Review of Fundamental Neutron Physics Experiments

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Types of Fundamental Neutron Physics Experiments

1. Neutron Decay Parameters (lifetime, angular corrleations)

2. Neutron-nuclear weak interactions (P, T violation)

3. Neutron Electric Dipole Moment

4. Neutron Interferometry

Advantages of Reactor Source

1. High time-averaged neutron flux

2. High capture flux (esp. neutron decay experiments)

$$\boxed{\phi_{\text{capture}} = \int \frac{v_0}{v}\phi(v)dv}$$

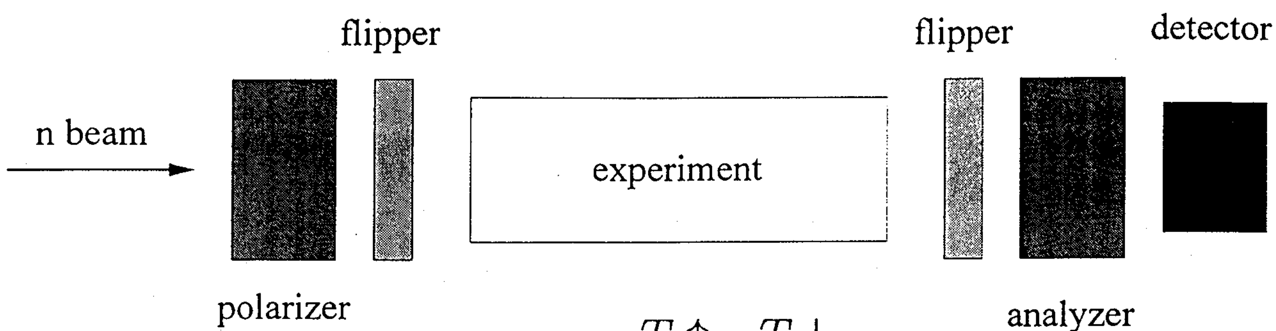
Advantages of Spallation Source

1. Evaluation of velocity-dependent systematics.

2. Precision neutron polarimetry.

3. Velocity selection (superthermal UCN production).

Precise Neutron Polarimetry



$$PA = \frac{T\uparrow - T\downarrow}{T\uparrow + T\downarrow}$$

In general, neutron polarization depends on both velocity and position.

Polarimetry precision better than 1% is challenging!

Using 3He spin filter: $T_{\pm} = e^{n_3 l\sigma(\lambda)(1\mp P_3)}$

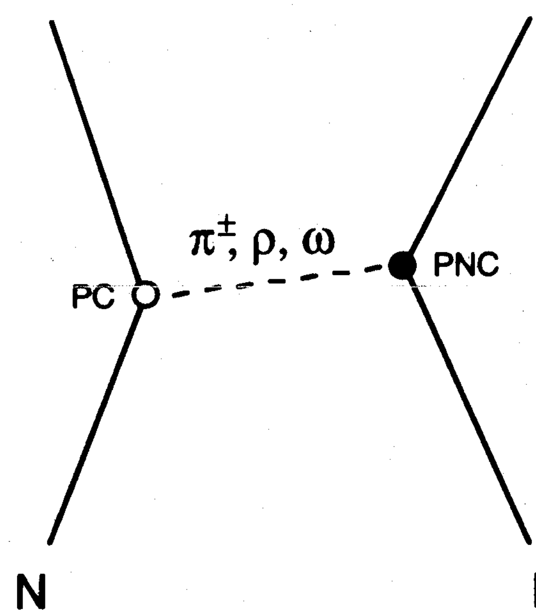
$$P = \frac{T_+ - T_-}{T_+ + T_-} = tanh(n_3 l\sigma(\lambda)P_3)$$

$$T_0 = \frac{T_+ + T_-}{2} = e^{-n_3 l\sigma(\lambda)} cosh(n_3 l\sigma(\lambda)P_3)$$

$$\frac{T_0(P_3)}{T_0(P_3 = 0)} = cosh(n_3 l\sigma(\lambda)P_3) = \frac{1}{\sqrt{1 - P(\lambda)^2}}$$

This has been demonstrated at LANSCE to a precision of 0.3%

Parity Violation in the Nucleon-Nucleon System



- Parity-non-conserving (PNC) observable isolates the weak-interaction contribution
- The weak charged and neutral currents (W, Z exchange) are contained within the PNC vertex.
- Experimental test of neutral current interaction between quarks.
- Difficult to calculate due to strong interaction (non-perturbative QCD)

DDH Values of weak nucleon coupling coefficients

Desplanques, Donoghue, and Holstein (1980)

Coefficient	meson exchanged	"reasonable range ($\times 10^{-6}$)"	"best value ($\times 10^{-6}$)"
f_π	π	0 — 1.1	0.45
h_ρ^0	ρ	–3.1 — 1.1	-1.1
h_ρ^1	ρ	-0.038 — 0	-0.02
h_ρ^2	ρ	-1.1 — 0.76	-0.95
h_ω^0	ω	-1.0 — 0.57	-0.19
h_ω^1	ω	-0.19 — -0.08	-0.11

PNC Observables

Circular polarization of capture gamma ray:

$$\vec{\sigma}_\gamma \cdot \vec{p}_\gamma$$

Asymmetry of capture gamma ray:

$$\vec{J}_N \cdot \vec{p}_\gamma$$

Longitudinal analyzing power:

$$\vec{J}_N \cdot \vec{p}_N$$

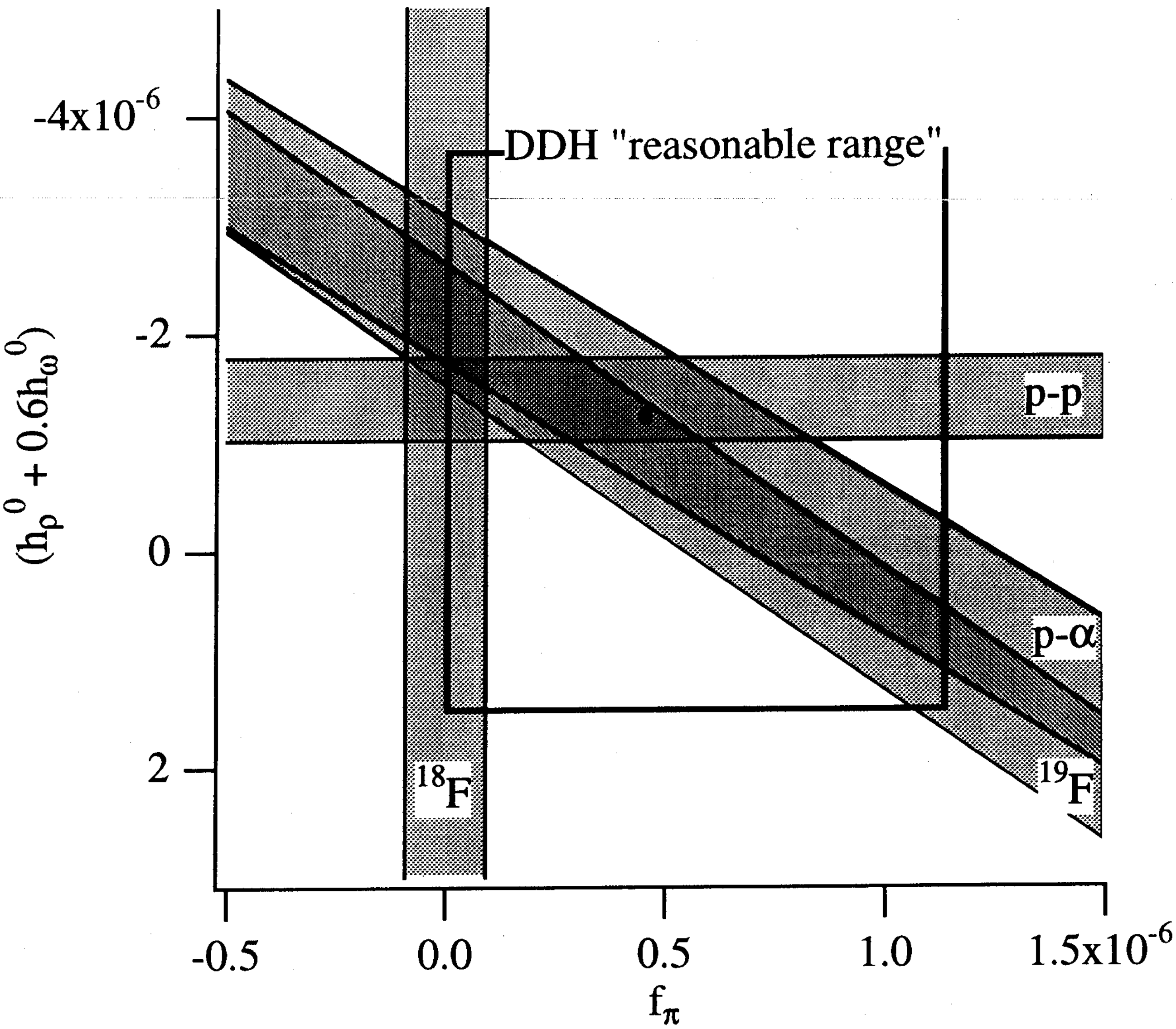
Spin rotation:

$$(\vec{J}_{init} \times \vec{J}_{final}) \cdot \vec{p}_N$$

Few nucleon systems:
  Observables are tiny ($\approx 10^{-7}$), theory is straightforward.

Light nuclear systems:
  A few special cases where observables are enhanced ($\approx 10^{-4}$) and theory is straightforward.

Heavy nuclear systems:
  Many cases where observables are enhanced but theory is problematic.



-4x10^{-6}
-2
0
2
DDH "reasonable range"
p-p
p-α
^{18}F
^{19}F
-0.5
0.0
0.5
1.0
1.5x10^{-6}
f_π
$(h_\rho^0 + 0.6h_\omega^0)$

Measurement of Parity Nonconservation and an Anapole Moment in Cesium

C. S. Wood, S. C. Bennett, D. Cho,* B. P. Masterson,† J. L. Roberts, C. E. Tanner,‡ C. E. Wieman§

The amplitude of the parity-nonconserving transition between the 6S and 7S states of cesium was precisely measured with the use of a spin-polarized atomic beam. This measurement gives $\mathrm{Im}(E1_{pnc})/\beta = -1.5935(56)$ millivolts per centimeter and provides an improved test of the standard model at low energy, including a value for the S parameter of $-1.3(3)_{exp}(11)_{theory}$. The nuclear spin–dependent contribution was 0.077(11) millivolts per centimeter; this contribution is a manifestation of parity violation in atomic nuclei and is a measurement of the long-sought anapole moment.

It has been recognized for more than 20 years that electroweak unification leads to parity nonconservation (PNC) in atoms (*1*). This phenomenon is the lack of mirror-reflection symmetry and is displayed by any object with a left or right handedness. Perhaps the most well-known example of a PNC effect is the asymmetry in nuclear beta decay first observed in 1957 by Wu and collaborators (*2*). Precise measurements of PNC in a number of different atoms have provided important tests of the standard model of elementary particle physics at low energy (*3*). Atomic PNC is uniquely sensitive to a variety of "new physics" (beyond the standard model) because it measures a set of model-independent electron-quark electroweak coupling constants that are different from those that are probed by high-energy experiments. Specifically, the standard model is tested by comparing a measured value of atomic PNC with the corresponding theoretical value predicted by the standard model. This prediction requires, as input, the mass of the Z boson and the electronic structure of the atom in question. The Z mass is now known to 77 parts per million (*4*), but the uncertainties in the atomic structure are 1 to 10%, depending on the atom. In recent years, PNC measurements in several atoms have achieved uncertainties of a few percent (*5, 6*). Of these atoms, the structure of cesium is the most accurately known (1%) because it is an alkali atom with a single valence electron outside of a tightly bound inner core. Thus, higher precision measurements of PNC in cesium provide a sensitive probe of physics beyond the standard model.

