Cold and Ultra-Cold Neutrons, The Particle Properties of the Neutron & A Brief Introduction to Spallation Source Physics

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Introduction to Cold & "Ultra-Cold" Neutrons

COLD NEUTRONS -

Characterized by a thermal velocity distribution with $T \approx 20K - 40K$

$v \approx 500$ m/s
$E_k \approx 5$ meV
$\lambda \approx 5$ Å

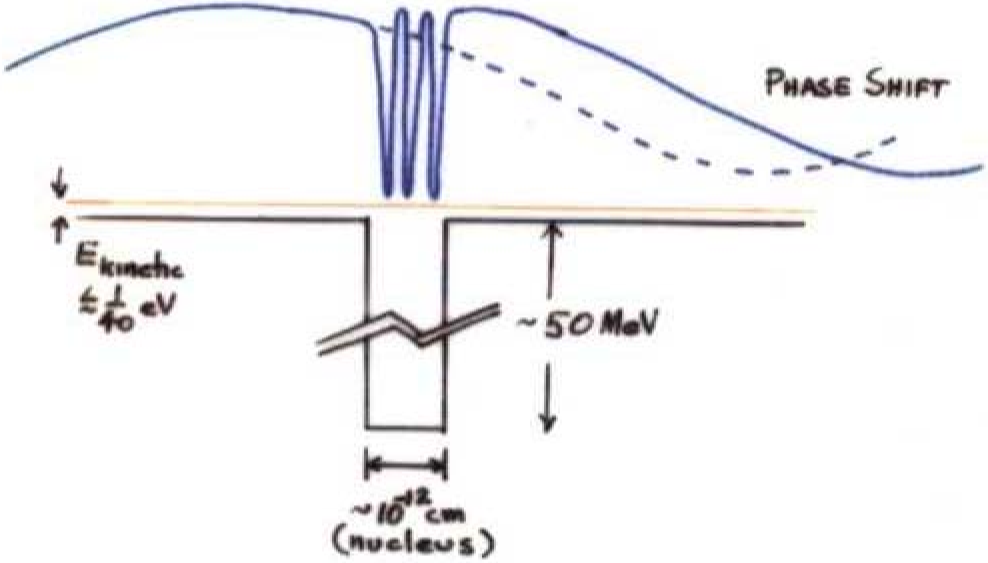
ULTRA-COLD NEUTRONS -

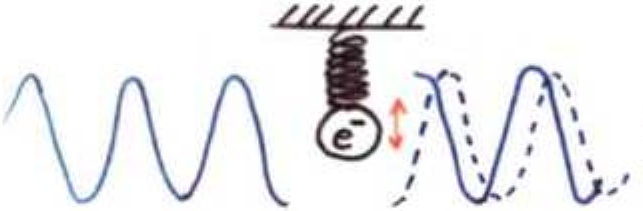
$v \approx 5$ m/s
$E_k \approx 100$ neV
$\lambda \approx 500$ Å

Can be "trapped" in -

- material bottle ($V_{eff} \approx 10^{-7}$ eV)
- magnetic bottle ($mv^2/2\mu_n \approx 1$ Tesla)
- gravitational well ($v^2/2g \approx 1$ m)

COHERENT ("OPTICAL") INTERACTION BETWEEN NEUTRONS AND MATTER





E-M WAVE INTERACTING WITH MATTER

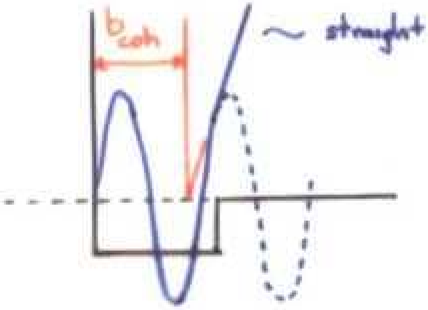
PHASE SHIFT ⇒ INDEX OF REFRACTION

$$n = \sqrt{1 - \frac{N\lambda^2 b_{coh}}{\pi}}$$

DEFINE <u>COHERENT</u> <u>SCATTERING</u> <u>LENGTH</u> b_{coh}

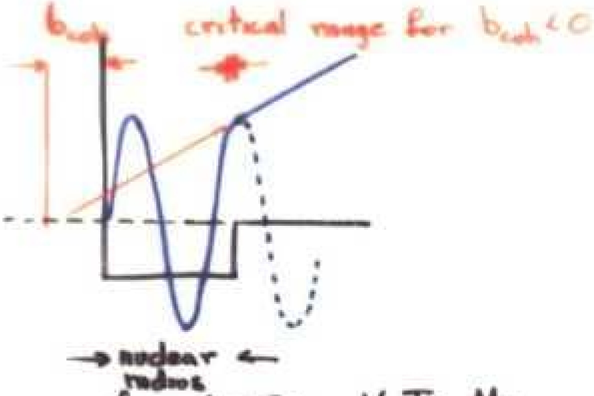
(consider only s-wave scattering – $k \to 0$)

$$k \cot \delta = \frac{-1}{b_{coh}}$$



~ straight line on this scale

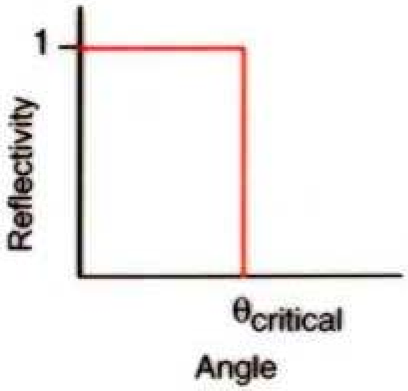
FOR MOST NUCLEI $b_{coh} > 0$

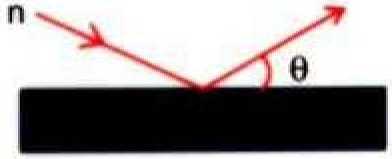


for $A \approx 50$ V, Ti, Mn

Reflectivity of Neutron Mirror

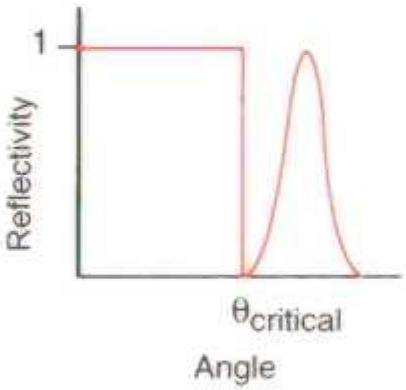
A Simple Neutron Mirror has Essentially Unit Reflectivity
Up to a Maximum Critical Angle

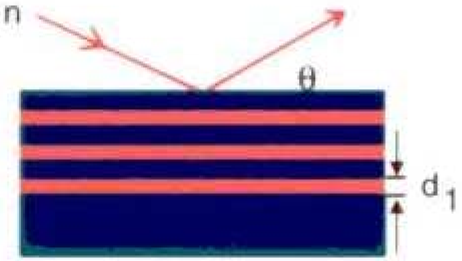




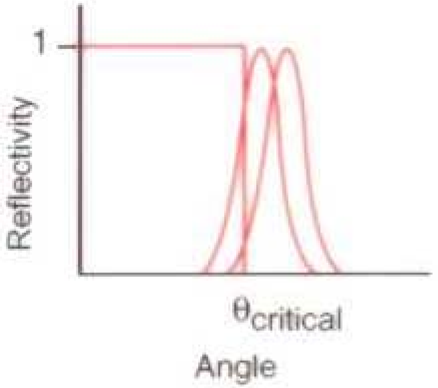
$\Theta_{critical} \cong 2$ mR/Å for ^{58}Ni

A Multilayer can add "Psuedo" Bragg Peak



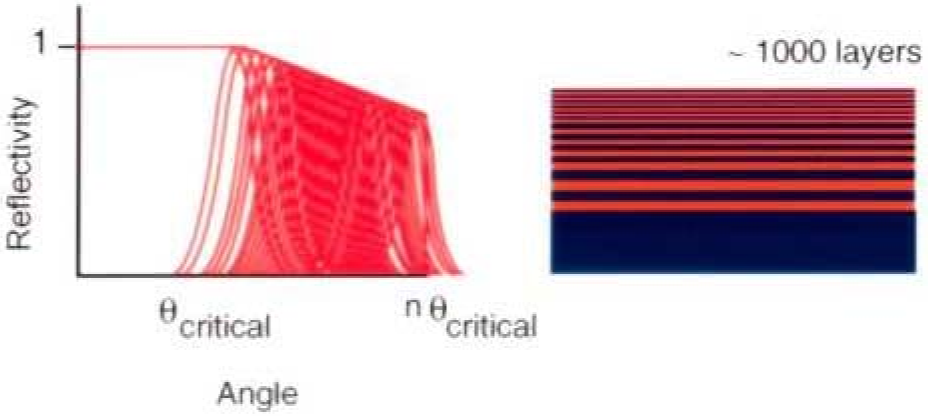


Additional Multilayers add More Peaks



The "Supermirror" Extends the "Effective" $\theta_{critical}$

Commercial Supermirror Neutron Guides are Available With $n \cong 3 - 4$



Neutron Polarization

Ferromagnetic Mirrors

Nuclear Spin Polarized ^{3}He

NEUTRON INDEX OF REFRACTION

$$n = 1 - \frac{\lambda^2 N b_{coh}}{2\pi}$$ for NON-MAGNETIC materials

$$n = 1 - \lambda^2 \left(\frac{N b_{coh}}{2\pi} \pm \frac{m}{4\pi^2 \hbar^2} \mu B \right)$$ for MAGNETIC materials

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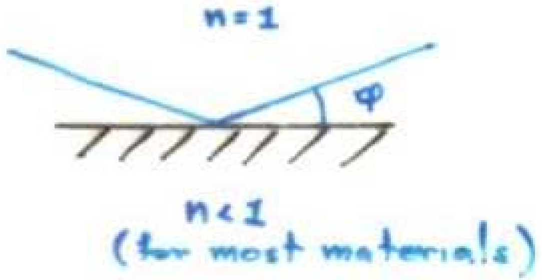
Critical Angle

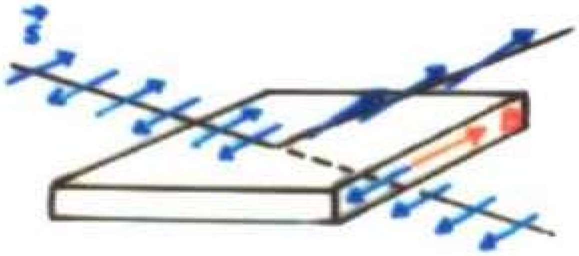
$$\cos \varphi_{crit} = n$$



POLARIZING MIRROR

PICK MATERIAL WHICH HAS $\frac{Nb_{coh}}{2\pi} = \frac{m\mu B}{4\pi^2\hbar^2}$

(Approximately true for 60% Fe - 40% Co
near magnetic saturation)



