Fundamental Neutron Physics

Geoffrey Greene

Physics Department University of Tennessee
&
Physics Division, Oak Ridge National Laboratory

- *Introduction to Cold and Ultra Cold Neutrons*
- *The Particle Properties of the Neutron*
- *Sources of Cold and Ultra Cold Neutrons*
- *Neutron Decay*
- *Neutron-Nucleon Weak Interaction*
- *The Neutron Electric Dipole Moment*

Bibliography

General Discussion of Low Energy Neutrons:

*J.Byrne **Neutrons, Nuclei, and Matter**, Institute of Physics, Bristol (1993)*

*R.Golub, D Richardson, S.Lamoreaux, **Ultra-Cold Neutrons**, Adam Hilger (1991)*

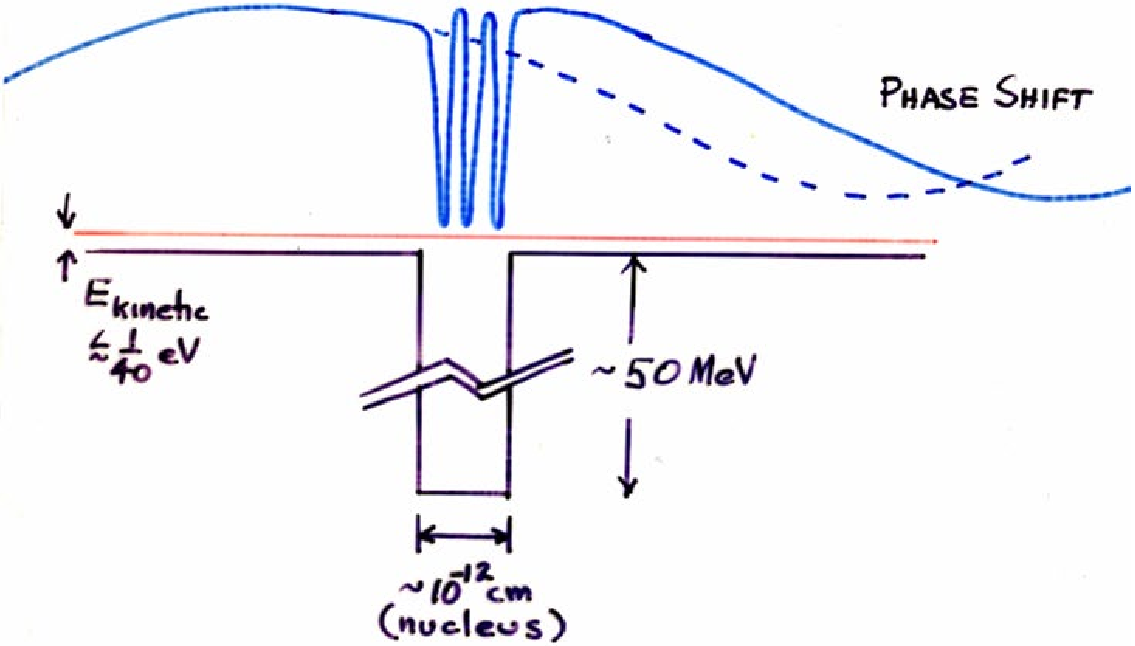
Recent Conference Proceedings

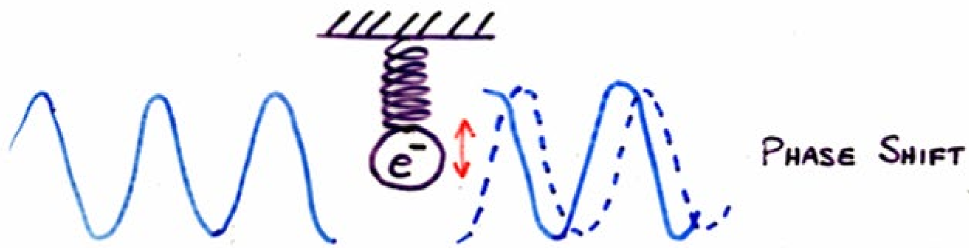
*Gould, Greene, Plasil, Snow, editors **Fundamental Physics with Pulsed Neutrons Beams**, World Scientific (2001)*

*Zimmer, Butterworth, Nesvizhevsky, Korobkina, **Particle Physics with Slow Neutrons**, Nuclear Instruments and Methods **A440**, 471-815 (2000)*

Introduction to Cold & “Ultra-Cold” Neutrons

Coherent ("Optical") Interaction Between Neutrons and Matter





E-M wave interacting with matter

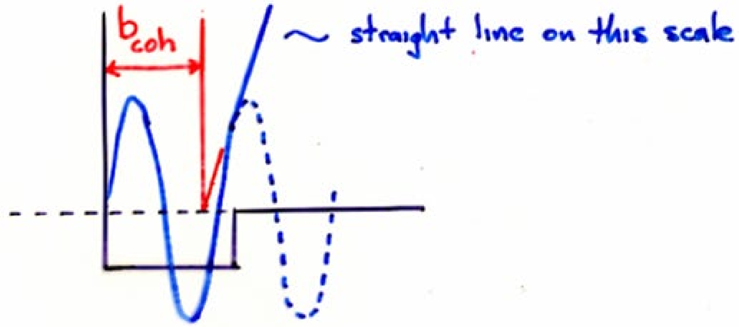
Phase Shift ⟹ Index of Refraction

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

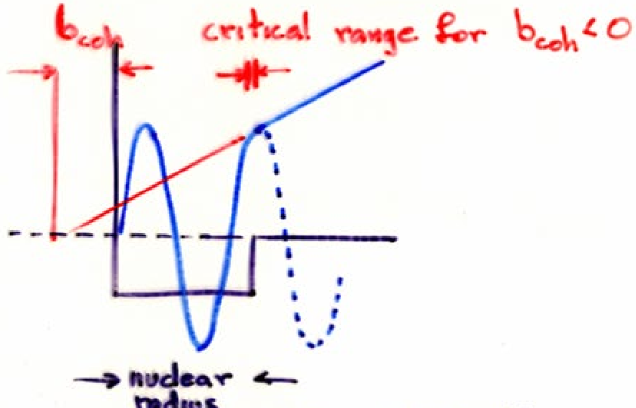
DEFINE COHERENT SCATTERING LENGTH b_{coh}

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

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



FOR MOST NUCLEI $b_{coh} > 0$



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

Neutron Index of Refraction

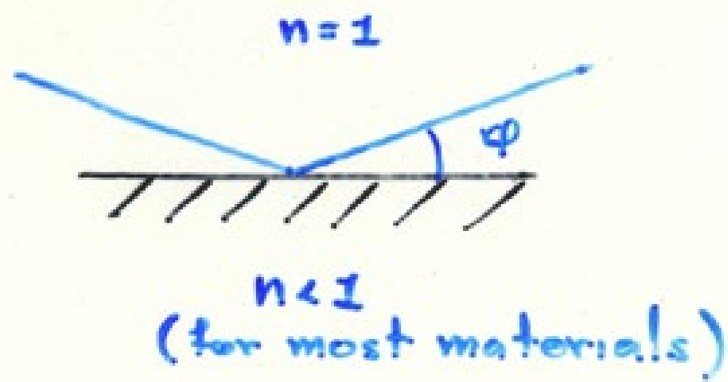
$$n = 1 - \frac{\lambda^2 N b_{coh}}{2\pi}$$ for non-magnetic materials

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

---

Critical Angle

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



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

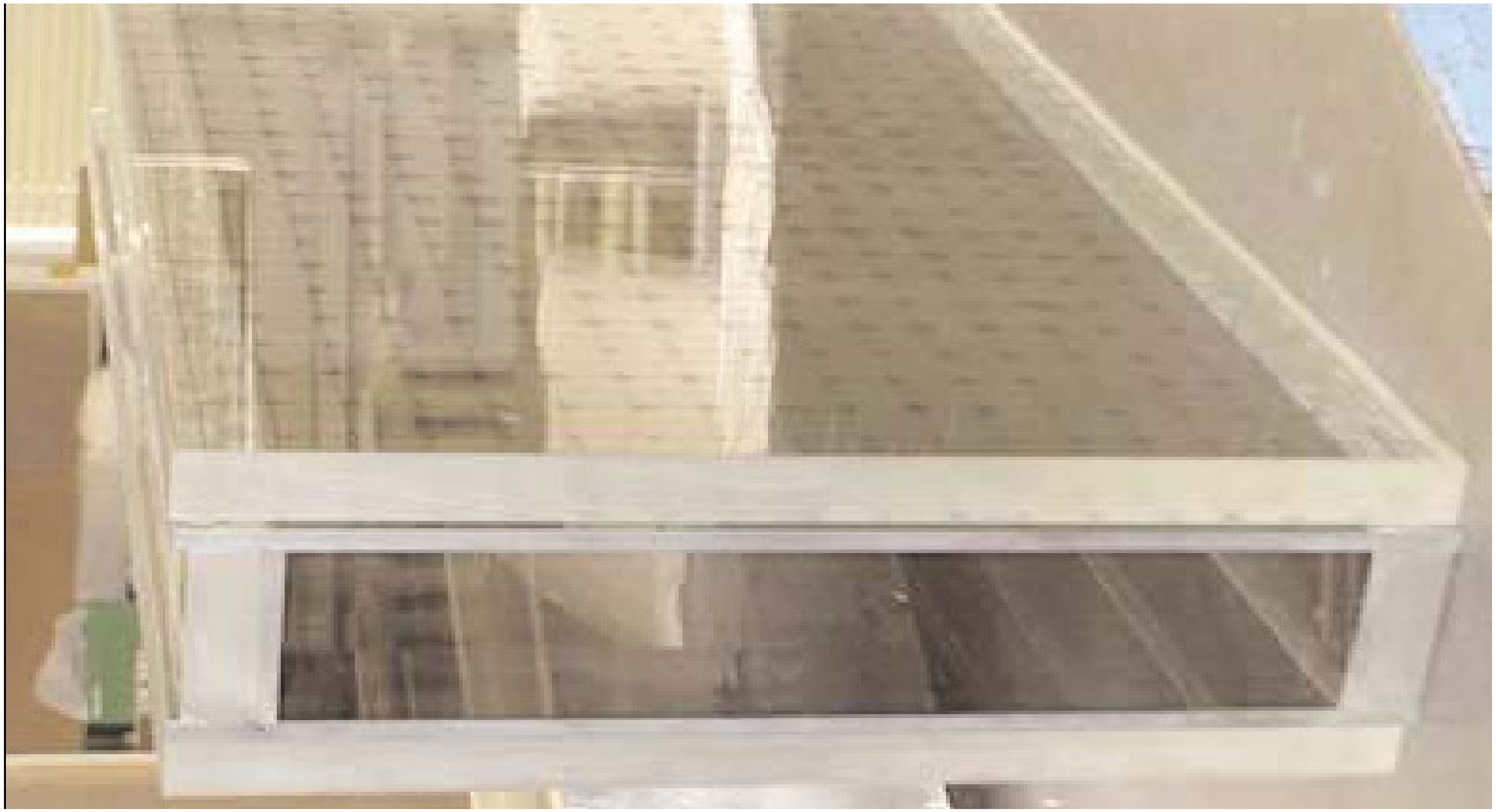
$E_k \approx 100$ neV

$\lambda \approx 500$ 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)

Neutron "Guides" can be assembled from neutron "mirrors"



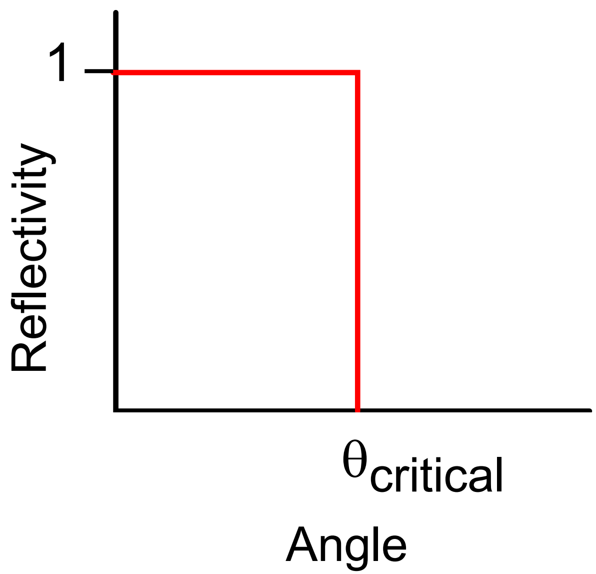
Neutron "Guides" are Used to Extract and Transport "Cold Neutrons

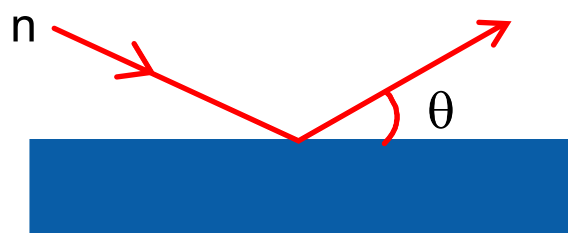
Photo courtesy of FRM-II Reactor (Munich, Germany)

Reflectivity of Neutron Mirror

A Simple Neutron Mirror has Nearly Unit Reflectivity

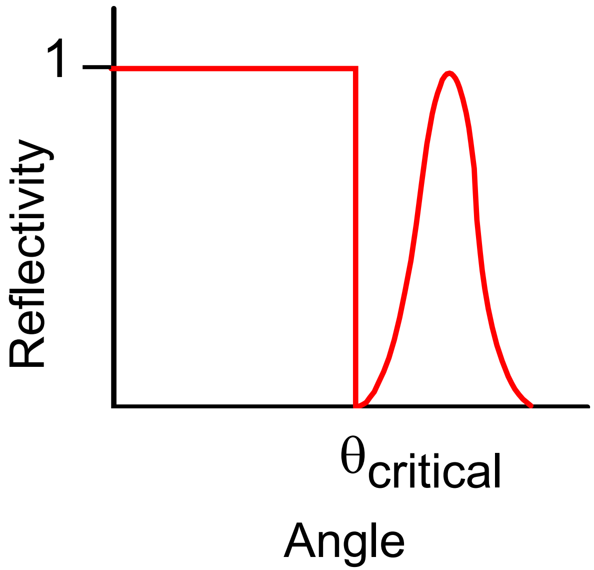
Up to a Maximum Critical Angle

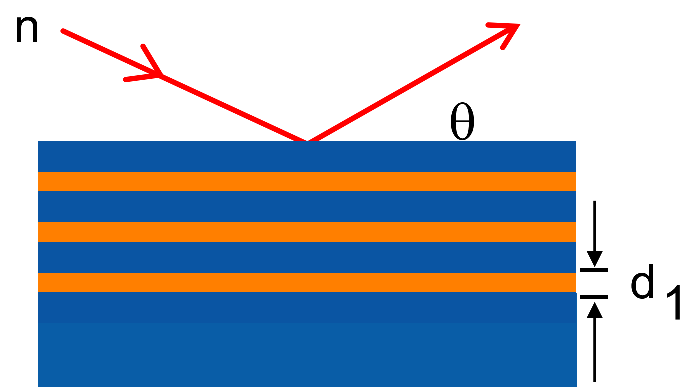




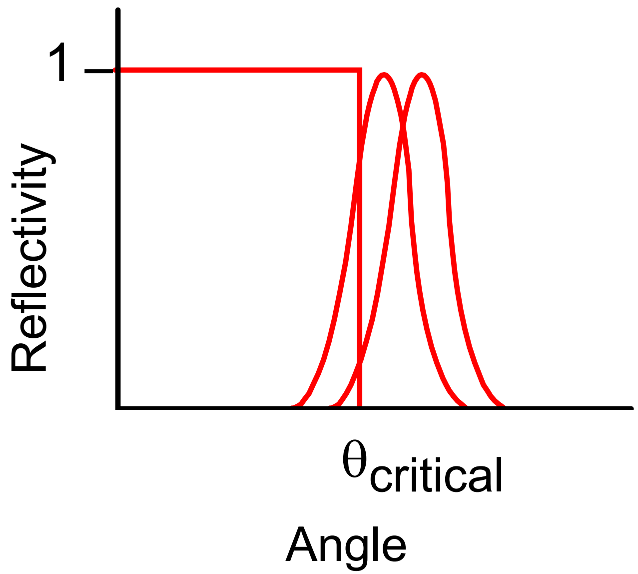
$\Theta_{critical} \cong 2\ mR/Å$ *for* ^{58}Ni

A Multilayer can add "Psuedo" Bragg Peak



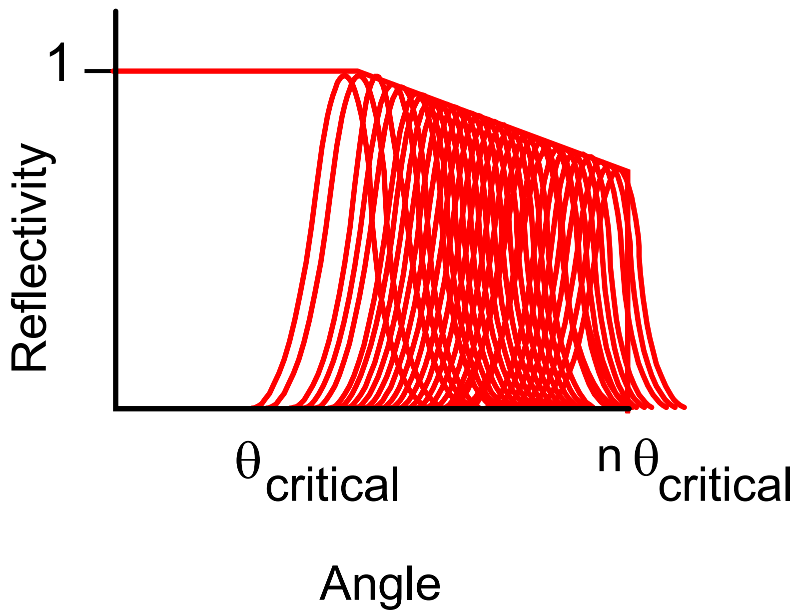


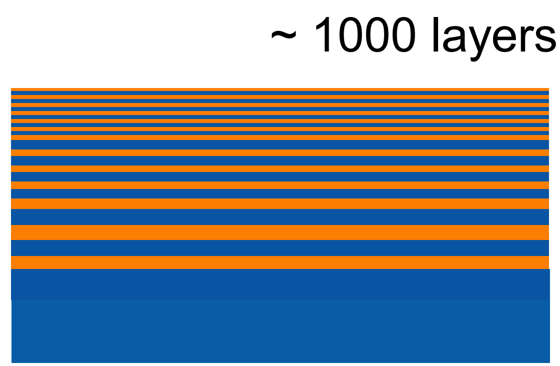
Additional Multilayers add More Peaks



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

Commercial Supermirror Neutron Guides
are Available With n ≅ 3 - 4





Since phase space goes as Θ^2, Total Neutron Fluence goes as m^2!

Neutron Polarization

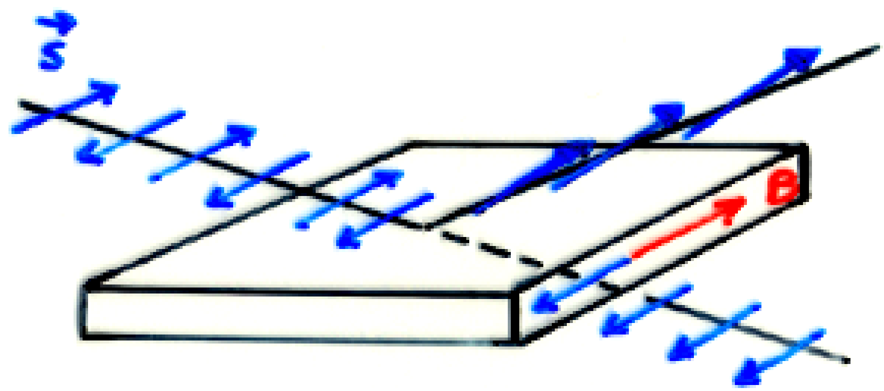
Ferromagnetic Mirrors

Nuclear Spin Polarized ^{3}He

POLARIZING MIRROR

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

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



ONLY $\uparrow\uparrow$ SPIN STATE IS REFLECTED

NIST Polarized ^{3}He Cell

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

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

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

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

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

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

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:

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

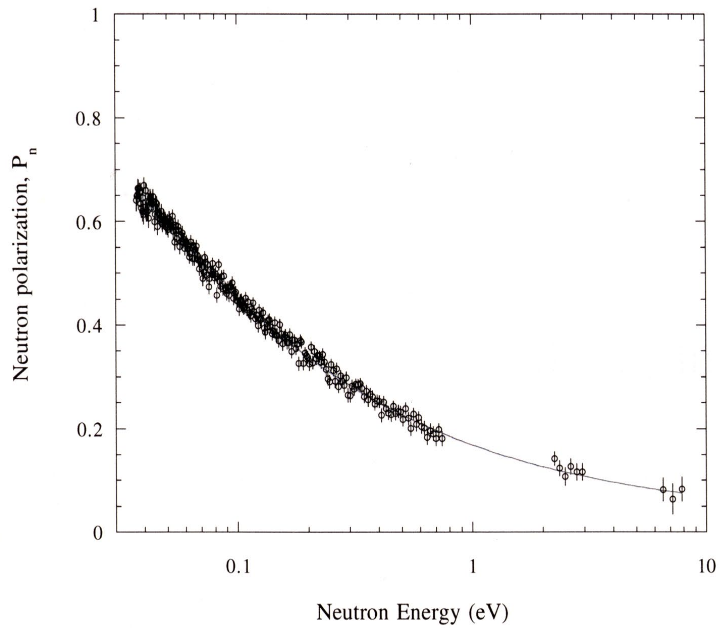
Where T_0 is the transmission with the cell unpolarized and T is the transmission with the cell polarized.

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

The Parametric relation for P_n has been verified

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

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



This has been verified at the level of ~0.2%, and should be capable of much better accuracy.

