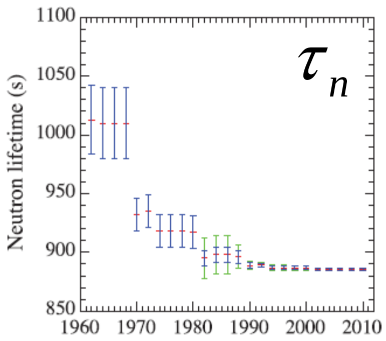
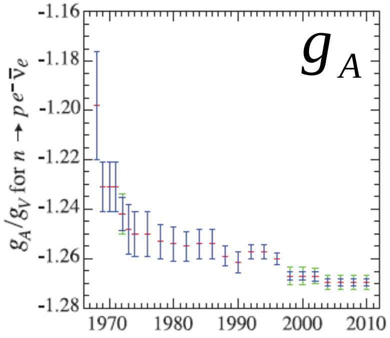
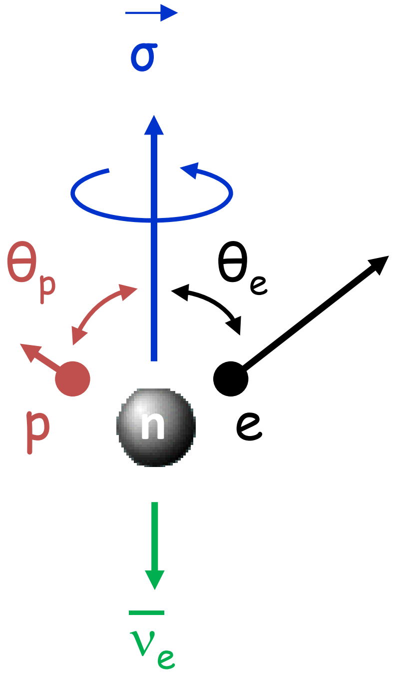
High-Precision Measurements of g_A and g_V in Neutron and Nuclear β-Decay

Brad Plaster, University of Kentucky





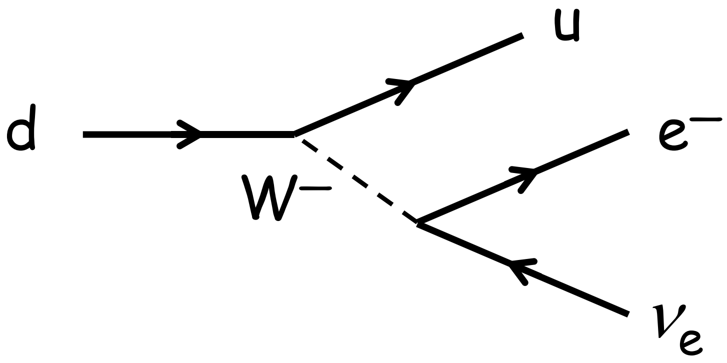


$$V_{\rm CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

FNAL Project X Physics Study

June 16, 2012

Neutron β-decay form factors



$$\mathcal{M} = \frac{G_F V_{ud}}{\sqrt{2}} \langle p | J^\mu | n \rangle L_\mu$$

$$\langle p | J^\mu | n \rangle = \overline{u}_p \left[g_V(q^2)\gamma^\mu - i\frac{g_{WM}(q^2)}{2M}\sigma^{\mu\nu}q_\nu + \frac{g_S(q^2)}{2M}q^\mu + g_A(q^2)\gamma^\mu\gamma^5 - i\frac{g_T(q^2)}{2M}\sigma^{\mu\nu}\gamma_5 q_\nu + \frac{g_P(q^2)}{M}\gamma_5 q^\mu \right] u_n$$

$g_V = g_V(0) = 1$ [CVC]

$g_A = g_A(0)$

$g_{WM}(0) = \kappa_p - \kappa_n$ [CVC]

g_P negligible

SCC g_S, $g_T = 0$ under G-parity

[but broken in SM by isospin-symmetry breaking]

Experiments probe :

$G_A = G_F V_{ud} g_A$

$G_V = G_F V_{ud} g_V$

Neutron β-decay observables

Lifetime :

$$\frac{1}{\tau_n} = \frac{G_F^2 m_e^5}{2\pi^3\hbar}\left|V_{ud}^2\right|\left(1+3\lambda^2\right) f\,\underbrace{\left(1+\mathrm{RC}\right)}_{= 1.0390(4)}$$

$$\lambda \equiv \frac{G_A}{G_V} = \frac{g_A}{g_V}$$

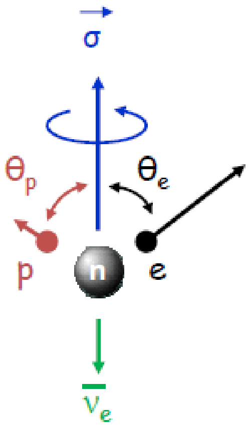
[Czarnecki et al. (2004)]

[Marciano and Sirlin (2006)]

Correlation coefficients :

[Jackson, Treiman, Wyld (1957)]

$$\frac{dW}{d\Omega_e d\Omega_\nu dE_e} \propto p_e E_e (E_0 - E_e)^2 \left[1 + a\frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + b\frac{m_e}{E_e} + \left\langle \frac{\vec{J}_n}{J_n} \right\rangle \cdot \left(A\frac{\vec{p}_e}{E_e} + B\frac{\vec{p}_\nu}{E_\nu} + D\frac{\vec{p}_e \times \vec{p}_\nu}{E_e E_\nu} \right)\right]$$



T_0 = 782 keV

T_p ~ 750 eV

$$a_0 = \frac{1-\lambda^2}{1+3\lambda^2}$$

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

$$B_0 = 2\frac{\lambda(\lambda-1)}{1+3\lambda^2}$$

→ A_0 greatest sensitivity to λ

[and most straightforward to measure]

b, D sensitive to beyond SM physics

[beyond recoil-order]

Recoil-order terms : Holstein (1974) Gudkov et al. (2006)
Harrington (1960) Gardner and Zhang (2001) Bhattacharya et al. (2012)

