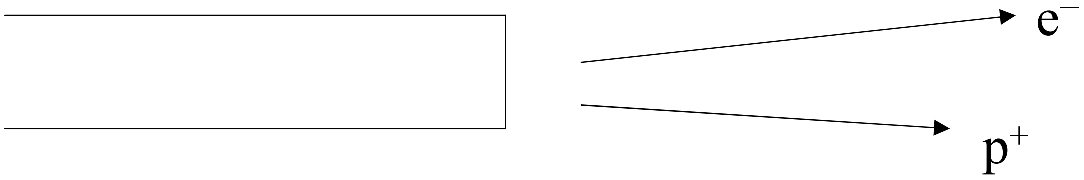
PERC = strong source of n-decay products …

conventional neutron beam line:

neutron guide

cold neutrons

PERC = proton-electron radiation channel:

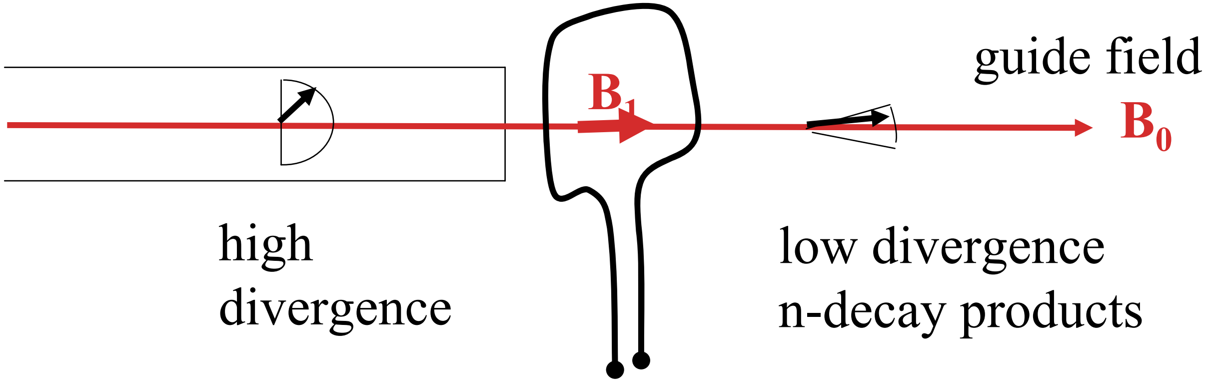


neutron guide

neutron decay products

10^6 neutron decays per meter of guide

… of variable beam divergence:



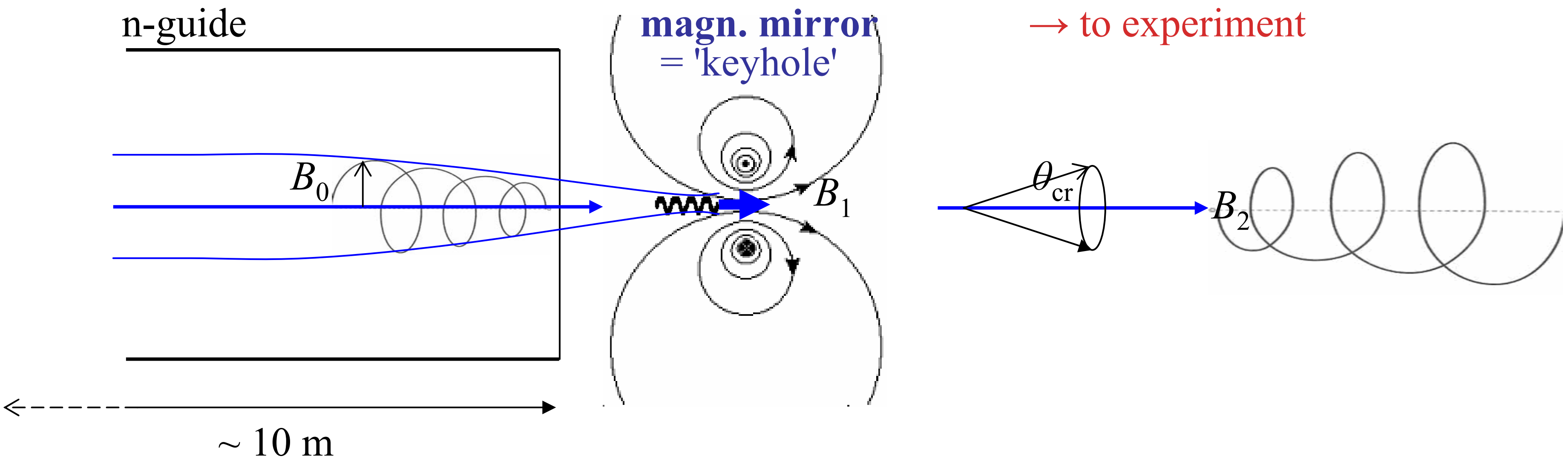
guide field

high
divergence

magnetic
mirror field

low divergence
n-decay products

Decay products pass through 'keyhole':



n-guide

magn. mirror
= 'keyhole'