D. R. Rich, et.al., Nucl. Instrum. Meth., **A481**,431 (2002)

A Brief Review of the

The Particle Properties of the Neutron

Some Neutron Properties

√Mass
√Gravitational Mass (equivalence principle test)

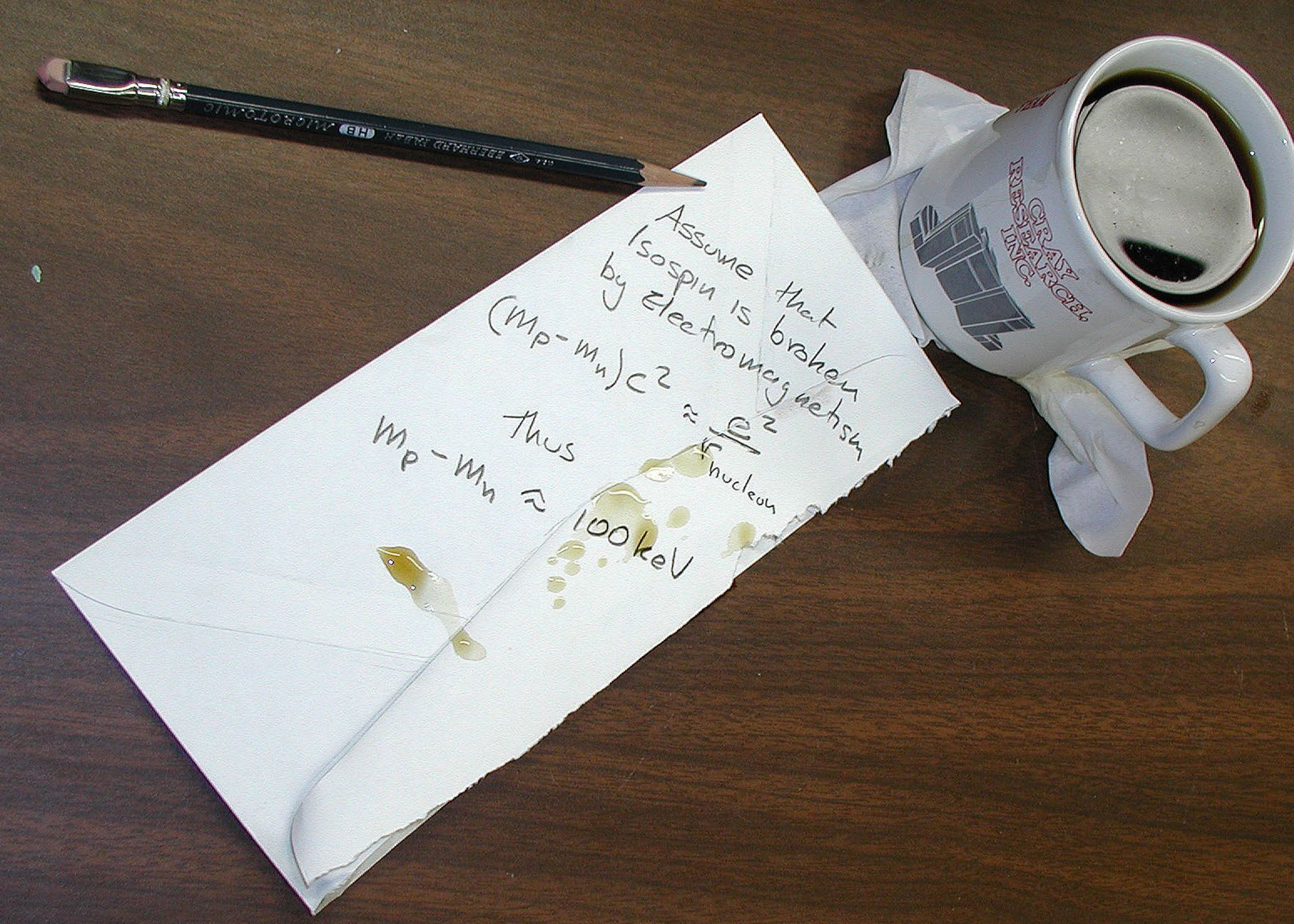
√Charge (limit on neutrality)
√Magnetic Dipole Moment
√Electric Dipole Moment
√Magnetic Monopole
Electric Polarizability
√Internal Charge Distribution

√Lifetime
√Decay Correlations
√Rare Decay Modes

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

√Denotes application for Cold/Ultra-Cold Neutrons

The Neutron Mass


Assume that
Isospin is broken
by Electromagnetism
(mp-mn)c² ≈ e²/r nucleon
thus
mp-mn ≈ 100keV
CRAY RESEARCH, INC.

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?

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:

$$h/m_n = \lambda \bullet v$$

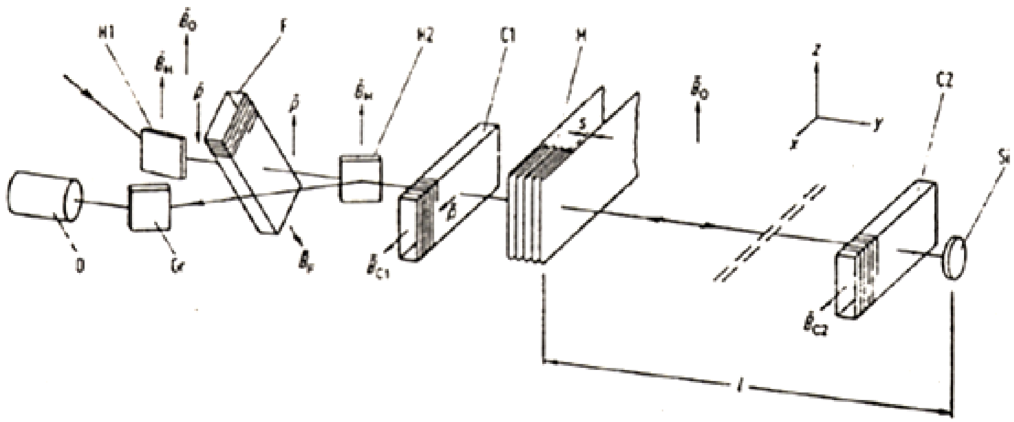


Fig. 1. Arrangement for measuring h/m_n. (H1, H2) Heusler crystals, (F) flipping coil, (C1, C2) $\pi/2$ coils, (M) meander coil, (Si) silicon crystal, (Gr) oriented graphite, (D) detector. B_0: magnetic induction of the guide field; B_H: magnetic induction magnetizing a Heusler crystal; ρ: polarization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

The Fine Structure Constant from the Neutron Mass

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

The Fine Structure Constant from the Neutron Mass

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

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

The Fine Structure Constant from the Neutron Mass

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

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

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

$$R_\infty = \frac{2\pi^2 m_e e^4}{h^3 c}$$

The Fine Structure Constant from the Neutron Mass

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

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

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

$$R_\infty = \frac{2\pi^2 m_e e^4}{h^3 c}$$

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

The Fine Structure Constant from the Neutron Mass

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

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

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

$$R_\infty = \frac{2\pi^2 m_e e^4}{h^3 c}$$

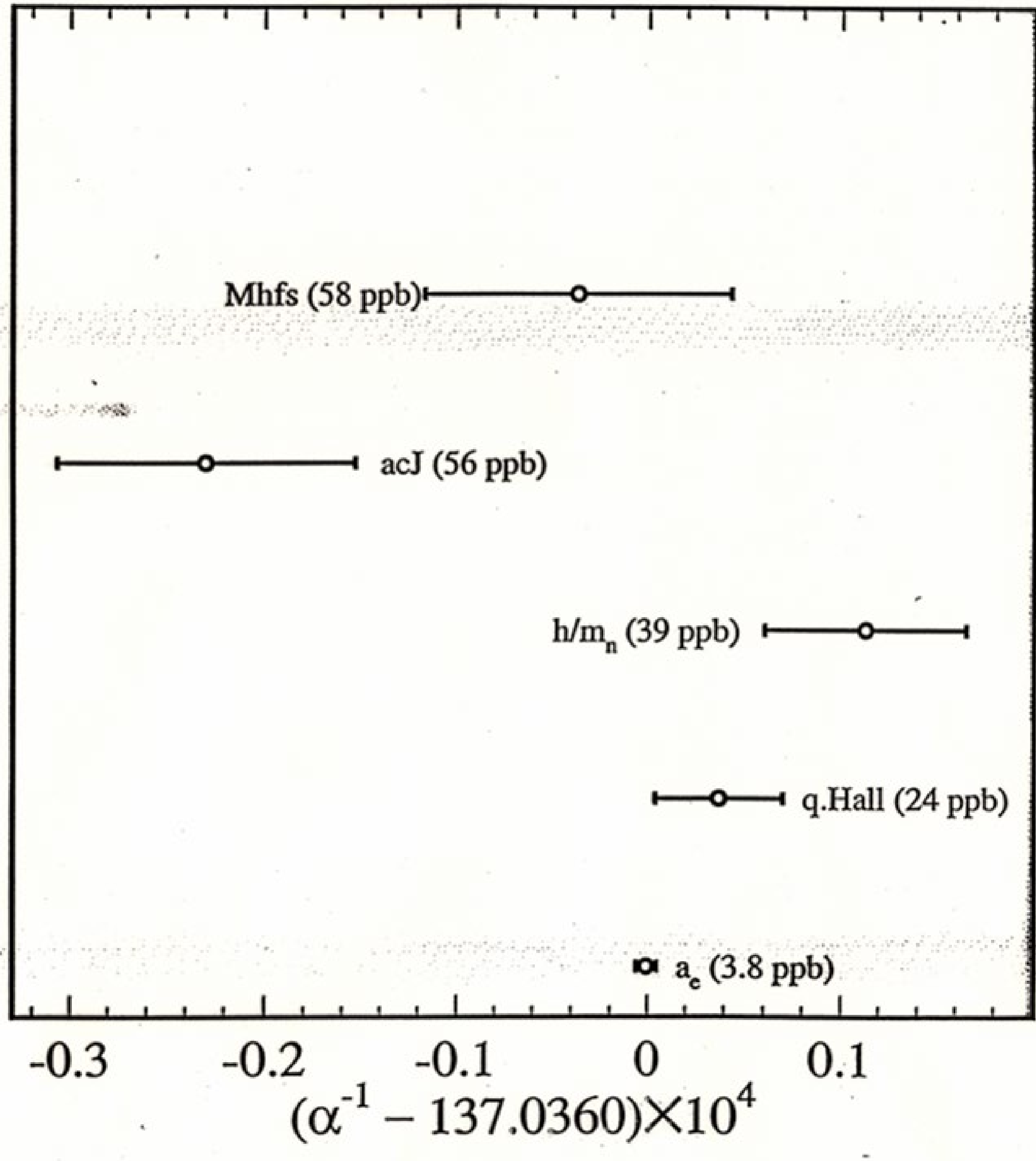
$$\alpha = \left[2R_\infty c \left(\frac{m_p}{m_e}\right)\left(\frac{m_n}{m_p}\right)\frac{h}{m_n}\right]^{1/2}$$

Approximate errors experimental quantities

- $R_\infty \sim 0.001$ ppm
- $m_p/m_e \sim 0.02$ ppm
- $m_n/m_p \sim 0.01$ ppm
- $h/m_n \sim 0.08$ ppm

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

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:

$$F_n = m_i a_n$$

$$m_g g = m_i a_n$$

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

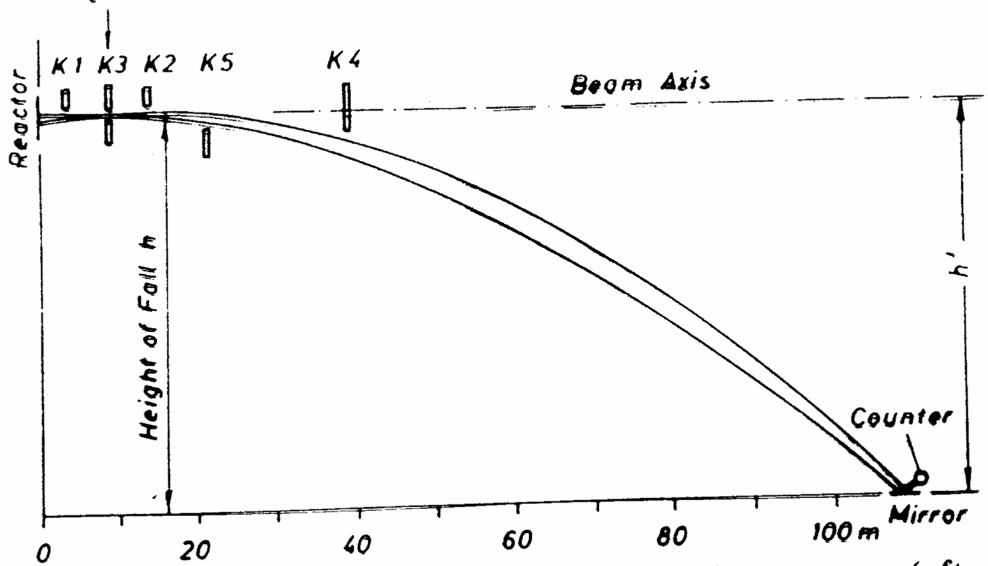
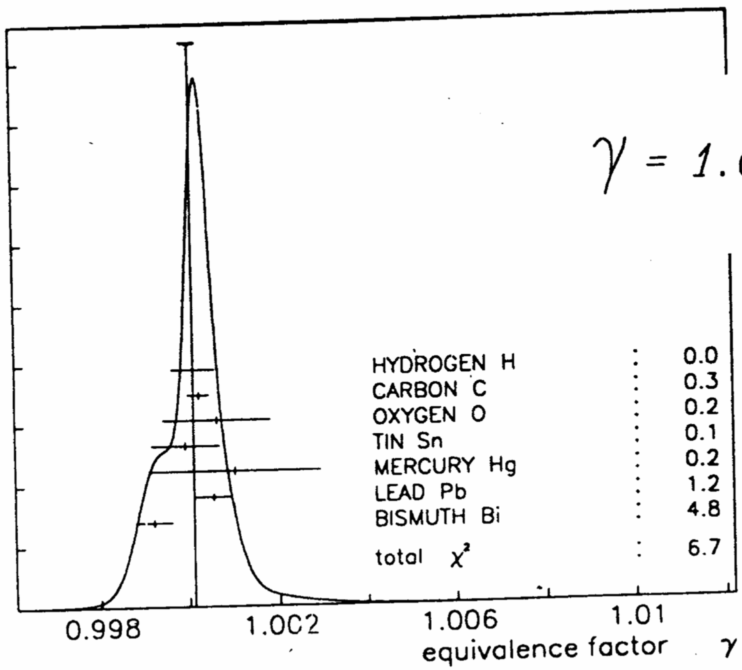


Fig. 1. Principle of the neutron-gravity refractometer (after



$$\gamma = 1.00011\,(17)$$

Fig. 2. *Ideogram* showing equivalence factors γ obtained from a compilation of the most accurate scattering length measurements.

See Schmiedmeyer, NIM A234 59 (1989)

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

---

*A limit on a possible magnetic "charge" (monopole) for the for the neutron of about 2×10^{-20} $e/\hbar\alpha$ has also been set

Finkelstein et all ('86)

The Neutron Magnetic Moment

The Neutron Magnetic Moment

Theory

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

Measurement

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

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

WHY IS THE AGREEMENT SO GOOD?

Sources of Cold and Ultra Cold Neutrons

- *The neutrons produced in any high intensity source (Reactors or Accelerators) have energies in the MeV regime.*

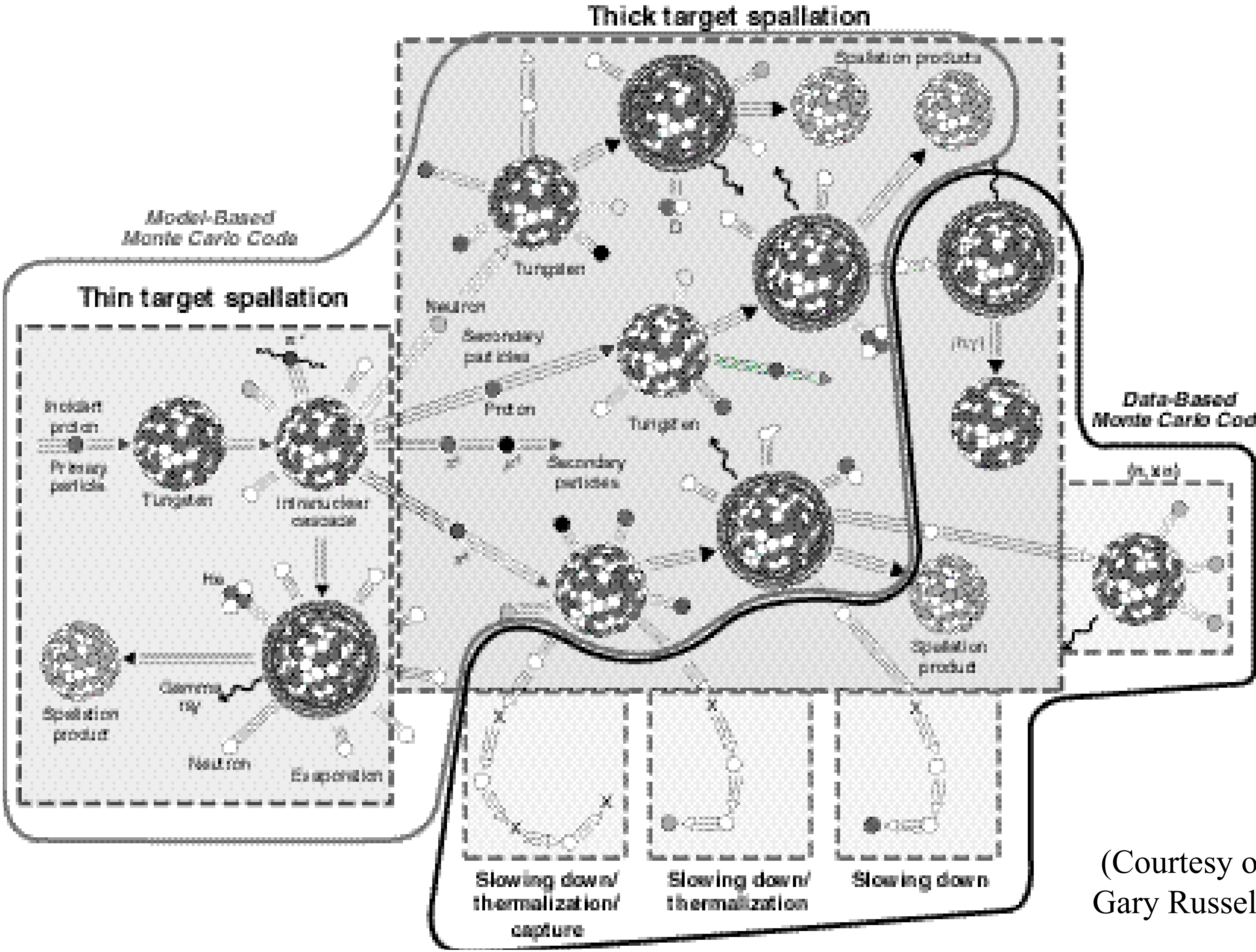
- *These fast neutrons must be slowed down and "moderated"*

- *In a "Thermal" Source, neutrons are brought to thermal equilibrium with a moderator (usually H, D, or C).*
  - *Thermal Neutrons T~300K*
  - *Cold Neutrons T~20K*

- *It is not practical to make a moderator that has a temperature comparable to Ultra-Cold Neutron Energies (100 neV~1 mK).*

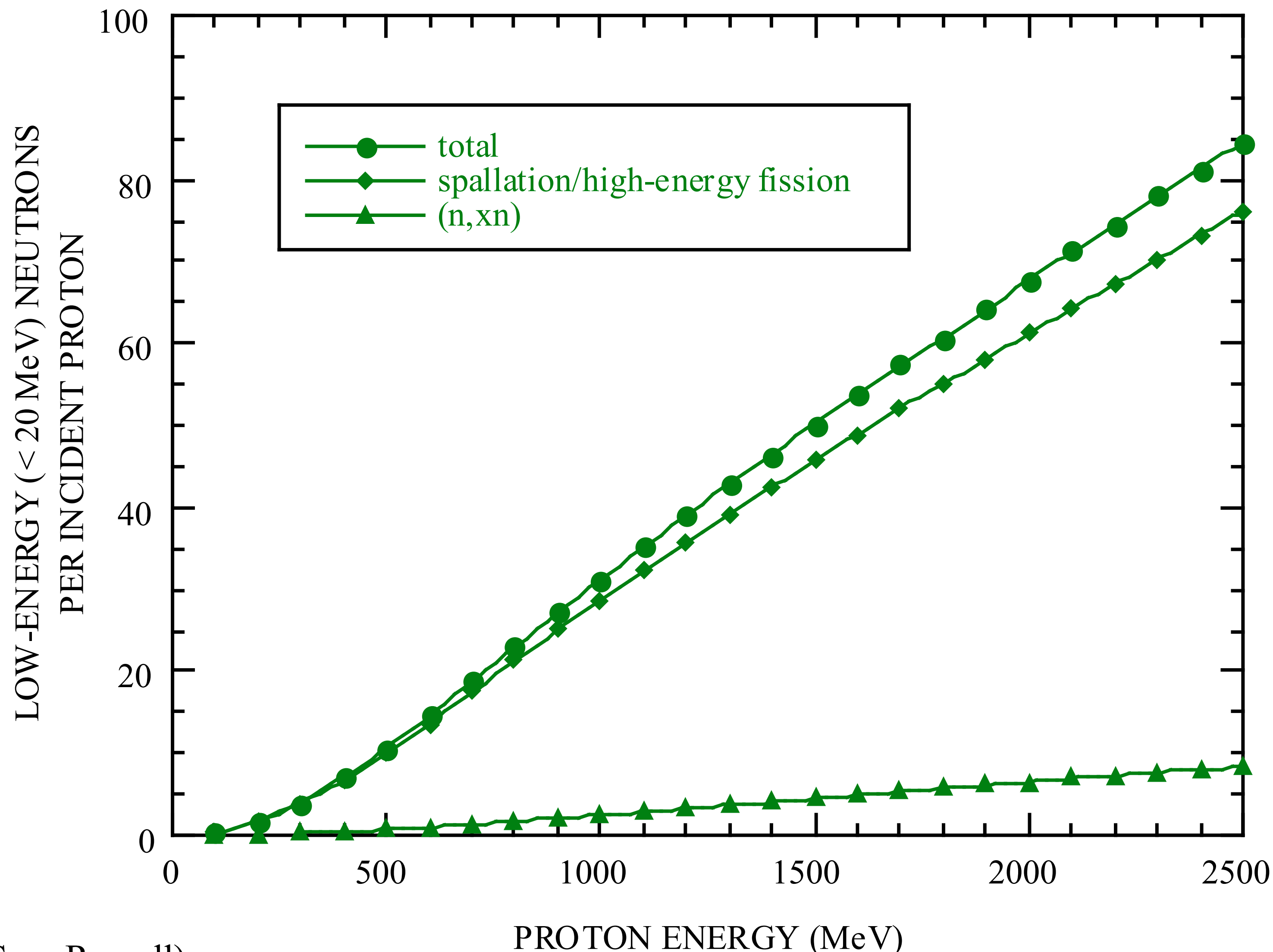
  "Thermal" sources of UCN depend only on the very low energy tail of a Boltzman Distribution with 5meV~20K energy.