Nuclear β-decay observables

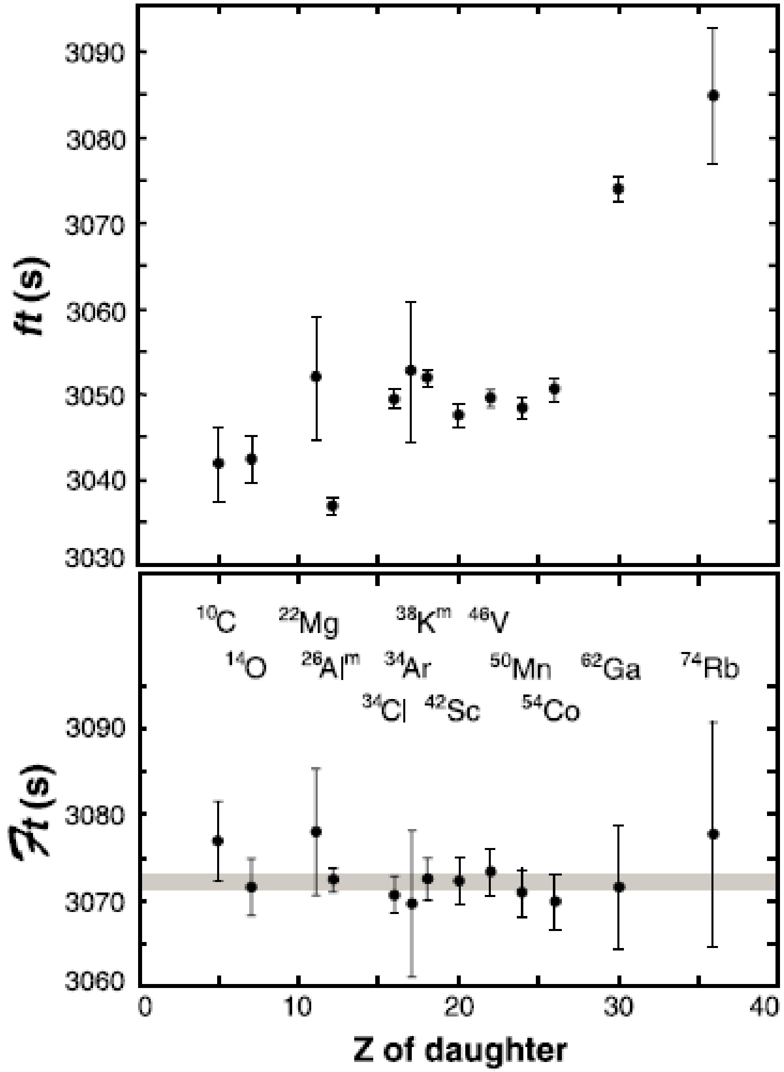
<u>Superallowed 0⁺ -> 0⁺ ft values</u> :

Experimental observables :
- half-life
- branching ratio
- Q-value

↓

$$\mathcal{F}t = ft(1+\delta'_{\mathrm{R}})(1+\delta_{\mathrm{NS}}-\delta_{\mathrm{C}})$$
$$= \underbrace{\frac{\pi^3 \ln 2}{m_e^5 G_F^2 \, g_V^2 V_{ud}^2} \, \frac{1}{(1+\Delta_R^V)}}$$

CVC: $g_V = 1$,
independent of medium



$\chi^2/\nu = 0.29$ [Saxon-Woods]
$\chi^2/\nu = 0.93$ [Hartree-Fock]
} CVC

Hardy and Towner (2009)
Towner and Hardy (2010)

V_{ud} from nuclear β-decay

Assuming CVC, $g_V = 1$:

$$|V_{ud}|^2 = 0.94916 \pm \underset{\text{exp't}}{0.00016} \pm \underset{\Delta_R^V}{0.00035} \pm \underset{\delta_C,\ \delta_{NS}}{0.00020} \pm \underset{\delta'_R}{0.00004}$$

Experimental error below theoretical error

Significant effort on testing validity of δ_C, δ_{NS} corrections

[e.g., Melconian (2011, 2012)]

CKM unitarity satisfied at present, using $g_V = 1$ nuclear β-decay V_{ud} and V_{us} : 0.9999 ± 0.0004 ± 0.0004

Experimentalist question to theorists : Are there prospects for reducing the error on Δ_R^V ?

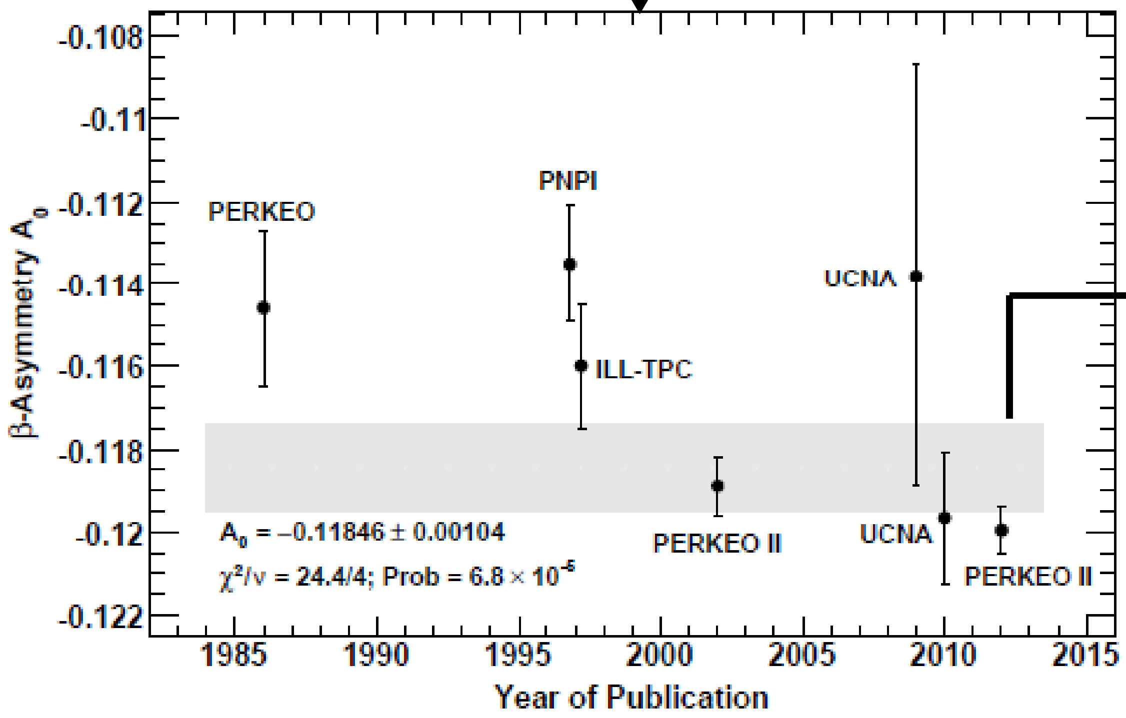
Hardy and Towner (2009)
Towner and Hardy (2010)

Status of neutron β-decay: g_A

Decay of polarized neutrons :

$$\frac{dW}{d\Omega_e d\Omega_\nu dE_e} \propto p_e E_e (E_0 - E_e)^2 \left[1 + a\frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + b\frac{m_e}{E_e} + \left\langle \frac{\vec{J}_n}{J_n} \right\rangle \cdot \left(A\frac{\vec{p}_e}{E_e} + B\frac{\vec{p}_\nu}{E_\nu} + D\frac{\vec{p}_e \times \vec{p}_\nu}{E_e E_\nu} \right) \right]$$

[Results for λ from a and B not competitive at present]



