The Fundamental Properties of the Neutron

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Fundamental Neutron Physics Summer School
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Why Study Neutrons?

The neutron exhibits much of the richness of nuclear physics, but is vastly simpler, and thus more interpretable, than nuclei.

The neutron can be used to probe Strong, Weak, EM and Gravitational phenomena as well as serving as probe for new interactions.

Neutron decay is the archetype for all nuclear beta decay and is a key process in astrophysics.

The neutron is well suited as a laboratory for tests of physics beyond the Standard Model.

The Neutron is complicated enough to be interesting…

But is simple enough to be understandable.

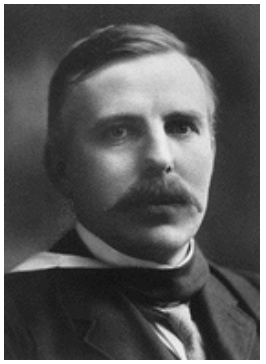
Some Useful References

Fermi, *Lecture Notes on Nuclear Physics*
Byrne, *Neutrons, Nuclei and Matter*
Golub, Lamoreaux, Richardson, *Ultracold Neutrons*
Commins and Bucksbaum, *Weak Interactions of Quarks and Leptons*
Particle Data Group, **pdg.lbl.gov**

Acknowledgements for images

Mike Snow, Fred Weitfeldt, Brad Fillipone, Jeff Nico, Paul Huffman, Scott Dewey,…

Short History Lesson



Ernest Rutherford

1920 Noting that atomic number (Z) does not correspond to atomic correspond to atomic weight, Rutherford suggests that, in suggests that, in addition to "bare" protons, the nucleus nucleus contains some tightly bound "proton- electron pairs" or electron pairs" or neutrons.

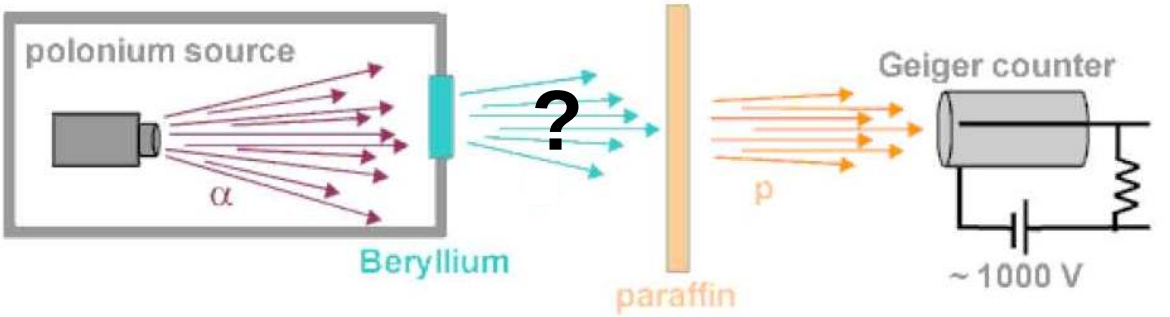
Walter Bothe

1930 Bothe and Becker discovered a penetrating, neutral radiation neutral radiation when alpha particles hit a Be target. target.

$$\alpha + {}^{9}Be \rightarrow {}^{12}C + n$$

Irene Curie

1931 Mme Curie shows that they are not gamma rays and they and they have sufficient momentum to eject p's from paraffin. from par