Brief Introduction to Spallation Neutron Sources



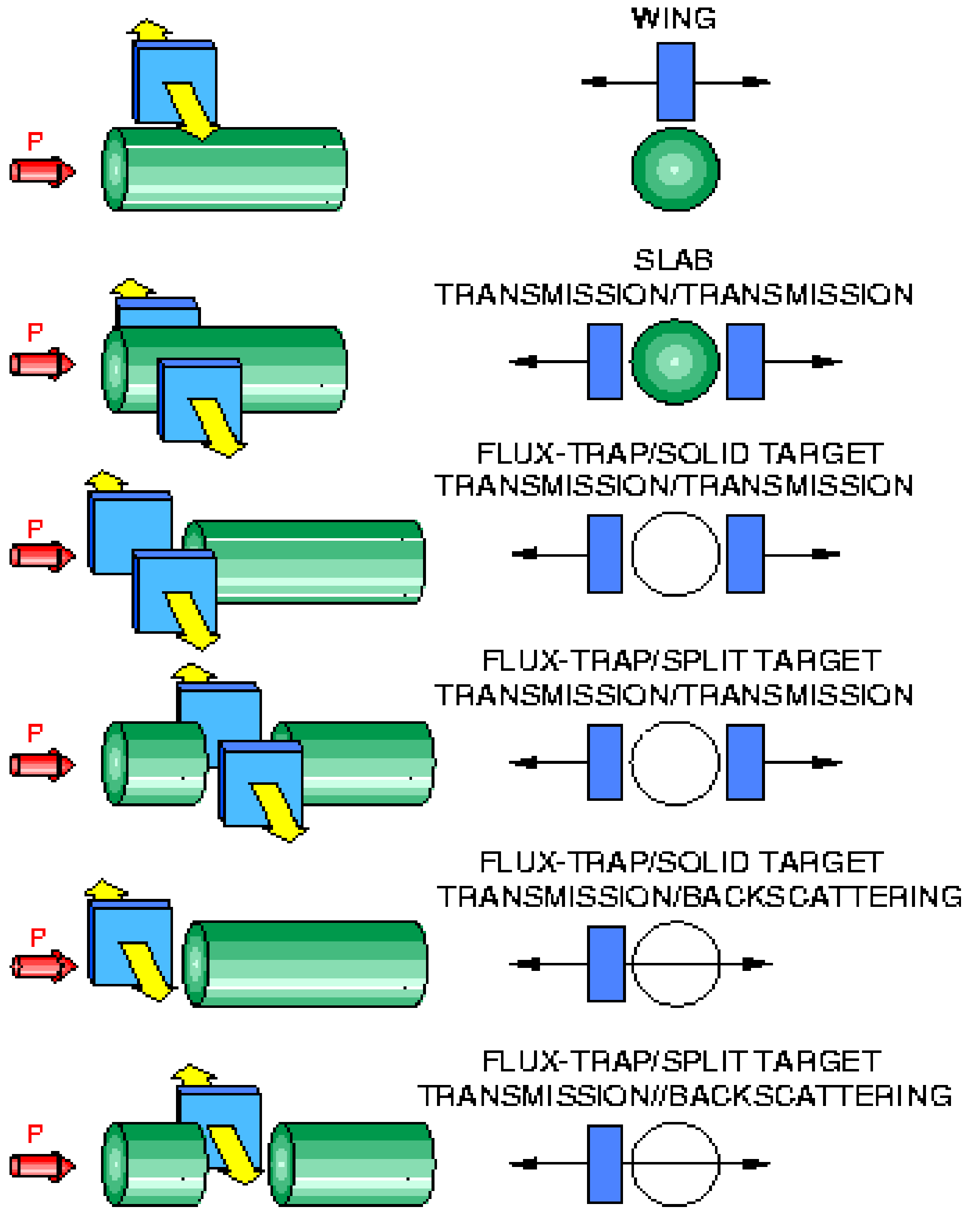
(Courtesy of Gary Russell)

Neutron Multiplicity in Spallation is High



(Courtesy,Gary Russell)

Moderators Thermalize the High Energy Neutrons



(Courtesy,Gary Russell)

Comparison of Cold Neutron Facilities

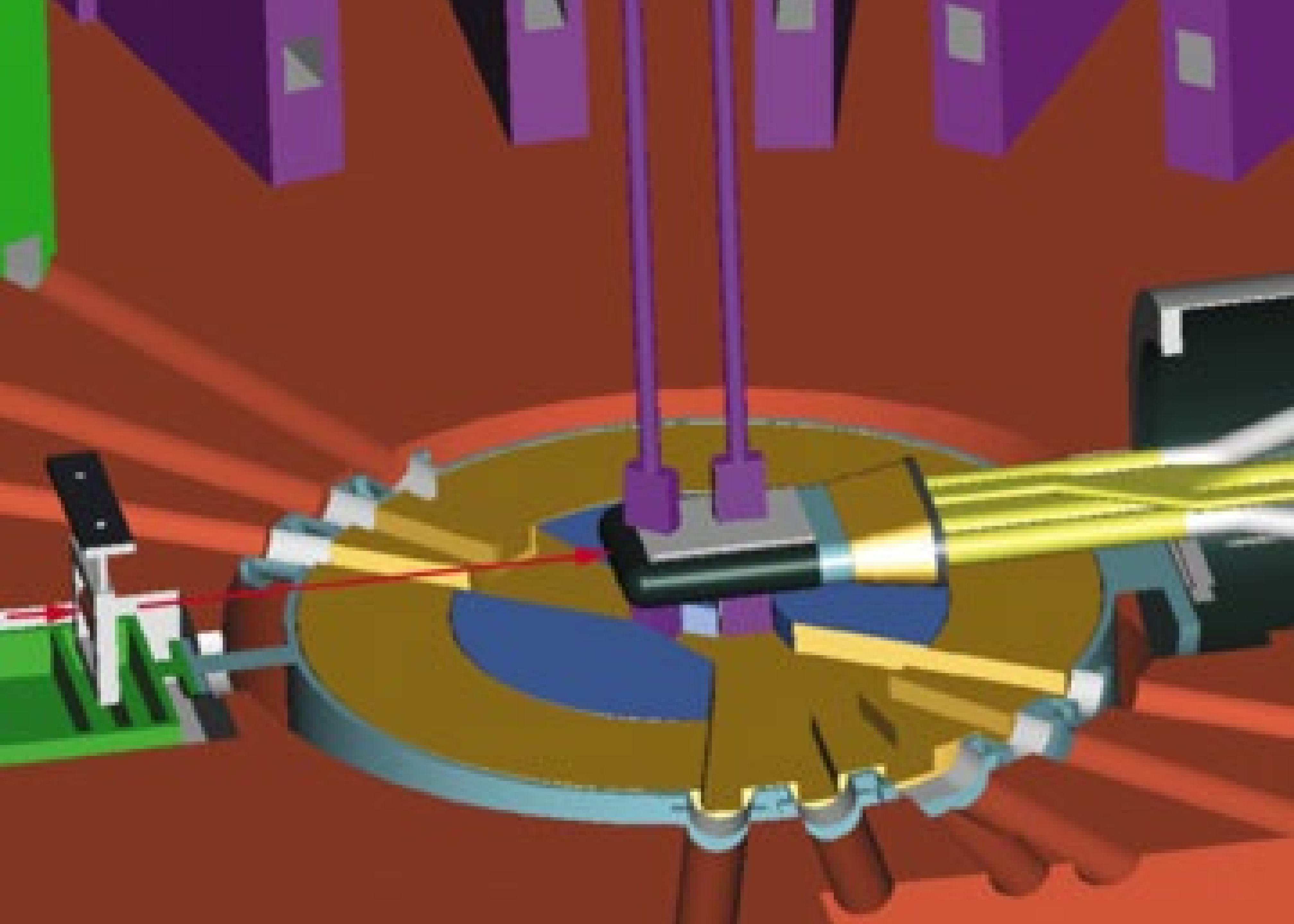
Worldwide Beamlines for Fundamental Physics

Facility	Rep Rate	Guide Size (cm x cm)	Coating (x θ_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}

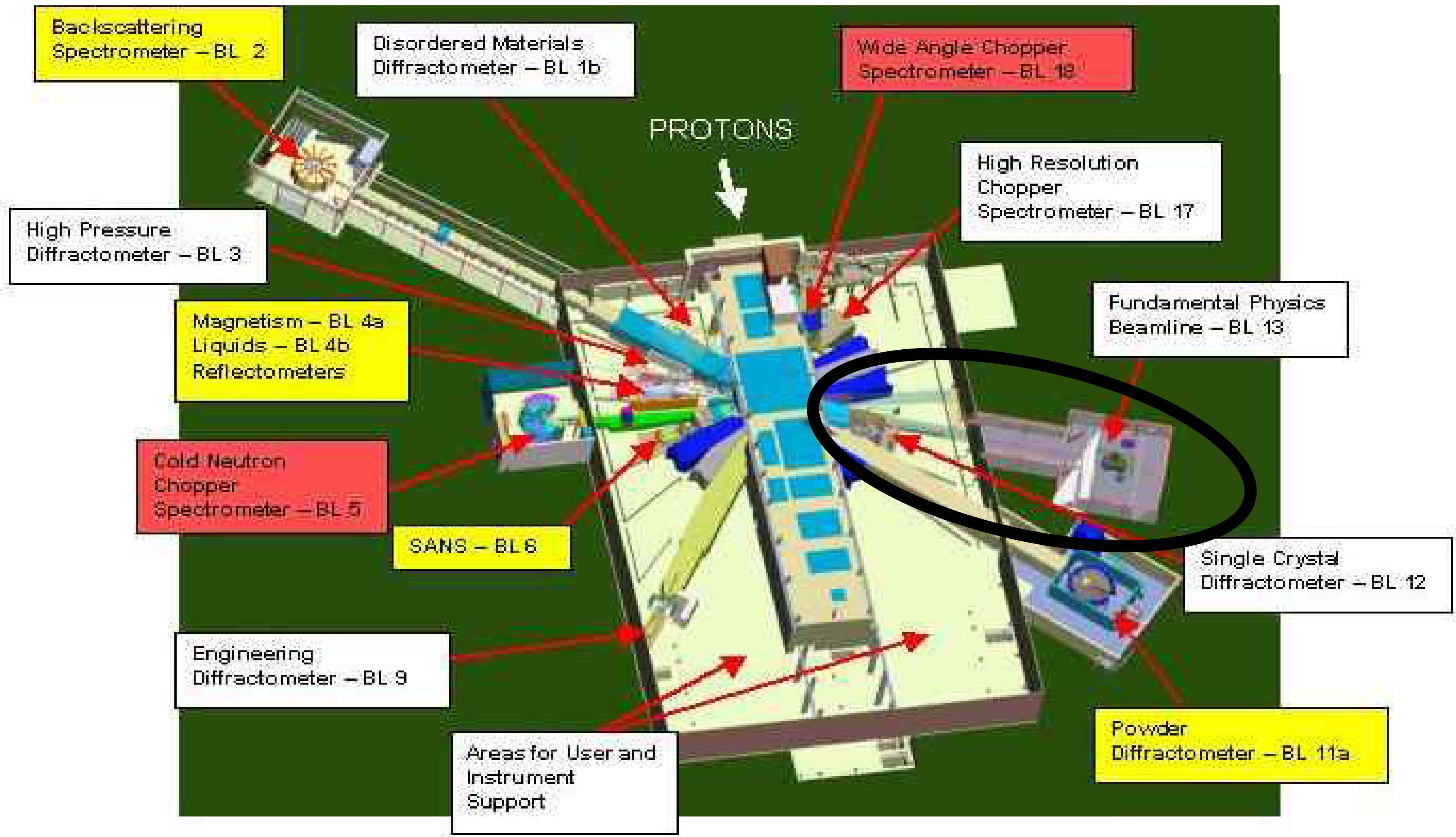
***VERY rough estimate good to within about x2, depends on experimental layout**

OAK RIDGE NATIONAL LABORATORY

The Spallation Neutron Source



The SNS Has Allocated a "Coupled" Cold Beam for Fundamental Neutron Physics



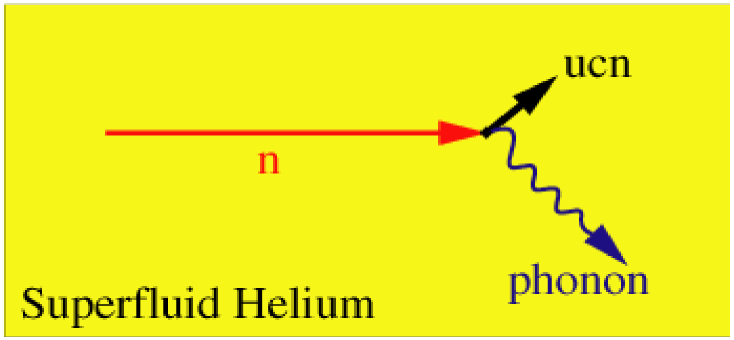
SNS Construction is on Schedule for 2006 Operation

photos, April 2003

“Super Thermal”

Sources of Ultra Cold Neutrons

Production of UCN from Cold Neutrons in Superfluid Helium

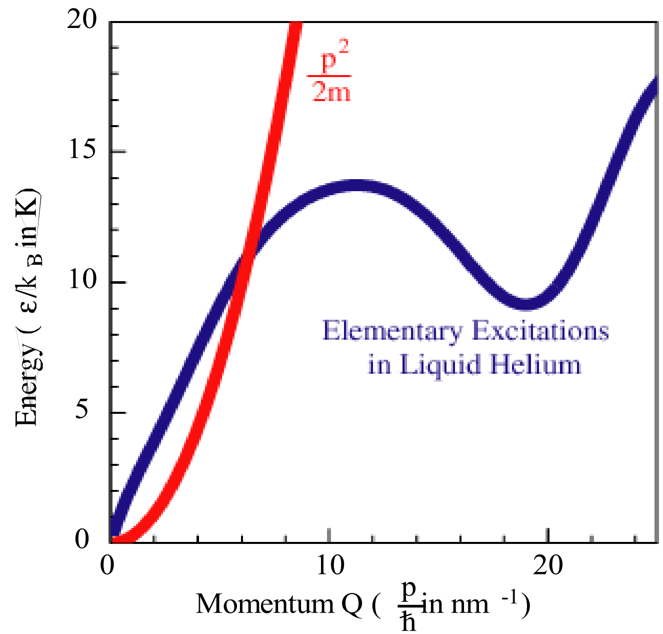


$$\vec{p}_{ucn} = \vec{p}_n - \vec{q}_{phonon}$$

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

- 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) ∝ Population of 11 K phonons $\sim e^{-11K/T_{bath}}$



The LANSCE Solid Deuterium UCN Source

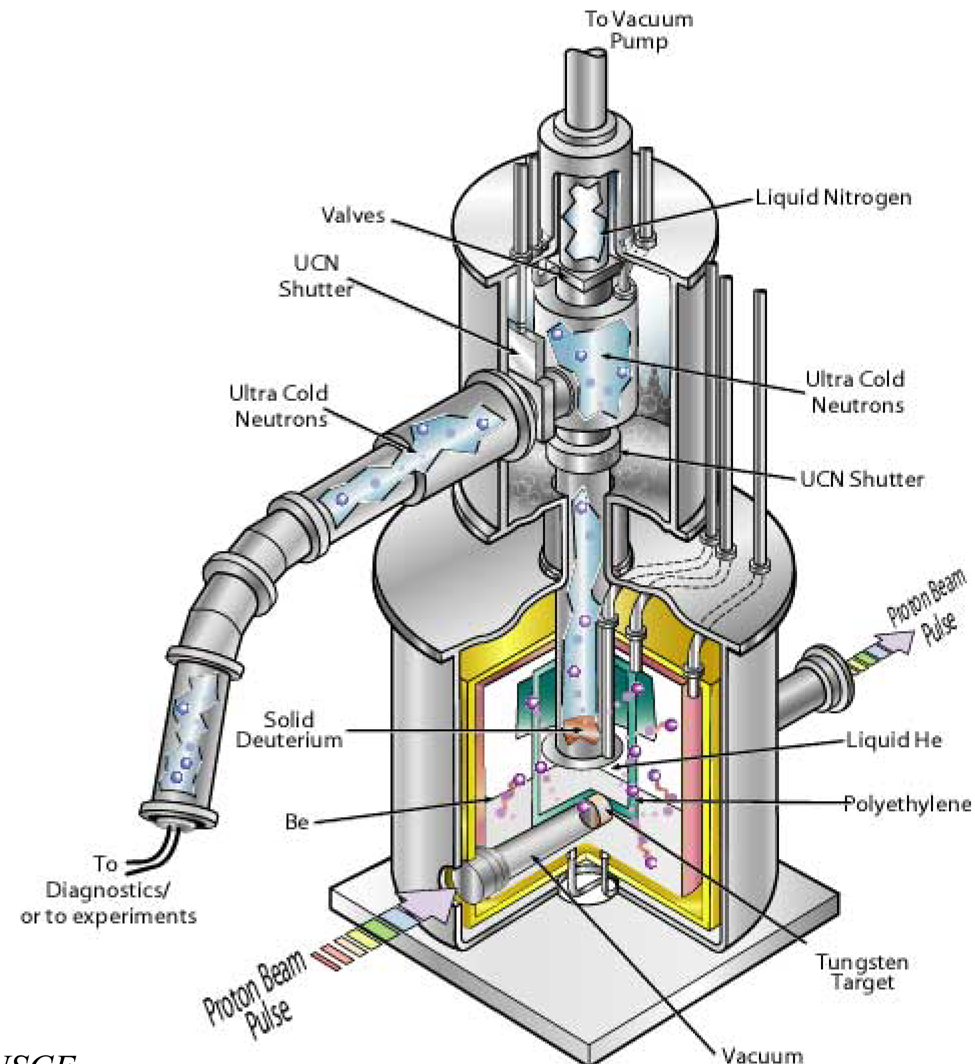


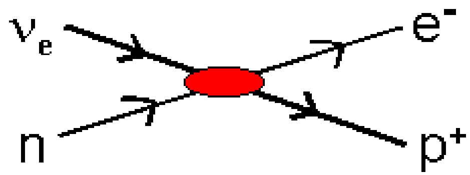
Figure compliments of LANSCE

Neutron Beta Decay

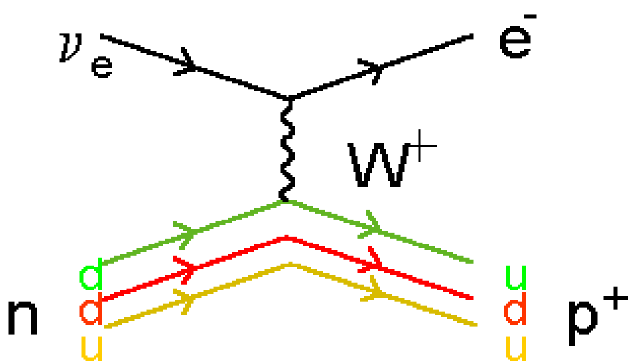
$$n \rightarrow p^+ + e^- + \bar{\nu}_e$$

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

Neutron decay is best viewed as an interaction:

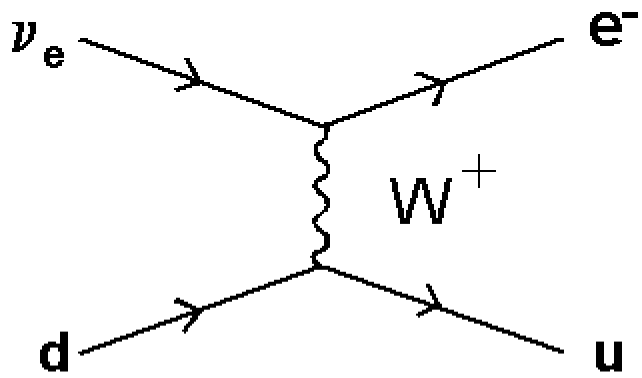


In the standard quark model this simple picture is complicated by the fact that it is the quarks within the nucleon which interact:



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.