In addition to exploring the physics of the standard model, high-precision atomic PNC experiments also offer a different approach for studying the effects of parity violation in atomic nuclei. In 1957, it was predicted that the combination of parity violation and electric charges would lead to the existence of a so-called anapole moment (*7*), but up until now, such a moment has not been measured. Fifteen years ago, it was pointed out that an anapole moment in the nucleus would lead to small nuclear-spin–dependent contributions to atomic PNC that could be observed as a difference in the values of PNC measured on different atomic transitions (*8*). With the determination of the anapole moment, the measurement of this difference thus provides a valuable probe of the relatively poorly understood PNC in nuclei.

Here, we report a factor of 7 improvement in the measurement of PNC in atomic cesium. This work provides an improved test of the standard model and a definitive observation and measurement of an anapole moment.

This experiment is our third-generation measurement of PNC in atomic cesium. Conceptually, the experiment is similar to our previous two (*6, 9*). As a beam of atomic cesium passes through a region of perpendicular electric, magnetic, and laser fields, we excite the highly forbidden 6S to 7S transition. The handedness of this region is reversed by reversing each of the field directions. The parity violation is apparent as a small modulation in the 6S-7S excitation rate that is synchronous with all of these reversals. There are numerous experimental differences from our earlier work, however, including the use of a spin-polarized atomic beam and a more efficient detection method. This paper describes the basic concept of the experiment, the apparatus, the data analysis, the extensive studies that have been done on possible systematic errors, and finally, the results and some of their implications. Because this experiment has involved 7 years of apparatus development and 5 years studying potential systematic errors, we provide only a relatively brief summary of the work here. Further details on both the technology and the systematic errors will be presented in subsequent, longer publications.

Experimental concept. In the absence of electric fields and weak neutral currents, an electric dipole (E1) transition between the 6S and 7S states of the cesium atom (Fig. 1) is forbidden by the parity selection rule. The weak neutral current interaction violates parity and mixes a small amount ($\sim 10^{-11}$) of the P state into the 6S and 7S states, characterized by the quantity $\mathrm{Im}(E1_{PNC})$ (Im selects the imaginary portion of a complex number). This mixing results in a parity-violating E1 transition amplitude A_{PNC} between these two states. To obtain an observable that is first order in this amplitude, we apply a dc electric field E that also mixes S and P states. This field gives rise to a "Stark-induced" E1 transition amplitude A_E that is typically 10^5 times larger than A_{PNC} and can interfere with it.

A complete analysis of the relevant transition rates is given in (*9*). To get a nonzero interference between A_E and A_{PNC}, we excite the 6S to 7S transition with an elliptically polarized laser field of the form $\epsilon_z\chi$ +

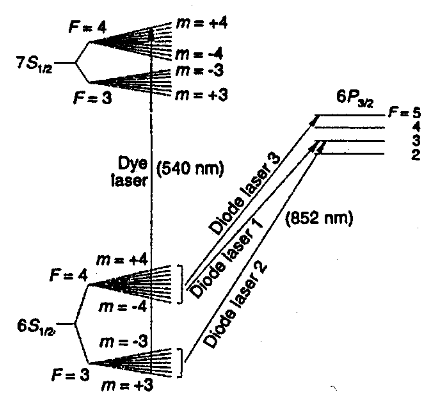


Fig. 1. Partial cesium energy-level diagram including the splitting of S states by the magnetic field. The case of 540-nm light exciting the $F = 3$, $m = 3$ level is shown. Diode lasers 1 and 2 optically pump all of the atoms into the (3, 3) level, and laser 3 drives the $6S_{F=4}$ (F_{det}) to $6P_{F=5}$ transition to detect the 7S excitation. PNC is also measured for excitation from the (3, −3), (4, 4), and (4, −4) 6S levels. The diode lasers excite different transitions for the latter two cases.

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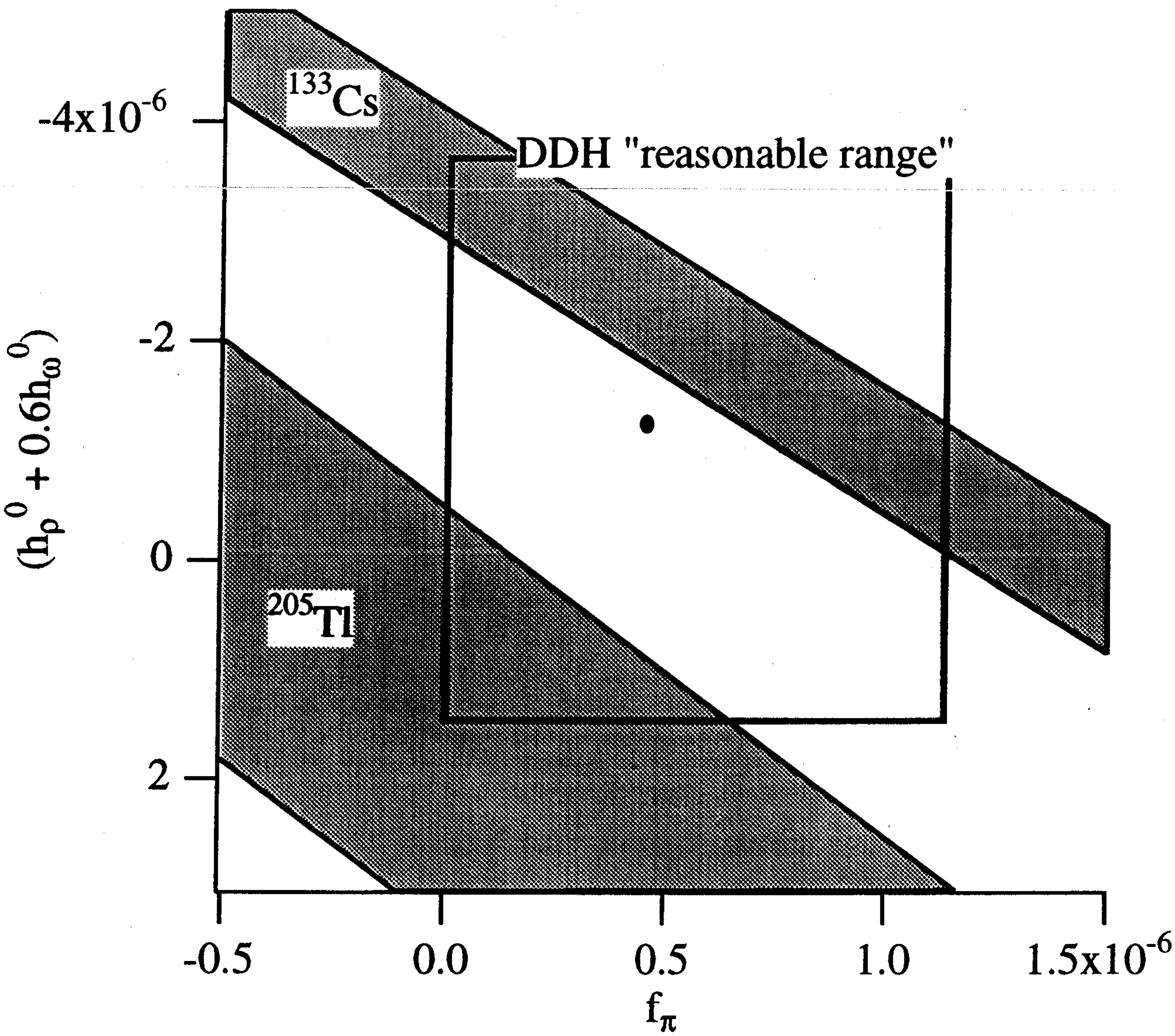

^{133}Cs
DDH "reasonable range"
^{205}Tl
-4x10^{-6}
-2
0
2
$(h_\rho^0 + 0.6h_\omega^0)$
-0.5
0.0
0.5
1.0
1.5x10^{-6}
f_π

The Importance of Determining the PNC Coupling Coefficients

1. The only practical way to study the quark-quark neutral current interaction at low energy.

2. Understand the interplay of low energy QCD and the neutral weak interaction. (compare to $\Delta I = 1/2$ rule for charged-currents).

3. Benchmark for non-perturbative QCD calulations.

4. Improve understanding of atomic anapole moments.

Cold Neutron Experiments

1. Gamma ray asymmetry in
   $$n + p \longrightarrow d + \gamma$$

2. Neutron spin rotation in He-4

3. Neutron spin rotation in H

n+p→d+γ

A Measurement of the Parity-Violating Gamma-Ray Asymmetry from the Capture of Polarized Neutrons in Hydrogen

J.D. Bowman, G.L. Greene, G.E. Hogan, J.N. Knudson, S.K. Lamoreaux, G.L. Morgan, C.L. Morris, S.I. Penttila, D.A. Smith, T. Smith, W.S. Wilburn, V.W. Yuan
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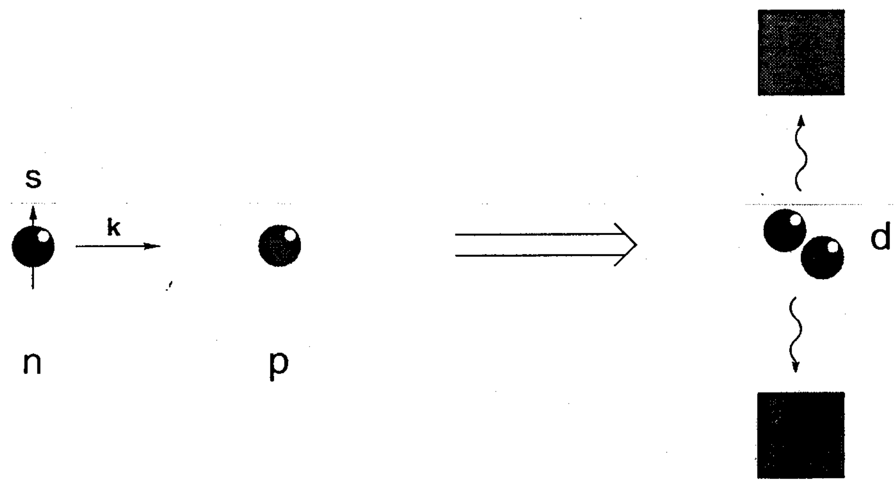
KEK National Laboratory, Japan