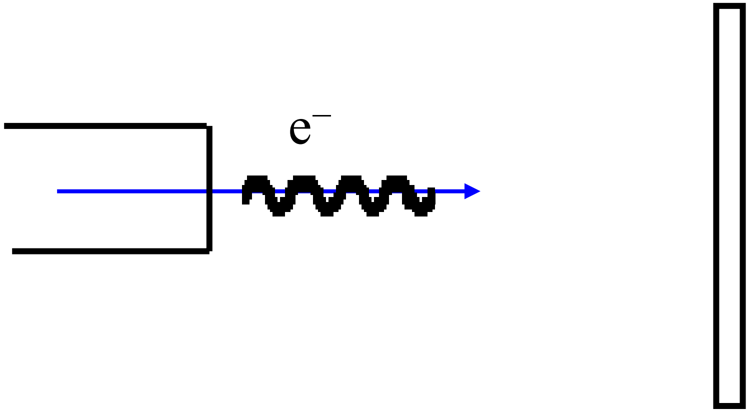
→ to experiment

~ 10 m

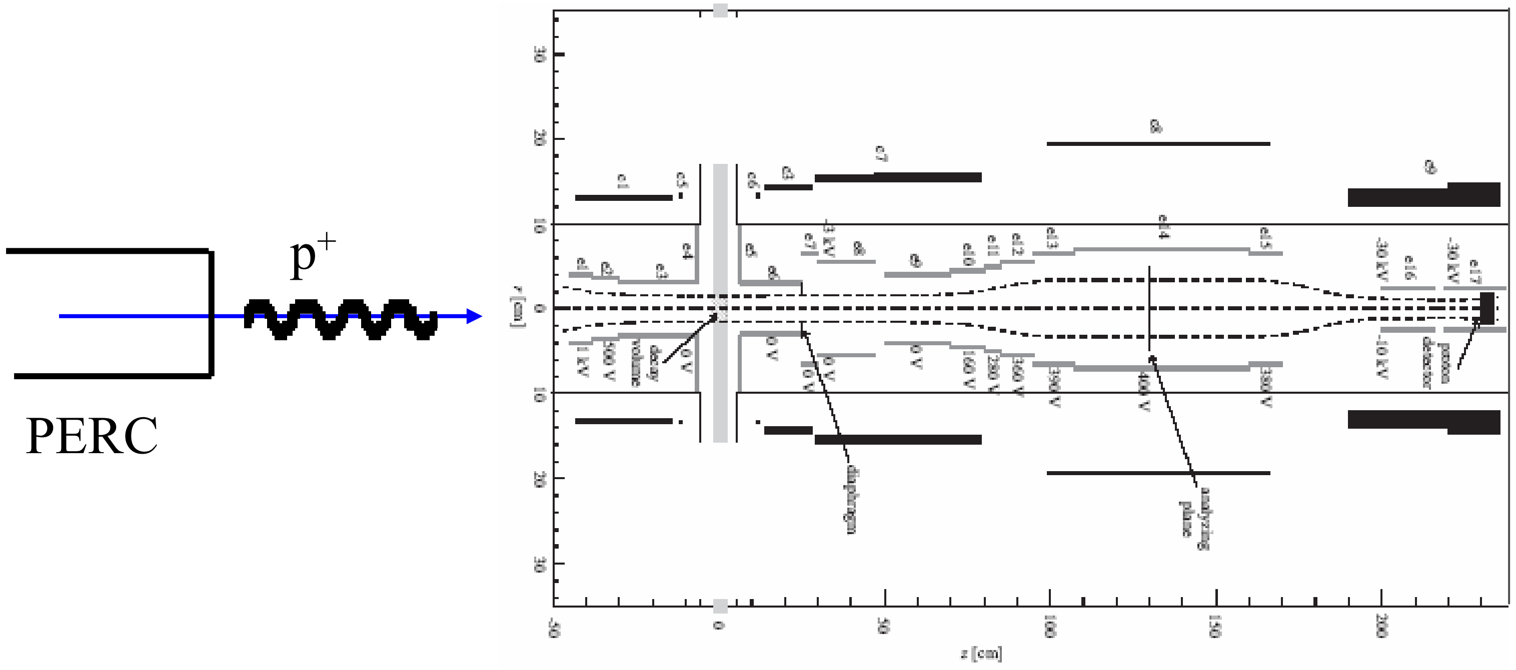
example:

magnetic field:	2 Tesla	8 Tesla	½ Tesla
gyration radius:	2 mm	½ mm	4 mm
critical angle:	30^0	90^0	15^0

PERC + Perkeo detector

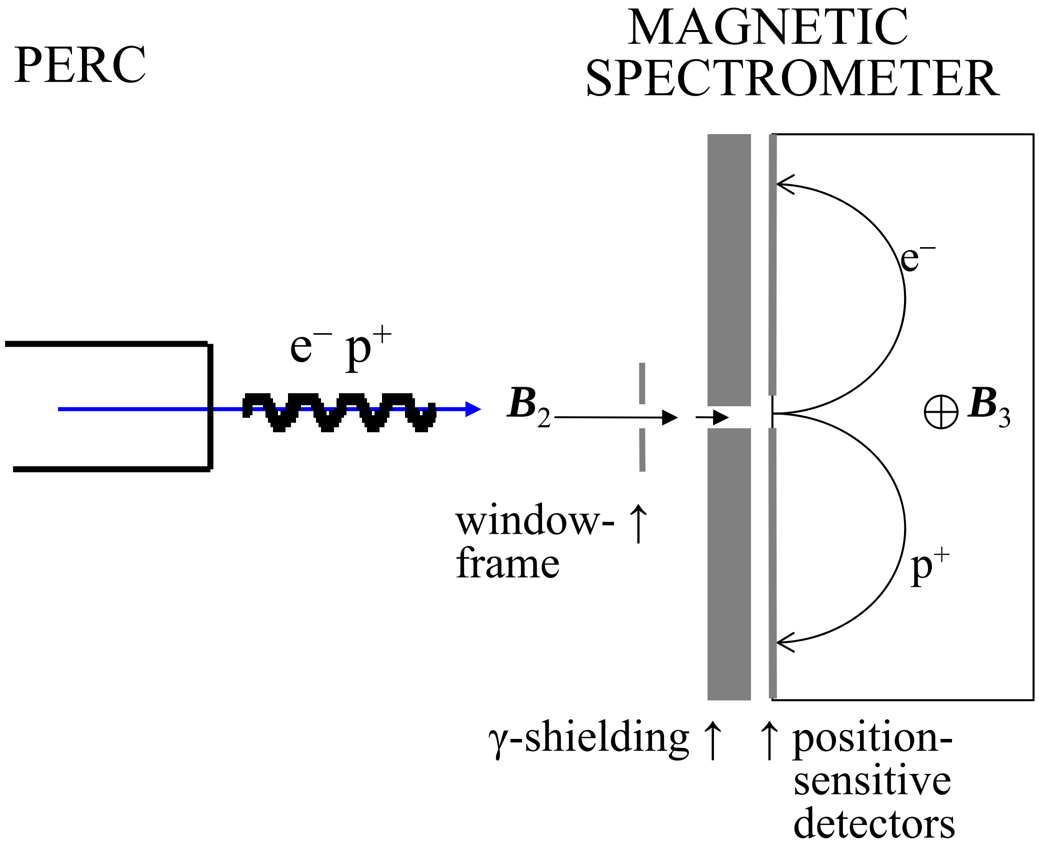


PERC + *a*SPECT retardation spectrometer:

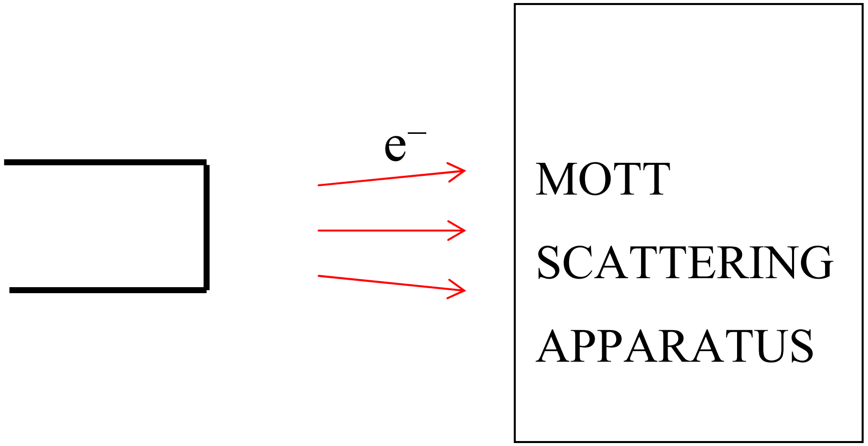


↑ aSPECT

PERC + magnetic p^+, e^- spectrometer:



PERC + Mott scattering device



MOTT

SCATTERING

APPARATUS

test of electron helicity $H_e \sim v_e/c$ in hadron decay

Observables accessible with PERC:

electron and proton spectra N_e, N_p
electron-neutrino correl. coeff. a

beta-asymmetry	A
neutrino-asymmetry	B
proton-asymmetry	C
Fierz interference	b
electron helicity	H_β
helicity-related correl. coeff.	

all in dependence of energy E_β, E_p
or of momentum p_β, p_p or TOF_p

aim: n-decay correlation coefficients to $\sim 10^{-4}$ rel. error
(today: $\sim 10^{-3}$)

2. Neutron oscillations

a) neutron-antineutron oscillations

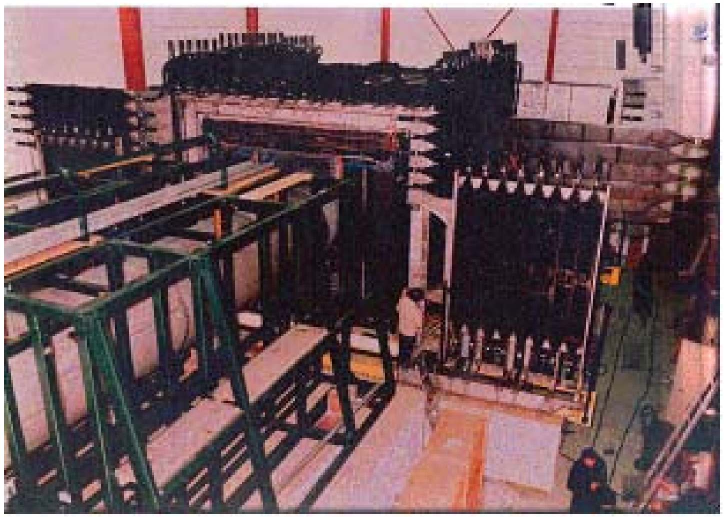
Neutrinos oscillate:	$\nu_e \leftrightarrow \nu_\mu$, etc.	$\Delta m \cdot c^2$:
Lepton number oscillations	$L_e \leftrightarrow L_\mu$, etc.	= 0.05 eV
Kaons oscillate:	$K \leftrightarrow K'$	
Strangeness oscillations	$S \leftrightarrow - S$	= 10^{-18} eV
Do neutrons oscillate?	n ↔ nbar	
Baryon-number oscillations	$B \leftrightarrow - B$	?

Neutron oscillations allowed in various Grand-Unified Theories

The ILL neutron oscillation experiment

The magnetically shielded beam <5nT

The antineutron detector



'Appearence experiment':

Experimental limit $\tau_{\text{n nbar}} > 0.86 \cdot 10^8$ s (90% c.l.)

👎m≺c^2 = <n✿H✿nbar> 🖫 10^{-23} eV

probes 10^5 GeV range (model dependent)

Heidelberg-ILL-Padova-Pavia collaboration (M. Baldo-Ceolin et al., 1994)

b) neutron – mirror-neutron oscillations

is there a sterile mirror world?

Mohapatra, 2005: $n \leftrightarrow n_{\text{mirror}}$

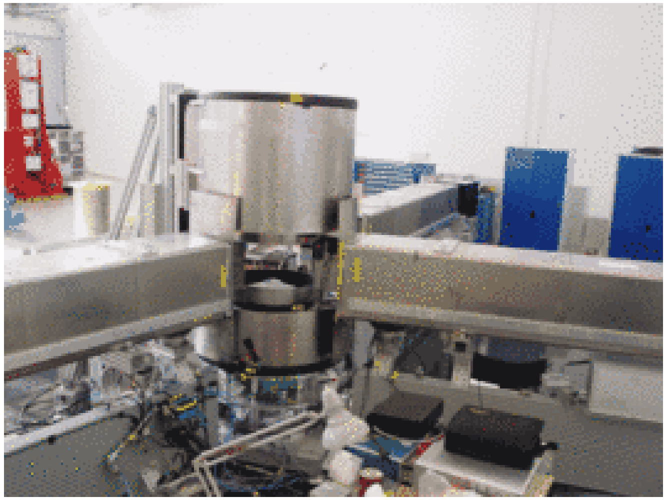
can neutrons spontaneously disappear into sterile,

i.e. unobservable mirror neutrons?