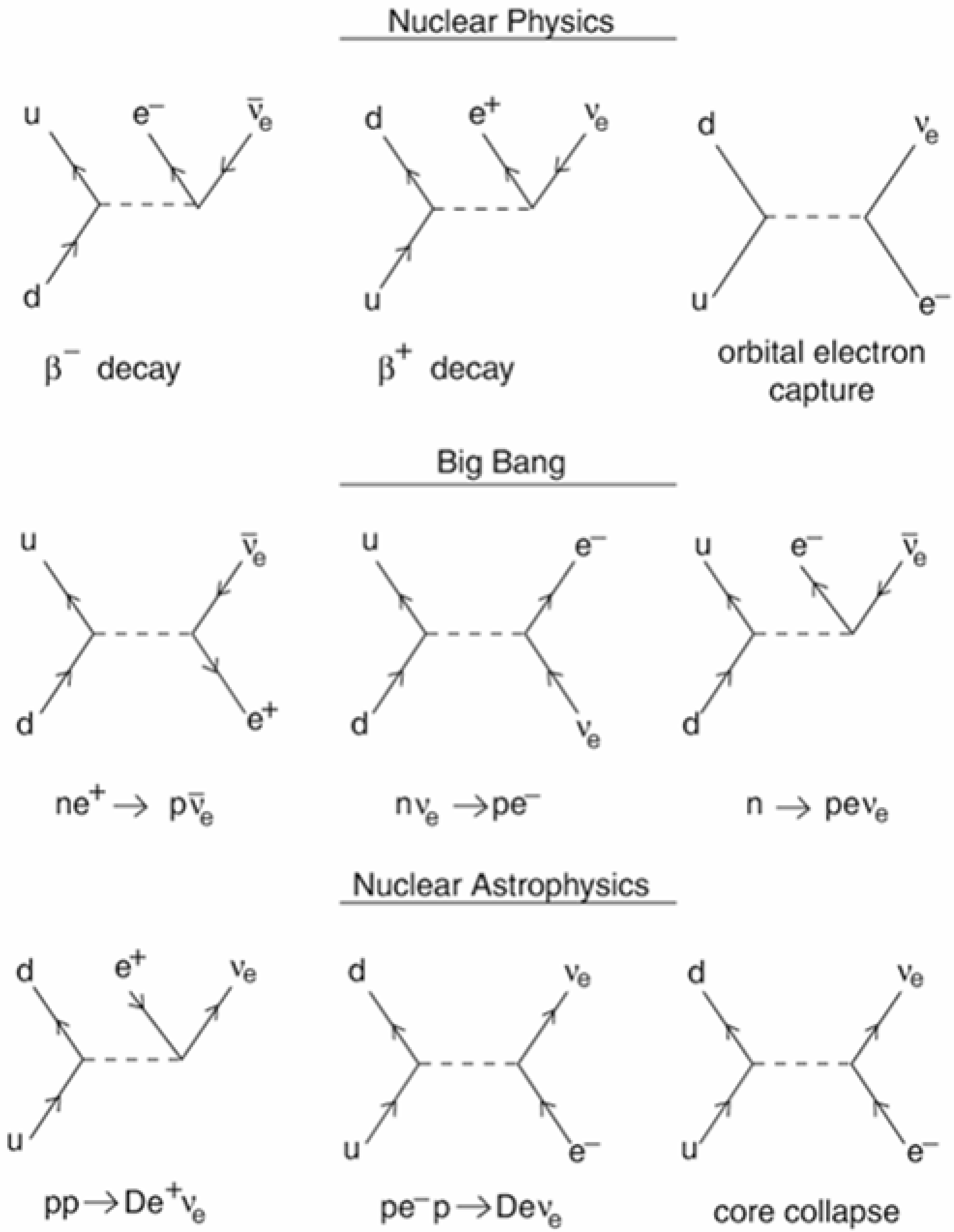
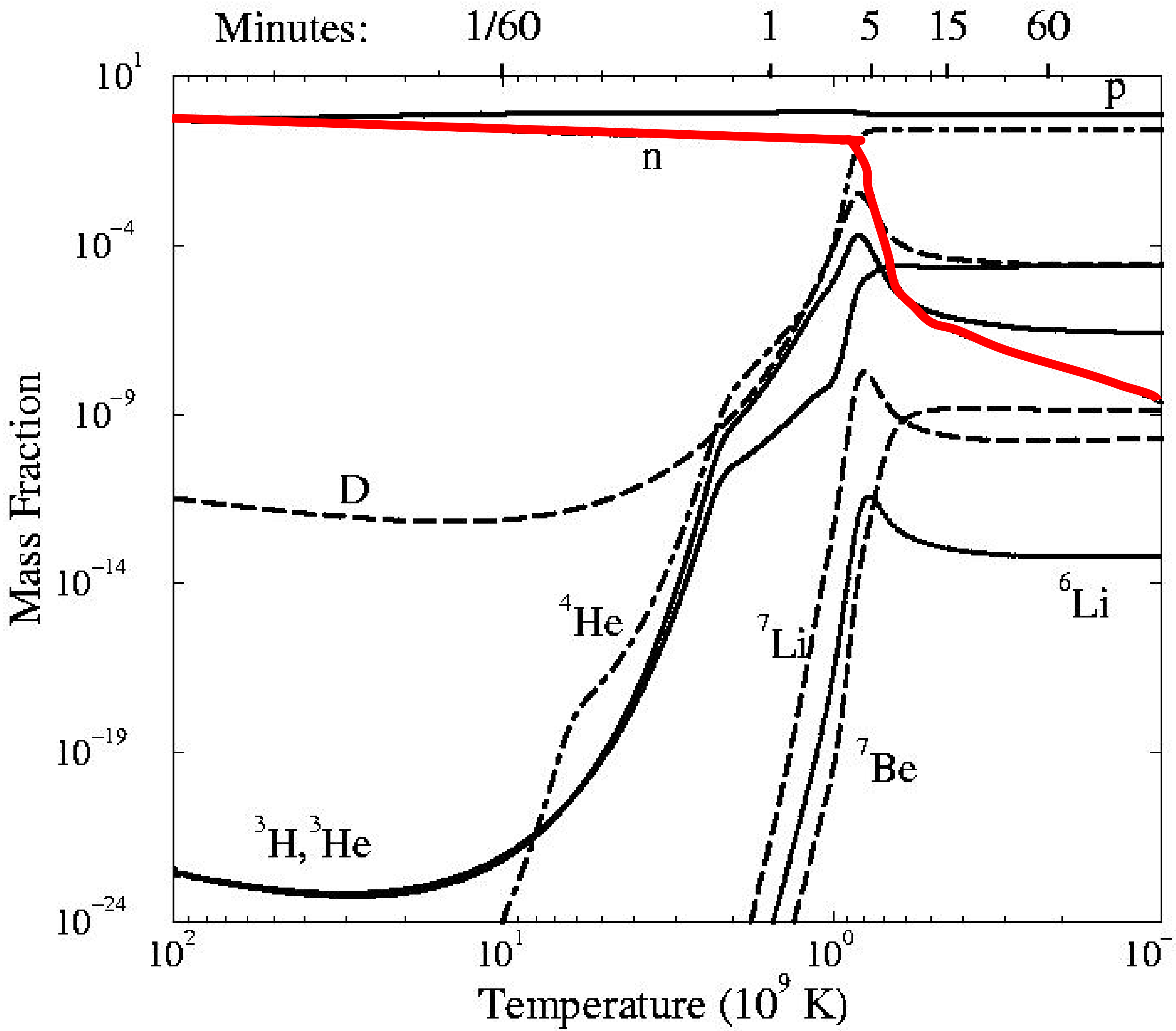


Figure courtesy J.Last


Minutes:
1/60
1
5
15
60
p
n
D
^{4}He
^{3}H, ^{3}He
^{7}Li
^{7}Be
^{6}Li
Mass Fraction
10^1
10^{-4}
10^{-9}
10^{-14}
10^{-19}
10^{-24}
10^2
10^1
10^0
10^{-1}
Temperature (10^9 K)

“After about three minutes, the cosmic hydrogen to helium ratio was fixed….

Steven Weinberg

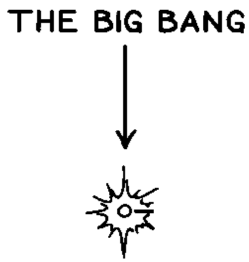
Lecture, Harvard University, 1975

"After about three minutes, the cosmic hydrogen to helium ratio was fixed….

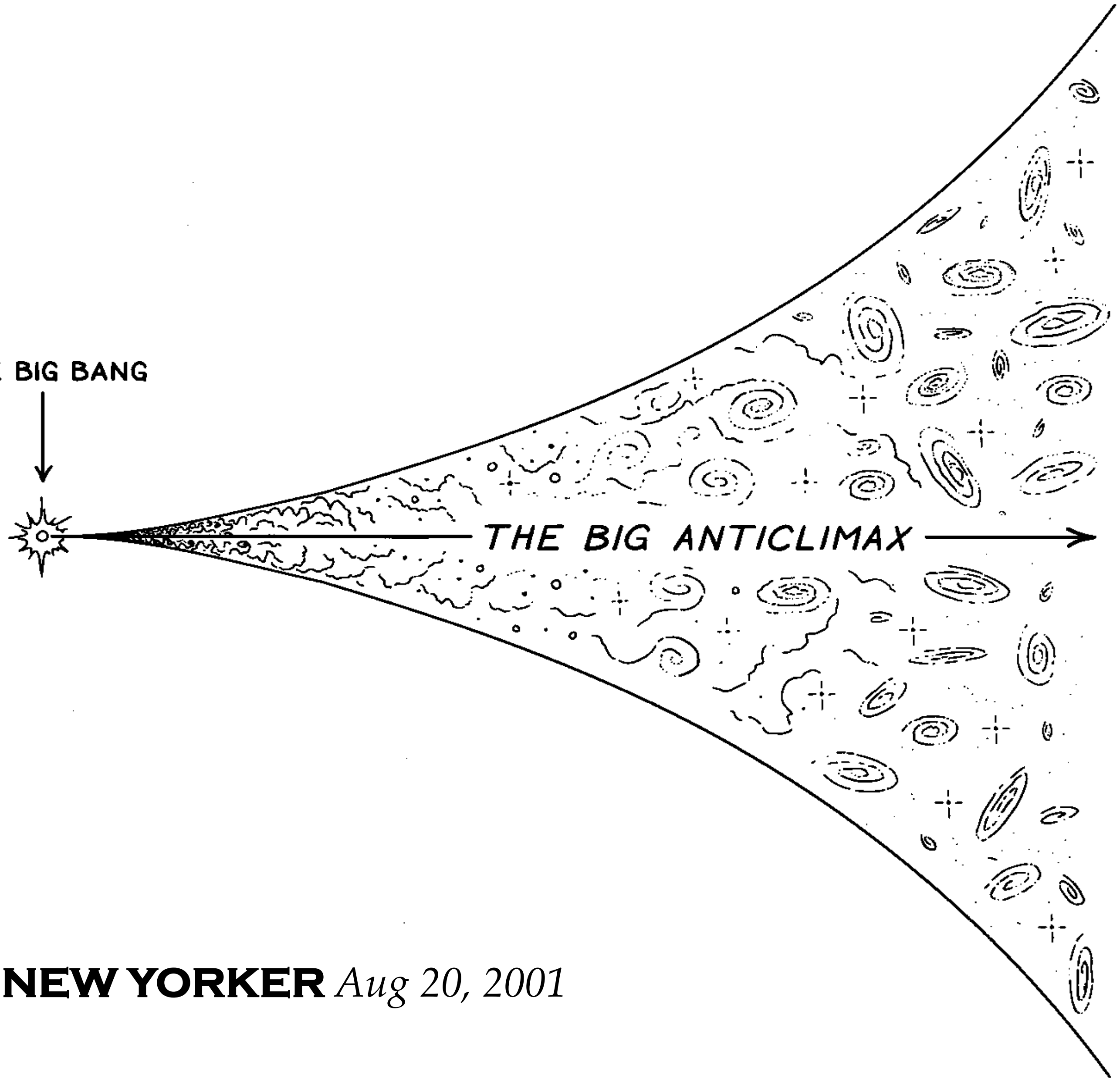
...Nothing of Interest has Happened Since"

Steven Weinberg

Lecture, Harvard University, 1975



from **THE NEW YORKER** *Aug 20, 2001*



from **THE NEW YORKER** *Aug 20, 2001*

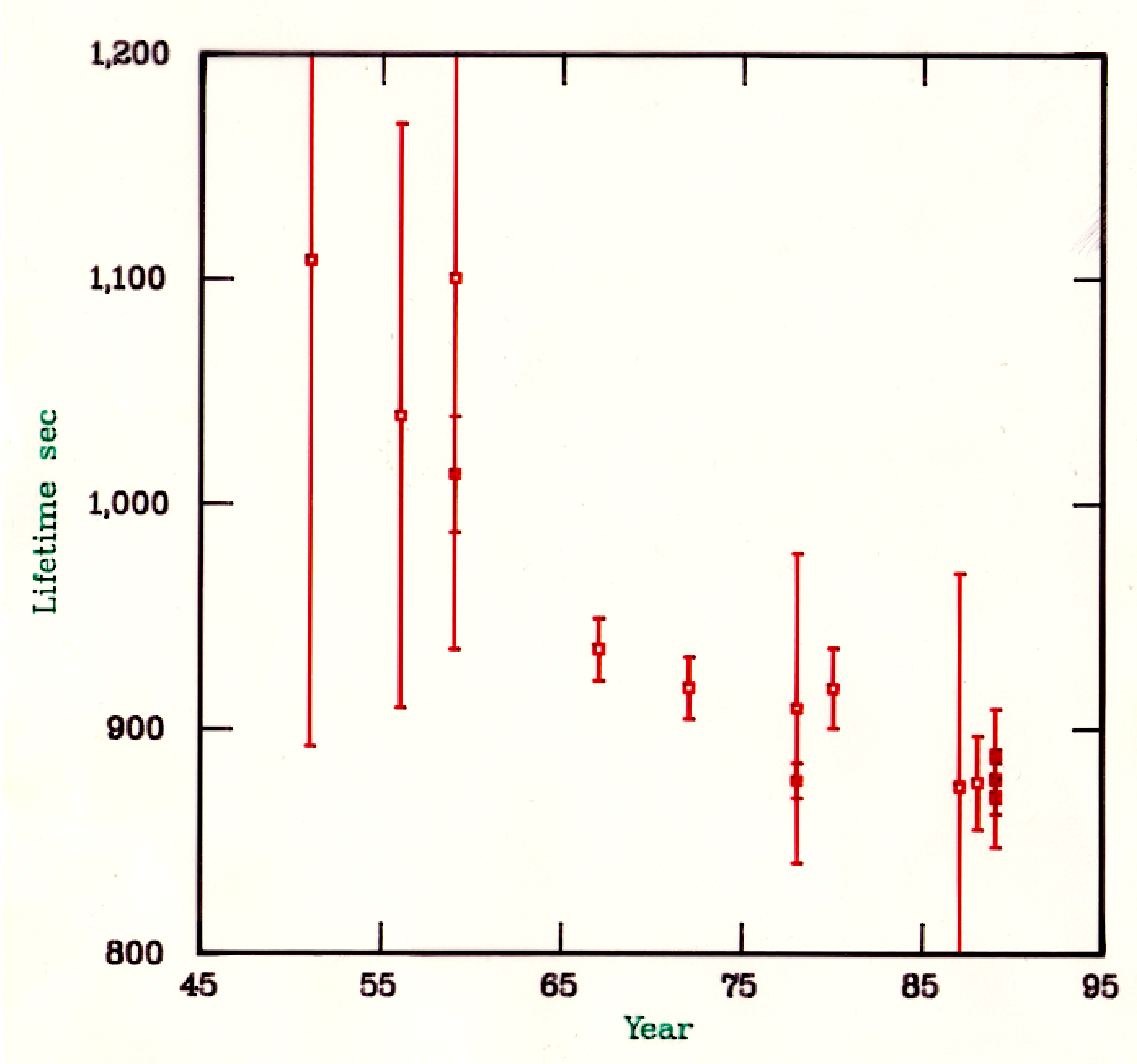
Particle Data Group 2002

VALUE (s)	DOCUMENT ID		TECN	COMMENT
885.7± 0.8 OUR AVERAGE				
885.4± 0.9± 0.4	ARZUMANOV	00	CNTR	UCN double bottle
889.2± 3.0± 3.8	BYRNE	96	CNTR	Penning trap
882.6± 2.7	[8] MAMPE	93	CNTR	Gravitational trap
888.4± 3.1± 1.1	NESVIZHEV...	92	CNTR	Gravitational trap
887.6± 3.0	MAMPE	89	CNTR	Gravitational trap
891 ± 9	SPIVAK	88	CNTR	Beam
• • • 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
878 ±27 ±14	KOSSAKOW...	89	TPC	Pulsed beam
877 ±10	PAUL	89	CNTR	Storage ring
876 ±10 ±19	LAST	88	SPEC	Pulsed beam
903 ±13	KOSVINTSEV	86	CNTR	Gravitational trap
937 ±18	[9] BYRNE	80	CNTR	
875 ±95	KOSVINTSEV	80	CNTR	
881 ± 8	BONDAREN...	78	CNTR	See SPIVAK 88
918 ±14	CHRISTENSEN	72	CNTR	

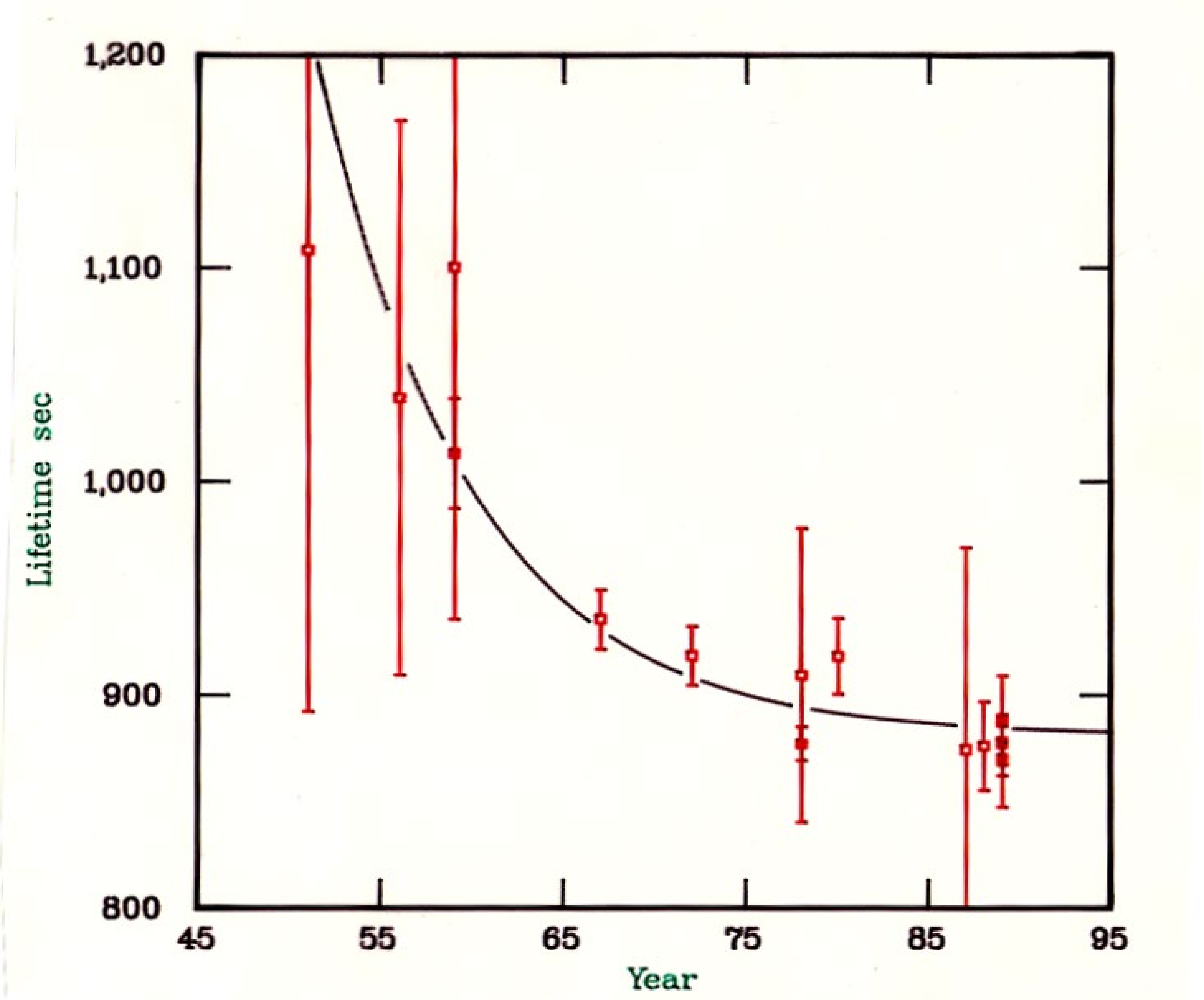
[8] IGNATOVICH 95 calls into question some of the corrections and averaging procedures used by MAMPE 93. The response, BONDARENKO 96, denies the validity of the criticisms.

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

Neutron Lifetime vs. Year of Measurement



Neutron Lifetime vs. Year of Measurement



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:

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

Measurement of the Neutron Lifetime Using a Proton Trap

M. S. Dewey, D. M. Gilliam, and J. S. Nico

National Institute of Standards and Technology, Gaithersburg, MD 20899

F. E. Wietfeldt

Tulane University, New Orleans, LA 70118

X. Fei and W. M. Snow

Indiana University, Bloomington, IN 47408

G. L. Greene

University of Tennessee/Oak Ridge National Laboratory, Knoxville, TN 37996

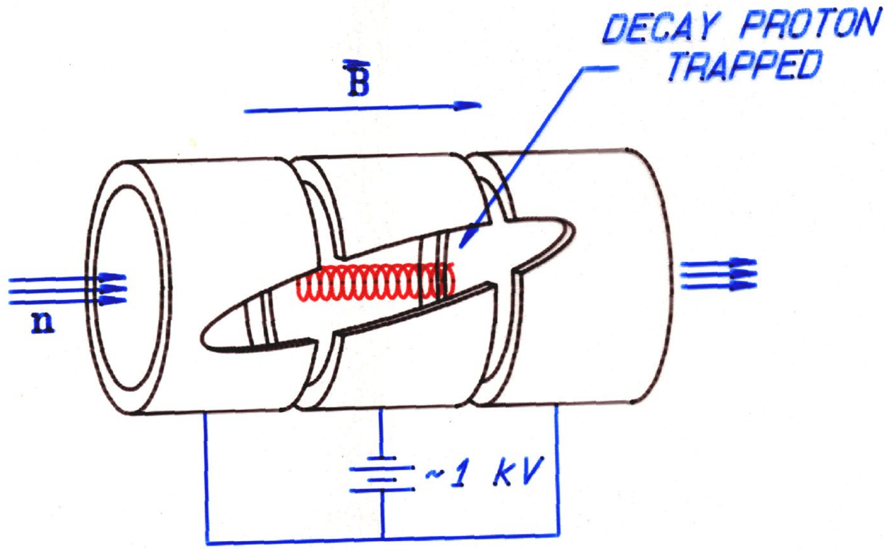
J. Pauwels, R. Eykens, A. Lamberty, and J. Van Gestel

European Commission, Joint Research Centre,

Institute for Reference Materials and Measurements, 2440 Geel, Belgium

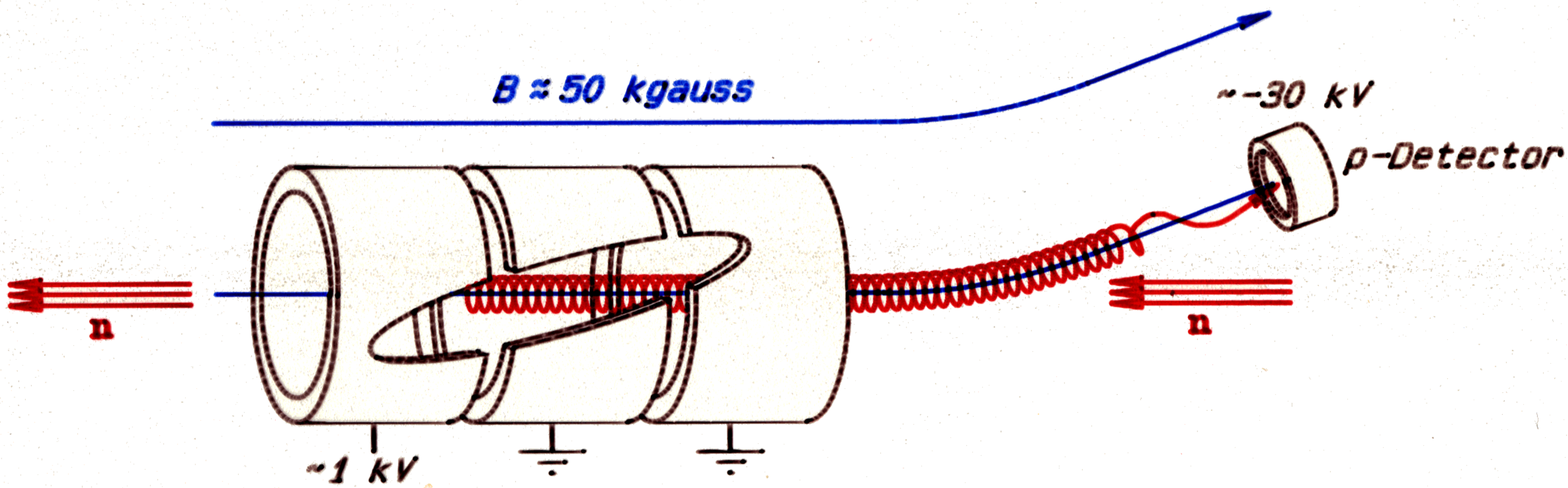
(Dated: May 2, 2003)

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 $10^{-6}-10^{-7}$.