0.2% determination

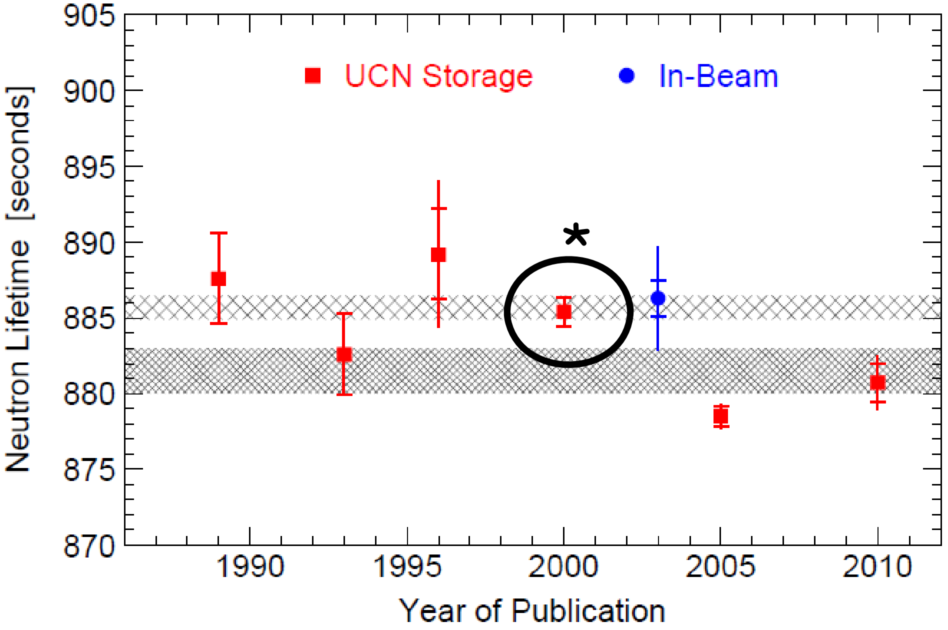
g_A/g_V = g_A = −1.2726(24)

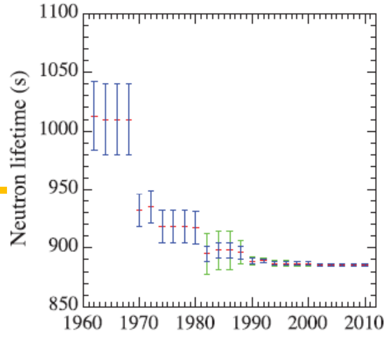
[from A_0 values and one combined A_0/B_0 result included in PDG]

Error subject to large $\chi^2/\nu = 5.1$

H. Abele et al. (2002)
R.W. Pattie et al. (2009)
J. Liu et al. (2010)
D. Mund et al. (2012)

Status of neutron β-decay: τ_n





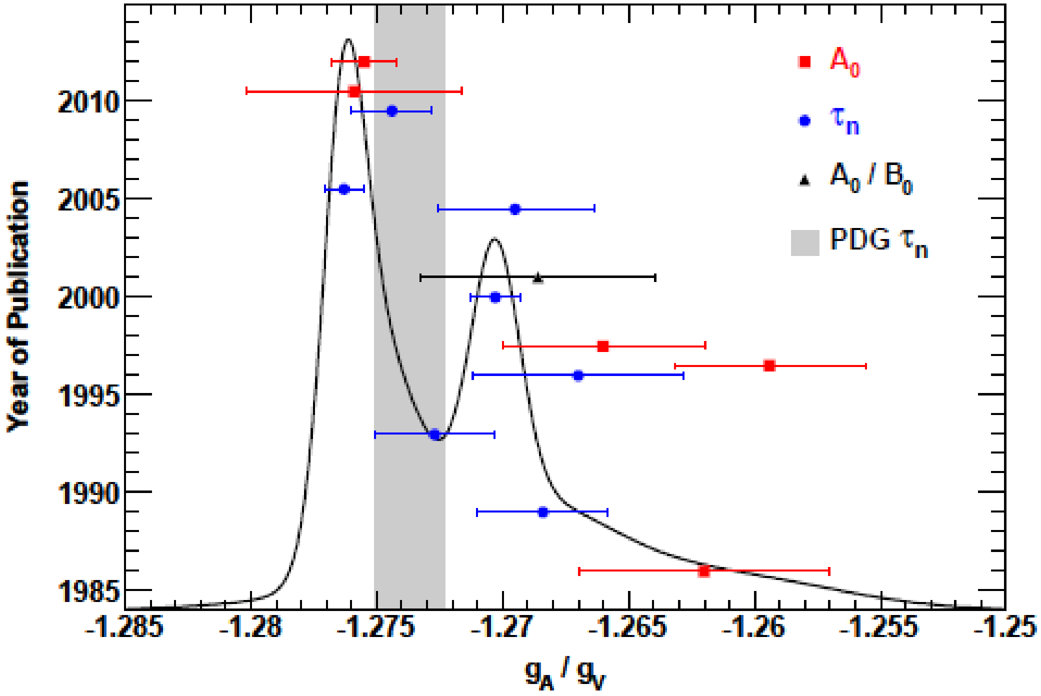
PDG Average

Pre-2011 : 885.7 ± 0.8 s

2011 – : 881.5 ± 1.5 s $\sqrt{\chi^2/\nu} = 2.7$

$$\frac{1}{\tau_n} = \frac{G_F^2 m_e^5}{2\pi^3 \hbar} \left|V_{ud}^2\right| \left(1 + 3\lambda^2\right) f \left(1 + \mathrm{RC}\right)$$

Compare τ_n with g_A treating $0^+ \rightarrow 0^+$ V_{ud} as input



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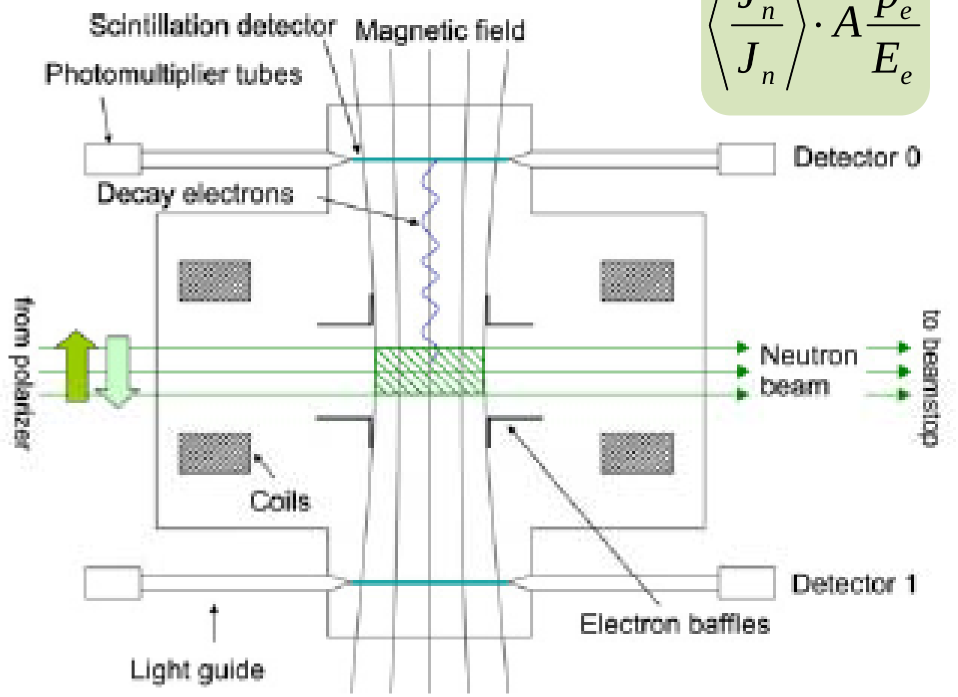
* New self-corrected result :
Arzumanov et al., JETP Lett. 95, 224 (2012) : 881.6 ± 0.8 ± 1.9 s