E.I. Sharapov
Joint Institute for Nuclear Research, Dubna, Russia

$$\vec{n} + p \to d + \gamma$$

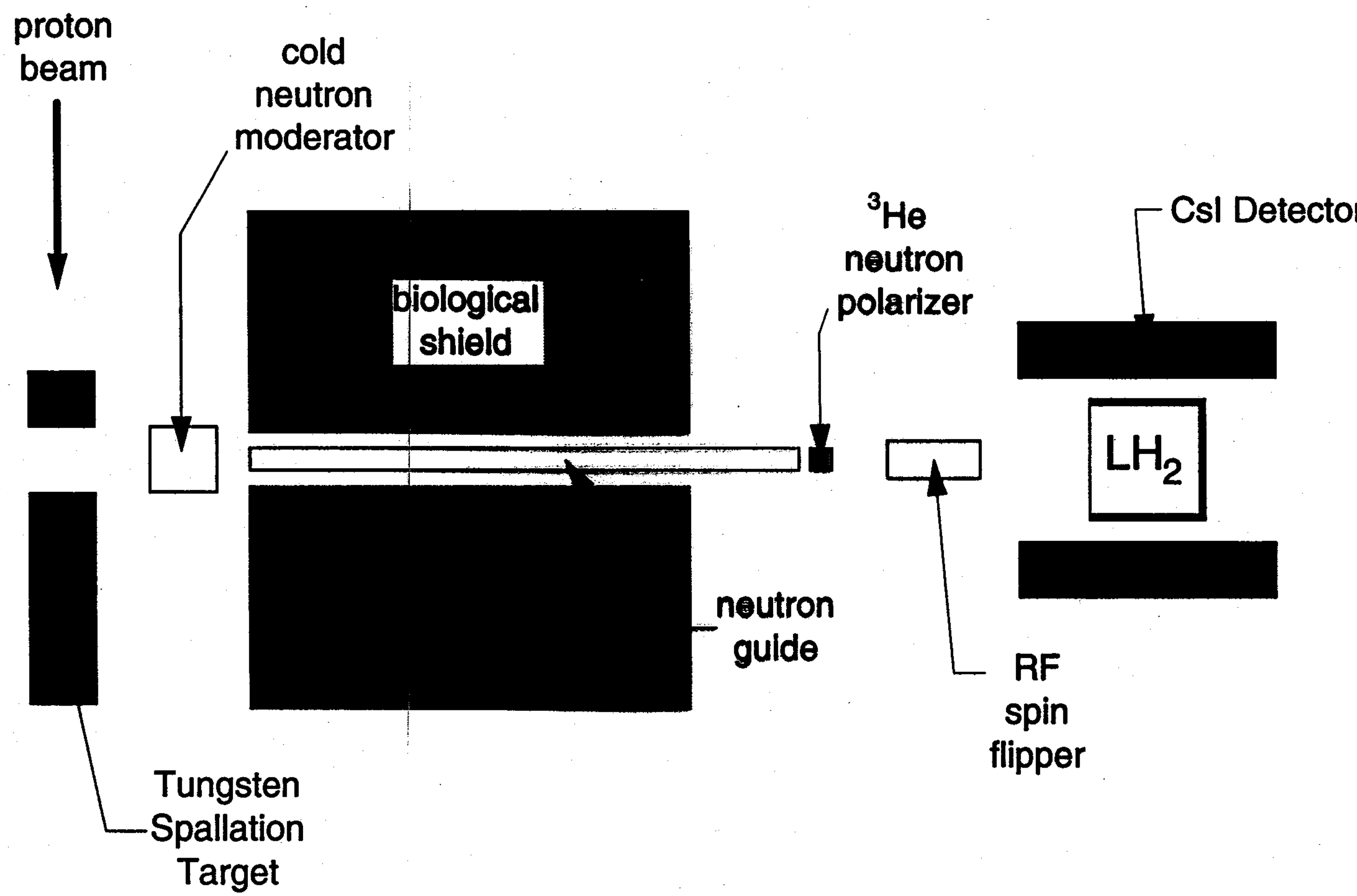


$$P_n A_\gamma = \frac{N_u - N_d}{N_u + N_d}$$

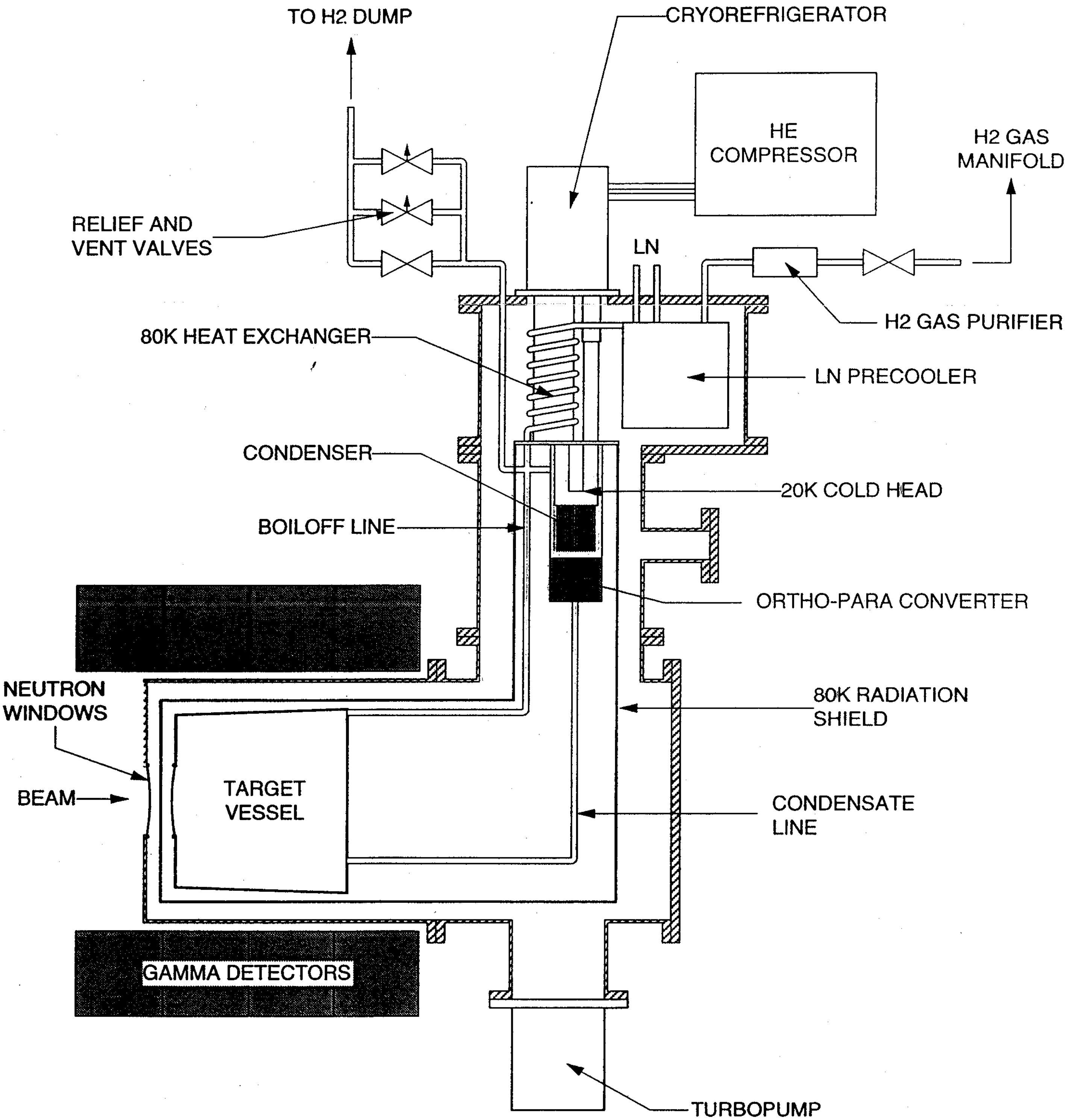
$$A_\gamma = -0.045 \left(H_\pi^1 - 0.02 H_\rho^1 + 0.02 H_\omega^1 + 0.04 H_\rho^{\prime 1} \right)$$

measure to $\sigma_{A_\gamma} = 5 \times 10^{-9}$

then $\sigma_{H_\pi} = 1 \times 10^{-7}$


proton beam
cold neutron moderator
biological shield
^{3}He neutron polarizer
CsI Detector
LH_2
neutron guide
RF spin flipper
Tungsten Spallation Target

Liquid Parahydrogen Target



Benefits of TOF signal for $n + p \rightarrow d + \gamma$

1. RF spin flipper - no B gradients needed

2. Understand velocity-dependent scattering effects that mimic PNC signal

3. Precise polarization analysis

PNC Spin Rotation of Neutrons in Liquid Helium

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North Carolina State University

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How spin rotation works:

neutron forward scattering amplitude contains a small PNC helicity dependence due to weak interaction:

$$f(0) = f_{PC} + f_{PNC}(\vec{\sigma} \cdot \vec{p}_n)$$

Start with transverse polarized beam, $\langle \sigma_x \rangle = +1$

In z basis (beam direction) this is:

$$|\chi\rangle = \frac{1}{\sqrt{2}}[\, |+\rangle + |-\rangle \,]$$

multiply by phase accumulated in target:

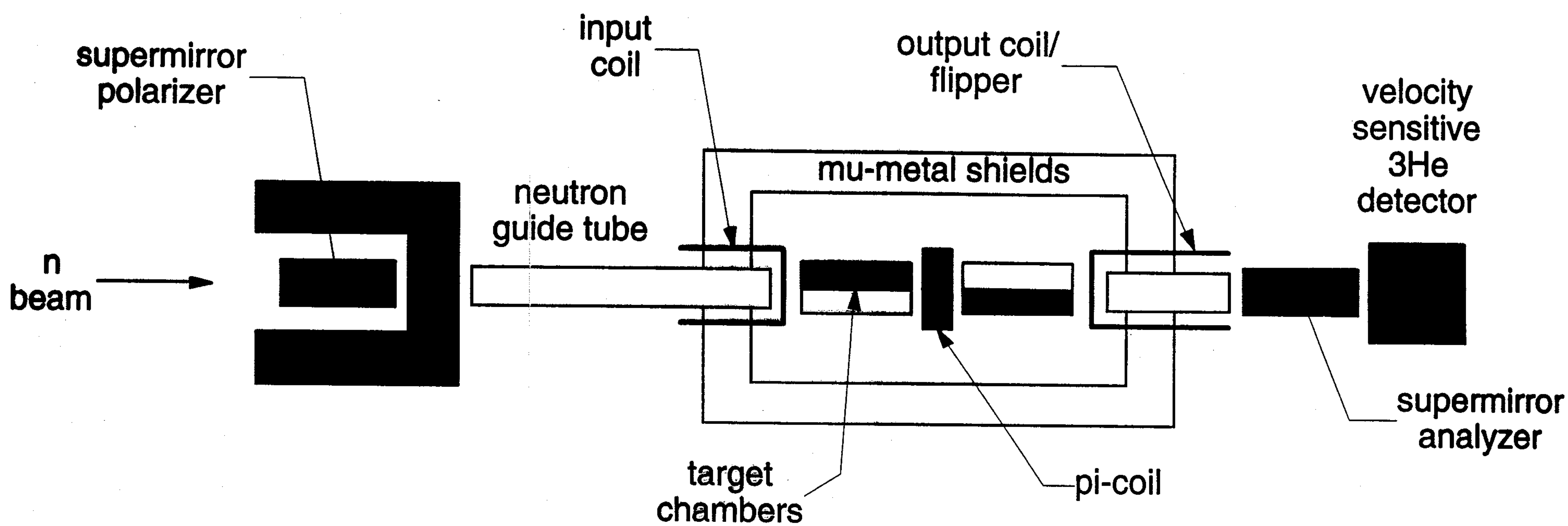
$$|\chi\rangle \Rightarrow \frac{1}{\sqrt{2}}\left[e^{\frac{i}{2}(\phi_{PC}+\varphi_{PNC})}|+\rangle + e^{\frac{i}{2}(\phi_{PC}-\varphi_{PNC})}|-\rangle \right]$$

Now we have:

$$\langle \sigma_x \rangle = \cos(\varphi_{PNC})$$
$$\langle \sigma_y \rangle = \sin(\varphi_{PNC})$$

and $\varphi_{PNC} = 4\pi\rho z\, f_{PNC}$

n spin rotation experiment



How we measure φ_{PNC}:

For each target:

$$\phi_{rot} = \frac{1}{\mathcal{P}}\left(\frac{N_+ - N_-}{N_+ + N_-}\right)$$

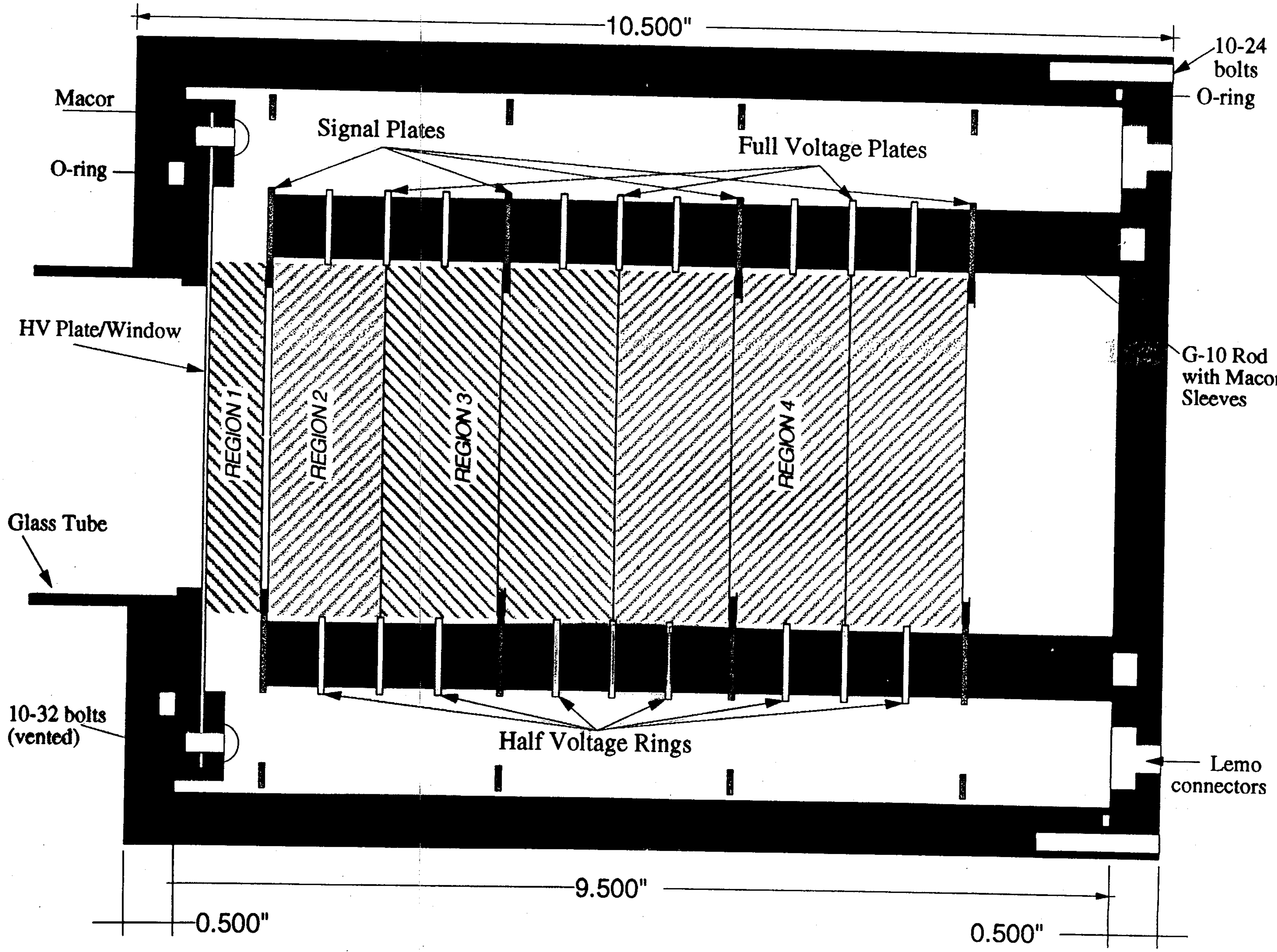
Combine the two targets:

$$\phi_{rot} = \frac{1}{2\mathcal{P}}\left(\frac{N_+^R\, N_-^L}{N_+^L\, N_-^R} - 1\right)$$

Sources of target-dependent PC background rotations

- diamagnetism of liquid helium
- index of refraction of liquid helium
- scattering in target
- reflection from target walls

Longitudinal Cut-away of ^{3}He Ionization Chamber



Result from 1996 run
at NIST:

$$\phi_{PNC} = 8.0 \pm 14\ (\text{stat}) \pm 2.2\ (\text{sys}) \times 10^{-7}\ \text{rad/m}$$

Using DDH "best values" the
expected result is:

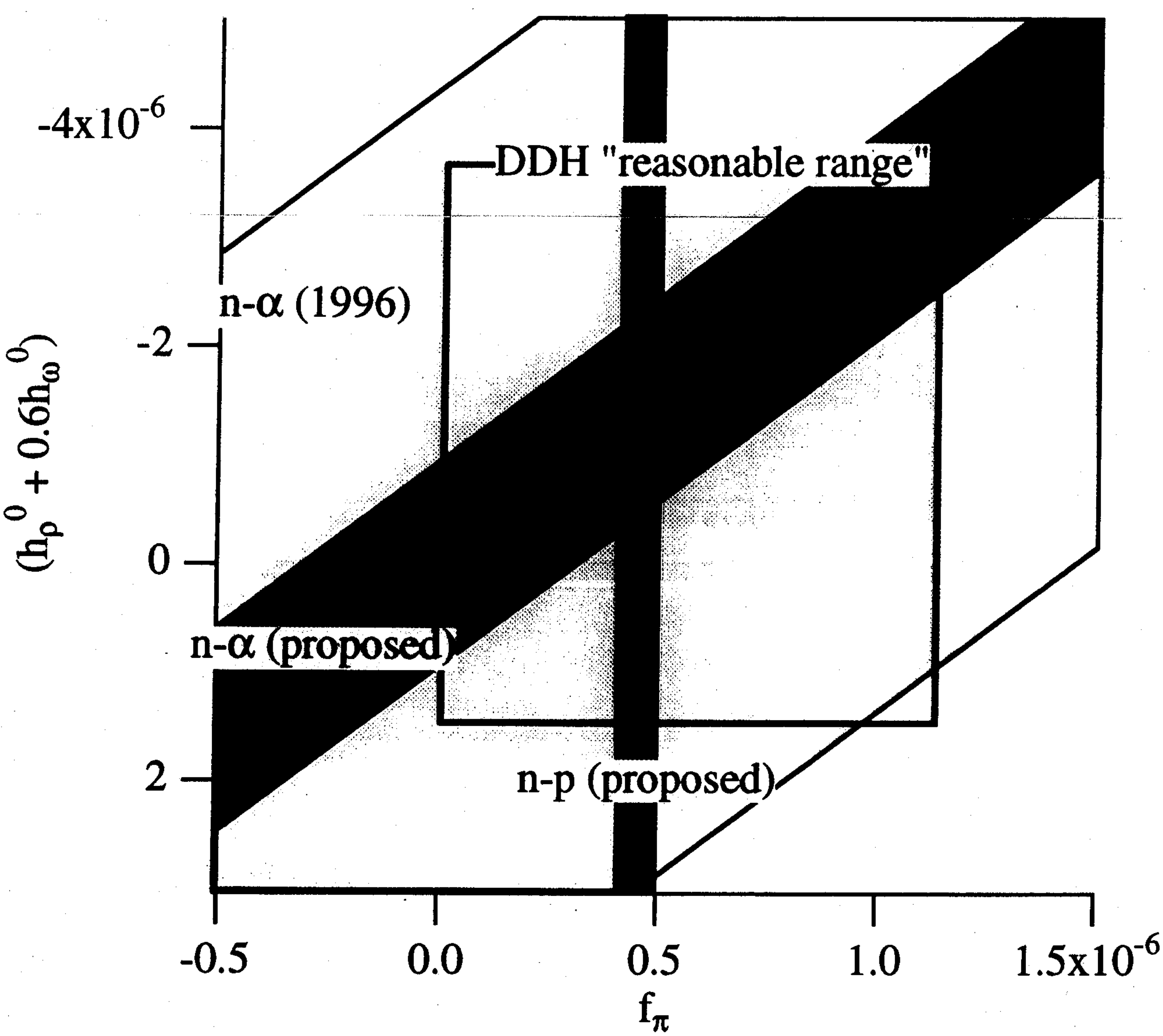
$$\phi_{PNC} = -0.6 \times 10^{-7}\ \text{rad/m}$$

Benefits of TOF signal neutron spin rotation experiment

1. Eliminate residual Larmor rotations (proportional to 1/v).

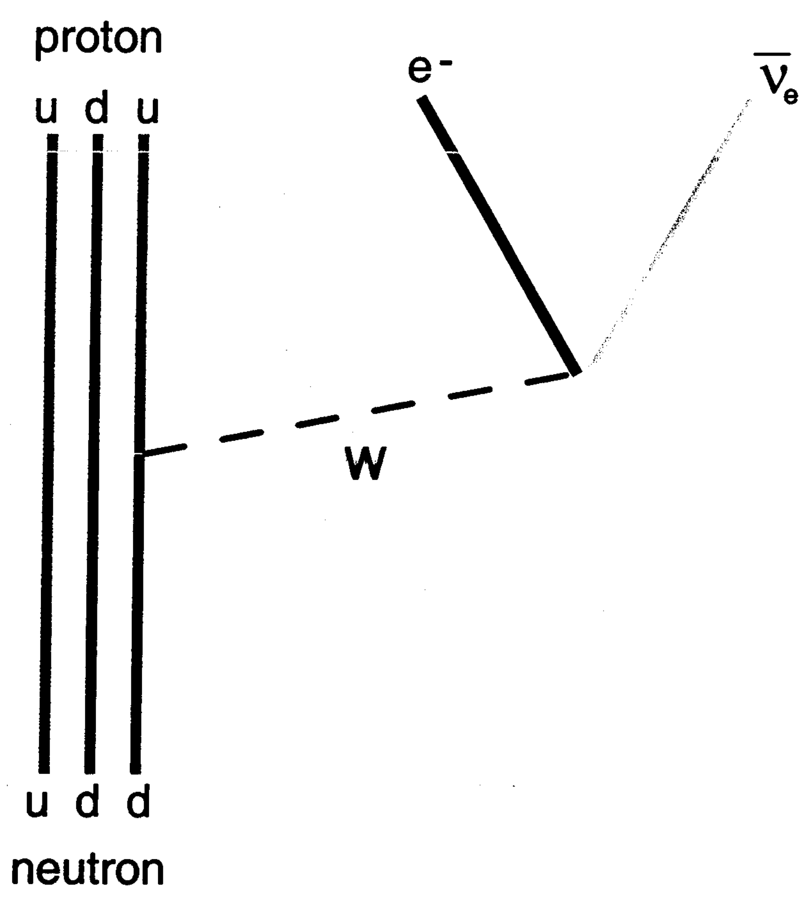
2. Ramp pi coil - increase useful range of wavelengths

3. Precise polarization analysis



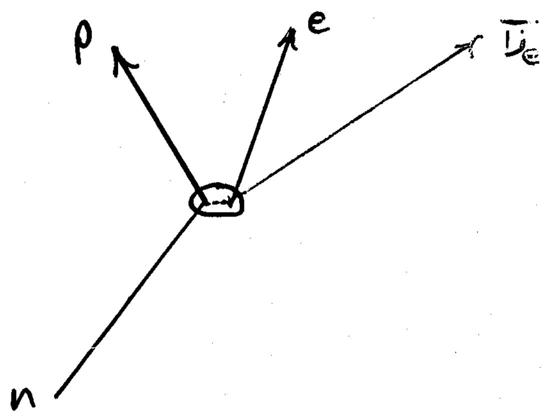
-4x10^-6
-2
0
2
DDH "reasonable range"
n-α (1996)
n-α (proposed)
n-p (proposed)
-0.5
0.0
0.5
1.0
1.5x10^-6
f_π
(h_ρ^0 + 0.6h_ω^0)

Neutron Beta Decay



$$n \rightarrow p + e^- + \overline{\nu}_e + 782\ \text{keV}$$

Neutron beta decay Hamiltonian:



$$\mathcal{H}_\beta = \frac{G_F}{\sqrt{2}} \sum_j \int d^3x \left[\bar{\Psi}_p \mathcal{O}_j \Psi_n\right]\left[\bar{\Psi}_e \mathcal{O}_j \left(C_j - C_j' \gamma_5\right) \Psi_{\nu_e}\right]$$

most generally includes all Lorentz-invariant terms:

scalar : C_S , C_S' $\quad \mathcal{O}_S = 1$

vector : C_V , C_V' $\quad \mathcal{O}_V = \gamma_\mu$

axial vector : C_A , C_A' $\quad \mathcal{O}_A = \gamma_\mu \gamma_5$

tensor : C_T , C_T' $\quad \mathcal{O}_T = \sigma_{\mu\nu}$

pseudoscalar : C_P , C_P' $\quad \mathcal{O}_P = \gamma_5$

The pseudoscalar term vanishes in the non-relativistic limit

Experimental evidence from beta decay shows (Paul 1970, Boothroyd et al. 1984):