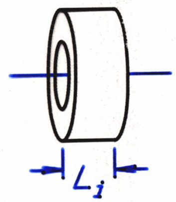
The Trap is "Opened" and the Emerging Protons are Accelerated and Detected



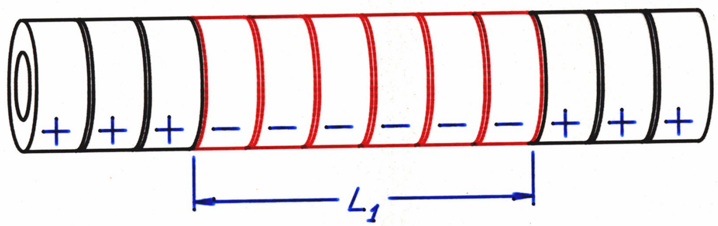
The trap volume (length) must be accurately known in order to extract an absolute decay rate

METHOD OF "VIRTUAL" TRAP LENGTH

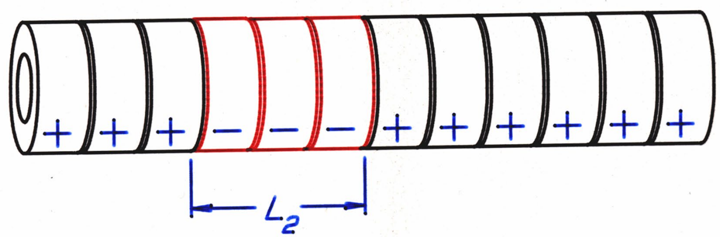
Step 1. Fabricate trap from many elements
each of which has a well known length



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

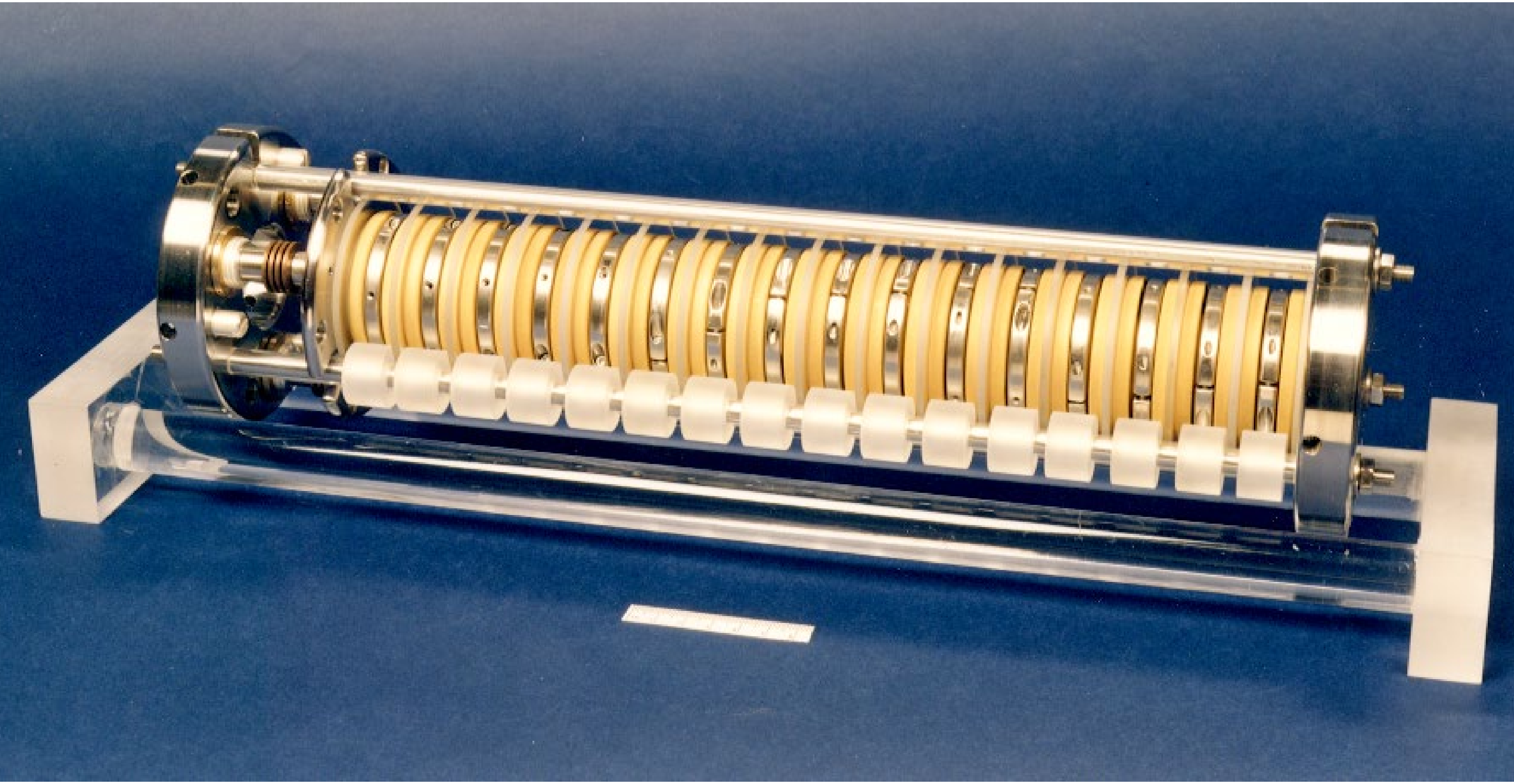


Step 3. Repeat with different value of N

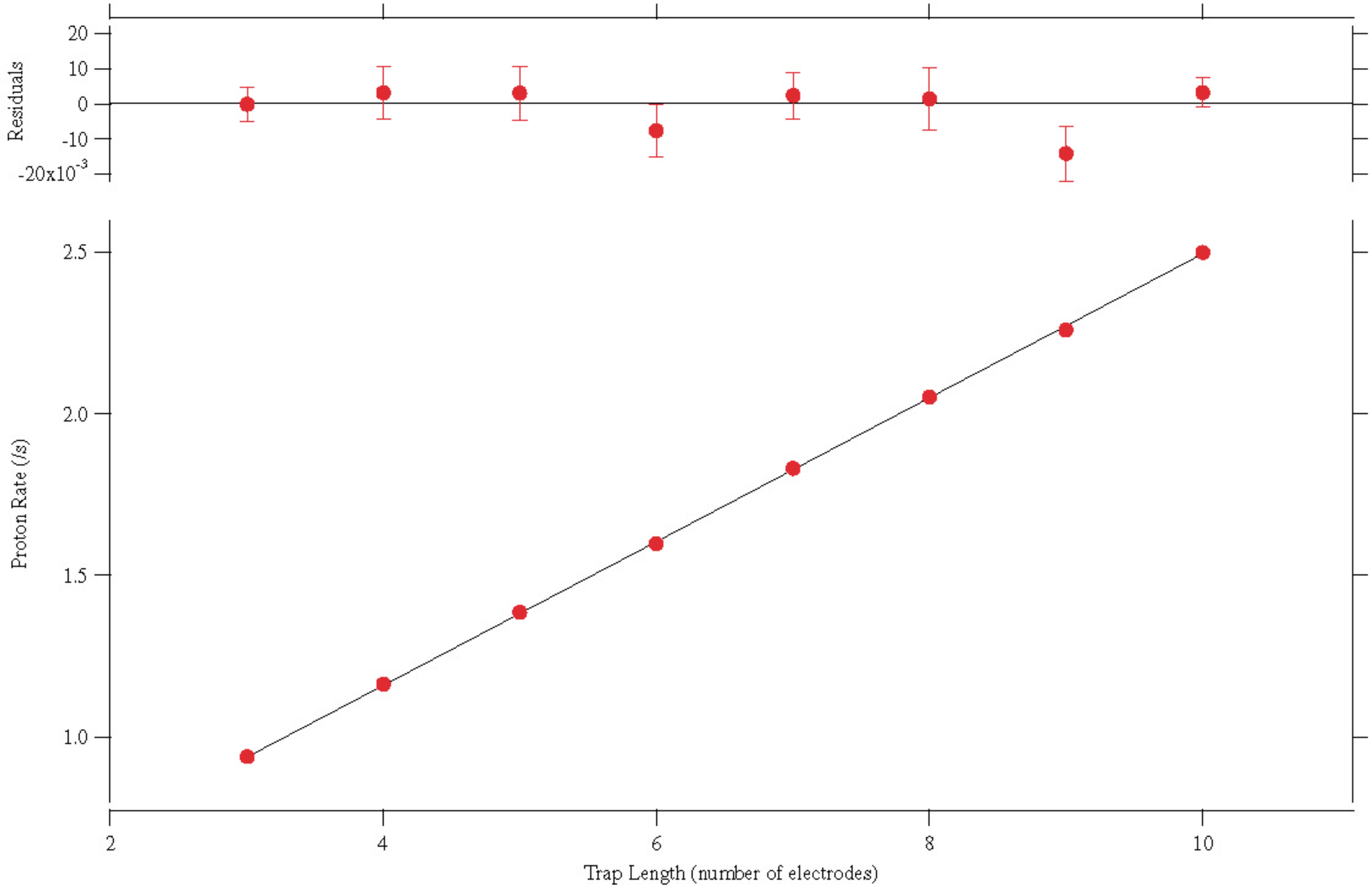


THOUGH NEITHER L_1 NOR L_2 ARE WLL KNOWN
THE DIFFERENCE $\Delta L = L_1 - L_2$ CAN BE GIVEN
WITH HIGH ACCURACY!

NIST Variable Length Trap *Mk II*

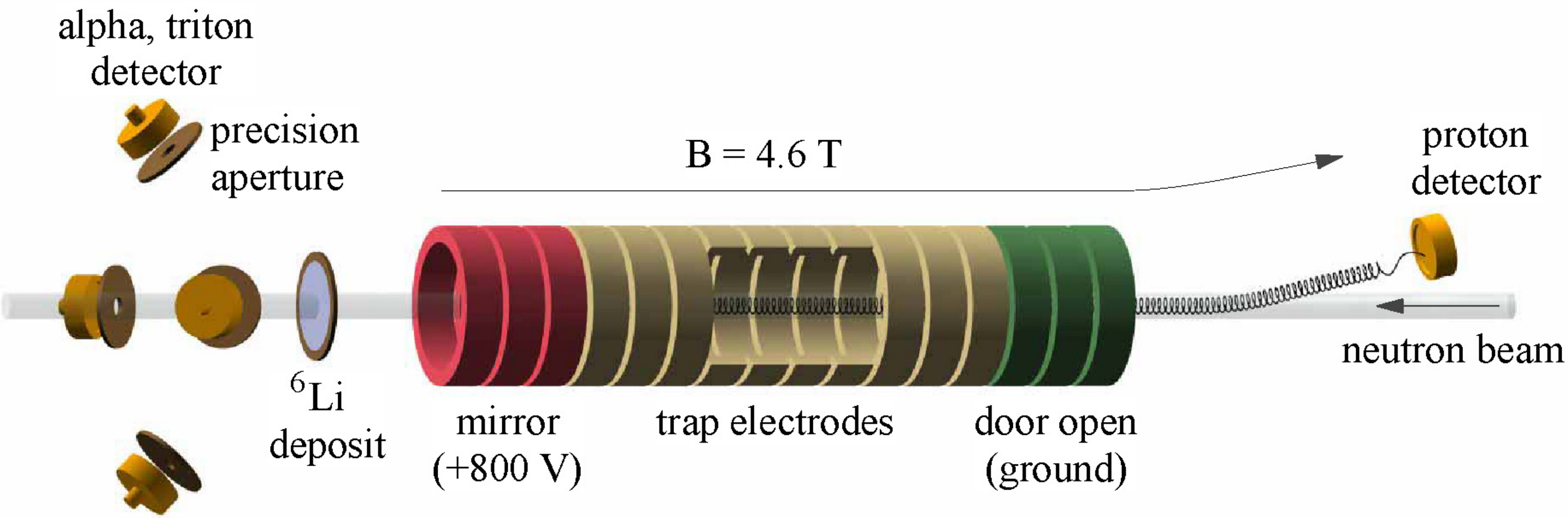


Effective Trap Length by Extrapolation

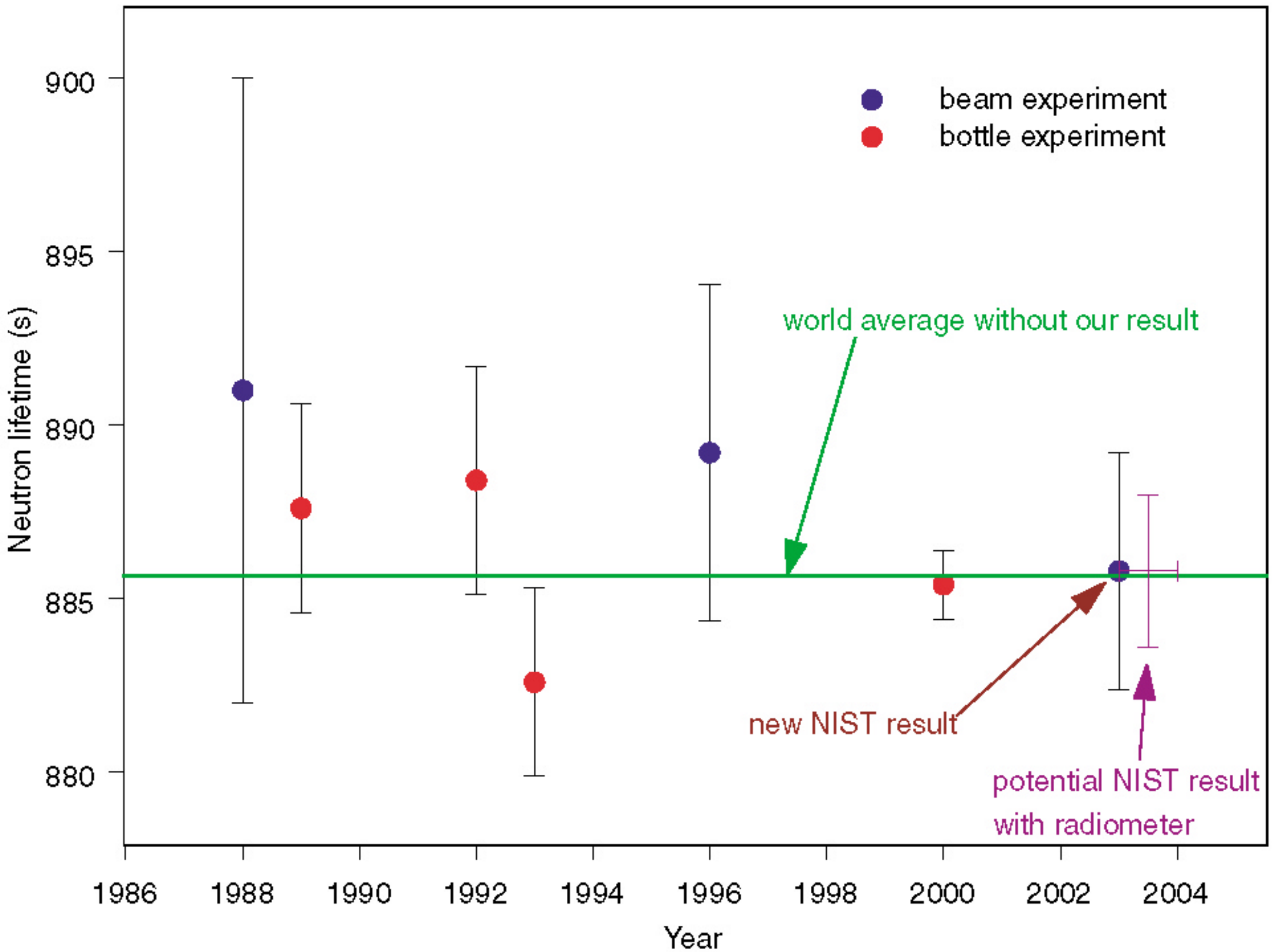


Proton rate versus trap length (below); residuals from a linear fit between the two (above).

The Penning Trap for Decay Protons




CAUTION
STRONG
MAGNETIC
FIELD
DANGER
HIGH VOLTAGE,
KEEP AWAY
DANGER
High voltage



Values of the neutron lifetime taken into account by the Particle Data Group *plus* our new result.

Determination of the Neutron Lifetime using An Ultra Cold Neutron Bottle

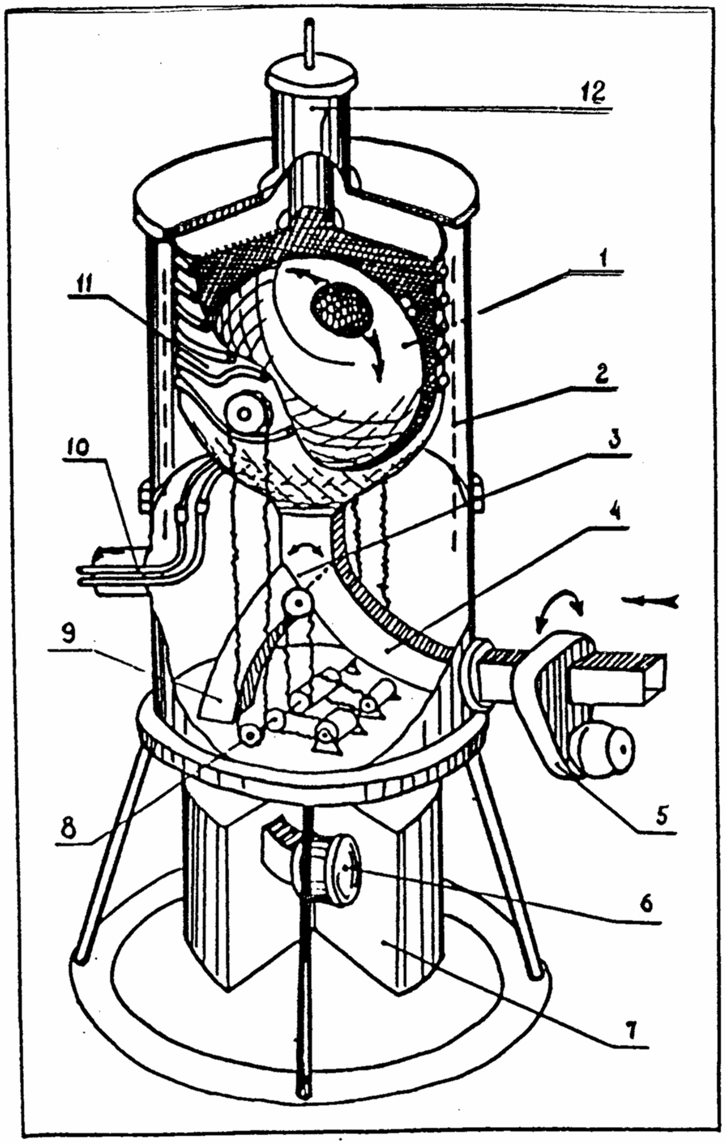


Image Courtesy of A. Serebrov

Magnetic Trapping of Ultracold Neutrons

[P. Huffman, et. al, *Nature*, 403, no.6765, 2000]