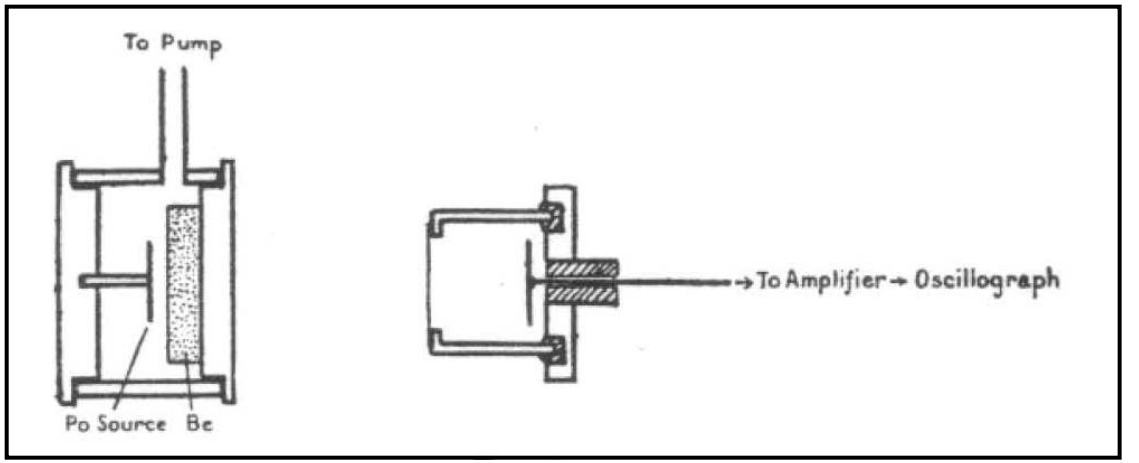


James Chadwick

1932 Chadwick replaced the paraffin with a variety of other of other

targets and, by measuring the recoil energies of the ejected the ejected

particles, was able to determine the mass of the neutral the neutral particle



J. Chadwick, Proc. Roy. Soc., A ***136*** *692 (1932)*

Chadwick claimed this was Rutherford's "Neutron" "Neutron"

1933 Bainbridge makes precision measurements of the atomic masses
atomic masses of the proton and the deuteron using the mass spectrograph
the mass spectrograph

1934 Chadwick and Goldhaber make the first "precision" measurement of the neutron mass by looking at the photo-disassociation of the deuteron

$$h\nu + d \rightarrow p + n$$

Using 2.62MeV gammas from Thorium and determining the
determining the recoil energy of the protons they were able to determine:*
able to determine:* $M_n = 1.0080 \pm 0.0005$

KEY OBSERVATION: $M_n > M_p + M_e$

1. The neutron cannot be a bound "proton-electron pair"

2. It is energetically possible for a neutron to decay to $e^- + p^+$

Some Neutron Properties

Mechanical Properties

Mass

Gravitational Mass (equivalence principle test)

Spin

Electromagnetic Properties

Charge (or limit on neutrality)

Internal Charge Distribution

Magnetic Dipole Moment

Electric Dipole Moment

Neutron Decay

Neutron Mean Lifetime

Correlations in Neutron Decay

"Exotic" Decay modes

Miscellaneous Quantum Numbers:

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

The Neutron Mass

Theory of the Neutron Mass

The neutron mass includes contributions from quark masses as well as the energy associated with the color field (gluons,…)

The quark masses are thought to be a minor contribution.

It is beyond the reach of current theory to provide an ab initio calculation of the nucleon masses.

The current challenge is to provide a robust estimate for the neutron-proton mass ***difference****.*

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 most accurate method for the 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

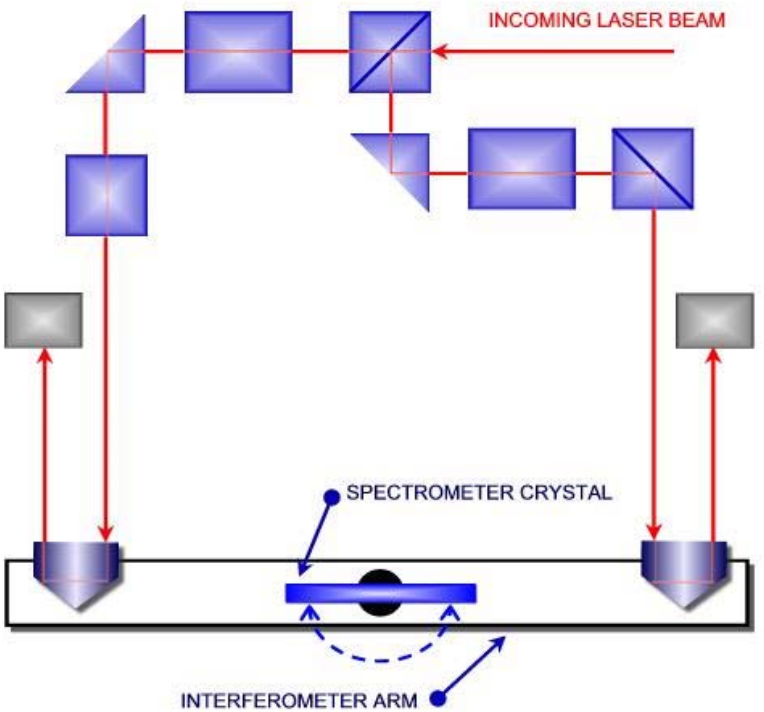
The actual experiment is the determination of the D – H mass difference in atomic mass units.