$C_V = C_V' \quad C_A = C_A'$ within $\approx 1\%$

$C_S,\ C_S',\ C_T,\ C_T' \approx 0$ within $\approx 10\%$

- basis for the V-A theory of weak interactions

- assumed by the EW Standard Model

But: non-standard physics (SUSY, GUT's, RHC, extra Higgs, etc.)

could lead to interesting deviations

Neutron decay is an excellent laboratory for testing this

- experimentally tractable (but difficult!)
- theoretically simple (no nuclear wave functions)

At the quark level :

$$J_q^{\mu} = \overline{\Psi}_q \gamma^{\mu}(1-\gamma_5)\Psi_q$$

The proton, neutron static quark wave functions give :

$$\frac{C_A}{C_V} = -\frac{5}{3}$$

Conservation of Vector Current (CVC)

requires $\quad C_V = 1$

but the value of C_A is altered by the strong interaction

$$\frac{C_A}{C_V} \equiv \lambda \quad \text{must be determined experimentally}$$

weak coupling constants : $\quad g_V = \cos\theta_c \, C_V \, G_F$

$\qquad\qquad\qquad\qquad\qquad\quad g_A = \cos\theta_c \, C_A \, G_F$

so $\quad \dfrac{g_A}{g_V} = \lambda$

Neutron Decay Parameters

Phenomenological ($J = 1/2 \rightarrow J = 1/2$) beta decay formula [Jackson, Treiman, Wyld, 1957] :

$$dW \propto \frac{1}{\tau} F(E_e) \left[1 + \boxed{a} \frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + \boxed{b} \frac{m_e}{E_e} + \boxed{A} \frac{\vec{\sigma}_n \cdot \vec{p}_e}{E_e} \right.$$

$$\left. + \boxed{B} \frac{\vec{\sigma}_n \cdot \vec{p}_\nu}{E_\nu} + \boxed{D} \frac{\vec{\sigma}_n \cdot (\vec{p}_e \times \vec{p}_\nu)}{E_e E_\nu} \right]$$

For allowed beta decay, neclecting recoil order terms, the standard electroweak model (Weinberg, Glashow, Salam, et al.) predicts:

$$a = \frac{1 - \lambda^2}{1 + 3\lambda^2} \qquad b = 0$$

$$A = -2 \frac{\lambda^2 + \mathrm{Re}(\lambda)}{1 + 3\lambda^2} \qquad B = 2 \frac{\lambda^2 - \mathrm{Re}(\lambda)}{1 + 3\lambda^2}$$

$$D = 2 \frac{\mathrm{Im}(\lambda)}{1 + 3\lambda^2} \approx 0 \qquad \tau \propto \frac{1}{g_V^2 + 3g_A^2}$$

where $\lambda \equiv \dfrac{g_A}{g_V}$

Testing the Standard Model

Standard Model predicts:

$$F_1 \equiv 1 + A - B - a = 0$$

$$F_2 \equiv aB - A - A^2 = 0$$

Present experimental values:

$$F_1 = 0.0025 \pm 0.0064$$

$$F_2 = 0.0034 \pm 0.0050$$

The uncertainty is dominated by the measurement of "a".

A departure could be caused by:

- **recoil order corrections ($\approx 10^{-3}$ in decay parameters)**
- right handed weak currents
- scalar, tensor weak forces
- CVC violation
- second class weak hadronic currents } Gardner and Zhang (2000)

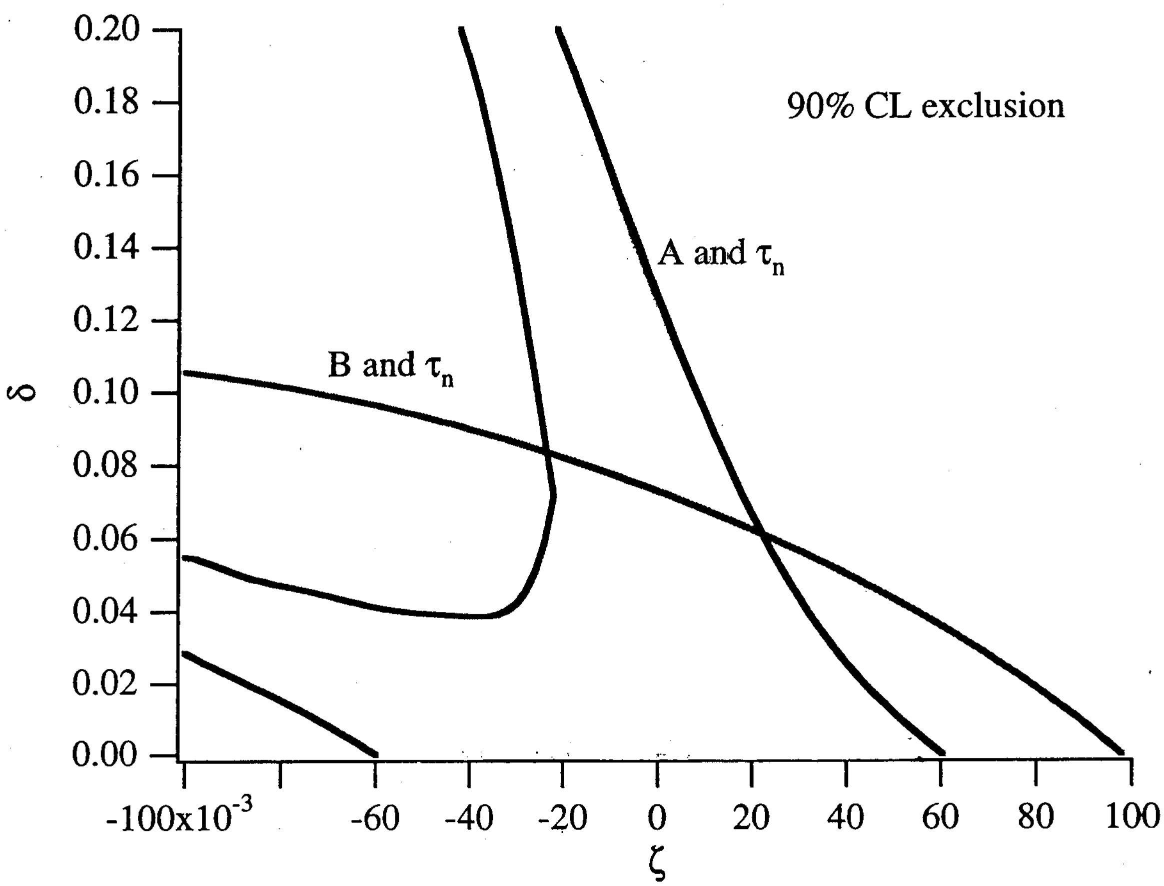
Limits on RHC from Neutron Decay

(J. Deutsch, 1997)

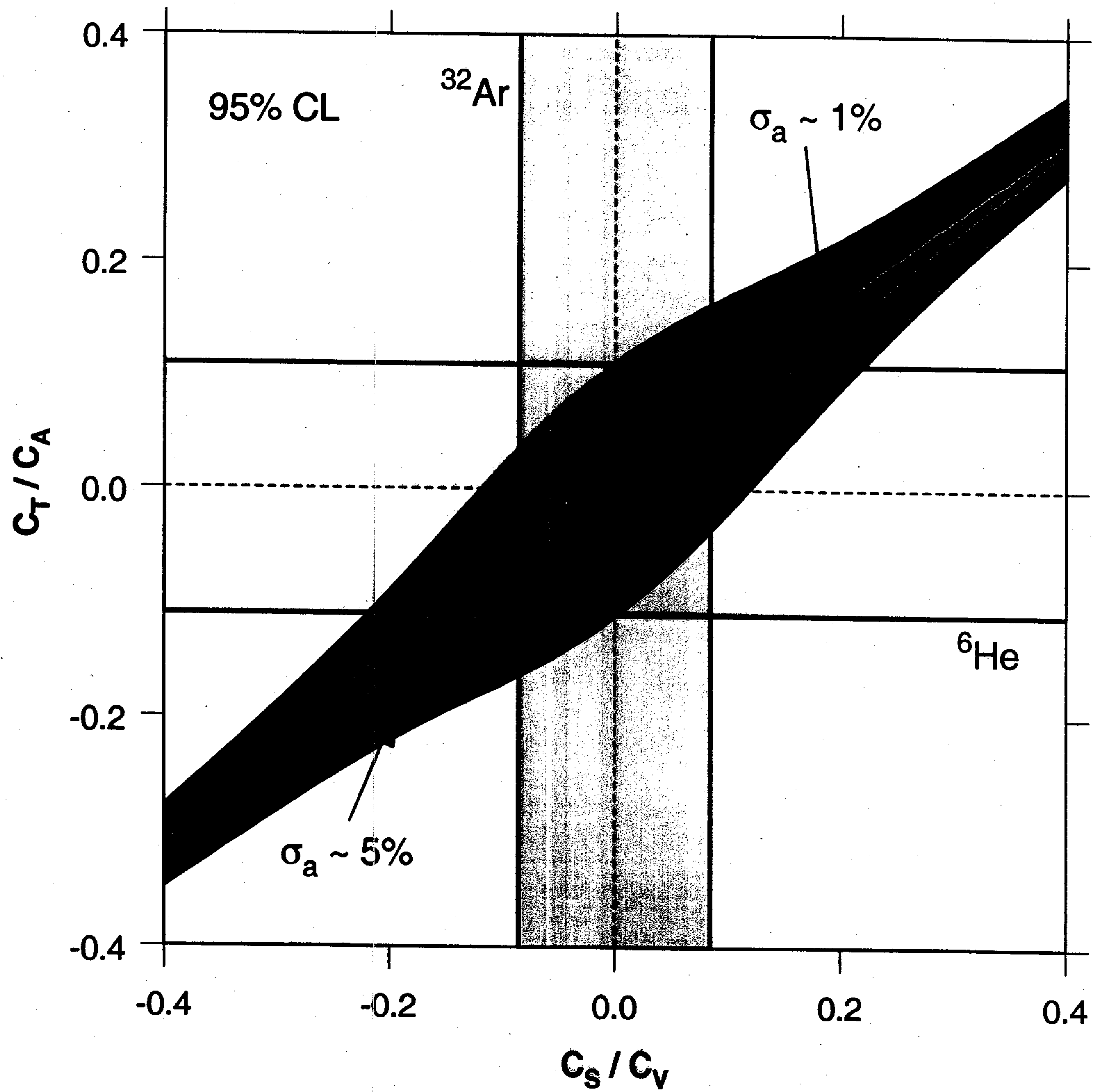
weak vector bosons:

$$W_L = W_1 \cos\zeta + W_2 \sin\zeta$$
$$W_R = -W_1 \sin\zeta + W_2 \cos\zeta$$

$$\delta = (m_1 / m_2)^2$$



Scalar and Tensor Currents



Unitarity of V_{CKM}

V_{CKM}: 3x3 matrix that transforms the quark mass eigenstates to weak eigenstates

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

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

From high energy experiments:

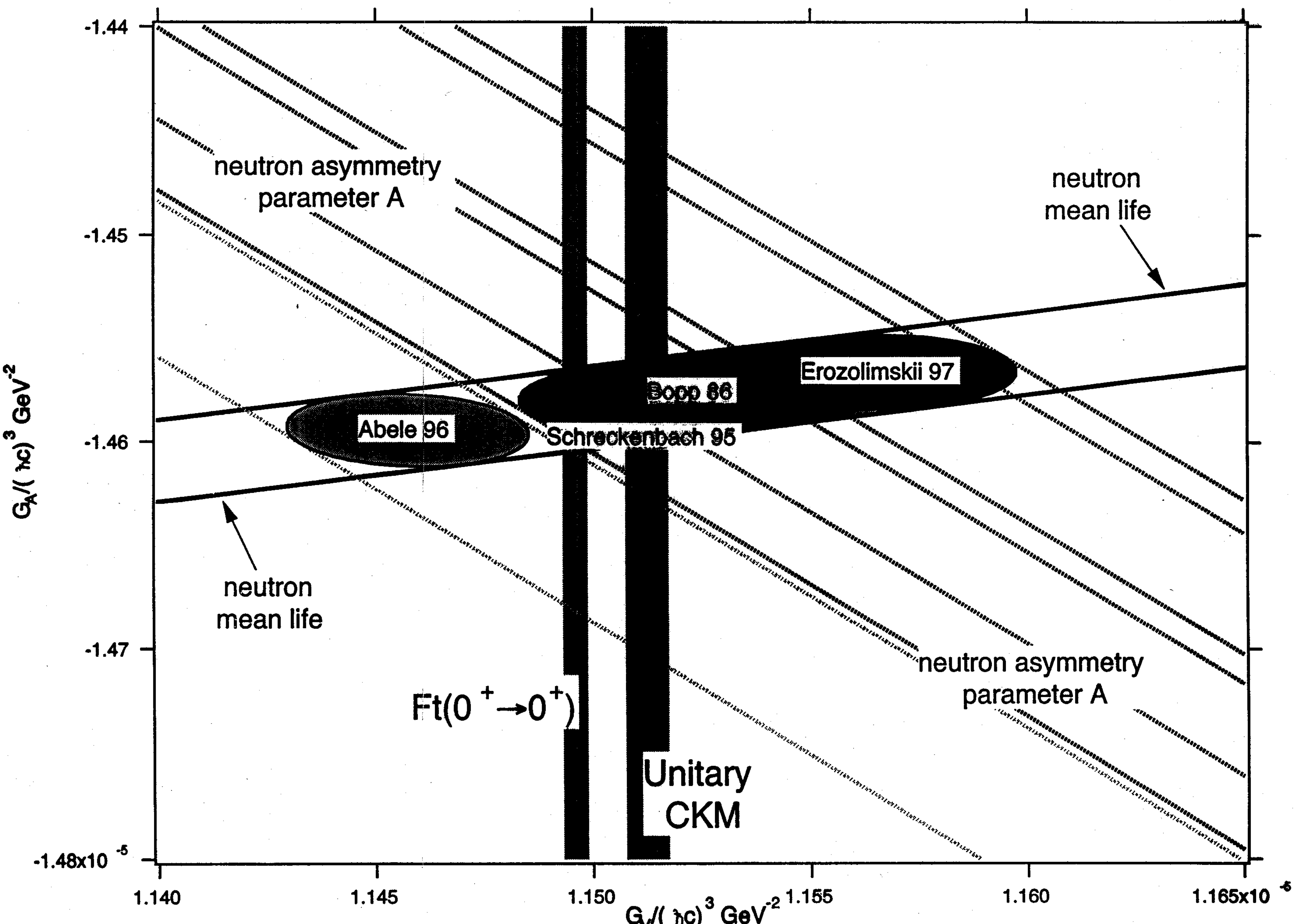
$$|V_{us}| = 0.2196 \pm 0.0023$$
$$|V_{ub}| = 0.0032 \pm 0.0008$$

$|V_{ud}|$ can be measured in three ways:

1. $0^+ \rightarrow 0^+$ nuclear beta decay

2. neutron decay parameters

3. pion beta decay



from B. Fujikawa

The Importance of Neutron Decay Parameters

τ_n : Big Bang nucleosynthesis - determines primordial ^4He abundance

g_V : determines V_{ud}, test of CKM unitarity

g_A : axial vector coupling in weak decays

D : search for new CP violation

a, A, B : precise comparison is sensitive to non-SM physics:

- right handed currents
- scalar and tensor forces
- CVC violation
- second class currents

Neutron Beta Asymmetry Coefficient (A):

PERKEO II (ILL, France)

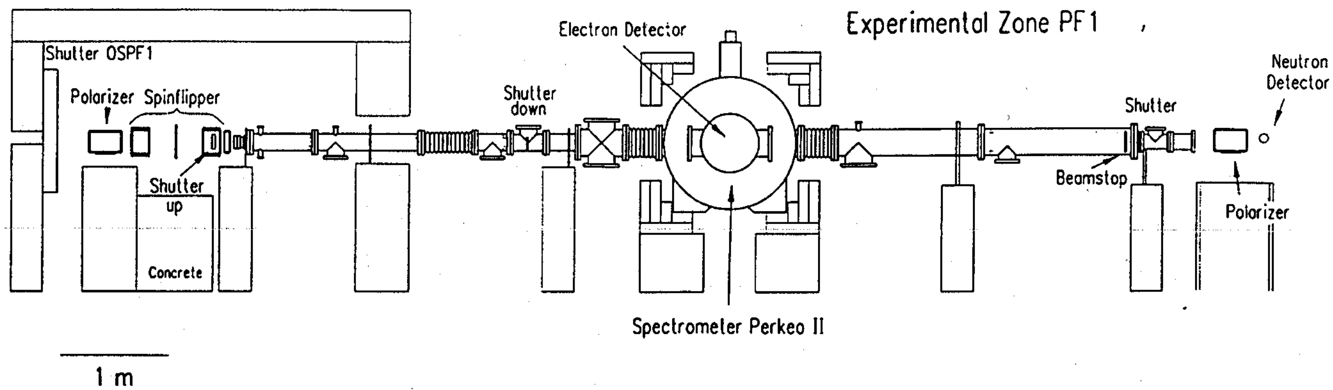


Fig. 1. View of the setup.

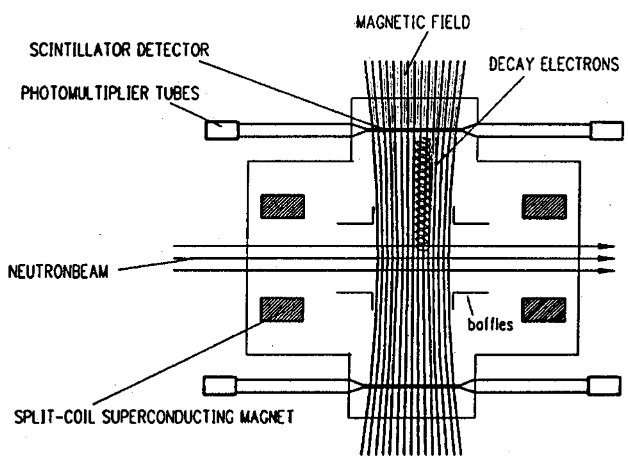


Fig. 2. A schematic view of the spectrometer.

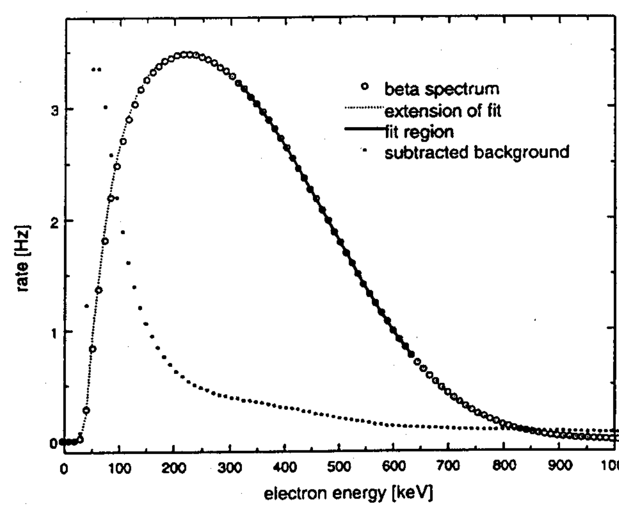


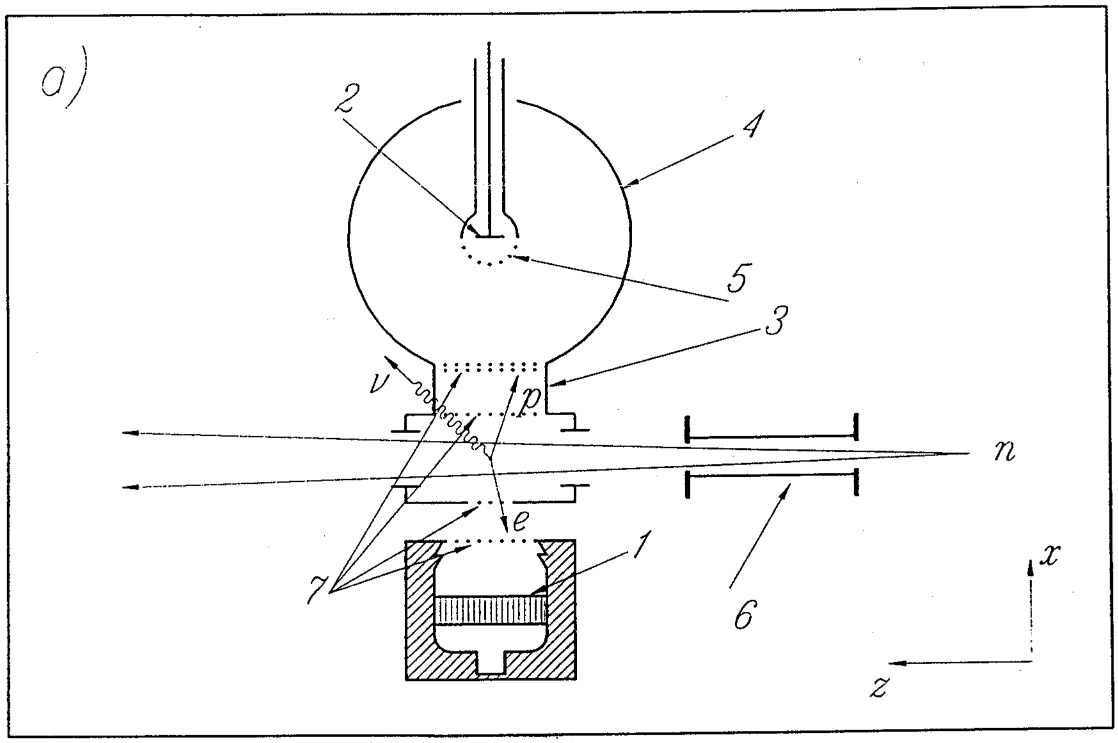
Fig. 3. The beta spectrum in detector 1 is shown, with a fit, its extrapolation and the subtracted background.

The experiment measures the product PA.
The beam polarization was determined to 0.1% using three different methods.

Result: A = -0.1189(8)

Neutron Antineutrino Asymmetry Coefficient (B):

Serebrov, et al. (ILL, France)



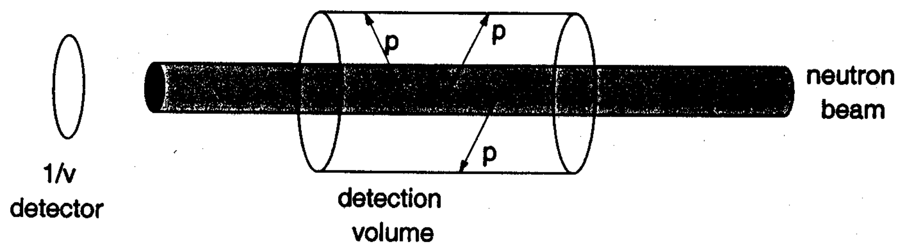
Measurement of the proton TOF
(gives x-component of momentum) and
beta energy is sufficient to determine $\cos\theta_{\sigma\nu}$

The experiment measures the product PB.
The beam polarization was determined to 0.4% .