ONLY ↑↑ SPIN STATE IS REFLECTED

Spin Polarized ^{3}He can Serve as a Neutron Spin Filter

$$n + {}^3\mathrm{He} \longrightarrow {}^3\mathrm{H} + p$$

$$\Phi = \Phi_0 e^{-\sigma x_3} \qquad \sigma = \sigma_u \mp P_3(\sigma_s - \sigma_t)/4 = \sigma_u \mp P_3\sigma_s/4$$

$$\sigma_s = \sigma_0(v_0/v) \qquad \sigma_0 = 54 \text{ kbarn at 4 meV} \qquad v = L/t$$

$$\Phi_+ = \Phi_0 e^{-\sigma_u x_3 + \frac{P_3 x_3 \sigma_0 v_0}{4L} t}$$

$$\Phi_- = \Phi_0 e^{-\sigma_u x_3 - \frac{P_3 x_3 \sigma_0 v_0}{4L} t}$$

Accurate determination of the Neutron Polarization from first principles is difficult as it requires requires detailed Knowledge of thickness of cell, pressure in cell, ^{3}He polarization, …

Neutron Polarization is Simply Related to Transmission

The application of few hyperbolic trigonometric identities provides a greatly simplified relation for the neutron polarization that is based only on (relatively) easy to measure Neutron transmission:

$$P_n = \sqrt{1 - T_0^2/T^2}$$

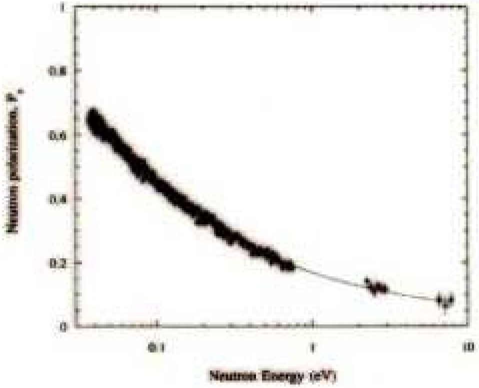
Where T_0 is the transmission with the cell unpolarized and T is the transmission with the cell polarized.

*Greene, Thompson, Dewey, **A356**, 177, (1994)*

The Parametric relation for P_n has been verified

$$P_n = \frac{\Phi_+ - \Phi_-}{\Phi_+ + \Phi_-} = \tanh\left(\frac{P_3 x_3 \sigma_0 v_0}{4L} t\right)$$

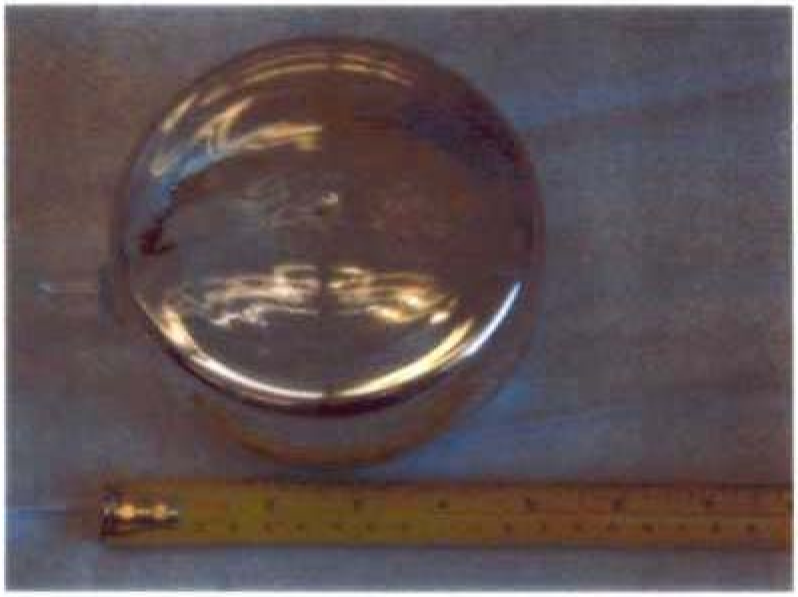
$$P_n = \tanh(t/\tau) \qquad \tau = \frac{4L}{P_3 x_3 \sigma_0 v_0}$$



$$\Delta P_n \leq 0.2\%$$

D.R. Rich, *et al.* Nucl. Instr. Meth., In press.

NIST Polarized ^{3}He Cell



Brief Review of the Particle Properties of the Neutron

Some Neutron Properties

√ *Mass*
√ *Gravitational Mass (equivalence principle test)*

√ *Charge (limit on neutrality)*
√ *Magnetic Dipole Moment*
√ *Electric Dipole Moment*
√ *Magnetic Monopole*
Electric Polarizabilitiy
√ *Internal Charge Distribution*

√ *Lifetime*
√ *Decay Correlations*
√ *Rare Decay Modes*

Spin (S)
Intrinsic Parity (P)
Isospin (I)
Baryon Number (B)
Strangeness (S)
...

√ *Denotes application for Cold/UltraCold Neutrons*

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The Neutron Mass

Assume that Isospin is broken by electromagnetism

$(m_p - m_n)c^2 \approx \frac{e^2}{r_{nucleon}}$

Thus

$m_p - m_n \approx 100 \text{ keV}$

Determination of the Neutron Mass

The best determination of the neutron mass considers the reaction:

$$n + p \rightarrow d + \gamma$$

and measures two quantities with high accuracy:

1. *A gamma ray energy*

   The actual experiment is an absolute determination of the 2.2MeV gamma ray wavelength in terms of the SI meter.

2. *A mass difference*

   The actual experiment is the determination of the D - H mass difference in atomic mass units.

Determination of the Neutron Mass

$\lambda^* = 5.573\ 409\ 78(99) \times 10^{-13}$ meters

E. G. Kessler, et. al., Phys Lett A, 255 **(1999)**

$M(D) - M(H) = 1.006\ 276\ 746\ 30(71)$ atomic mass units (u)

F. DiFilippo, et. al., Phys Rev Lett, 73 **(1994)**

which gives

$M(n) = 1.008\ 664\ 916\ 37(99)$ atomic mass units (u)

Who cares about all those decimal places?

THE FINE STRUCTURE CONSTANT FROM h/m_n

$$\alpha = \frac{e^2}{\hbar c}$$

$$\alpha = \left[\frac{4\pi^2 e^4}{h^2 c^2}\right]^{1/2}$$

$$\alpha = \left[2R_\infty c\,\frac{h}{m_e}\right]^{1/2} \qquad R_\infty = \frac{2\pi^2 m_e e^4}{h^3 c}$$

$$\alpha = \left[2R_\infty c\left(\frac{m_p}{m_e}\right)\left(\frac{m_n}{m_p}\right)\frac{h}{m_n}\right]^{1/2}$$

$$\begin{array}{c}\text{Approximate errors}\\ \text{experimental quantities}\end{array}\begin{cases} R_\infty \sim 0.001\ \text{ppm}\\ m_p/m_e \sim 0.02\ \text{ppm}\\ m_n/m_p \sim 0.01\ \text{ppm}\\ h/m_n \sim 0.08\ \text{ppm}\end{cases}$$

$$\boxed{\alpha^{-1} \sim 0.04\ \text{ppm}}$$

This is comparable to the best "non-QED" value for α and requires no electrical measurements or solid state theory !

DETERMINATION OF h/m_n

Planck relation: $\lambda = h/m_n v$

A simultaneous measurement of both λ *and* v *for a neutron provides a determination of the ratio of the Planck constant to the neutron mass:*

$$\boxed{h/m_n = \lambda / v}$$

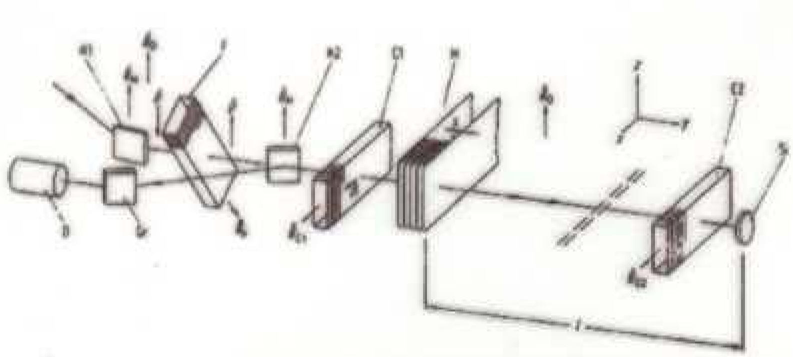
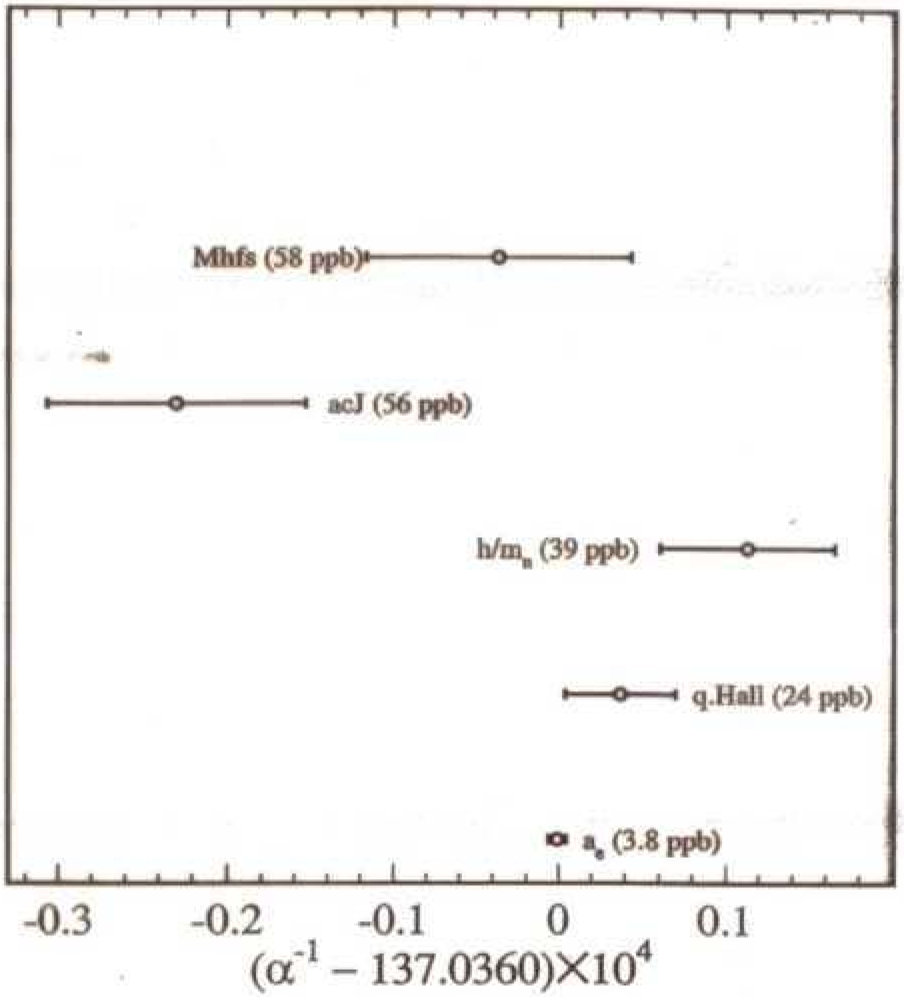


Fig. 1. Arrangement for measuring h/m_n. (H1, H2) Heusler crystals, (F) flipping coil, (C1, C2) $\pi/2$ coils, (M) meander coil, (S) silicon crystal, (Gr) oriented graphite, (D) detector. B_0: magnetic induction of the guide field; B_H: magnetic induction magnetizing a Heusler crystal; p: polarization vector if the meander coil is turned off.

$$h/m_n = 3.95603330(30) \times 10^{-7}\ m^2 s^{-1}$$

Kuger, Nistler & Weirauch, NIM, A284, 143 (1989)
Kuger, Nistler & Weirauch, PTB Ann Rep (1992) . . .