Experimental techniques for g_A

PERKEO II: Cold Neutron Beam

$$\left\langle \frac{\vec{J}_n}{J_n} \right\rangle \cdot A \frac{\vec{p}_e}{E_e}$$

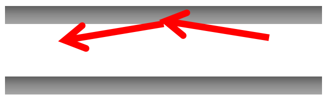


$$A_{\text{meas}}(E_e) = \frac{N_i^{\uparrow} - N_i^{\downarrow}}{N_i^{\uparrow} + N_i^{\downarrow}} = P\langle \beta_e \cos\theta \rangle A$$

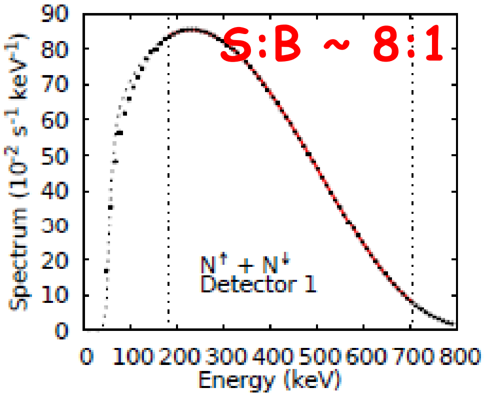
Cold Neutron Beam

~50 μeV – 25 meV

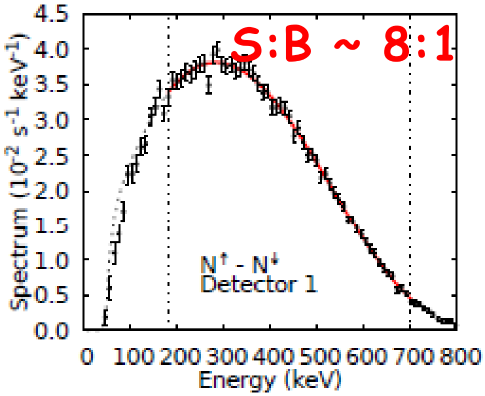
High Statistics



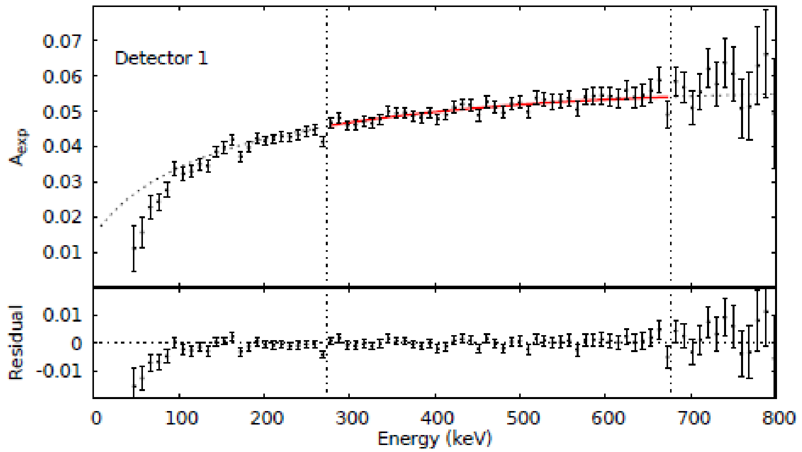
glancing angles



S:B ~ 8:1



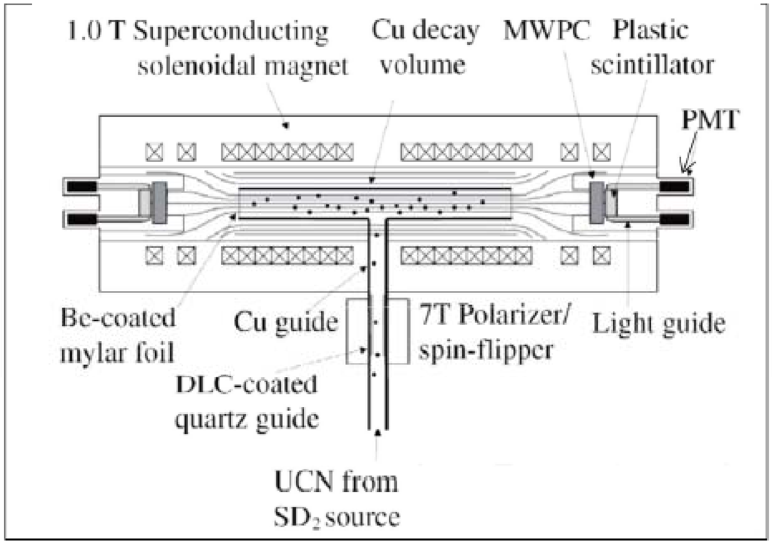
S:B ~ 8:1

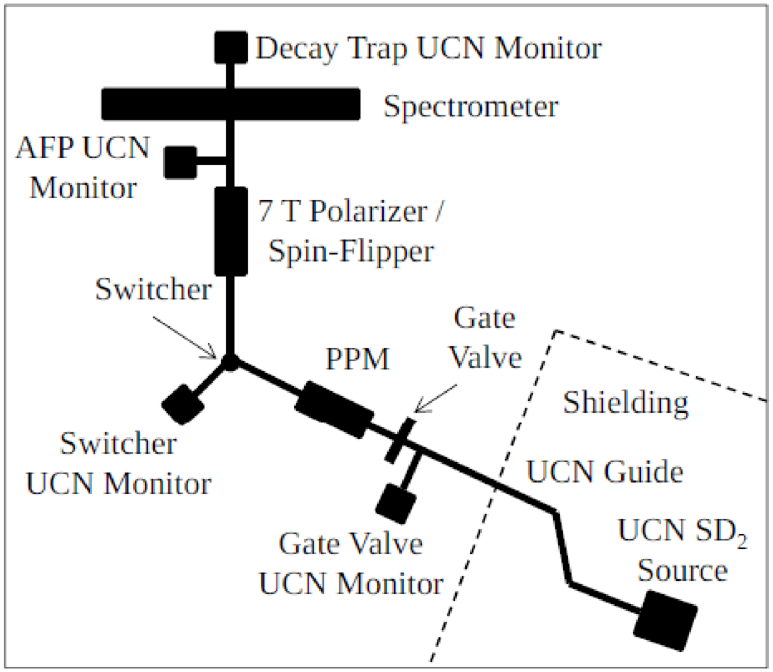


H. Abele et al. (2002)
H. Abele (2008)

D. Mund et al. (2012)

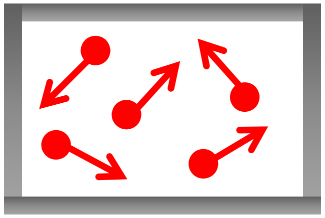
Experimental techniques for g_A





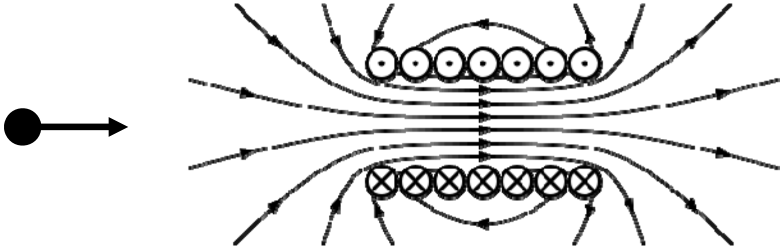
UCNA: Stored Ultracold Neutrons (UCN)