Experiment: U. Schmidt, thesis B. Böhm, 2007:

using zero-field spin-echo apparatus at FRM2, developed by U. Schmidt et al.

and ultrafast 'CASCADE' n-detector, developed by M. Klein, Chr. Schmidt



'disappearence experiment':

experimental limit:

rate $(\tau_{\text{n-nmirror}})^{-1} > 2.7\ \text{s}^{-1}$ (90% c.l.)

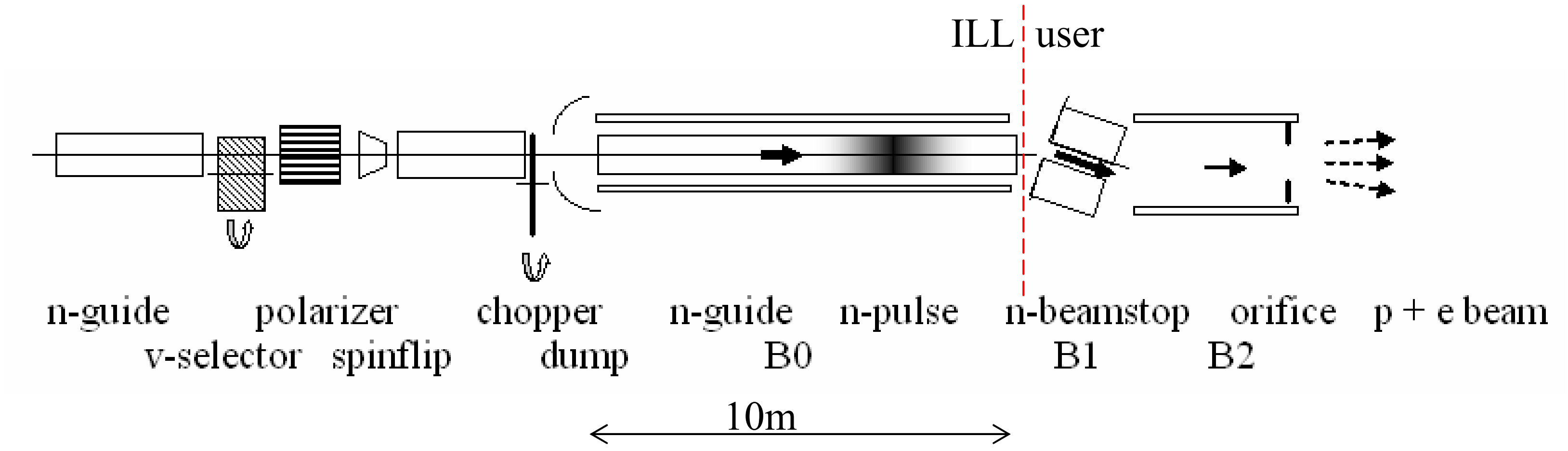
Summary

'Precision Measurements at Low Energy':

Physics very far beyond the Standard Model is best tested:
at low energy in the first family, where precision is highest;
in the electroweak or gravitational sector, where reliable predictions exist.

In neutron decay (as elsewhere) there is still a lot of homework to do.