Values of the Fine Structure Constant



Equivalence Principle Test with Neutrons

The measurement of the neutron mass represents a determination of the neutron's INERTIAL mass. To determine the neutron's GRAVITATIONAL mass, one must compare the free fall acceleration of the neutron with the acceleration g of macroscopic test masses:

$$F_n = m_i a_n$$
$$m_g g = m_i a_n$$

$$m_g / m_i = a_n / g \equiv \gamma$$

The Neutron Charge

Is The Neutron Neutral ?

Theory: From time to time, the neutrality of matter and/or the equality of the electron and proton charges have been questioned.

Einstein ('24), Blackett ('47), Bondi ('59), Chu ('87)...

THE NEUTRON IS THE ONLY NEUTRAL PARTICLE ON WHICH A PRECISION TEST OF NEUTRALITY HAS BEEN MADE

Experiment: "BRUTE FORCE" - Deflection of neutron beam transverse electric field.

NEUTRON VELOCITY	- 200 m/s
FLIGHT PATH	- 10 m
ELECTRIC FIELD	- 60 kV/cm

DEFLECTION SENSITIVITY - 1 nm

$$Q_n = (-0.4 \pm 1.1) \times 10^{-21} e$$

Baumann et al ('88)

NEUTRALITY OF NEUTRON
Plus
EQUALITY OF Q_e AND Q_p
Provides
TEST OF CHARGE CONSERVATION
IN THE WEAK INTERACTION

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*A limit on a possible magnetic "charge" (monopole) for the for the neutron of about 2 x $10^{-\text{[illegible]}}$ e/hc has also been set

Finkelstein et all ('86)

The Neutron Magnetic Moment

The Neutron Magnetic Moment

STATIC SU(6) MODEL: (Bég, Lee & Pais '64)

1. Baryons are color singlets with correct symmetry
2. Baryon magnetic moments arise solely from the static sum of the quark moments
3. Quark moments are proportional to quark charges (i.e. $\mu_u = -2\mu_d$)

1.
$$n_\uparrow = \sqrt{2/3}\, d_\uparrow d_\uparrow u_\downarrow - \sqrt{1/3}\left(\frac{d_\uparrow d_\downarrow + d_\downarrow d_\uparrow}{\sqrt{2}}\right) u_\uparrow$$
$$p_\uparrow = \sqrt{2/3}\, u_\uparrow u_\uparrow d_\downarrow - \sqrt{1/3}\left(\frac{u_\uparrow u_\downarrow + u_\downarrow u_\uparrow}{\sqrt{2}}\right) d_\uparrow$$

2.
$$\mu_n = -1/3\, \mu_u + 4/3\, \mu_d$$
$$\mu_p = -1/3\, \mu_d + 4/3\, \mu_u$$

3. $\mu_n / \mu_p = -2/3$

$$\mu_n / \mu_p = -0.68497935(17)$$

[Greene, et.al. Physics Letters, **71B**, 297 (1977)]

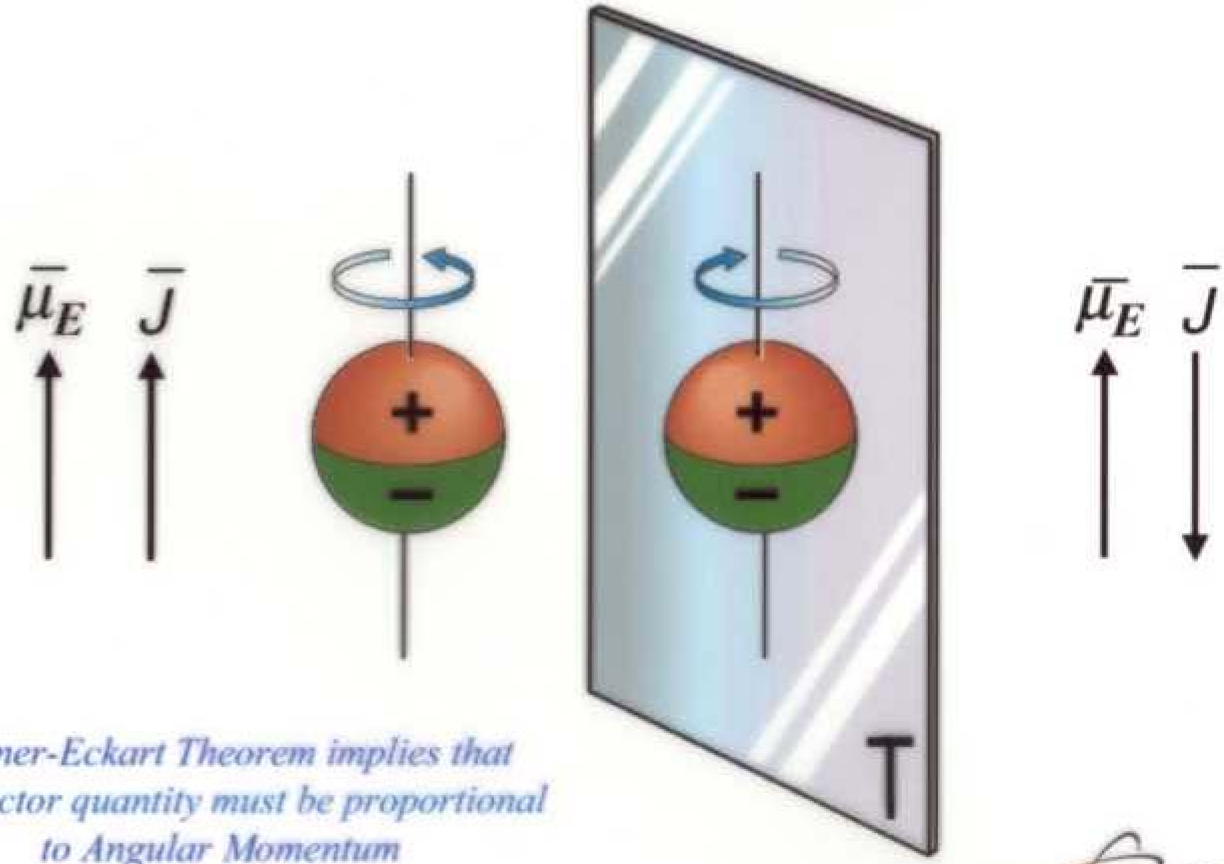
WHY IS THE AGREEMENT SO GOOD?

The Neutron Electric Dipole Moment

"It is generally assumed on the basis of some suggestive theoretical symmetry arguments that nuclei and elementary particle can have no electric dipole moments. It is the purpose of this note to point out that although these theoretical arguments are valid when applied to molecular and atomic moments whose electromagnetic origin is well understood, their extension to nuclei and elementary particles rests on assumptions not yet tested"

E.M.Purcell and N.F.Ramsey,
Physical Review 78, 807 (1950)

An Electric Dipole Moment Violates T Non-Invariance



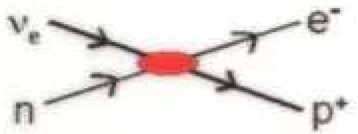
Wigner-Eckart Theorem implies that any vector quantity must be proportional to Angular Momentum

Neutron Beta Decay

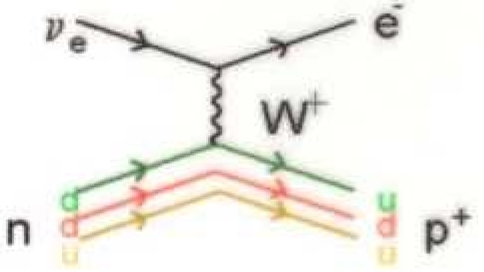
$$n \rightarrow p^+ + e^- + \overline{\nu}_e$$

$$n + \nu_e \rightarrow p^+ + e^- + \overline{\nu}_e + \nu_e$$

Neutron decay is best viewed as an interaction:

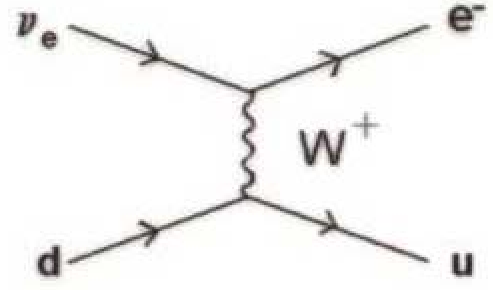


In the standard quark model this simple picture is complicated by the fact that it is the quarks within the nucleon which interact:



This is the point of departure For the construction of a theory of beta decay.

Theoretical Framework for Neutron Decay



We construct a Weak Hamiltonian that couples a down quark to an up quark, and an electron to an electron neutrino:

$$< \nu_e \mid H_{weak} \mid e^- > < d \mid H_{weak} \mid u >$$

Theoretical Implications the Neutron Beta-Decay Lifetime

Cosmology:

The neutron lifetime sets the time scale over which nucleosynthesis occurs during the Big-Bang. The comparison of the neutron lifetime, the cosmological He/H (or D/H) ratio, and the number of neutrino species provides a prediction for the Universal Baryon Density. This is a critical component of the "Dark Matter Problem."