S. N. Dzhosyuk, C. E. H. Mattoni, D. N. McKinsey, L. Yang and J. M. Doyle
Harvard University

P. R. Huffman and A. K. Thompson
NIST, Gaithersburg

R. Golub
HMI, Berlin

S. K. Lamoreaux, G. Greene
Los Alamos National Laboratory

K. J. Coakley
NIST, Boulder

Ioffe-Type Magnetic Trap

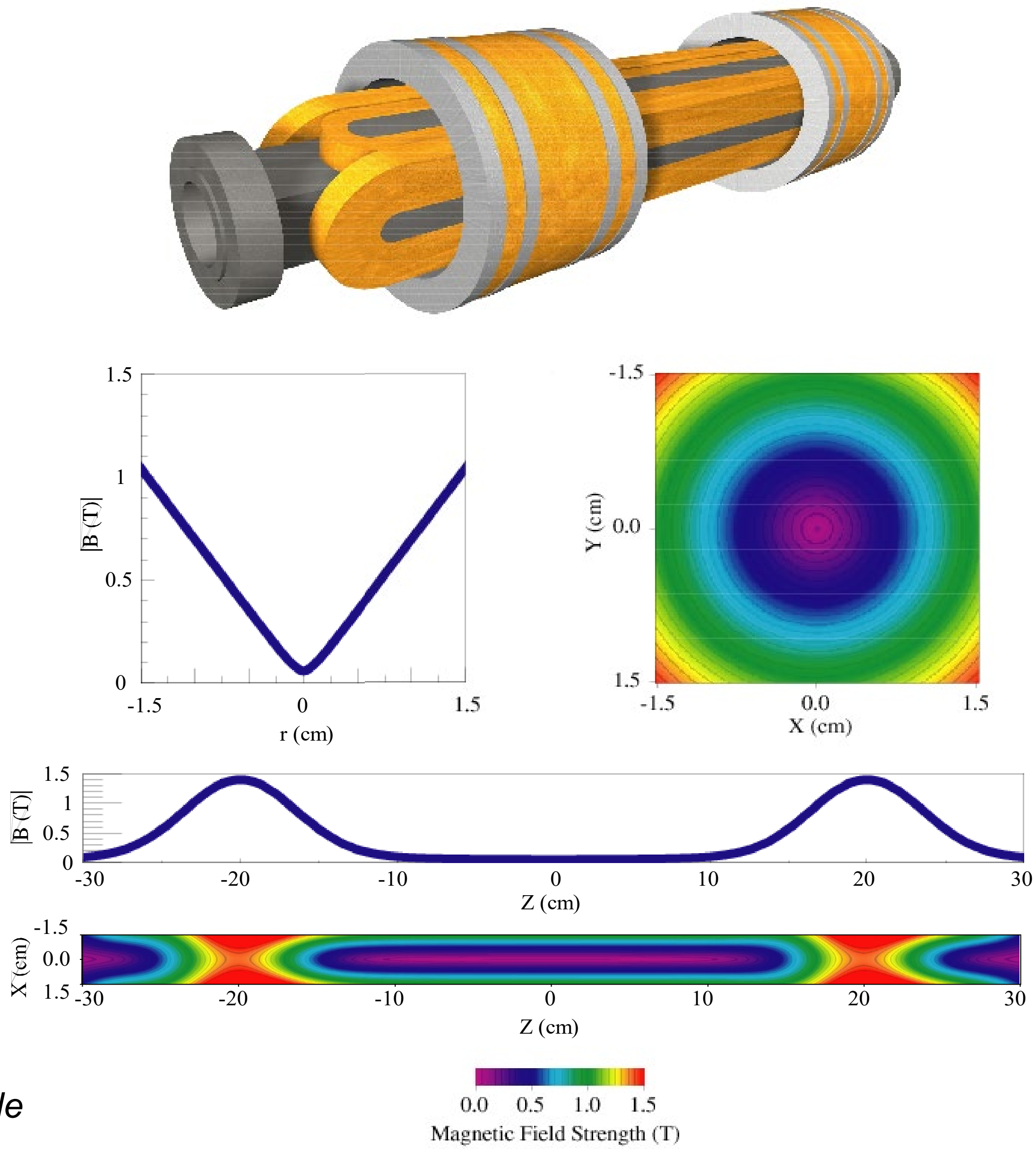


figure courtesy J. Doyle

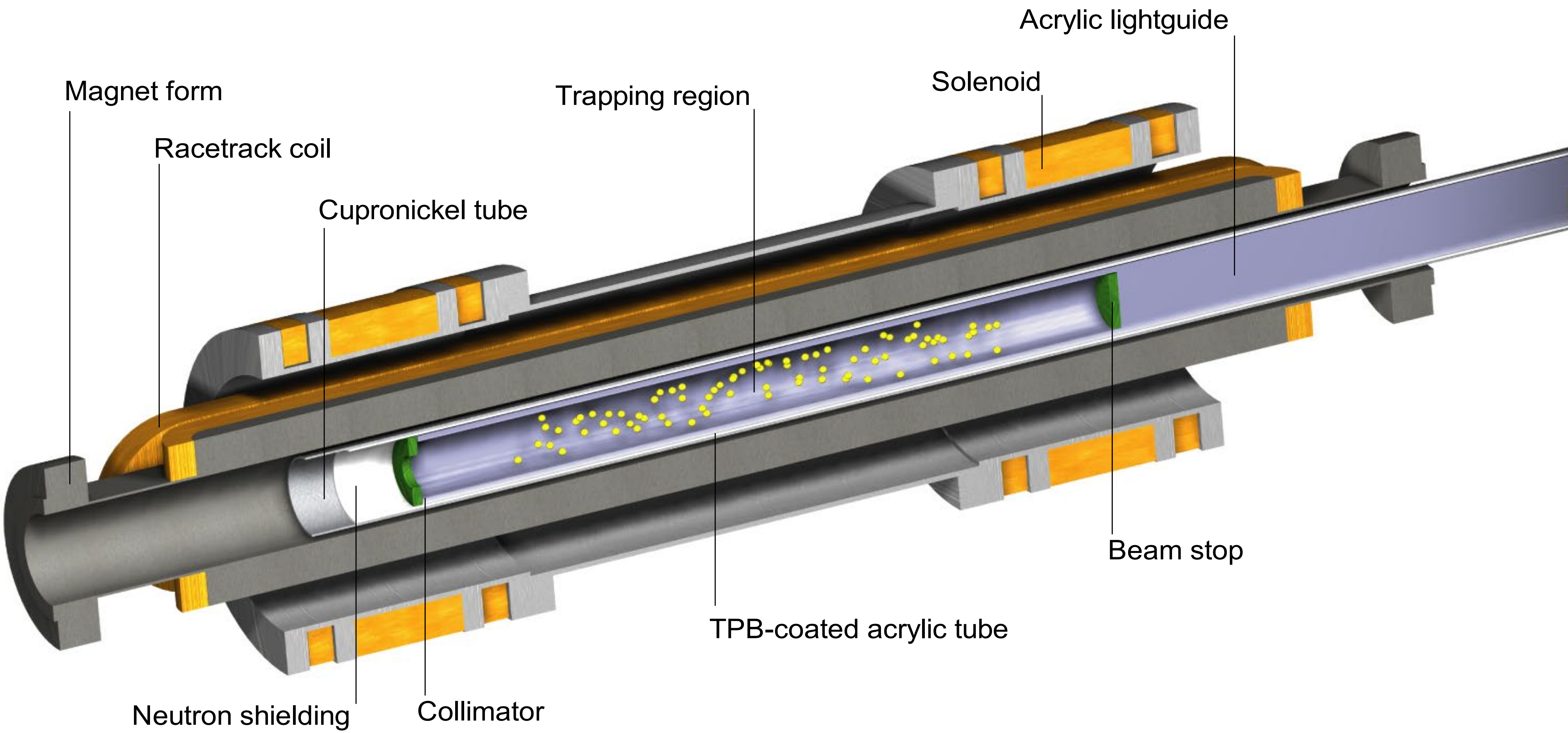
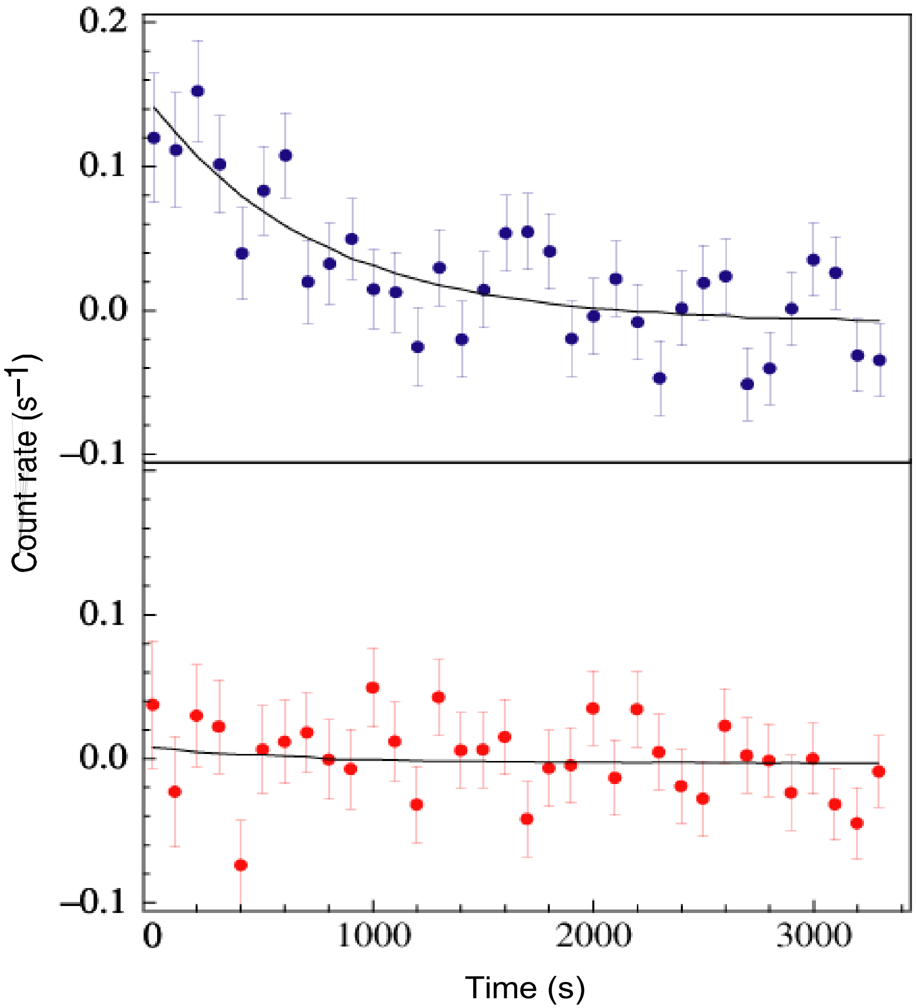


figure courtesy J.Doyle

Preliminary Trapped Neutron Decay Data



$W_1 = a_1 e^{-t/\tau} + C_1$
$W_2 = a_2 e^{-t/\tau} + C_2$

Trapping data (blue)

$a = 0.16\ s^{-1} \pm 0.03\ s^{-1}$
$C = 0.003 \pm 0.007$
$\tau = 660\ s\ +290\ s/-170\ s$

^3He data (red)

$a = -0.040\ s^{-1} \pm 0.045\ s^{-1}$
$C = -0.011 \pm 0.011$
τ = fixed at 750 s

Total number trapped:

$N = 453 \pm 100$

Theory Predicts:

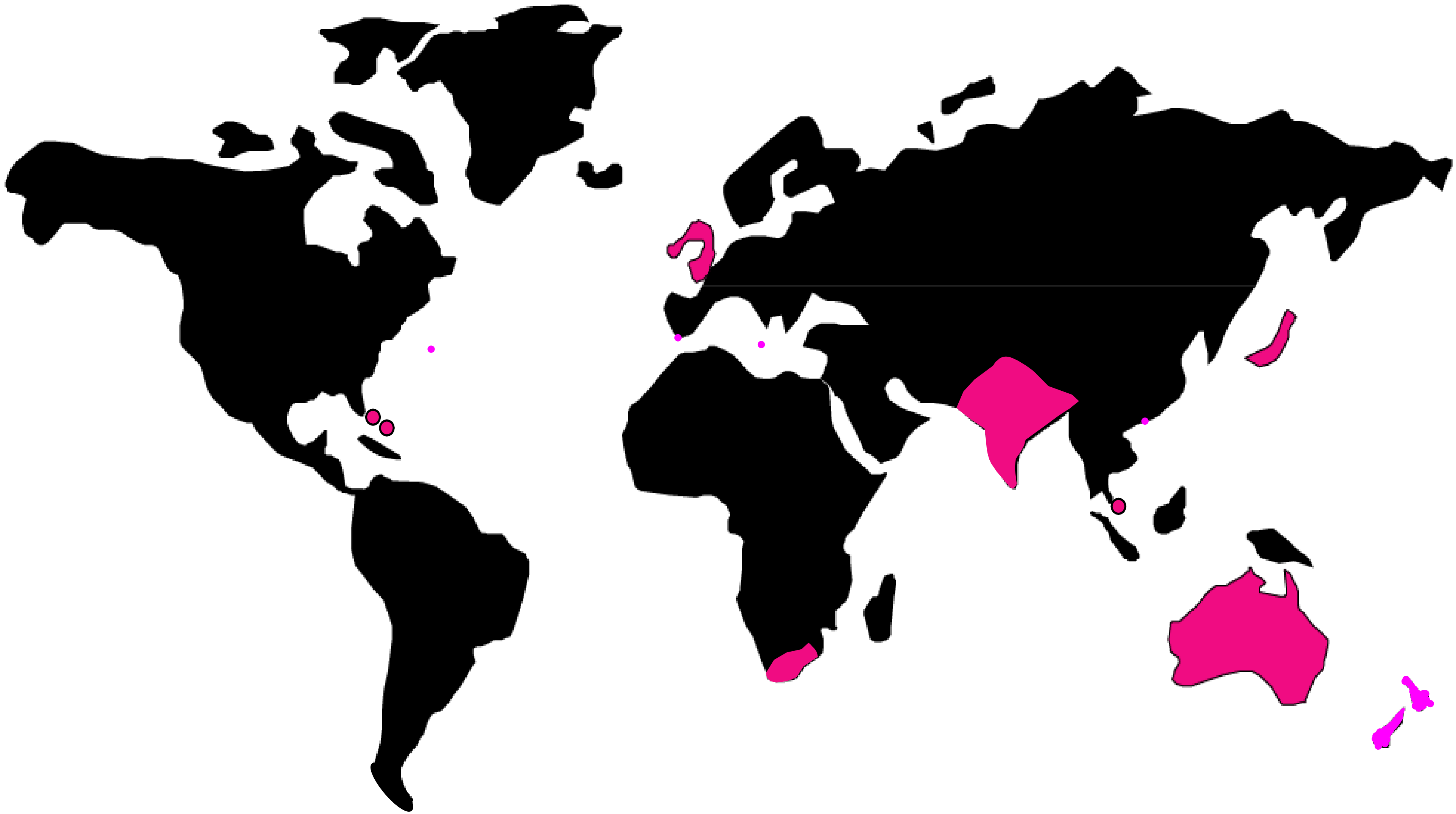
$N = 500 \pm 170$

Introduction to
Parity Violation in Neutron Decay

Parity Violation…Chance or Necessity?*

* See Democritos, circa 400 BCE

Some Domains of "Left-Handedness" in a Right-Handed World



Broken Symmetry

A situation in which the ground state of a many-body system (or the vacuum state of a relativistic quantum field theory) has a lower symmetry than the Hamiltonian which defines the system.

Some Characteristics of “Spontaneous Symmetry Breaking”

- ***There is an underlying symmetry to the system.***
- ***The physical state has lower symmetry than the underlying symmetry***
- ***The symmetry breaking may not be complete.***
- ***Incomplete symmetry breaking may be manifested by a residue of other symmetry states or domains in which the other symmetry is manifested***

Is this an Accident?

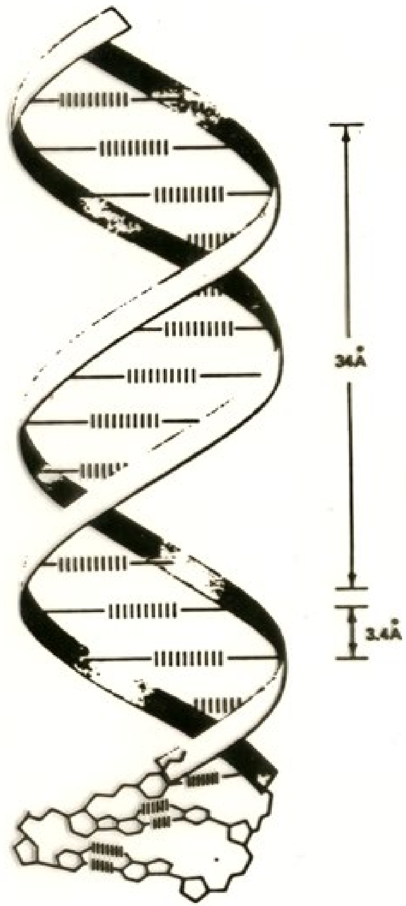


FIGURE 1-5

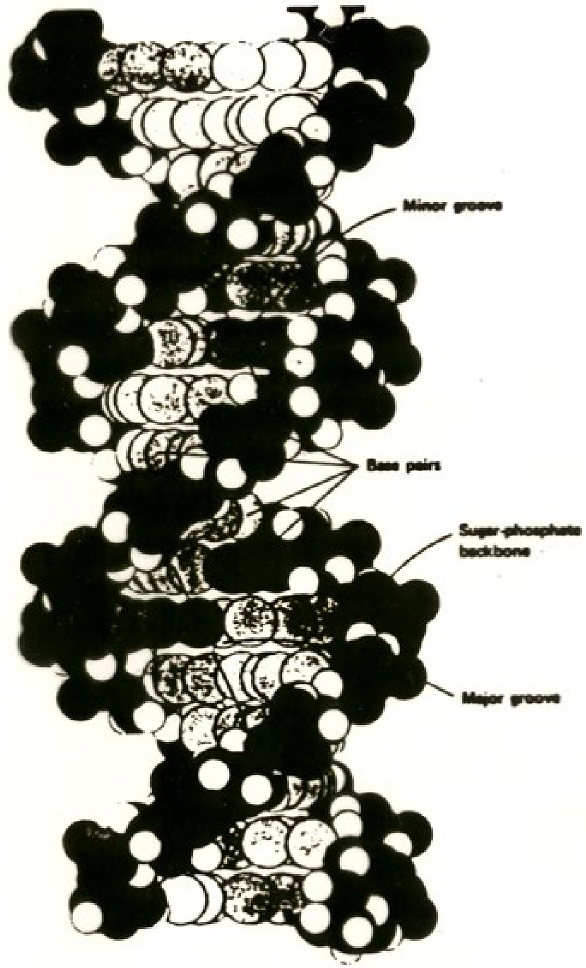
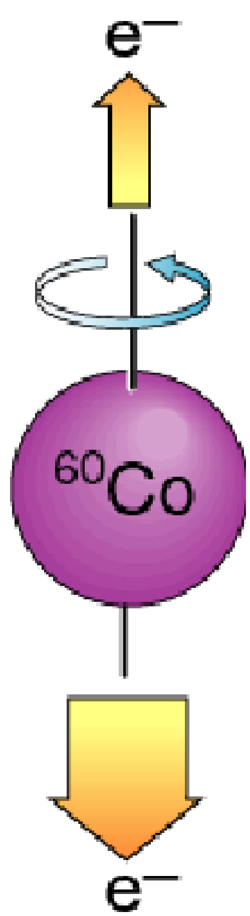


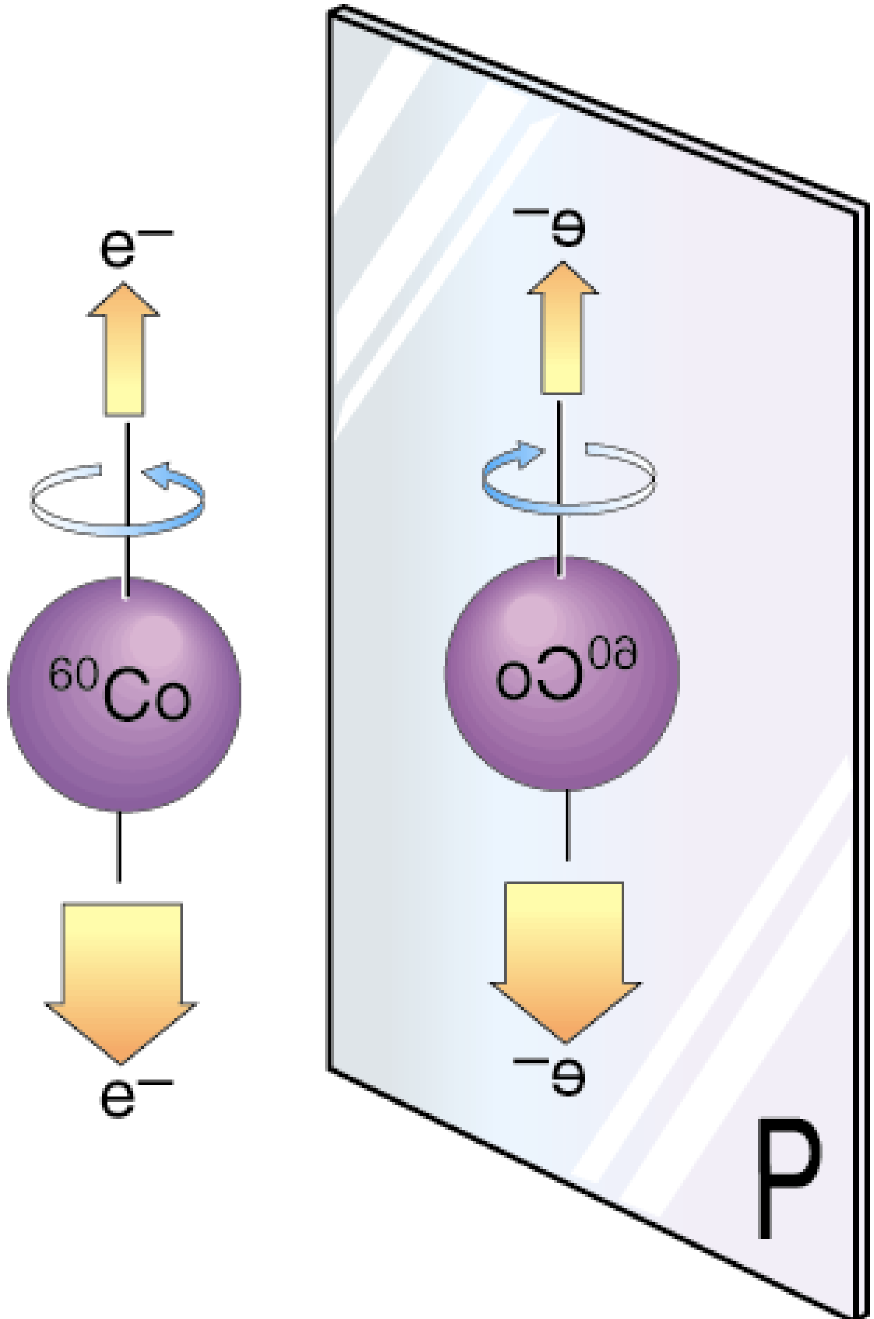
FIGURE 1-6
Space-filling model of the DNA double helix.

$$^{60}Co \rightarrow {}^{60}Ni + e^- + \bar{\nu}_e$$

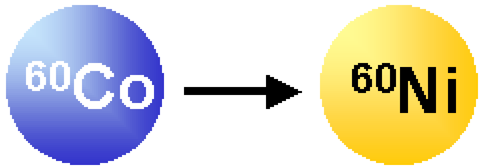


Wu, Ambler, Hudson, Hoppes, Hayward (NBS) 1957

Is this an "accident"?

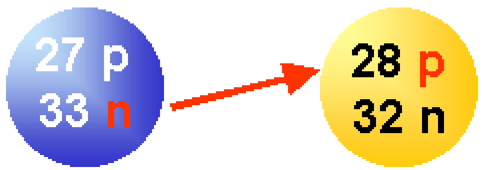

e−
60Co
e−
P

Nuclear Beta Decay:



$$+ e^- + \bar{\nu}_e$$

Is "really" Neutron decay complicated by nucleon-nucleon forces:



$$+ e^- + \bar{\nu}_e$$

These nuclear forces perturb the bare neutron decay and lead to the wide variation of radioactive lifetimes as well as to the stability of nuclei.