Result: B = 0.9821(40)

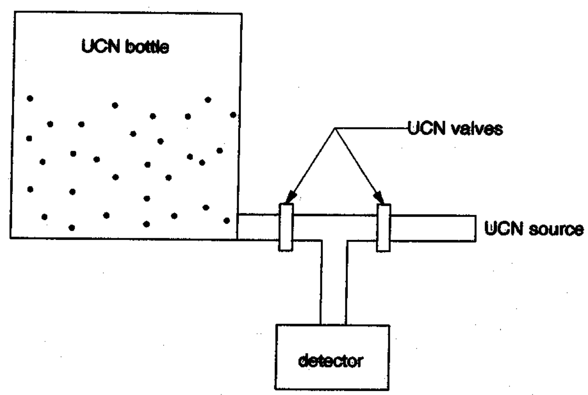
Neutron Lifetime

1) Beam:



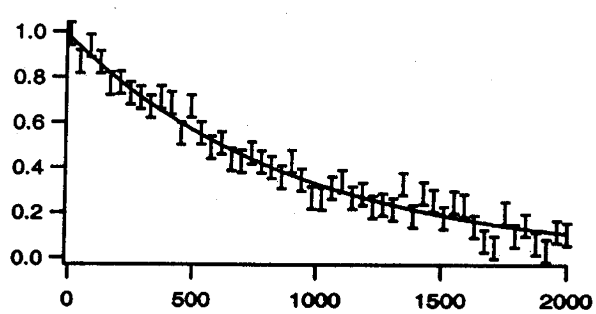
$$\tau = \frac{N}{\Gamma} = \frac{1}{\Gamma}\left(\frac{\phi}{v}\right)V_{det}$$

2) Bottle:



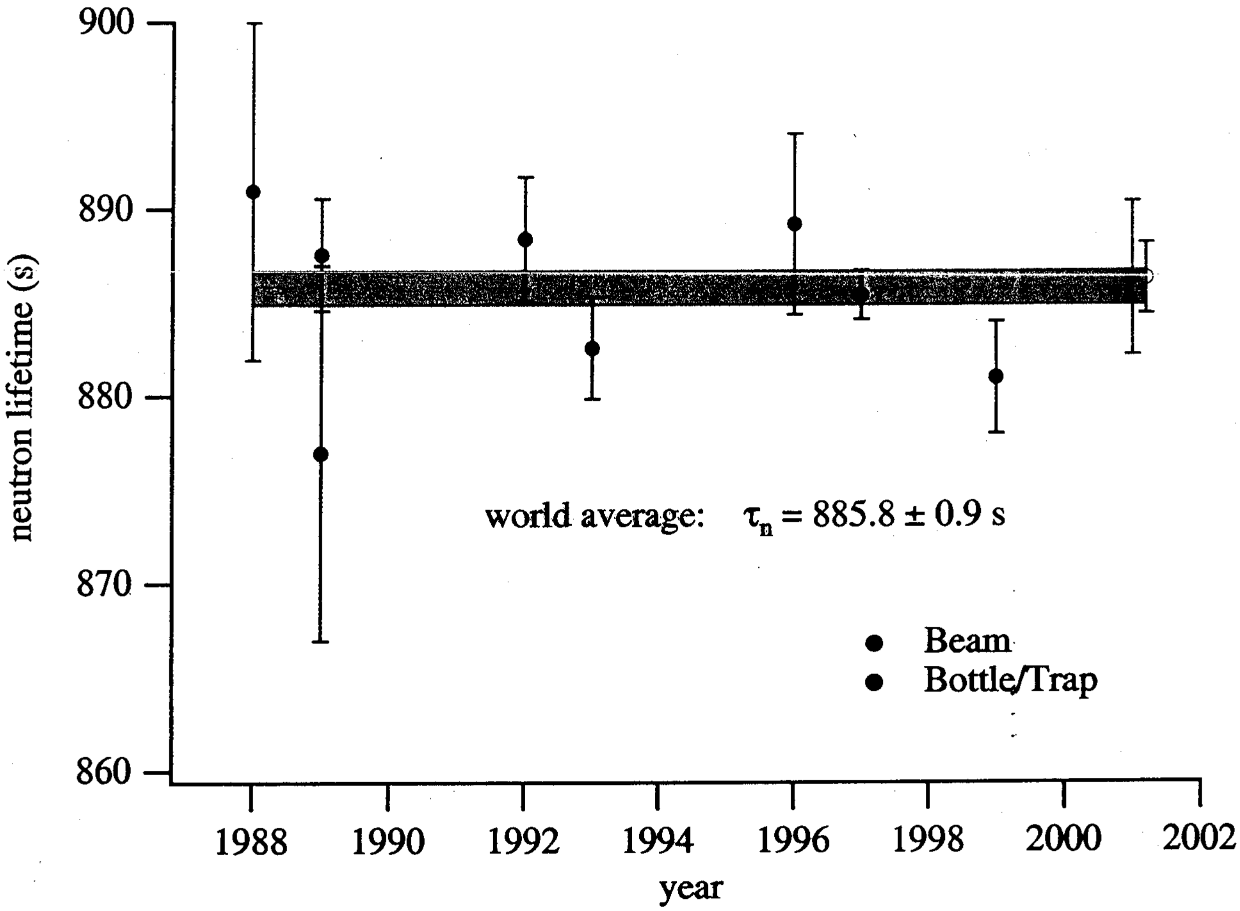
$$\tau = \frac{\Delta T}{\log\left(\frac{N_0}{N_1}\right)}$$

3) Exponential decay:



$$N(t) = N_0 e^{-\frac{t}{\tau}}$$

Recent Measurements of the Neutron Lifetime



Year	Value	Error	Who
1988	891	9	Spivak (USSR)
1989	887.6	3	Mampe (France, UK, USA)
1989	877	10	Paul (Germany, France, USA)
1992	888.4	3.3	Serebrov (Russia)
1993	882.6	2.7	Morozov (Russia)
1996	889.2	4.8	Byrne (UK, USA, France)
1997	885.4	1.3	Morozov (Russia, France)
1999	881	3	MAMBO II (France, UK, USA)

Nature 403, 62 (2000)

Magnetic Trapping of Ultracold Neutrons

C. R. Brome, J. S. Butterworth, S. N. Dzhosyuk, P. R. Huffman, C. E. H. Mattoni, D. N. McKinsey and J. M. Doyle
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S. K. Lamoreaux and G. L. Greene
Los Alamos National Laboratory

VE RI TAS HARVARD

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NIST

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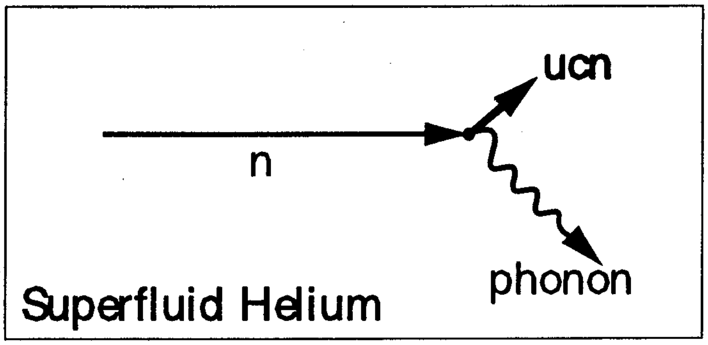
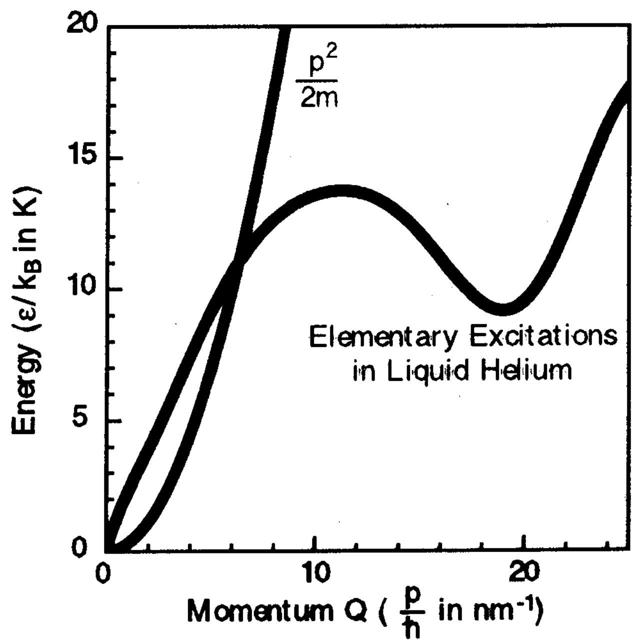
Superthermal UCN Production



$$\vec{p}_{ucn} = \vec{p}_n - \vec{q}_{phonon}$$

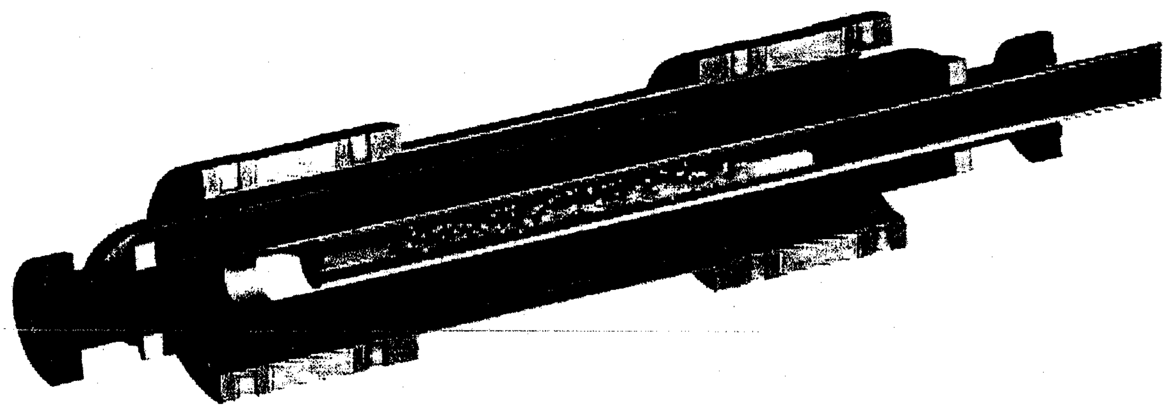
$$E_{ucn} = E_n - E_{phonon}$$

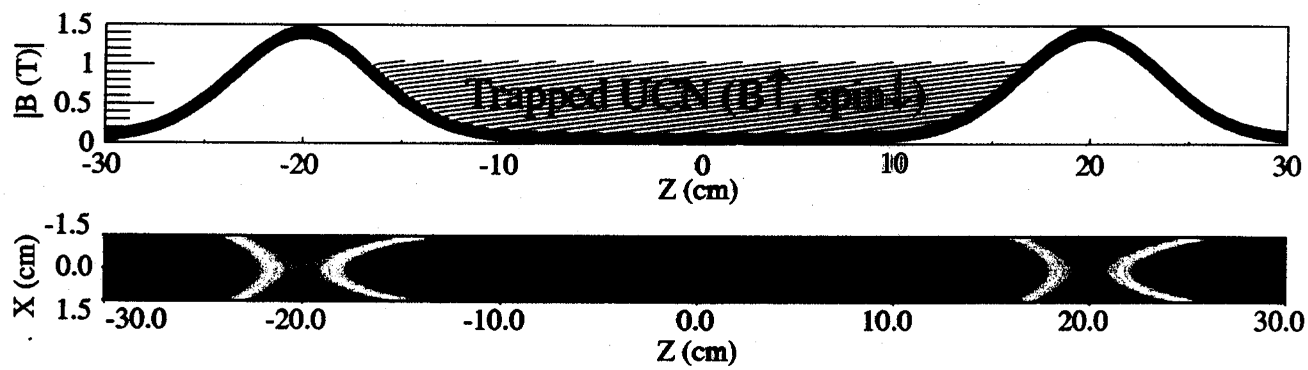


- Neutrons of energy E ≈ 0.95 meV (11 K or 0.89 nm) can scatter in liquid helium to near rest by emission of a single phonon.