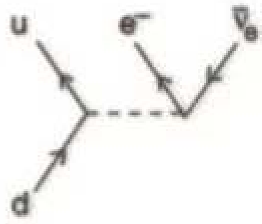
Astrophysics:

The reaction which provides the dominant source of energy in the Sun (pp fusion) is governed by the same matrix element as neutron decay. The neutron lifetime is a key parameter of the solar models which are involved in the "Solar Neutrino Problem"

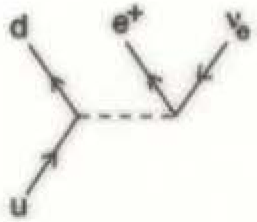
Particle Physics:

A comparison between the neutron lifetime and neutron decay correlations provides a unique test of the standard model, as well as providing an insight into the origin of parity violation.

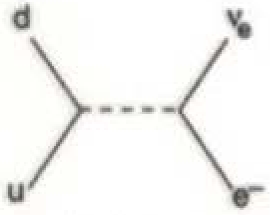
Nuclear Physics



β^- decay

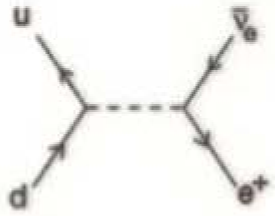


β^+ decay

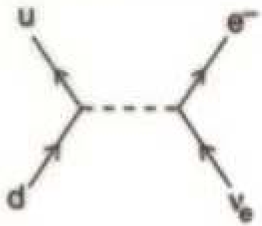


orbital electron capture

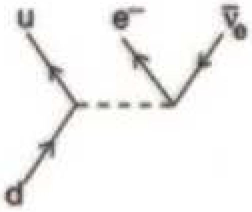
Big Bang



$ne^+ \to p\bar{\nu}_e$

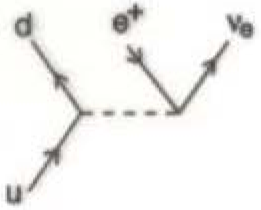


$n\nu_e \to pe^-$

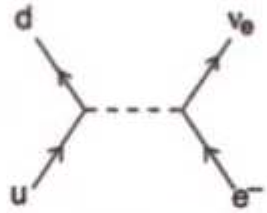


$n \to pe\nu_e$

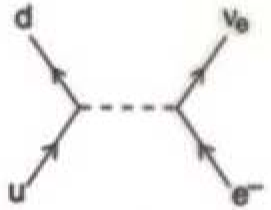
Nuclear Astrophysics



$pp \to De^+\nu_e$



$pe^-p \to De\nu_e$



core collapse

There Have Been Many Measurements of the Neutron Lifetime

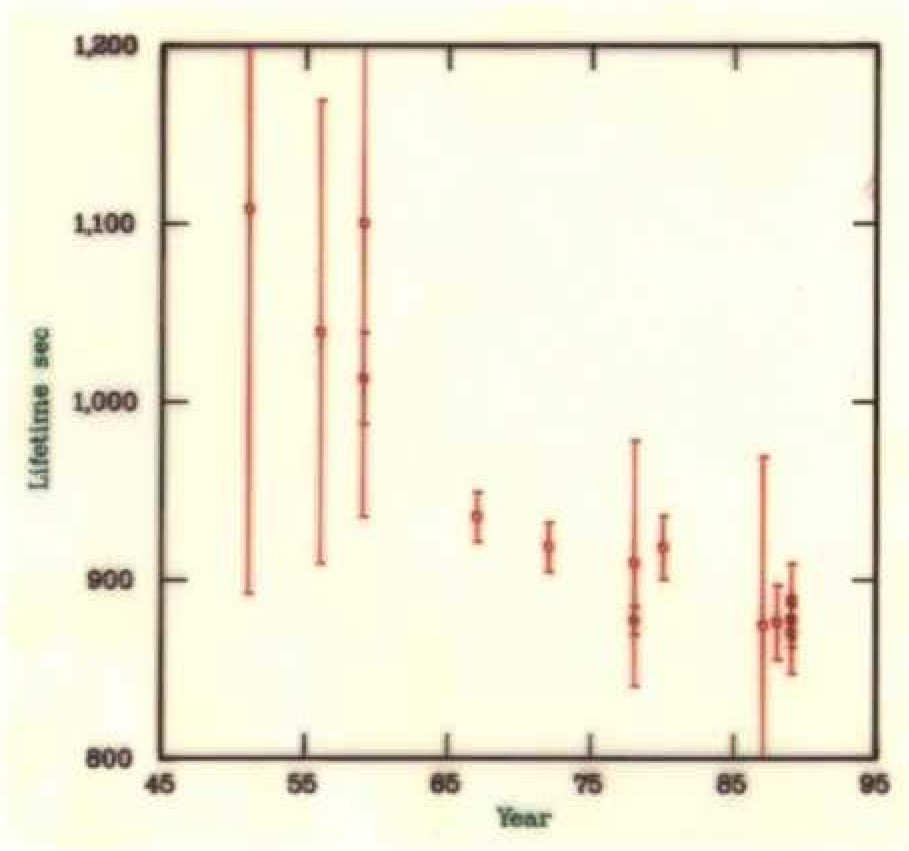
VALUE (s)	DOCUMENT ID	TECN	COMMENT
886.7± 1.9 OUR AVERAGE Error includes scale factor of 1.2			
889.2± 3.0± 3.8	BYRNE 96	CNTR	Penning trap
882.6± 2.7	[10] MAMPE 93	CNTR	Gravitational trap
888.4± 3.1± 1.1	NESVIZHEV... 92	CNTR	Gravitational trap
878 ±27 ±14	KOSSAKOW... 89	TPC	Pulsed beam
887.6± 3.0	MAMPE 89	CNTR	Gravitational trap
877 ±10	PAUL 89	CNTR	Storage ring
876 ±10 ±19	LAST 88	SPEC	Pulsed beam
891 ± 9	SPIVAK 88	CNTR	Beam
903 ±13	KOSVINTSEV 86	CNTR	Gravitational trap
918 ±14	CHRISTENSEN72	CNTR	
• • • We do not use the following data for averages, fits, limits, etc. • • •			
888.4± 2.9	ALFIMENKOV 90	CNTR	See NESVIZHEVSKII 92
893.6± 3.8± 3.7	BYRNE 90	CNTR	See BYRNE 96
937 ±18	[11] BYRNE 80	CNTR	
875 ±95	KOSVINTSEV 80	CNTR	
881 ± 8	BONDAREN... 78	CNTR	See SPIVAK 88

[10] IGNATOVICH 95 calls into question some of the corrections and averaging procedures used by MAMPE 93. The response, BONDARENKO 96, denies the validity of the criticisms.

[11] This measurement has been withdrawn (J. Byrne, private communication, 1990).

Particle Data Group, 2000
http://pdg.lbl.gov

Neutron Lifetime vs. Year of Measurement



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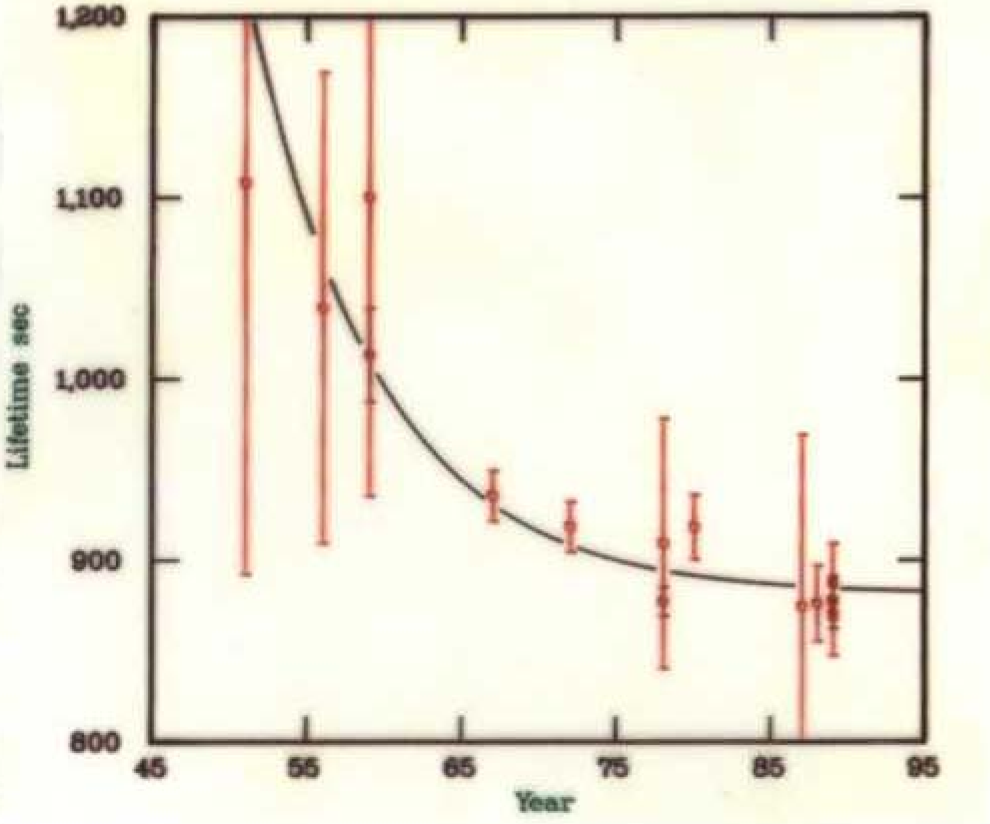
Neutron Lifetime vs. Year of Measurement



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Measurement of the Neutron Lifetime

"BOTTLE" METHOD

An ensemble of "ultra-cold" neutrons is confined in a material or magnetic bottle. The population decreases as:

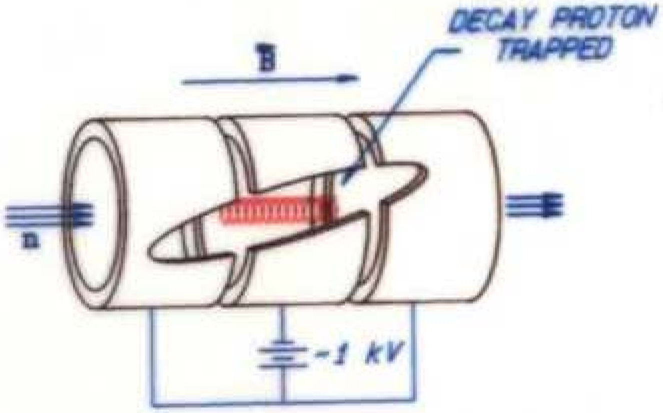
$$N=N_0 e^{-t/\tau_n}$$

"IN BEAM" METHOD

A counter detects decay products from a well defined volume traversed by a neutron beam. The decay rate will be:

$$-\frac{dN}{dt}=\frac{N}{\tau_n}$$

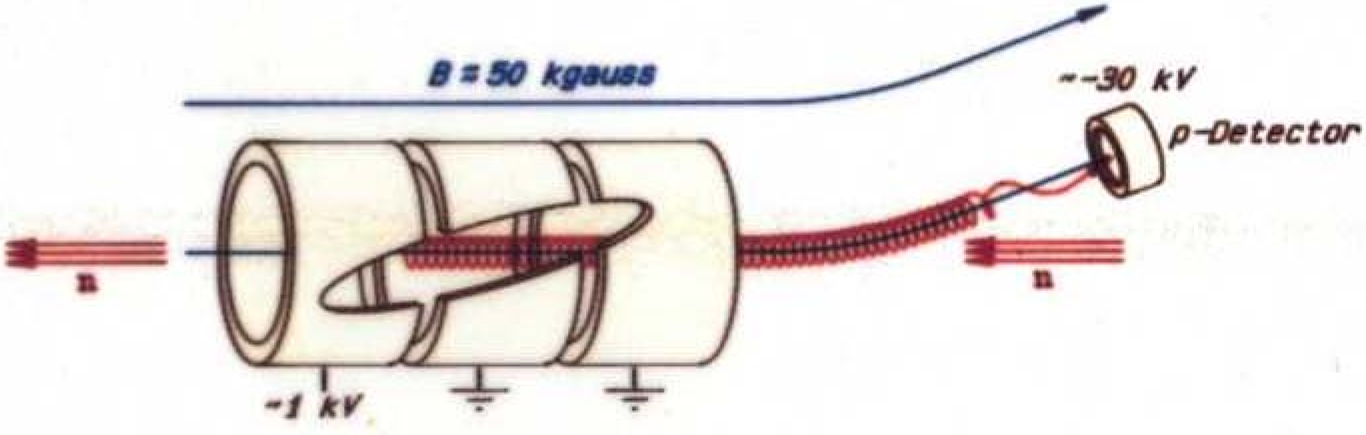
Decay Protons are Trapped in the NIST "Beam" Neutron Lifetime Experiment*



Uncharged neutrons pass through the "Penning" trap.. Protons left from neutron decay ($E_p < 750$ eV) are trapped in combination of electric and magnetic fields. The probability of decay within the trap is 10^{-6}-10^{-7}.

*NIST, Indiana U., Tulane U.,& Los Alamos

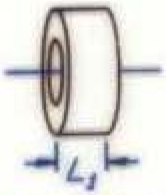
The Trap is "Opened" and the Emerging Protons are Accelerated and Detected



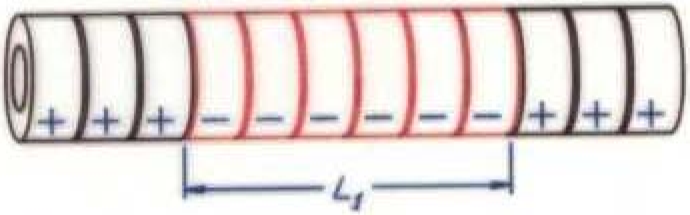
The trap volume (length) must be accurately known in order to extract an absolute decay rate

METHOD OF "VIRTUAL" TRAP LENGTH

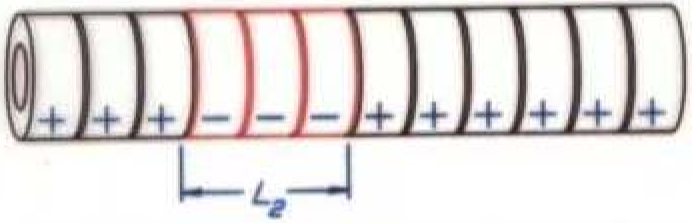
Step 1. Fabricate trap from many elements
each of which has a well known length



Step 2. Determine proton production rate in
trap having N elements

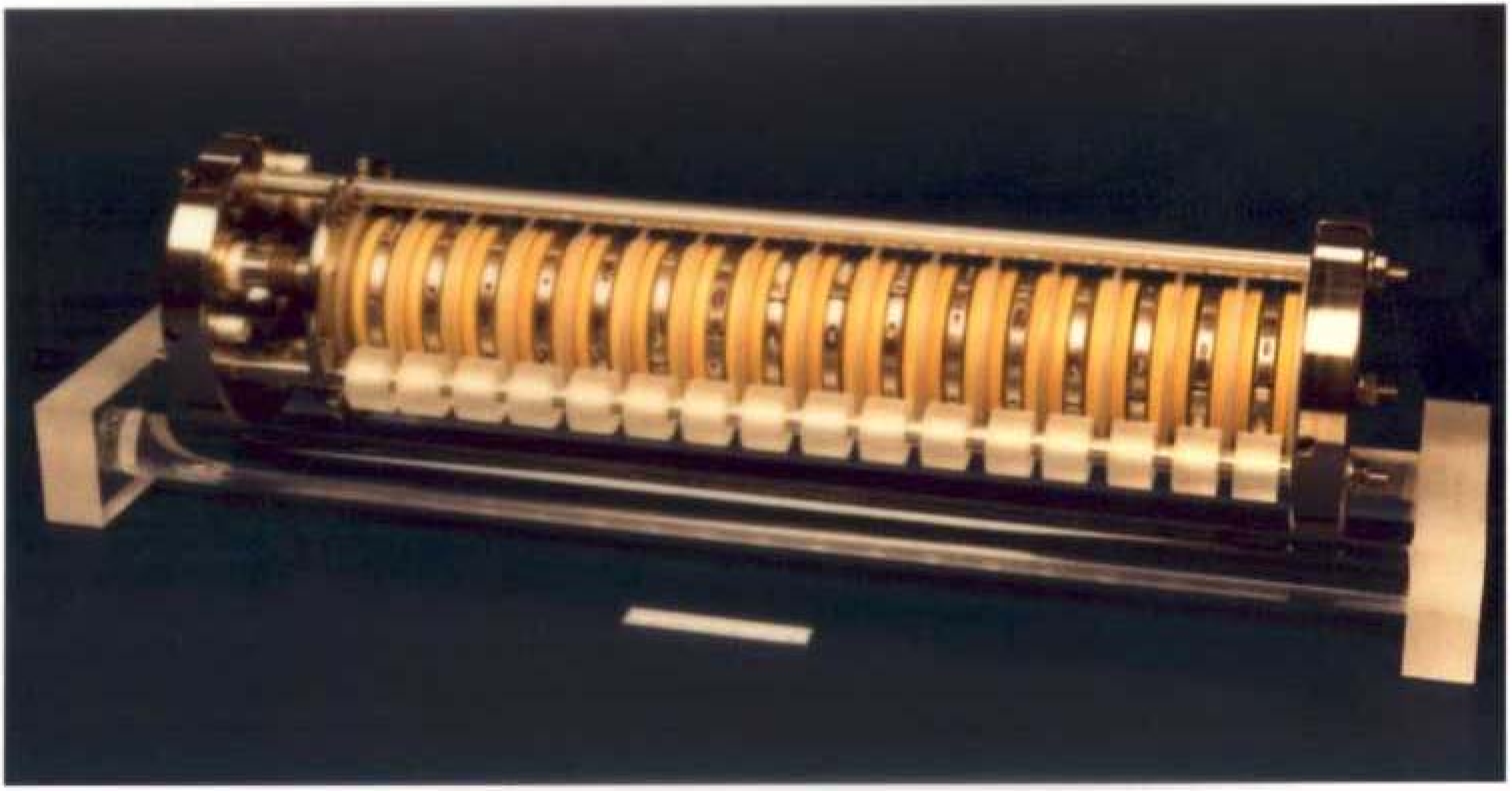


Step 3. Repeat with different value of N

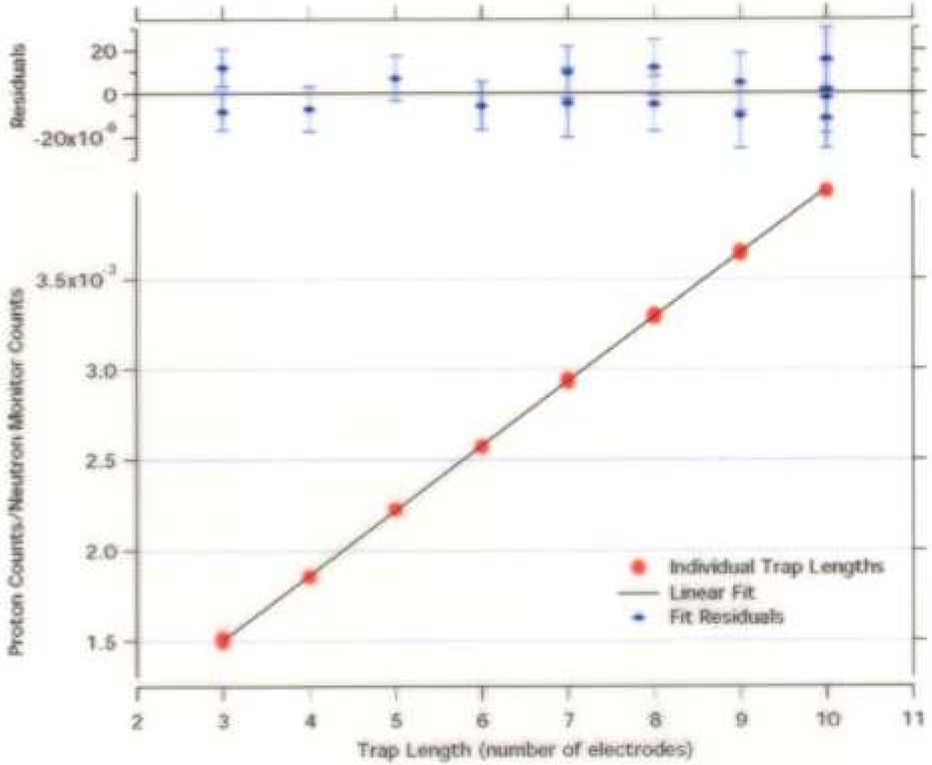


THOUGH NEITHER L_1 NOR L_2 ARE WLL KNOWN
THE DIFFERENCE $\Delta L = L_1 - L_2$ CAN BE GIVEN
WITH HIGH ACCURACY!