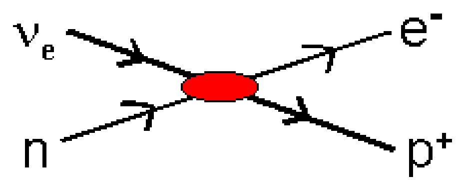
To understand beta decay (as well as parity violation in beta decay), it is very useful to study the prototype decay of the FREE neutron:

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

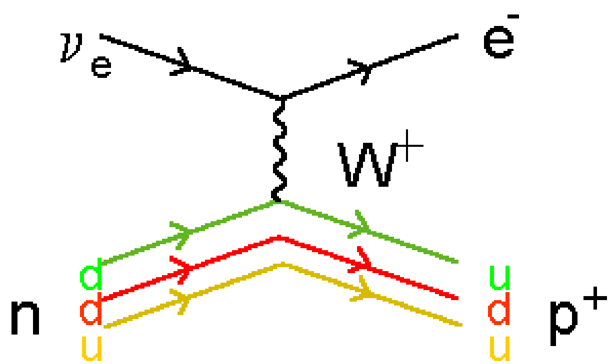
$$n \rightarrow p^+ + e^- + \overline{\nu}_e$$

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

Neutron decay is best viewed as an interaction:

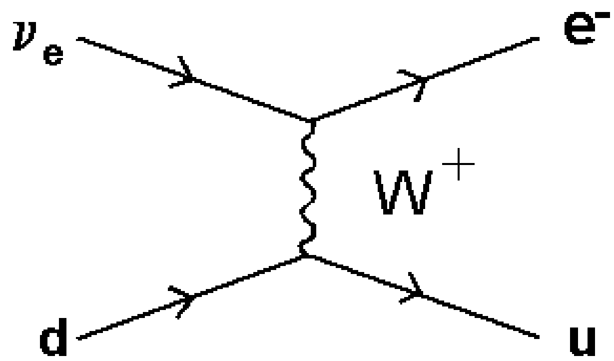


In the standard quark model this simple picture is complicated by the fact that it is the quarks within the nucleon which interact:



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

Theoretical Framework for the Theory of Neutron Decay

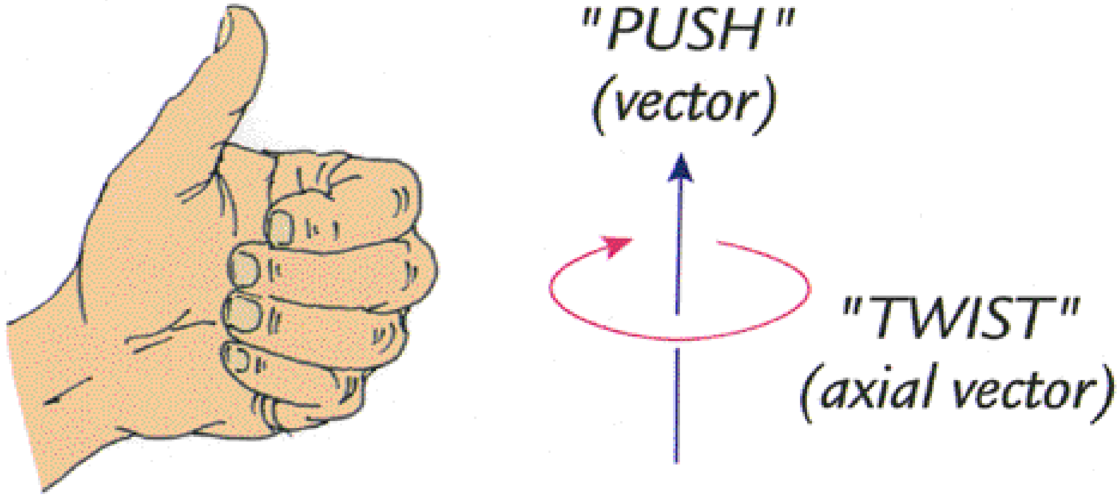


We construct a Weak Hamiltonian that couples a down quark to an up quark, and an electron to an electron neutrino:

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

Question: How to include parity violation?

How to Include Parity Violation ("Handedness")?



$$H_{weak} = G_{weak} \langle \nu_e | \gamma_\mu - \gamma_\mu \gamma_5 | e^- \rangle \langle d | \gamma_\mu - \gamma_\mu \gamma_5 | u \rangle$$

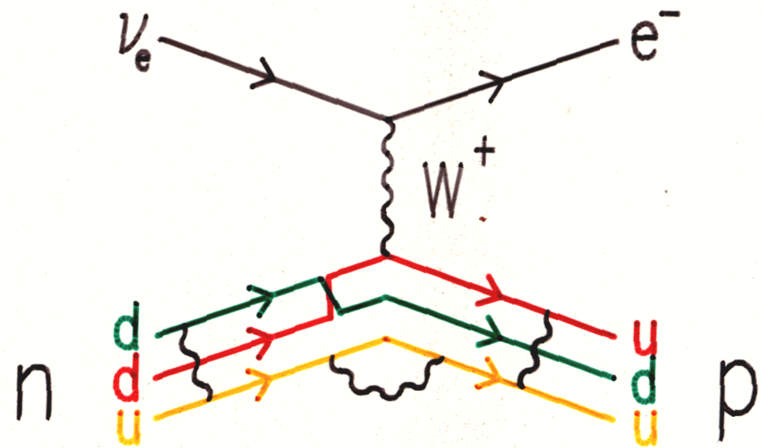
"V-A"

Vector – Axial Vector

The V-A theory implies pure "left-handedness"

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:

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

Correlations in Neutron Decay

Parity violation implies a rich phenomenology in neutron decay:

$$dW \propto \frac{1}{\tau} F(E_e) \left[1 + a \frac{\mathbf{p}_e \cdot \mathbf{p}_\upsilon}{E_e \cdot E_\upsilon} + b \frac{m_e}{E_e} + A \frac{\sigma_n \cdot \mathbf{p}_e}{E_e} + B \frac{\sigma_n \cdot \mathbf{p}_\upsilon}{E_\upsilon} \right]$$

τ *is the neutron lifetime*

$\mathbf{p}_e$, $\mathbf{p}_p$, *and* $\mathbf{p}_\nu$ *are the momenta of the decay particles*

$\boldsymbol{\sigma}_n$ *is the spin of the neutron*

Correlation Coefficients in Neutron Decay can be Simply Related to Fundamental Couplings

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

$$b = 0$$

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

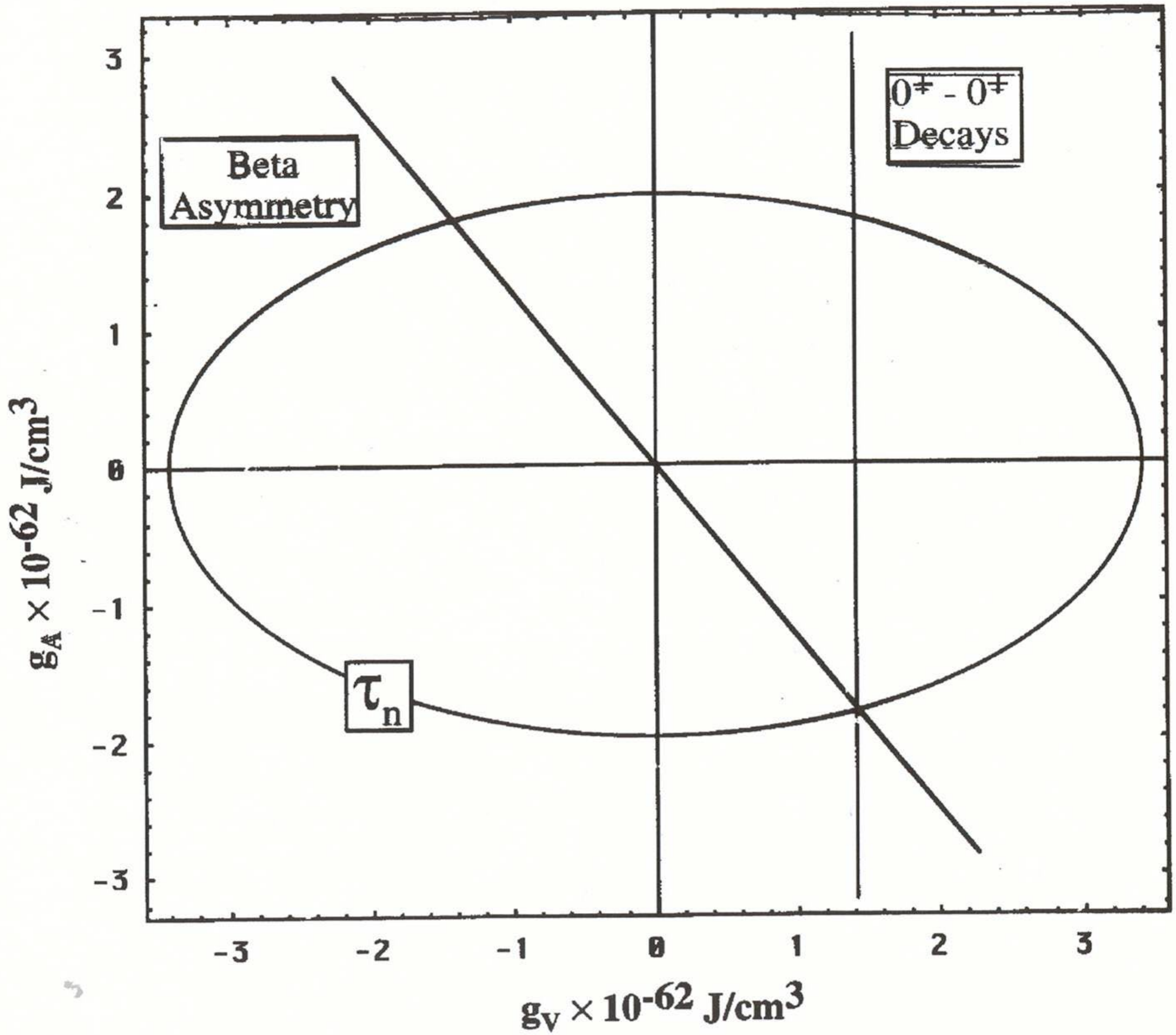
$$B = 2\frac{\lambda^2-\lambda}{1-3\lambda^2}$$

$$\tau_n \propto 1/(g_A^2 + 3g_V^2)$$

$$\lambda = g_A/g_V$$

In the Electroweak Model, the vector current, is conserved (along with electric charge) so the vector coupling constant g_V is a "fundamental" constant that can be determined from in several ways. ($0^+ \rightarrow 0^+$ decays, n-decay, CKM unitarity,…). Consistency between these determinations provides a sensitive test of the Standard Model.

Accurate Measurements of a, b, A, and B ,as well as the neutron lifetime, provide critical data for tests of the Standard Model.



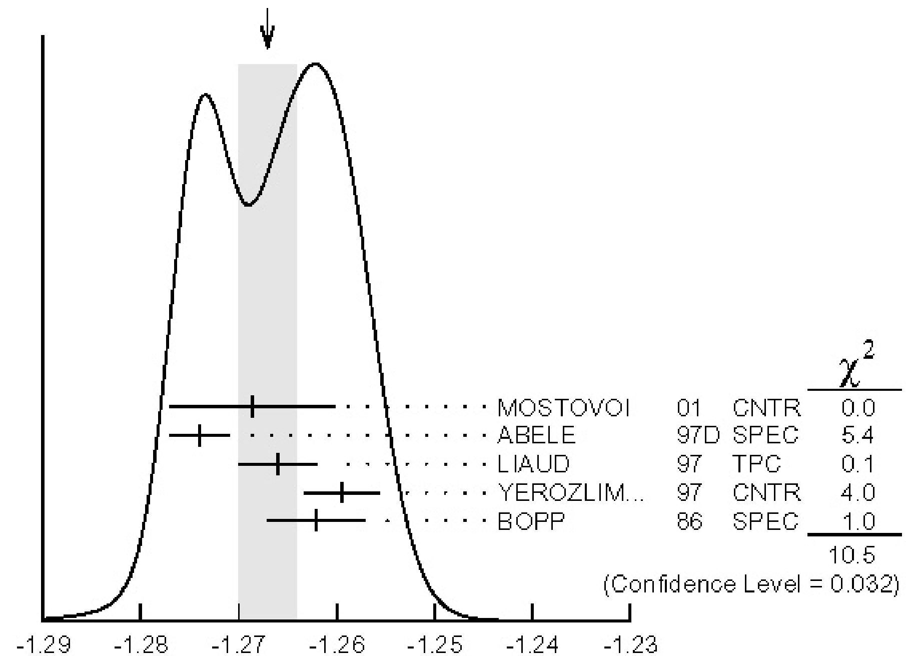
3
2
1
0
-1
-2
-3
-3
-2
-1
0
1
2
3
Beta Asymmetry
0+ - 0+ Decays
τ_n
$g_A \times 10^{-62}$ J/cm^3
$g_V \times 10^{-62}$ J/cm^3

Particle Data Group 2002

$\lambda \equiv g_A / g_V$

VALUE	DOCUMENT ID		TECN	COMMENT
−1.2670±0.0030 OUR AVERAGE	Error includes scale factor of 1.6. See the ideogram below.			
−1.2686±0.0046±0.007	[20] MOSTOVOI	01	CNTR	A and $B \times$ polarizations
−1.274 ±0.003	ABELE	97D	SPEC	Cold n, polarized, A
−1.266 ±0.004	LIAUD	97	TPC	Cold n, polarized, A
−1.2594±0.0038	[21] YEROZLIM...	97	CNTR	Cold n, polarized, A
−1.262 ±0.005	BOPP	86	SPEC	Cold n, polarized, A
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−1.266 ±0.004	SCHRECK...	95	TPC	See LIAUD 97
−1.2544±0.0036	EROZOLIM...	91	CNTR	See YEROZOLIMSKY 97
−1.226 ±0.042	MOSTOVOY	83	RVUE	
−1.261 ±0.012	EROZOLIM...	79	CNTR	Cold n, polarized, A
−1.259 ±0.017	[22] STRATOWA	78	CNTR	p recoil spectrum, a
−1.263 ±0.015	EROZOLIM...	77	CNTR	See EROZOLIMSKII 79
−1.250 ±0.036	[22] DOBROZE...	75	CNTR	See STRATOWA 78
−1.258 ±0.015	[23] KROHN	75	CNTR	Cold n, polarized, A
−1.263 ±0.016	[24] KROPF	74	RVUE	n decay alone
−1.250 ±0.009	[24] KROPF	74	RVUE	n decay + nuclear ft

[20] MOSTOVOI 01 measures the two P-odd correlations A and B, or rather SA and SB, where S is the n polarization, in free neutron decay.
[21] YEROZOLIMSKY 97 makes a correction to the EROZOLIMSKII 91 value.
[22] These experiments measure the absolute value of g_A/g_V only.
[23] KROHN 75 includes events of CHRISTENSEN 70.
[24] KROPF 74 reviews all data through 1972.



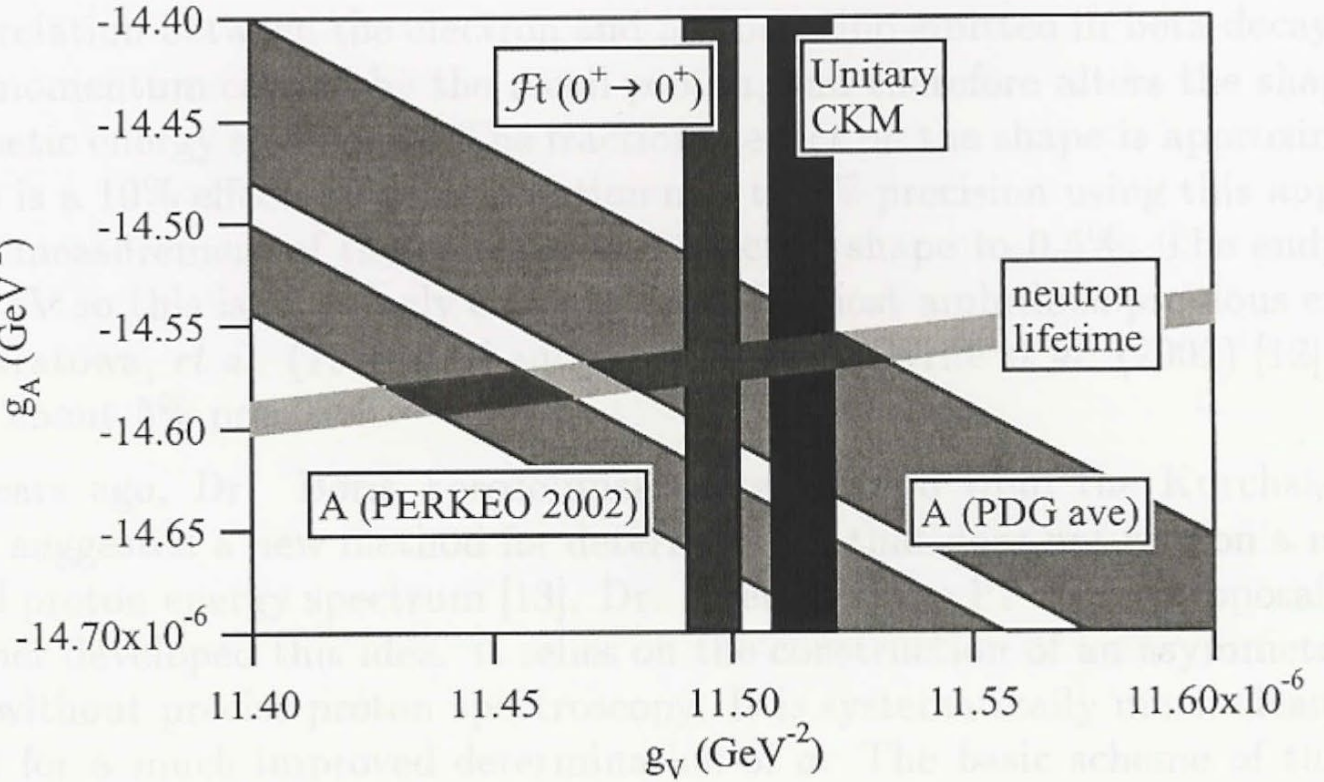
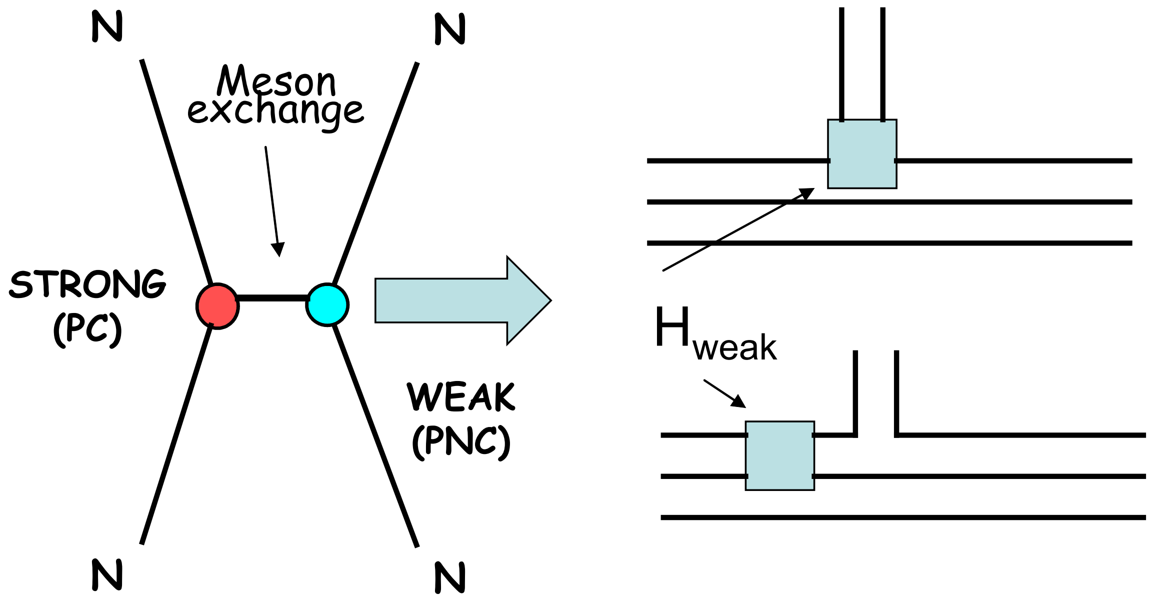


Figure 1: A current experimental summary of the weak nuclear force coupling constants g_A and g_V. Both superallowed β decay and neutron decay now indicate a violation of unitarity of the CKM matrix by more than two standard deviations.

figure courtesy F.Weidtfeldt

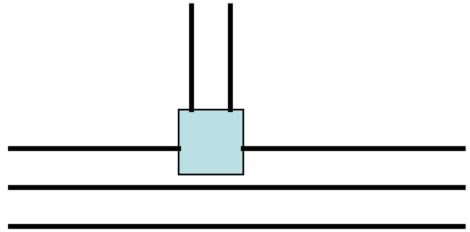
Neutron Nucleon Weak Interaction

Weak NN Interaction

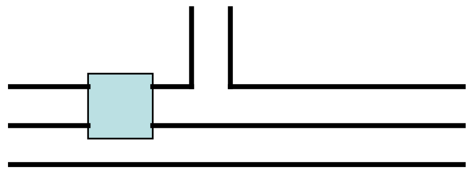


- P-odd partial waves [5 S->P transition amplitudes]
- Meson exchange model for weak NN [effect of qq weak interactions parametrized by ~6 couplings]
- χ perturbation theory [Musolf&Holstein, under construction, incorporates chiral symmetry of QCD]
- Physical description starting from Standard Model [need QCD in strong interaction regime, lattice+EFT extrapolation (Beane&Savage)]

What qq weak processes are hidden in the weak NN vertex?