UCN storage

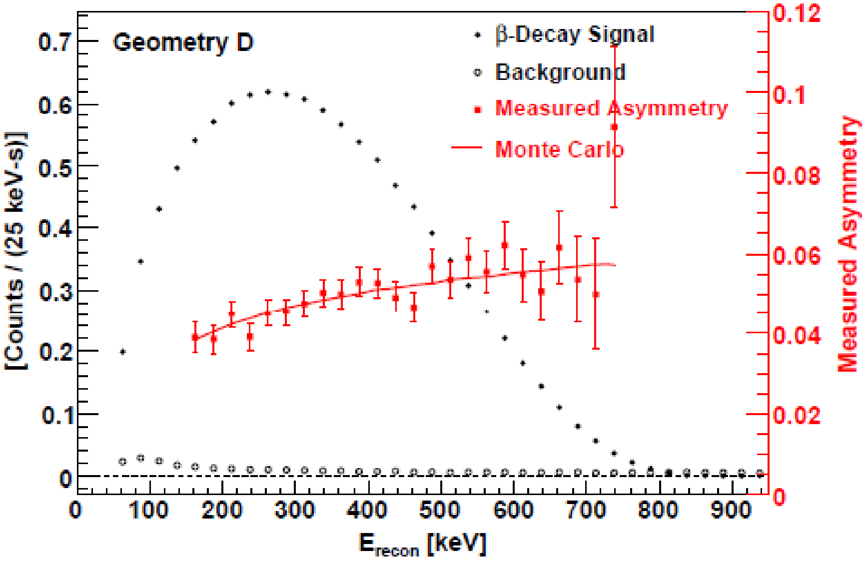


< 7 m/s
< 350 neV

Low Backgrounds
[esp. n-induced]



High Polarization



S:B ~ 40:1

R.W. Pattie et al. (2009)
J. Liu et al. (2010)

B. Plaster et al. (2012)

Future neutron β-decay prospects

Current published precision on A_0 :

PERKEO II : 0.42%

UCNA : 1.3% [later this summer: ~0.75%]

$$\frac{\delta|\lambda|}{|\lambda|} = 0.24\frac{\delta|A|}{|A|} = 0.27\frac{\delta|a|}{|a|} = 2.0\frac{\delta|B|}{|B|}$$

Near-term projected precision :

PERKEO III : ~ 0.2%

UCNA : < 0.5% [data in hand]

Precision on g_A could approach ~0.05% in next several years

Longer-term projected precision :

PERC : < 0.1% on A, a

Nab : 0.1% on a, 0.3% on b

abBA : 0.1% on a, 0.08% on A

also aCORN, aSPECT, etc.

Neutron lifetime :

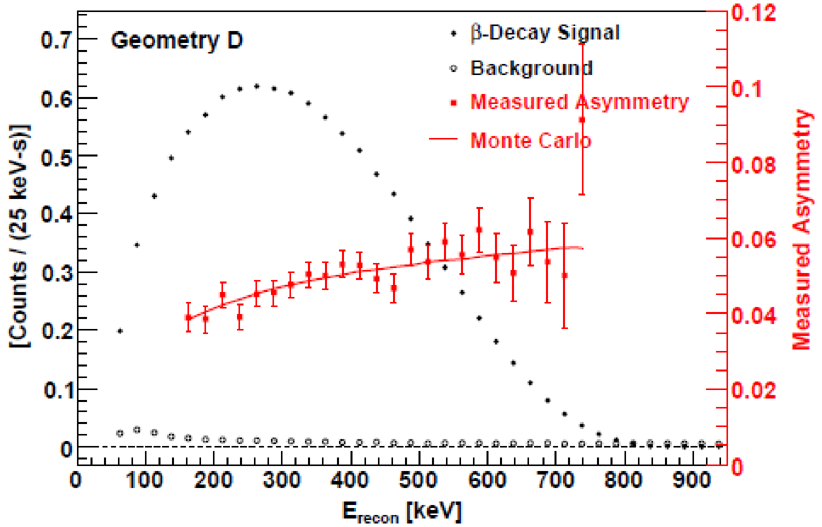
Many world-wide experiments aimed at < ±1.0 s precision

Future neutron β-decay prospects

Tests of CVC / Search for second-class currents in neutron β-decay

[Holstein (1974), Gardner and Zhang (2001)]

Recoil-order energy-dependence of the asymmetries (a, A)



$$A_{\text{meas}}(E) = P_n \langle \beta \cos\theta \rangle_{\text{bin}} A(E)$$

$$A(E) = A_0 + \text{recoil order terms}$$

all 6 form factors

CVC Hypothesis Test

[assume SCC = 0]

OR

SCC Test

[assume CVC]

examples

A: best for λ

0.1% on a :

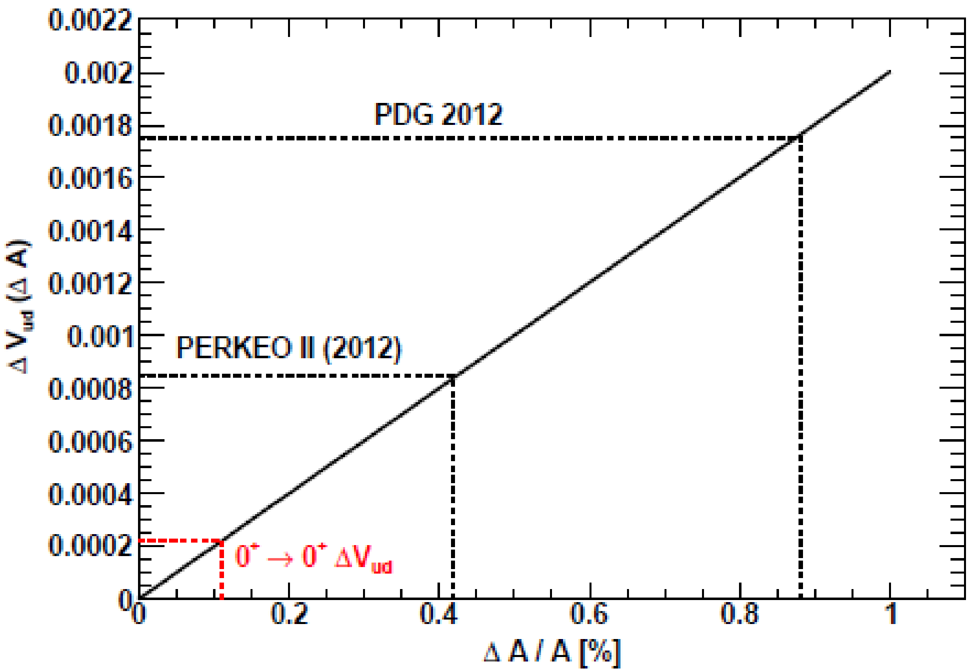
2.5% on g_{WM} ;