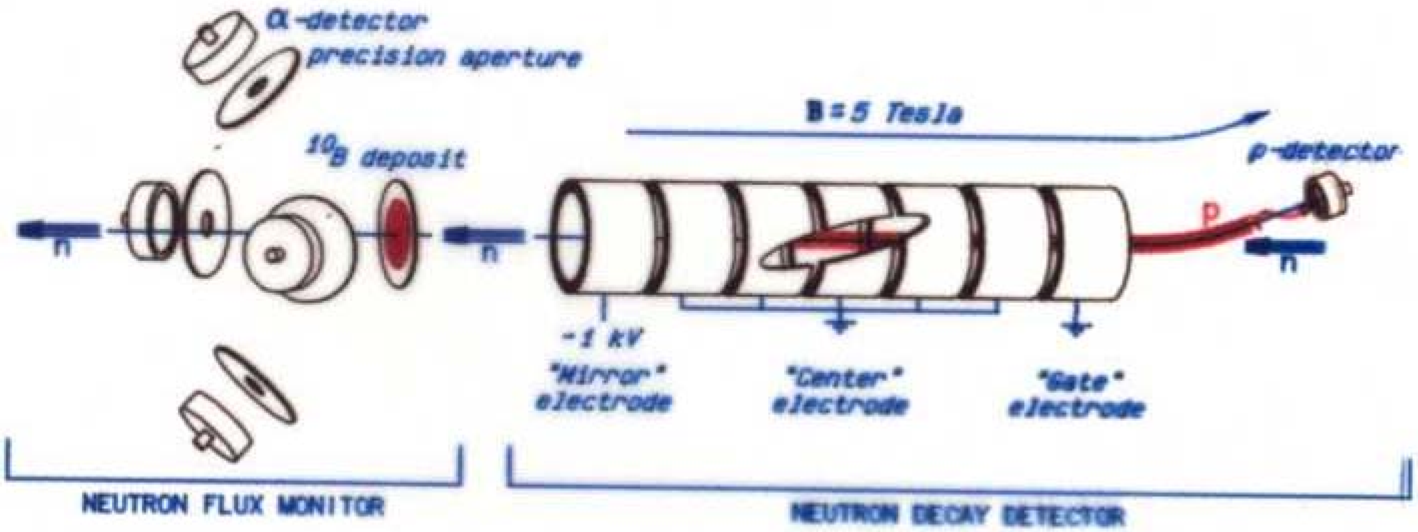
NIST Variable Length Trap *Mk II*



Neutron Decay Rate vs. Trap Length



Neutron Monitor Measures Neutron Density in Beam



Determination of the Neutron Lifetime using An Ultra Cold Neutron Bottle

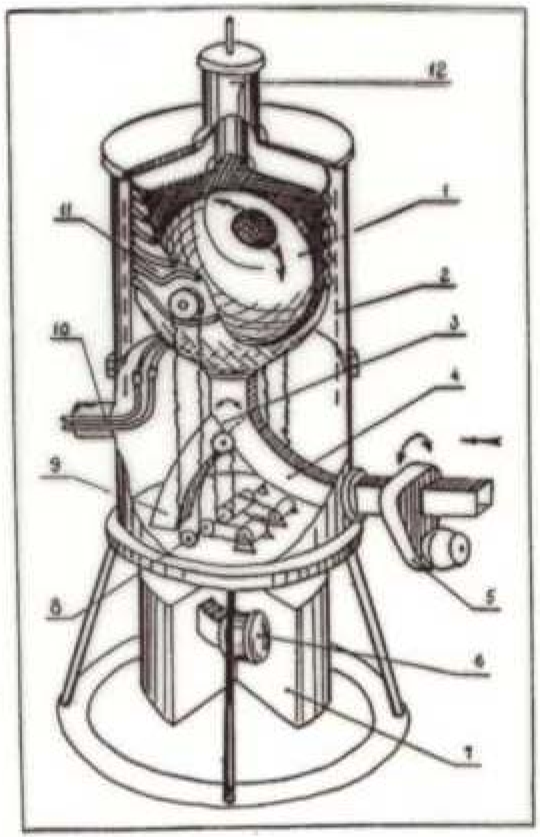
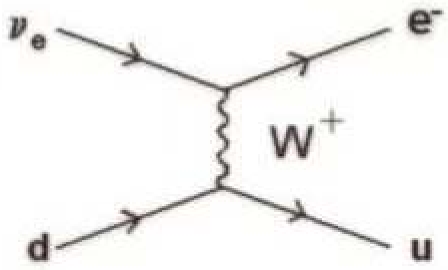


Fig.1. Setup for the measurement of the neutron lifetime with a gravitational trap: (1) UCN storage trap; (2) nitrogen screen; (3) distribution valve; (4),(9) neutron guide; (5) injection valve; (6) UCN detector; (7) detector shield; (8) (8) system for rotation; (10) cryopipes; (11) cryostat; (12) system for frozen cover.

Serebrov, et. al.

Parity Violation in Neutron Decay

Theoretical Framework for the Theory of Neutron Decay



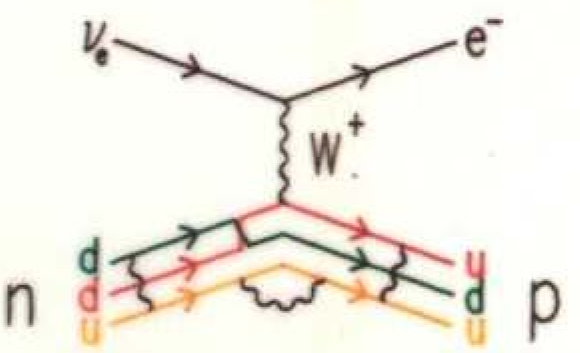
We construct a Weak Hamiltonian that couples a down quark to an up quark, and an electron to an electron neutrino:

$$< \nu_e \,|\, H_{weak} \,|\, e^- > < d \,|\, H_{weak} \,|\, u >$$

Question: How to include parity violation?

Neutron Decay is Described by Two Parameters

Neutron Decay is actually more complicated due to other interactions among the quarks:



However, these interactions still lead to a simple Hamiltonian with only two parameters:

$$H \propto \langle \nu_e | \gamma_\mu - \gamma_\mu \gamma_5 | e \rangle \langle d | g_V \gamma_\mu - g_A \gamma_\mu \gamma_5 | u \rangle$$

Testing the Standard Model

Testing the standard model involves looking for consistency among the neutron lifetime

$$ft(n \rightarrow p) = \frac{2\pi^3 \log 2}{G^2 g_V^2 \cos^2\theta_c \,(1+3|\lambda|^2)} \frac{\hbar^7}{m_e^5 c^4} \qquad \lambda = g_A/g_V \ ,$$

ft values for $0^+ \rightarrow 0^+$ superallowed Fermi transitions in nuclei

$$ft(0^+ \rightarrow 0^+) = \frac{2\pi^3 \log 2}{G^2 g_V^2 \cos^2\theta_c \, 2} \frac{\hbar^7}{m_e^5 c^4} \ ,$$

and values of neutron beta decay angular correlation coefficients

$$d^3W(\vec{p}_e, \vec{p}_\nu, <\vec{J}>) =$$

$$dW(p_e)\, d\Omega_e\, d\Omega_\nu \left[1 + a\frac{p_e}{E_e}\frac{p_\nu}{E_\nu} + \frac{<\vec{J}>}{J} \cdot \left(A\frac{\vec{p}_e}{E_e} + B\frac{\vec{p}_\nu}{E_\nu} + D\frac{\vec{p}_e \times \vec{p}_\nu}{E_e E_\nu}\right)\right]$$

where

$$\begin{aligned} a &= \frac{1-|\lambda|^2}{1+3|\lambda|^2} \\ A &= -2\frac{|\lambda|^2 + |\lambda|\cos\phi}{1+3|\lambda|^2} \\ B &= 2\frac{|\lambda|^2 - |\lambda|\cos\phi}{1+3|\lambda|^2} \\ D &= 2\frac{|\lambda|\sin\phi}{1+3|\lambda|^2} \ . \end{aligned}$$

T Violation in Neutron Decay

THE emiT EXPERIMENT

Time Reversal Invariance Violation in Neutron ß Decay

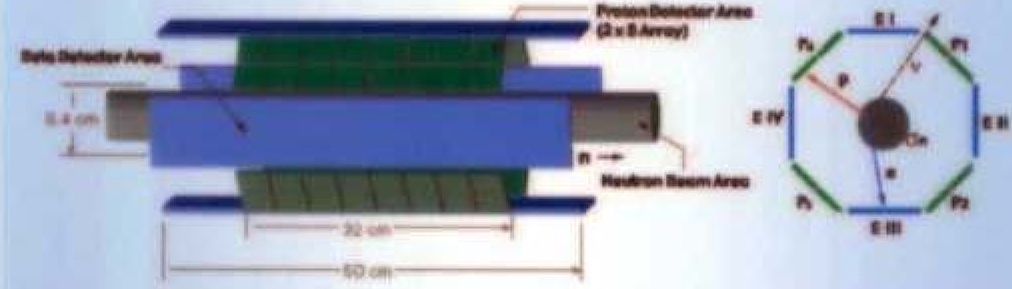
University of Washington, University of California/Lawrence Berkeley National Laboratory, Los Alamos National Laboratory, The University of Michigan, National Institute of Standards and Technology, University of Notre Dame

The neutron decay distribution can be expressed as

$$\frac{d\omega}{dE_e d\Omega_e d\Omega_\nu} = G(E_e)\left(1 + a\frac{p_e \cdot p_\nu}{E_e E_\nu} + \frac{m}{E_e} + \sigma_n \cdot \left(A\frac{p_e}{E_e} + B\frac{p_\nu}{E_\nu} + D\frac{p_e \times p_\nu}{E_e E_\nu}\right)\right)$$

where the last term violates time reversal symmetry. Standard Model extensions such as Lepto-Quarks, Left-Right Symmetry and Super-Symmetry can lead to D ≠ 0

The emiT detector - An octagonal array of four electron and four proton detectors



emiT collected coincidence data on the NG-6 beamline at the NIST Center for Neutron Research from Jan. 1997 until Sep. 1997.

$$D = [-0.6 \pm 1.2(\text{stat.}) \pm 0.5(\text{syst.})] \times 10^{-3}$$

L.J. Lising et al., Phys. Rev. C, 62, 055501 (2000)

A second run is planneded for 2001. Major upgrades in the apparatus should result in greater detector stability, increased efficiency and increased livetime.