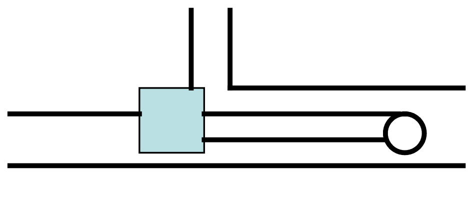
"factorization" amplitude
[<N| H_{weak}|Nm>
~<0|qq|m><N|q γ_5q|N>]



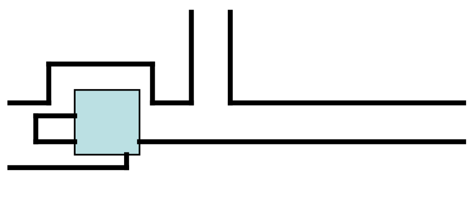
P-odd admixture into N

Valence quarks

DDH



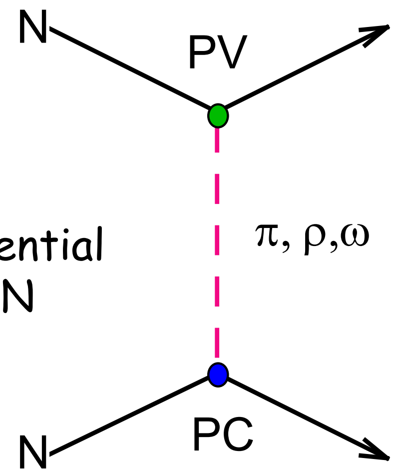
sea quarks



"disconnected" sea quarks
from χ corrections [Zhu et al]

- Non-negligible amplitudes from u,d,s sea quarks
- Sign cancellations among different contributions

Meson Exchange Model (DDH)



assumes p, r , and ω exchange dominate the low energy PNC NN potential as they do for strong NN

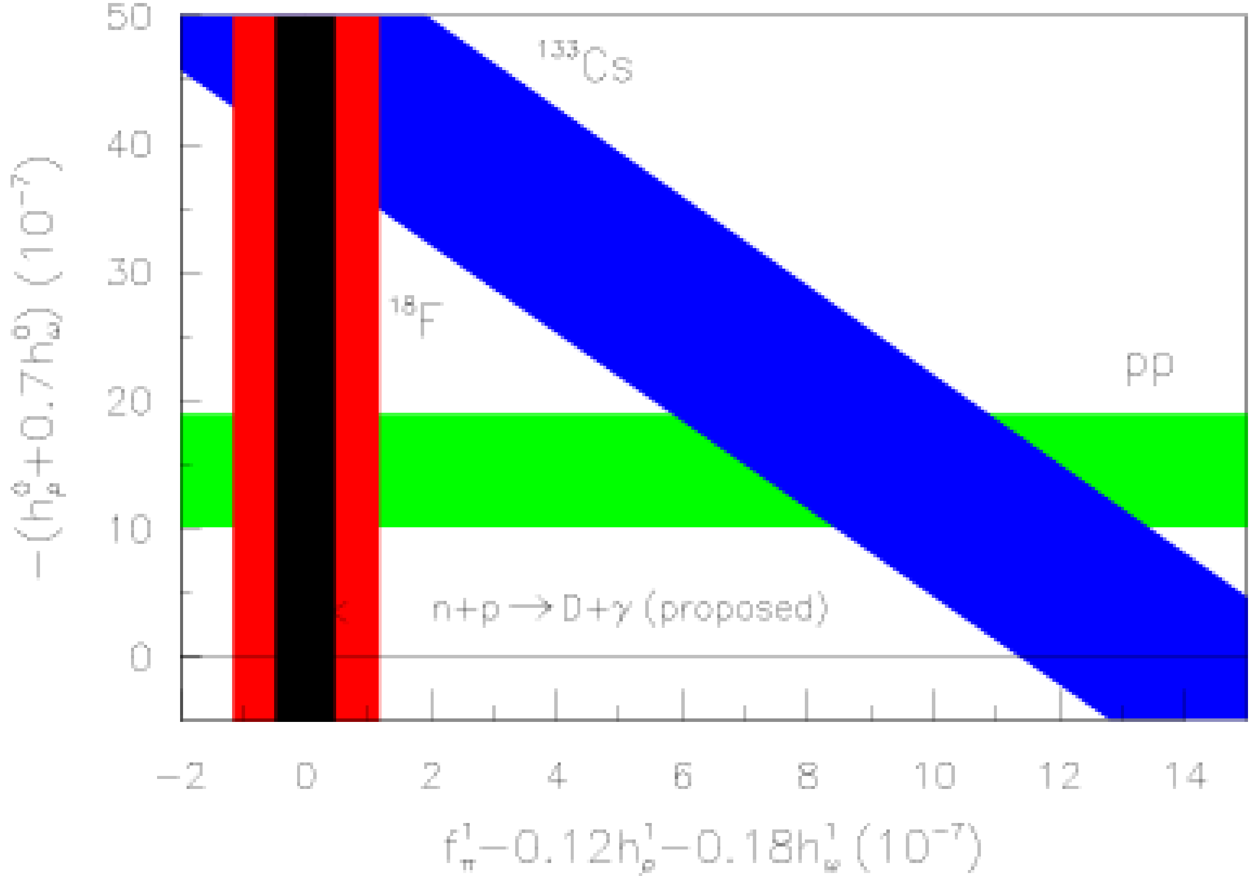
Barton's theorem [CP invariance forbids coupling between S=0 neutral mesons and on-shell nucleons] restricts possible couplings

one consequence: pp parity violation blind to weak pion exchange [need np system to probe $H_{weak}^{?\, I = 1}$]

weak meson exchange coupling constants

f_π, h_r^0, h_r^1, h_ρ^2, h_ω^0, h_ω^1

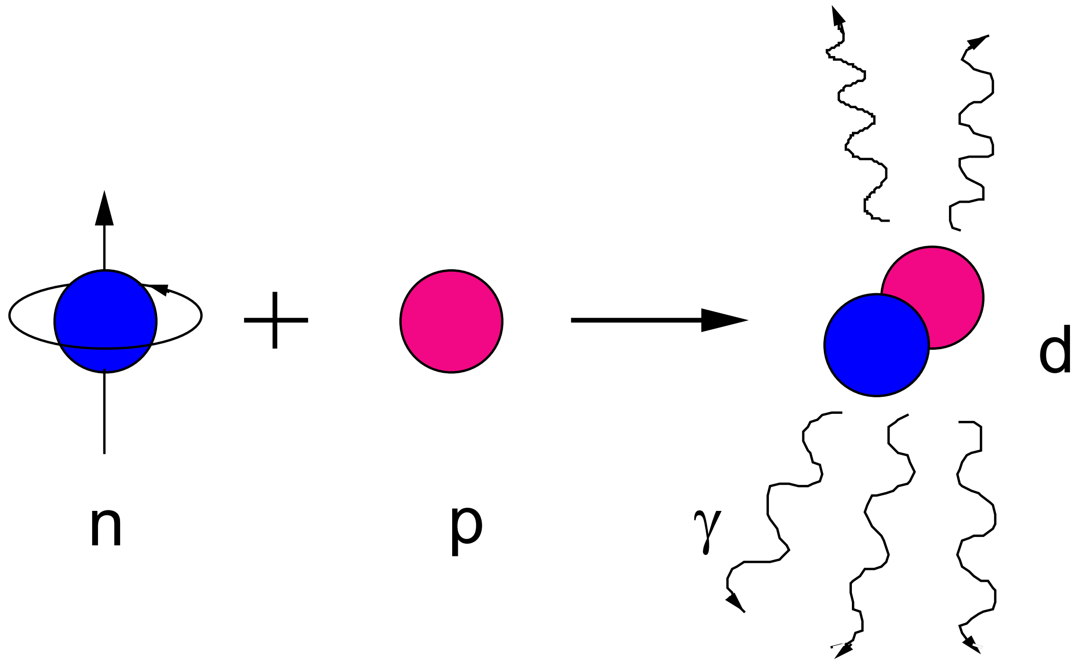
"should" suffice [but are chiral corrections large?]



data from p-p, 133Cs anapole moment, and 18F are inconsistent, adding p-4He and 19F does not help [Haxton et al]

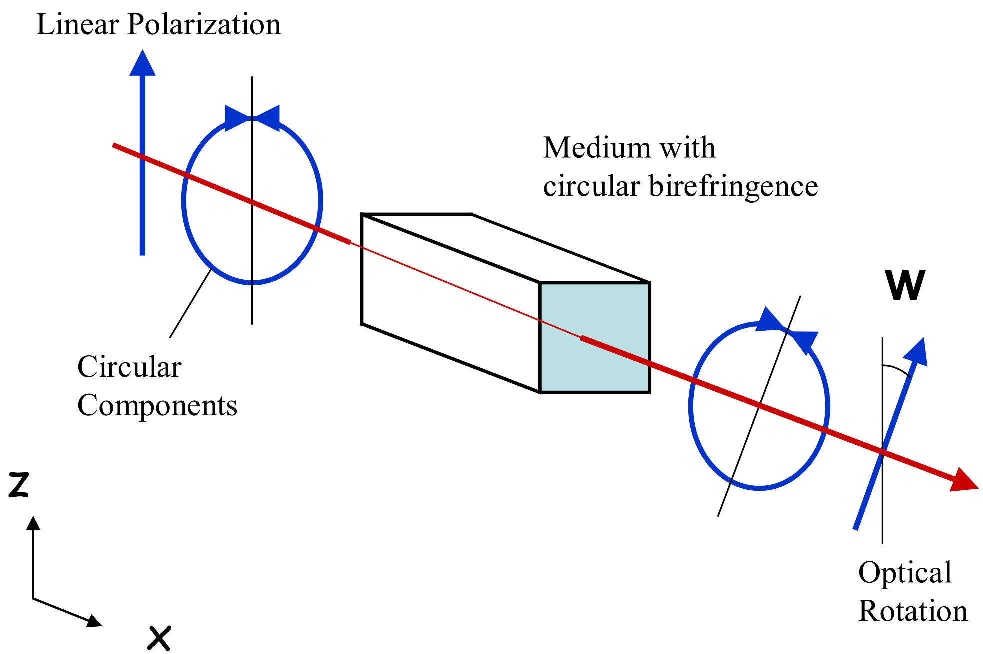
odds are low for more progress in theory for PV in medium/heavy nuclei

PV Gamma Asymmetry in Polarized Neutron Capture



- polarized neutron capture due to weak NN interaction [from $s_n \bullet p_\gamma$]
- A_γ independent of neutron energy away from resonances
- 5x10^{-9} for A_γ in n+p->D+γ @ SNS (4 months)
- 1x10^{-7} for A_γ in n+D->T+γ @ SNS (4 months) Pulsed SNS beam needed for systematic effects in n+D

PV Neutron Spin Rotation

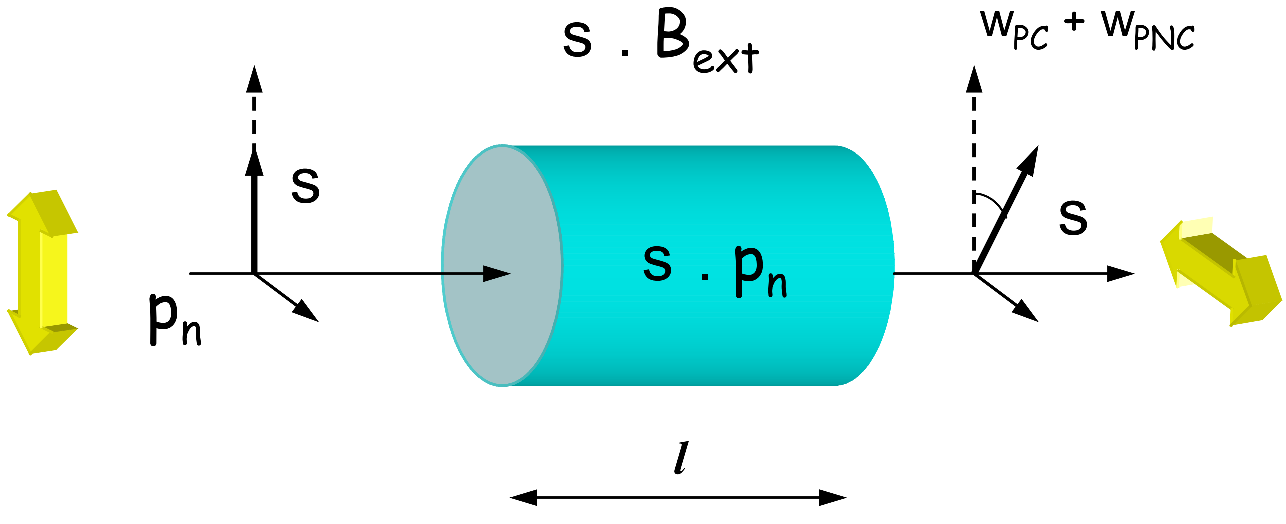


- transversely polarized neutrons corkscrew due to weak NN interaction [opposite helicity components of $|\uparrow\rangle_z = 1/\sqrt{2}(|\uparrow\rangle_x + |\downarrow\rangle_x)$ accumulate different phases from $s_n \bullet p_n$ term in forward scattering amplitude]

- PV rotation angle per unit length $d\phi/dx$ approaches a finite limit for zero neutron energy [$\phi=(n-1)px$, $n-1=2\pi f/p^2$, $f_{weak}=gp \to d\phi/dx \sim g$]

- $d\phi/dx$ is constant for low energy neutrons

PV Neutron Spin Rotation in 4He and H



- only 4He and H have low A and negligible neutron spin-flip scattering (D difficult)
- precision goals for $d\phi/dx$:
- 1×10^{-7} rad/m for n-4He @ NIST
- 1×10^{-7} rad/m for n-H @ SNS. Pulsed SNS beam needed for systematic effects in n-H

	np A_γ	np ϕ	nD A_γ	nα ϕ	Pp A_z	pα A_z
f_π	-0.11	-3.12	0.92	-0.97		-0.34
h_r^0		-0.23	-0.50	-0.32	0.08	0.14
h_r^1	-0.001		0.10	0.11	0.08	0.05
h_ρ^2		-0.25	0.05		0.03	
h_ω^0		-0.23	-0.16	-0.22	0.07	0.06
h_ω^1	-0.003		-0.002	0.22	0.07	0.06

Accuracies for NN weak couplings:

few body systems	add in 19F, 21Ne, 133Cs
f_π=4%	f_π=3%
h_r^0=7%	h_r^0=6%
h_ρ^2=34%	h_ρ^2=28%
h_ω^0=26%	h_ω^0=22%

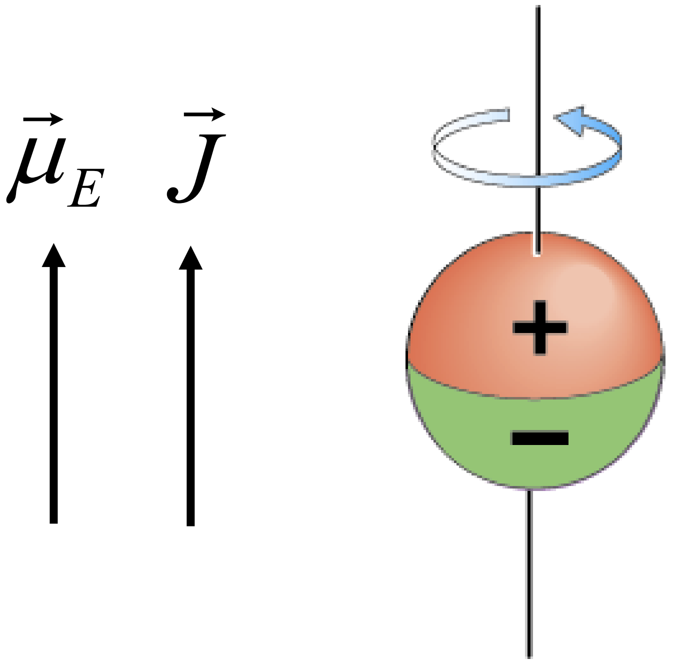
assumes calculations of PV in few body systems are reliable (new pp and np calculations using Argonne V18, CD-Bonn, Nijmegen-I by Carlson, Schiavilla et al insensitive to strong NN)

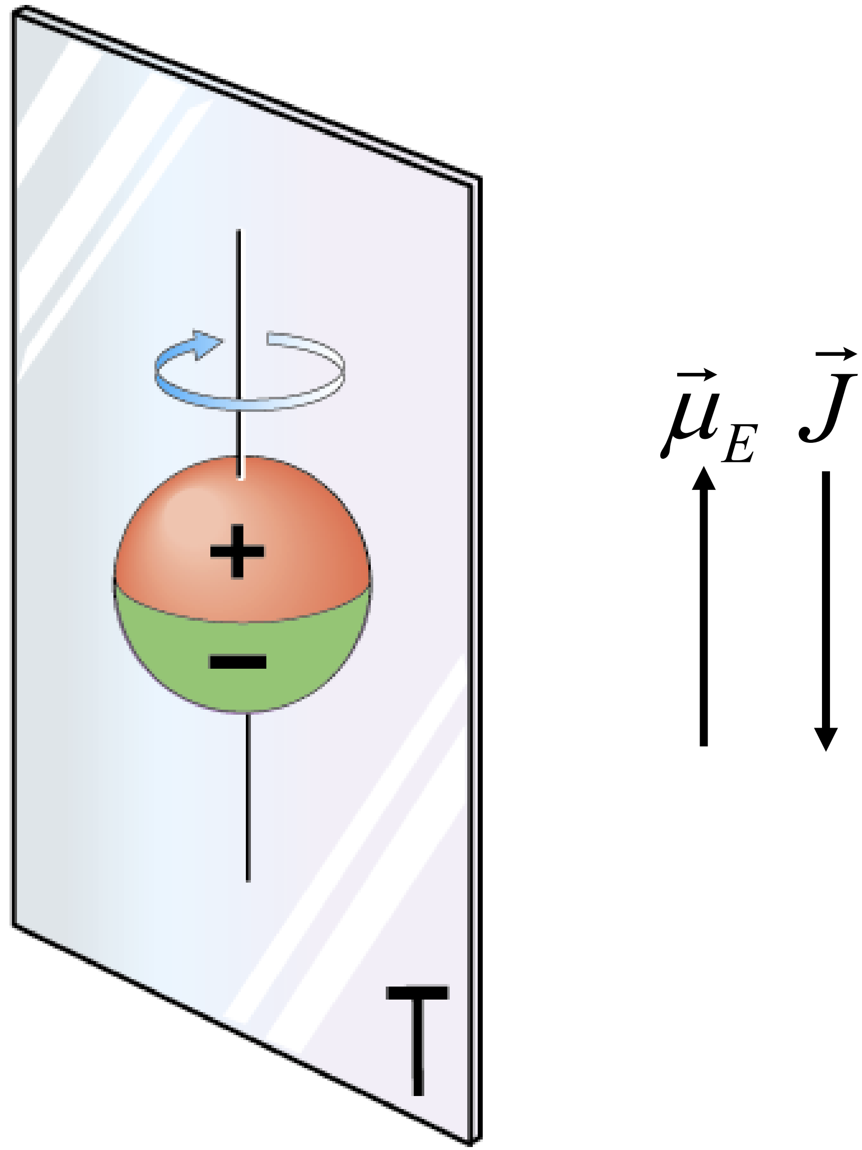
The Neutron Electric Dipole Moment

"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



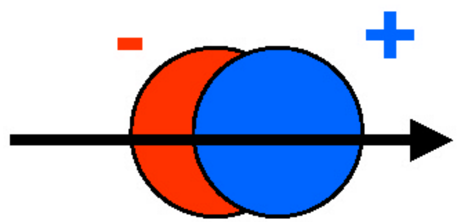


Wigner-Eckart Theorem implies that any vector quantity must be proportional to Angular Momentum

The Permanent EDM of the Neutron

- A permanent EDM $\vec{d}$

$\vec{d} \cdot \vec{E}$



s = 1/2

- The current value is < 6 x 10^{-26} e•cm (90% C.L.)
- We hope to obtain roughly < 10^{-28} e•cm with UCN in superfluid He

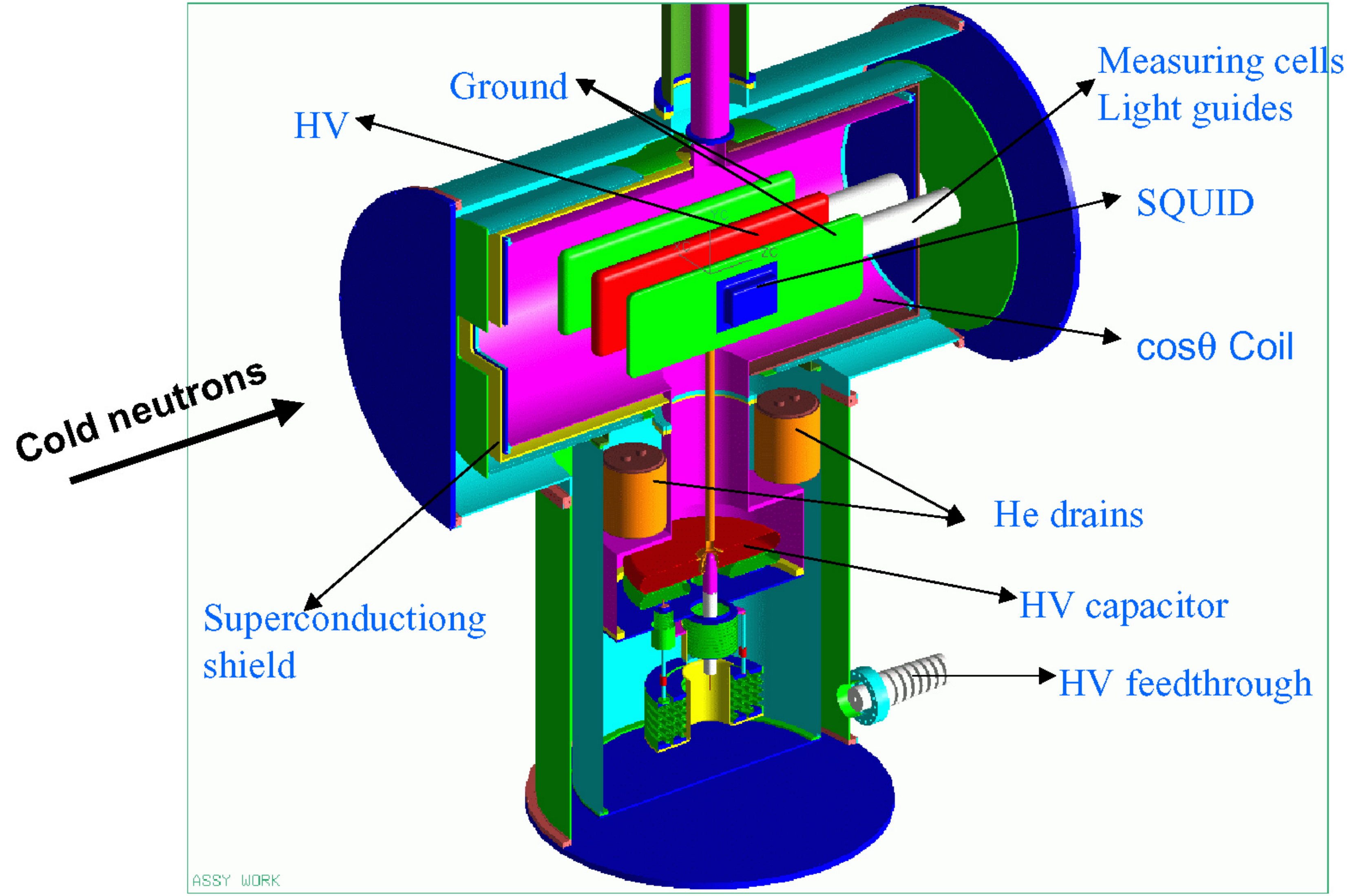
EDM Slides compliments of Martin Cooper

- *A non-zero permanent neutron electric dipole moment would be a direct violation of T-invariance and through the CPT a violation of CP*

- *An observed edm OR an improved limit will set important constraints on theories which seek to explain observed CP violation*

- *The next few orders of magnitude in sensitivity will be particularly interesting for theories that seek to explain the cosmological Baryon Asymmetry by CP violating processes during the first ~10^{-6} second of the Big Bang.*

New Concept for Measurement of the Neutron EDM in a Superfluid Helium Bottle



EDM Slides compliments of Martin Cooper and The EDM collaboration

END