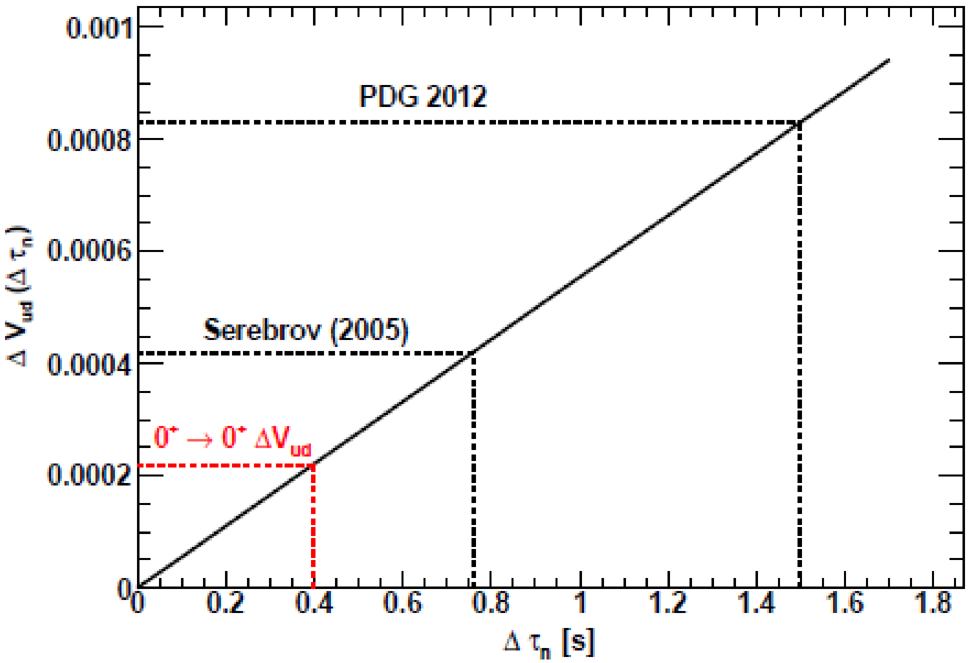
$\delta g_T \sim 0.22\lambda/2$

Future neutron β-decay prospects

Extractions of g_V*V_{ud} in $0^+ \rightarrow 0^+$ nuclear β-decay limited by theoretical errors

What will it take for neutron β-decay to challenge nuclear β-decay ?





Need $\delta A/A < 0.11\%$ AND Need $\delta\tau_n < 0.4$ s

Final notes

Also recent theoretical work on searches for new physics (S, T) in neutron β-decay: b, B. [Bhattacharya et al. (2012)]

Apologies for lack of time to discuss this, as focus was on g_A, g_V.

Comment :

FNAL source of UCN for β-decay studies would be very interesting

UCNA limited by statistics at present

Max ~60 Hz of β-decay rate from ~2/cm^3 in decay volume

If could achieve, say, extracted UCN density of ~10/cm^3 -> 300 Hz

$$\frac{\sigma_A}{A} \approx \frac{2.7}{\sqrt{N}} \Big/ A \longrightarrow$$

~500M counts for 0.1% statistics on A

-> ~0.025% on g_A [V_{ud} extraction]

@ 300 Hz -> ~20 days of 100% running

UCNA Collaboration

H.O. Back, T.J. Bowles, L.J. Broussard, R. Carr, S. Clayton, S. Currie, B.W. Filippone, A. Garcia, P. Geltenbort, S. Hasan, K.P. Hickerson, J. Hoagland, G.E. Hogan, A.T. Holley, T.M. Ito, C.-Y. Liu, J. Liu, M. Makela, R.R. Mammei, J.W. Martin, D. Melconian, M.P. Mendenhall, C.L. Morris, R.W. Pattie, A. Perez Galvan, M.L. Pitt, B. Plaster, J.C. Ramsey, R. Rios, R. Russell, A. Saunders, S. Seestrom, W.E. Sondheim, E. Tatar, R.B. Vogelaar, B. VornDick, C. Wrede, A.R. Young, B. Zeck

The End

Why measure A with UCN ?

Systematic *Corrections* [%]

	Polarization / Spin-Flip	Backgrounds	Others
PERKEO I (1986)	2.6	~ 3	~13 magnetic mirroring
ILL (1997)	2.9	~ 3	strong $\cos\theta$ variation
PNPI (1997)	23	*small*	~3 $\langle \cos\theta \rangle$
PERKEO II (2002)	1.4	0.5	~0.1 $\langle \cos\theta \rangle$
UCNA (2008-2009)	0.0	0.015	~0.5 - ~1.0 backscattering + $\langle \cos\theta \rangle$

Neutron lifetime experiments

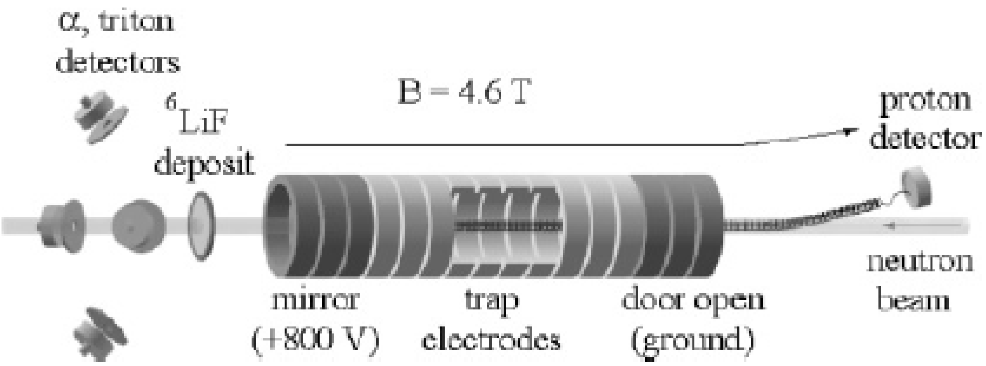
In-Beam Technique

Cold neutron beam

$$\left|\dot{N}\right| = N_0 / \tau_\beta$$

Count N_0 and decay product(s)

Detector efficiencies, volume !



e.g.,, NIST Experiment

Nico et al., PRC 71, 055502 (2005)

Dewey et al., PRL 91, 152302 (2003)

Storage Technique

Stored UCN: walls, gravity, $\vec{B}$

$$N(t) = N_0 e^{-t/\tau_\beta}$$

Load, then count "surviving" UCN

and/or decay products in "real time"

Losses other than β-decay !