Expected sensitivity of $D \leq 4 \times 10^{-4}$

Brief Introduction to Spallation Neutron Sources

For an excellent review see:
Garry Russell, Proceedings FPPNP 2000

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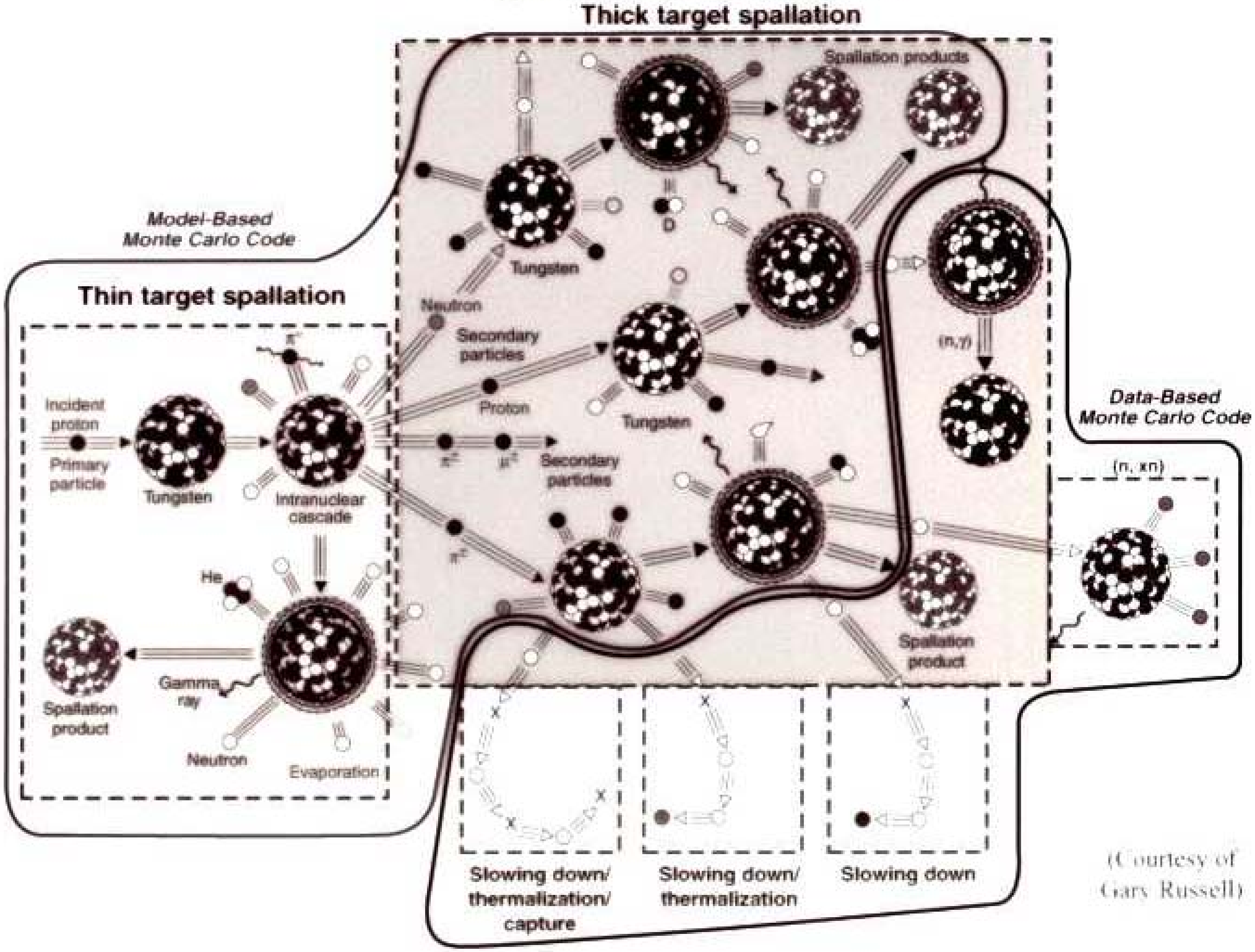
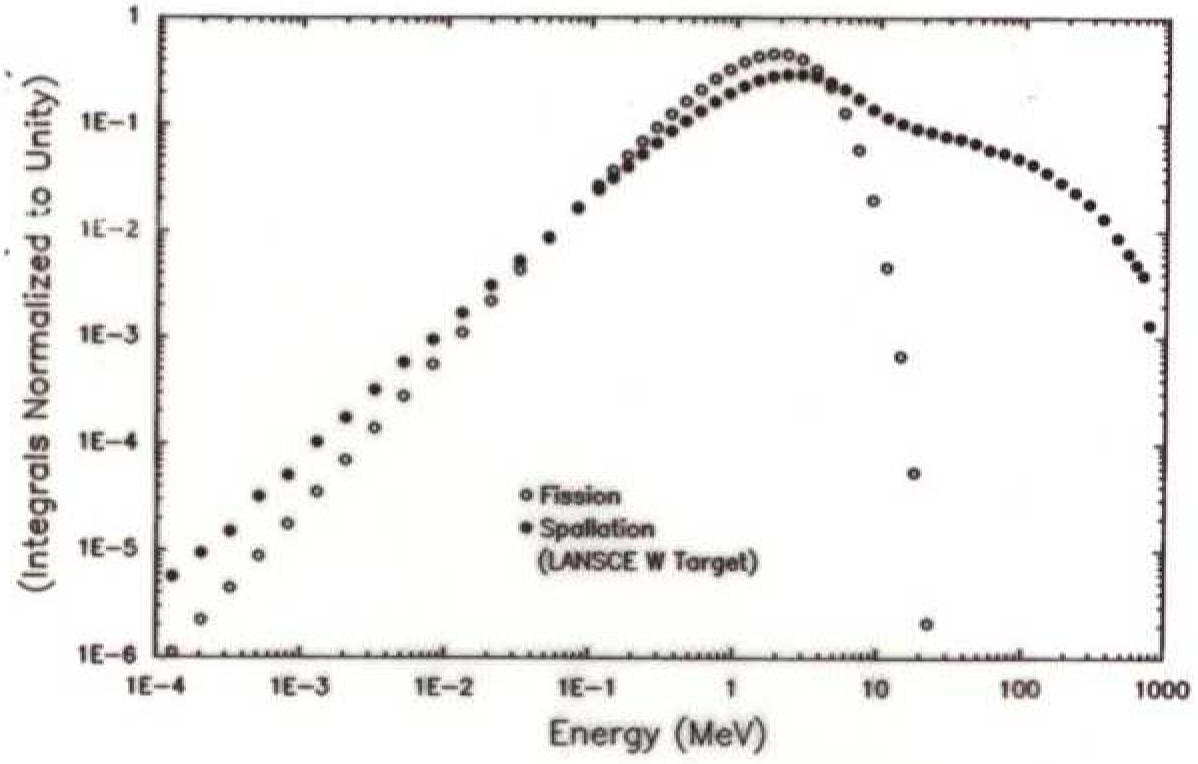
Spallation and MCNPX



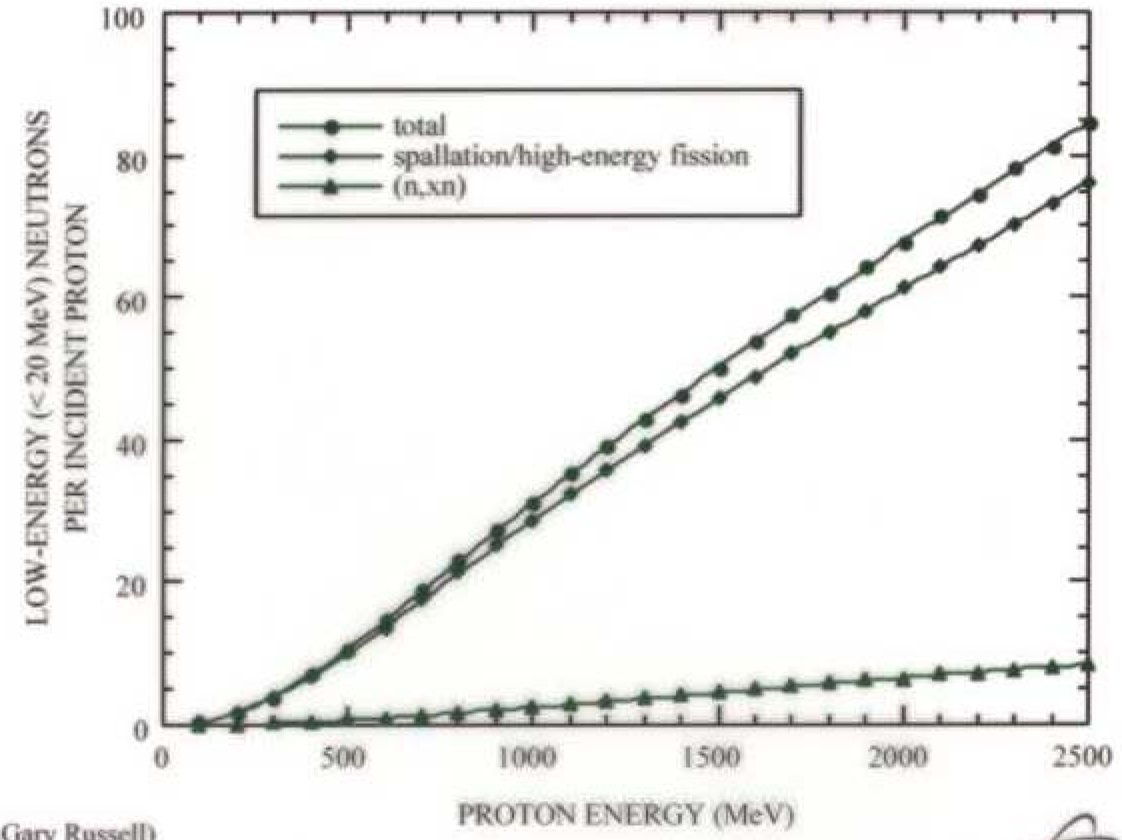
(Courtesy of
Gary Russell)

The Spallation Neutron Spectrum is Broad



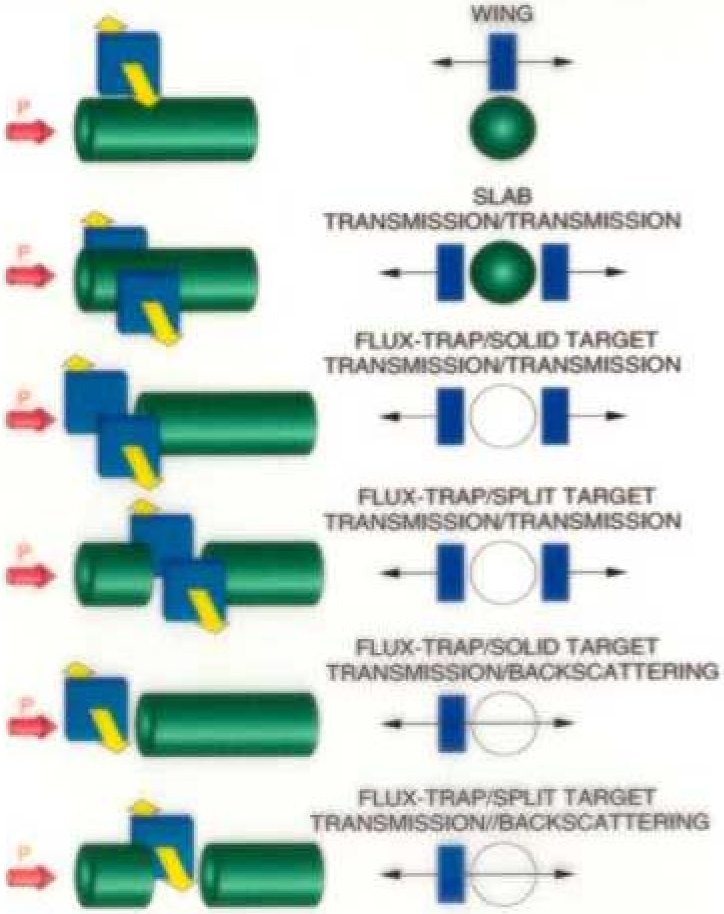
(Courtesy,Gary Russell)