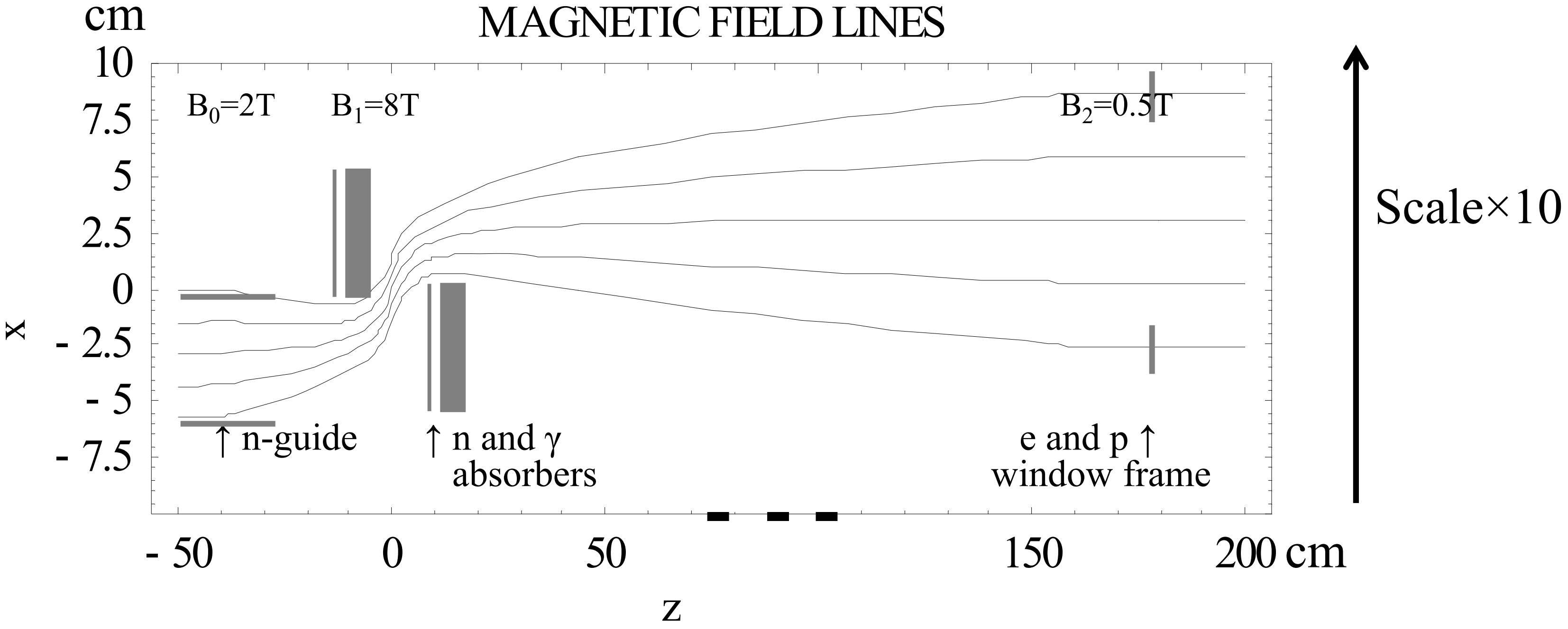
PERC details



PERC neutron beamstop:

Charged neutron decay products can be guided anywhere (electro-)magnetically

Example:

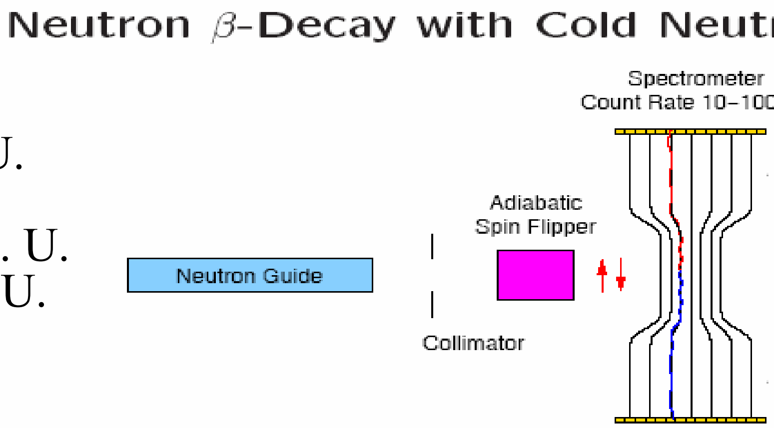


Competitors: Neutrons

Europe: by far strongest continuous neutron sources;
leading in neutron-particle physics
US: strong new effort
but: SNS has much weaker continuous neutron beams

"Fundamental neutron physics-instrument development team":

Argonne NL
Arizona State U.
BARC
Cal-Tech
Depauw U.
Duke U.
Harvard U.
Indiana U.
Jefferson Lab.
KEK
Kentucky U.
Los Alamos NL
Maryland U.
Michigan U.
New Hampshire U.
NIST
N.-Carolina Centr. U.
N.-Carolina State U.
Oak Ridge NL
South Carolina U.
Tennessee U.
Tulane U.
Virginia U.
Washington U.
Yale U.



≈ old PERKEO

Defense of a leading position in a field of high visibility.

Finance (DOE): 26 M$