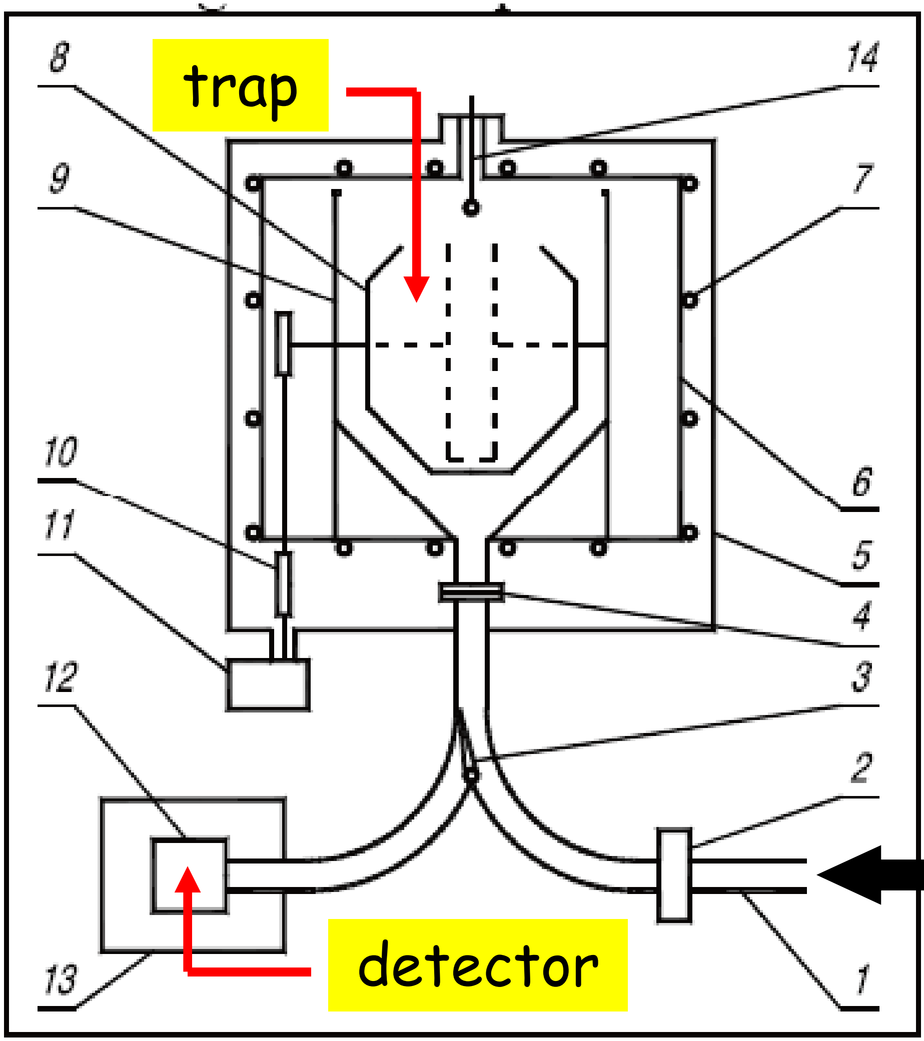
e.g., NIST Experiment

Ioffe Trap: Superposition of 2x solenoid with quadrupole

Brome et al., PRC 63, 055502 (2001)

O'Shaughnessy et al., arXiv: 0903.5509

Most recent lifetime result



trap

detector

Serebrov et al., PLB 605, 72 (2005)

UCN from source

$$\boxed{\frac{1}{\tau_{\text{storage}}} = \frac{1}{\tau_{\beta}} + \frac{1}{\tau_{\text{loss}}}}$$

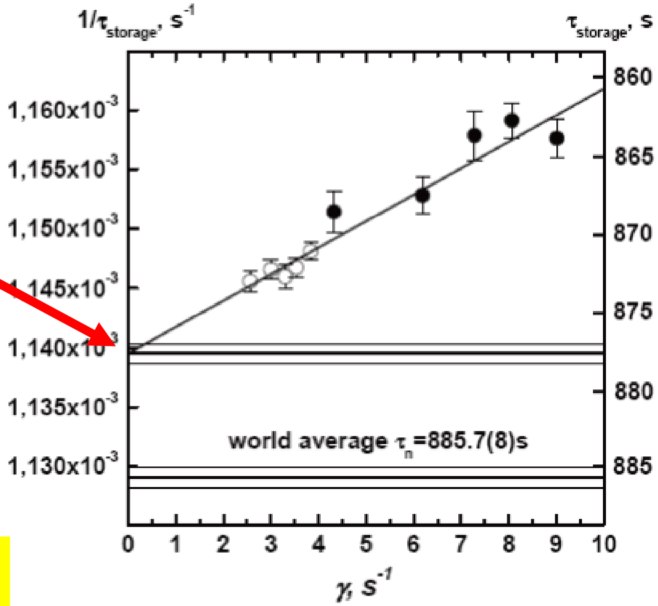
measured

extract

must account for these

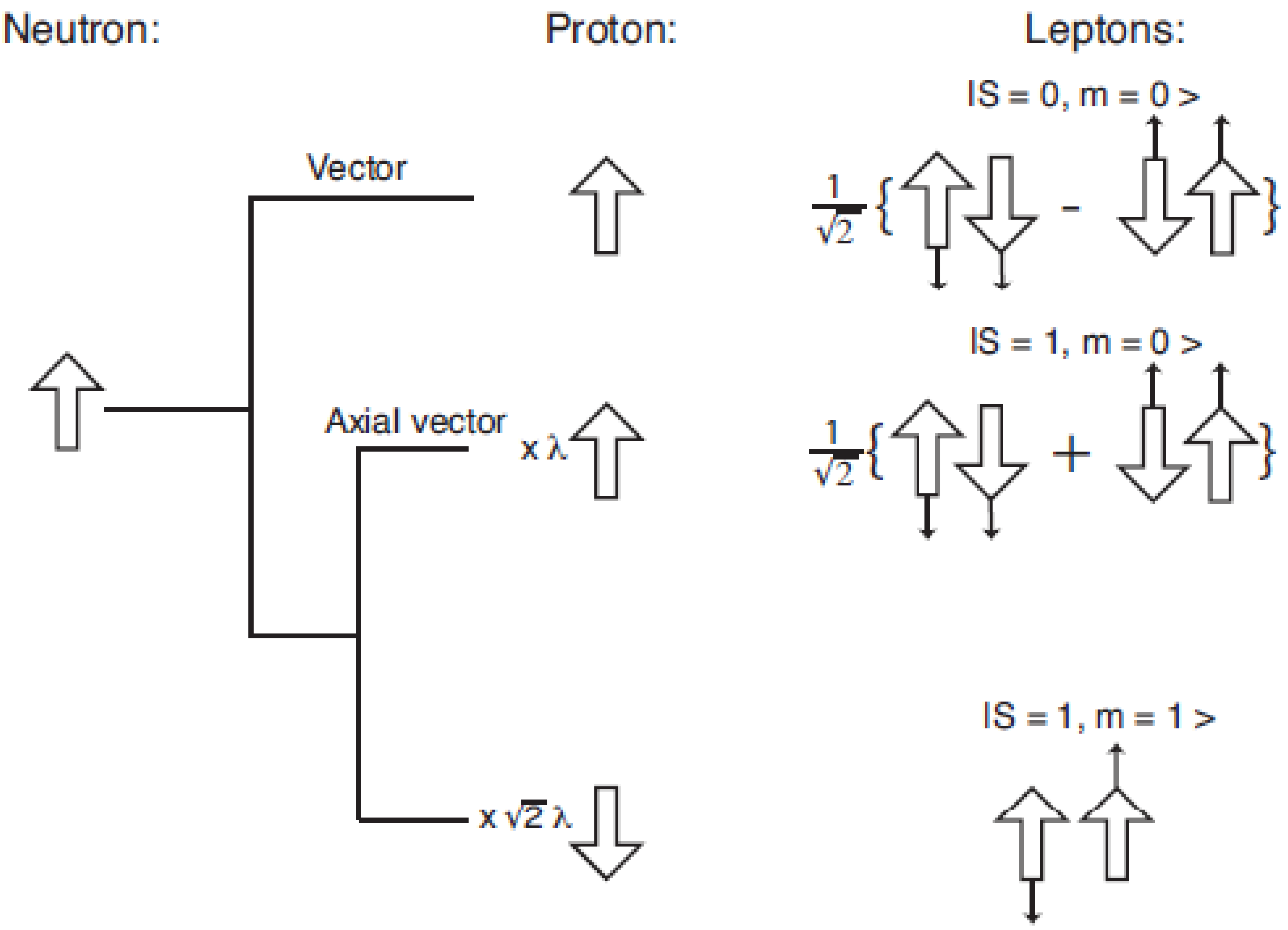
(absorption, upscattering)