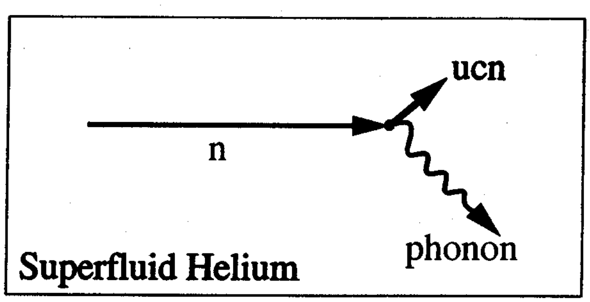
- Upscattering (by absorption of an 11 K phonon) μ
  Population of 11 K phonons ~ $e^{-11K/T_{bath}}$

Magnetic Trapping of Ultracold Neutrons

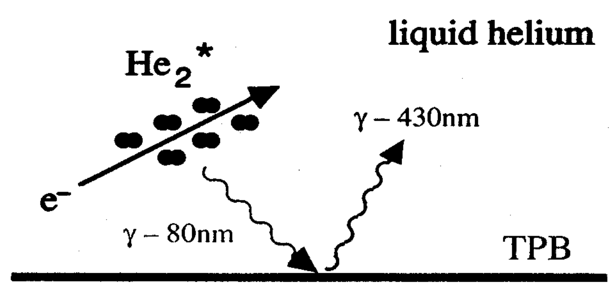




Trap Depth of 1 Tesla (0.7 mK)



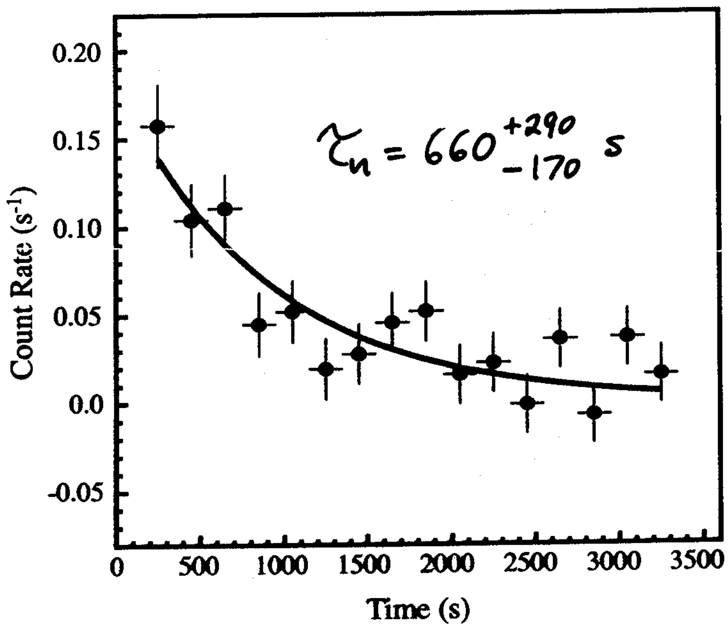
Neutrons Scatter in a 300 mK Helium Bath



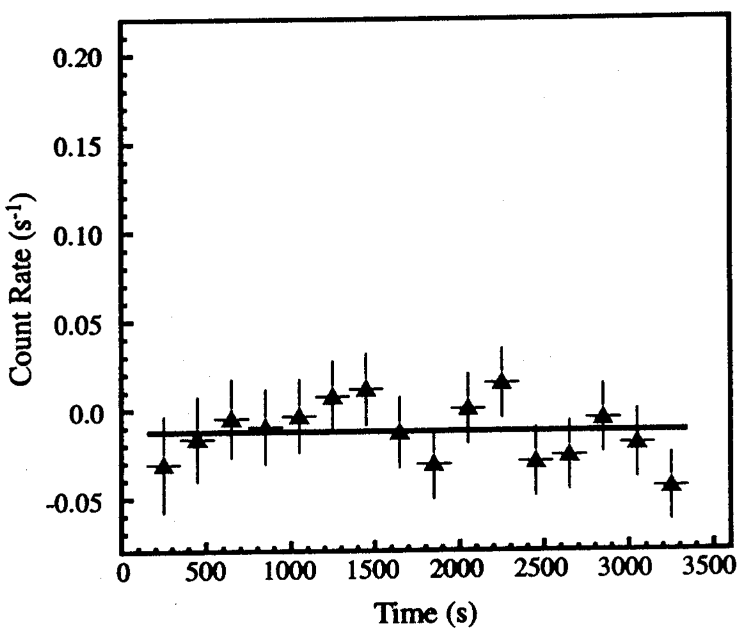
Liquid Helium Scintillations

Magnetic Trapping of Ultracold Neutrons

Loading 560 ± 160 UCN into trap



Trapping Signal



^{3}He Non-Trapping Signal

Magnetically trapped UCN lifetime experiment

biggest problems: n activation background
luminescence background

at start of counting cycle signal/bkgd = 0.03

A big part of the solution to the background problem is to illuminate the cell with 8.9Å neutrons only.

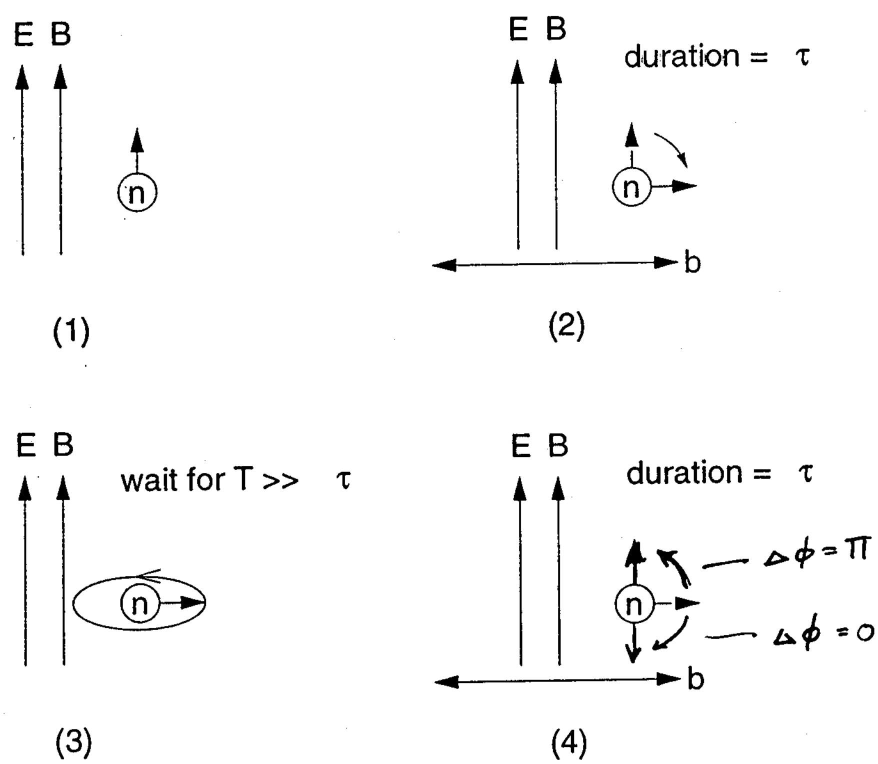
Efficient velocity selection!

Neutron Electric Dipole Moment

Hamiltonian: $$\mathrm{H} = -2(\mu_n \sigma \cdot \mathbf{B} + d_n \sigma \cdot \mathbf{E})$$

violates P and T

spin precession frequency: $$\nu = -2\left(\frac{\mu_n B}{\hbar} + \frac{d_n E}{\hbar}\right)$$



(5) analyze polarization

(6) repeat for opposite E

Results:

Institute Laue-Langevin
[Harris, *et al.*, Phys. Rev. Lett.. 82, 904 (1999)]

$$d_n = -1.0 \pm 3.6 \times 10^{-26} \text{ e cm}$$

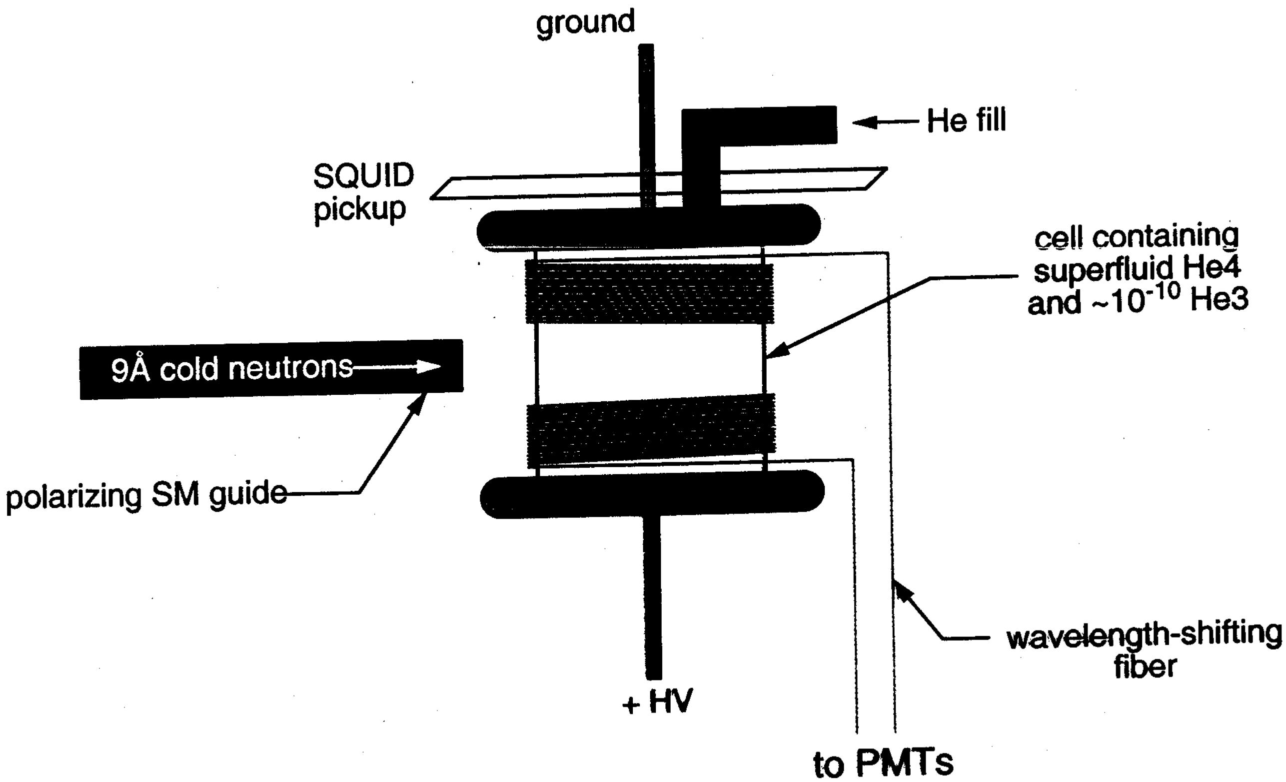
Petersburg Nuclear Physics Institute
[Altarev, *et al.*, Phys. Atom. Nucl. 59,1152 (1996)]

$$d_n = 2.6 \pm 4.8 \times 10^{-26} \text{ e cm}$$

Resulting limit on QCD theta parameter:

$$\theta_{eff} < 10^{-9}$$

Los Alamos Superthermal UCN EDM Experiment



signal: scintillation from 3He(n,p) reaction

σ = 10 kb (singlet)

σ = 0 (triplet)

$$N(t) = (\gamma_n - \gamma_3)Bt \pm 2ed_nE/\hbar$$

expected sensitivity ~ 10^{-28}e cm