Neutron Multiplicity in Spallation is High



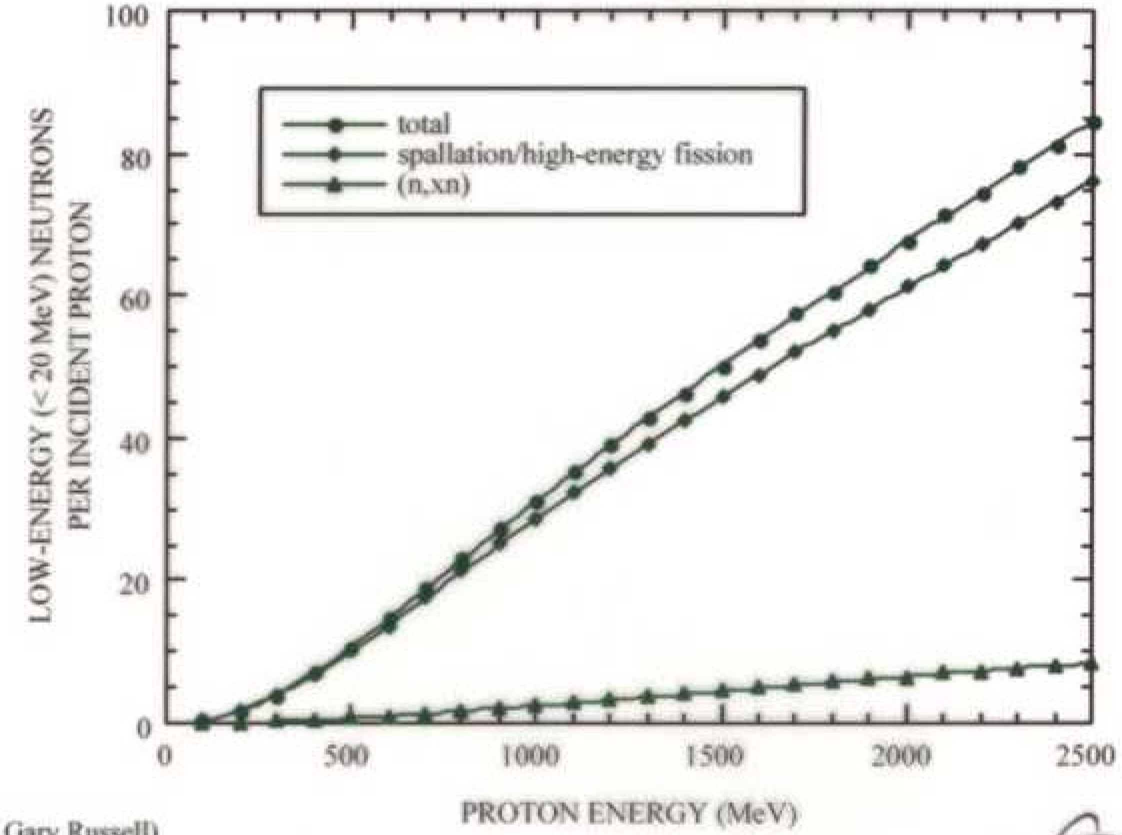
(Courtesy,Gary Russell)

Moderators Thermalize the High Energy Neutrons



(Courtesy,Gary Russell)

Neutron Multiplicity in Spallation is High



(Courtesy,Gary Russell)

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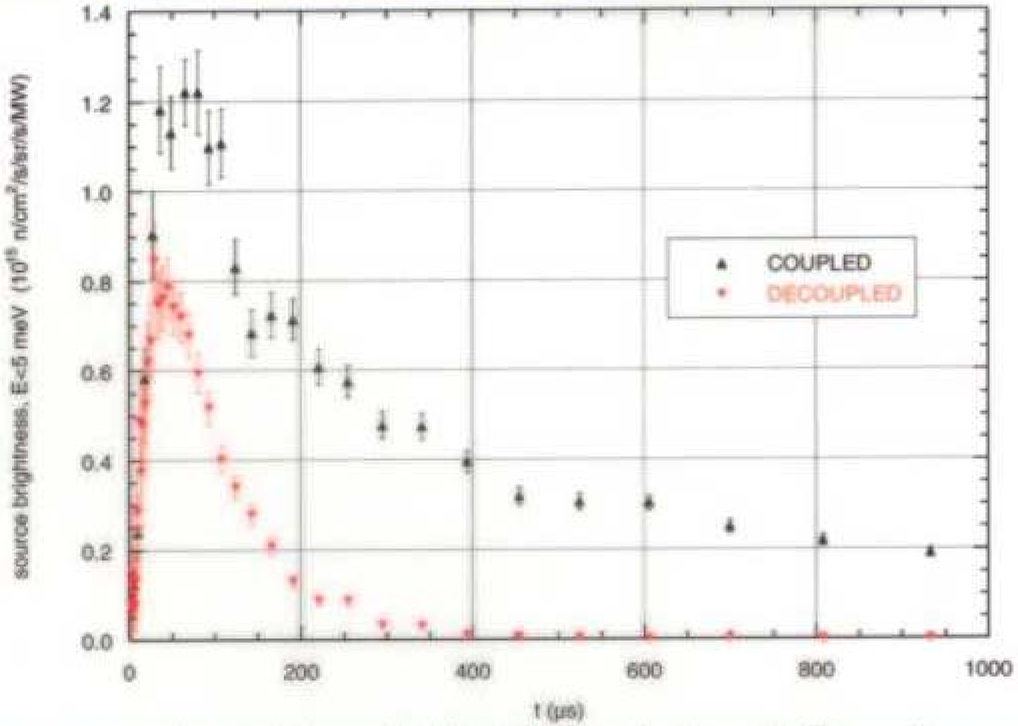
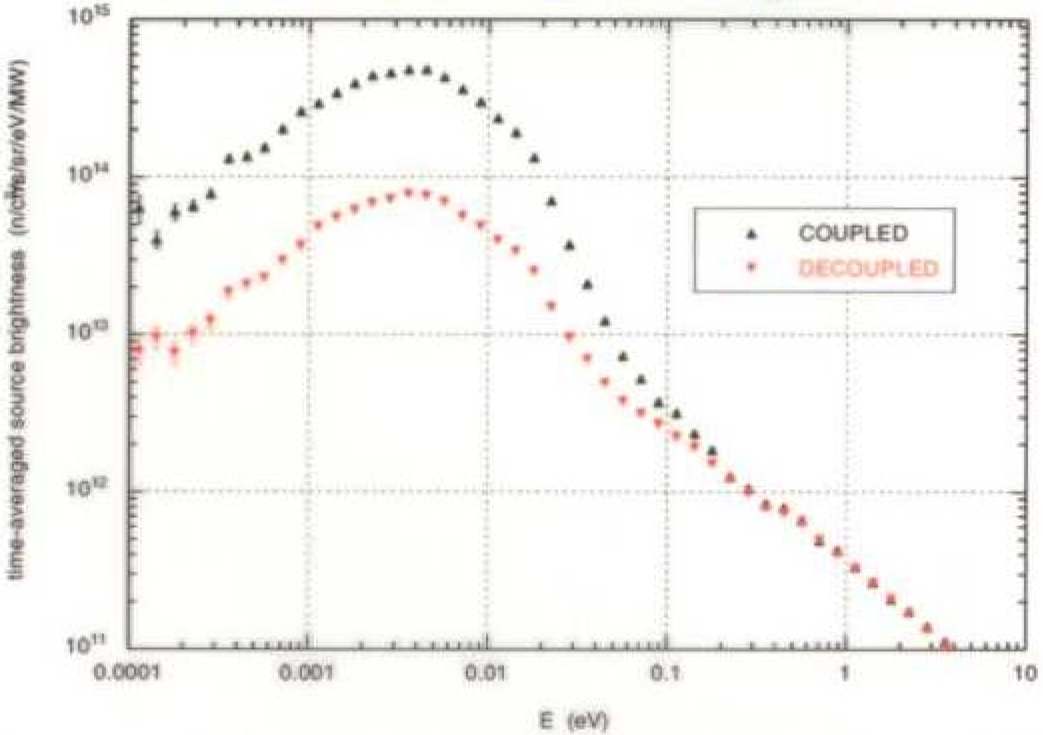
"Decoupled" Moderators Provide Short Neutron Pulses



Time distributions for coupled and decoupled liquid H2 (ortho/para 50/50) moderators in flux-trap geometry, showing the time-dependent differences of leakage neutrons. The 5-cm by 13-cm by 13-cm moderators are unpoisoned. The Be/D2O reflector is 85/15 v% Be/D_2O. (courtesy Garry Russell)

"Coupled" Moderators Have Higher Flux



Flux spectrum for coupled and decoupled liquid H_2 (ortho/para 50/50) moderators showing the energy-dependent differences of leakage neutrons. The 5-cm by 13-cm by 13-cm moderators are unpoisoned. The Be/D2O reflector is 85/15 v% Be/D_2O. (Courtesy, Garry Russell)

Comparison of Cold Neutron Facilities

Worldwide Beamlines for Fundamental Physics

Facility	Rep Rate	Guide Size (cm x cm)	Coating ($\times \theta_c$ Ni)	Time Averaged Fluence (n/s)*
NIST	CW	6 x 15	1	8×10^{10}
ILL (PF1)	CW	6 x 12	1	1.5×10^{11}
ILL (H113)	CW	6 x 20	3	1×10^{12}
LANSCE	20Hz	10 x 10	3	2×10^{10}
SNS	60Hz	10 x 10	3.5	3×10^{11}

*VERY rough estimate good to within about x2, depends on experimental layout