extrapolated to zero loss



previous smallest extrapolation ~ 105 s

Spin and Momentum Analysis


Neutron:

Proton:

Leptons:

Vector

Axial vector

$\times\,\lambda$

$\times\,\sqrt{2}\,\lambda$

$|S = 0, m = 0>$

$\frac{1}{\sqrt{2}}\{\ \ -\ \ \}$

$|S = 1, m = 0>$

$\frac{1}{\sqrt{2}}\{\ \ +\ \ \}$

$|S = 1, m = 1>$

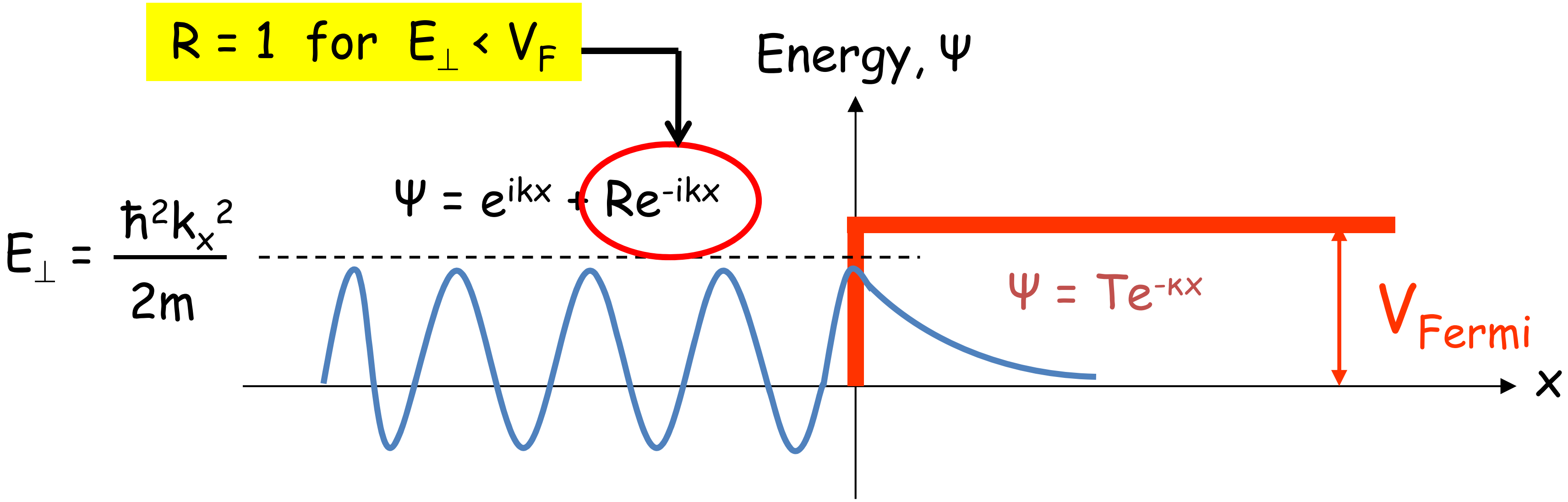
[*assuming the electron and anti-neutrino are massless*]

From D. McKinsey Ph.D. Thesis, Harvard University (2002)

Ultracold neutrons (UCN)

1980's – … Neutron EDM searches performed with UCN

Kinetic Energies < 350 nano-eV Speeds < 8 m/s



R = 1 for $E_\perp < V_F$

Energy, Ψ

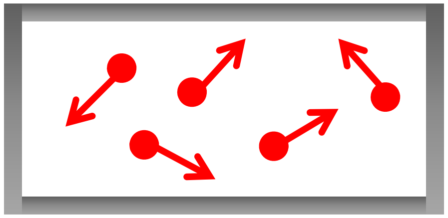
$\Psi = e^{ikx} + Re^{-ikx}$

$$E_\perp = \frac{\hbar^2 k_x^2}{2m}$$

$\Psi = Te^{-\kappa x}$

V_{Fermi}

	V_{Fermi}
^{58}Ni	335 neV
Fe	210 neV
Teflon	123 neV



UCN "storage bottle"

Long coherence times

Small $\vec{E} \times \vec{v}$ fields

TABLE IX. Summary of systematic corrections and uncertainties. All numbers quoted are fractional [%] relative to A_0. Upper Table: Geometry-Independent systematic uncertainties. No systematic corrections were applied for these effects (with the exception of the radiative corrections, already discussed in Section VII G). Lower Table: Geometry-Dependent systematic corrections and uncertainties. The quoted value denotes the systematic correction, with the error the systematic uncertainty. As discussed in the text, Δ_2 represents the correction for backscattering, and Δ_3 the correction for the angle effect. ϵ_{MWPC} denotes the systematic uncertainty associated with the MWPC efficiency.

Geometry-Independent Effect	Uncertainty [%]
Dead Time	±0.01
Energy Reconstruction	±0.47
Fiducial Cut and Coordinate Systems	±0.24
Gain Fluctuations	±0.20
Live Time	±0.24
Magnetic Field Nonuniformity	$^{+0.20}_{-0.00}$
Muon Veto Efficiency	±0.30
Neutron-Generated Backgrounds	±0.02
Polarization	$^{+0.52}_{-0.00}$
Radiative Corrections	±0.05
Rate-Dependent Gain Shifts	±0.08

	Geometry-Dependent Effects			
	A [%]	B [%]	C [%]	D [%]
Δ_2	1.34 ± 0.40	4.32 ± 1.30	1.07 ± 0.32	1.08 ± 0.32
Δ_3	-1.81 ± 0.45	-3.22 ± 0.81	-0.60 ± 0.15	-0.36 ± 0.09
ϵ_{MWPC}	0.00 ± 0.02	0.00 ± 0.01	0.00 ± 0.16	0.00 ± 0.50

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
Electron backscattering	0.25	0.04
Edge effect (1)	(−1.6)	0.5
Magnetic mirror effect	0.6	0.2
Dead time (2)	(−1.2)	0.1
Radiative Correction	0.9	0.5
Statistics	0.0	3.8

TABLE I. Summary of corrections and uncertainties to the beta asymmetry $\Delta A_0/A_0$. (1) is included in the fit function, (2) is measured by the data acquisition system and accounted for in the data set.