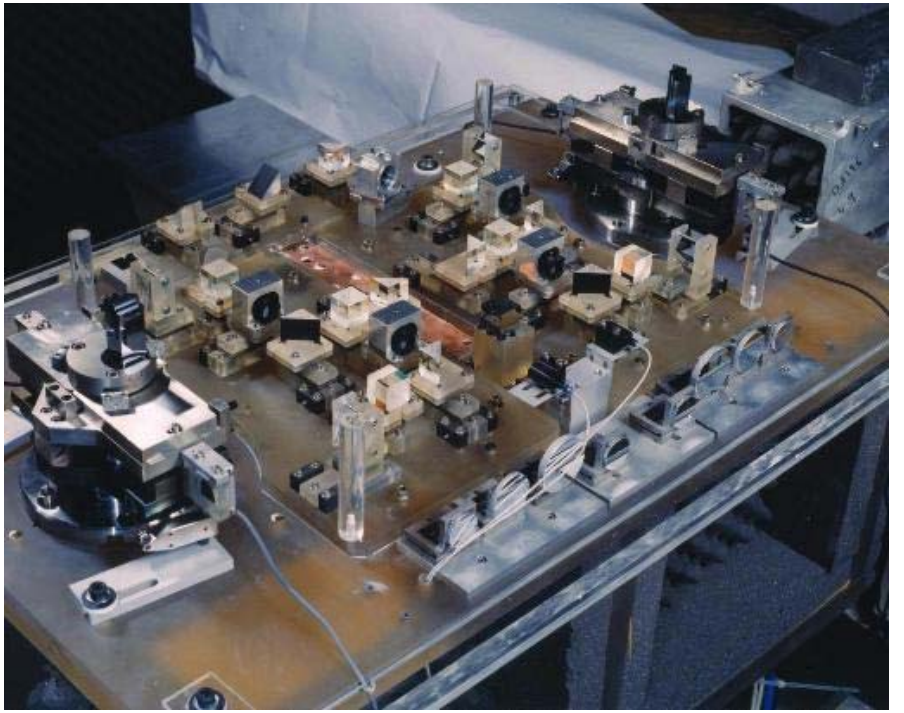
Absolute Measurement of 2.2Mev n-p Capture Gamma Energy

Measure Bragg angle for diffraction of 2.2MeV gamma from a perfect single crystal of Silicon with an accurately measured lattice spacing d.

$$n\lambda = 2d\sin\theta \qquad E_\gamma = h\nu = \frac{hc}{\lambda}$$

Bragg Angle is a few milli-radian
Need nano-radian precision!

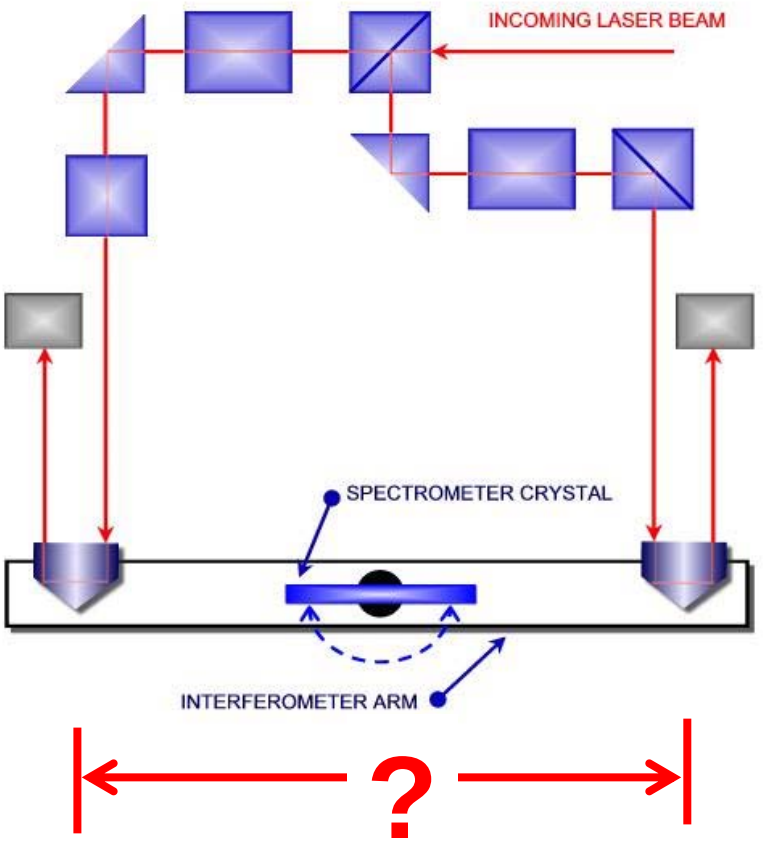




See: http://www.ill.fr/YellowBook/PN3/

Precision vs. Accuracy

Angle Interferometer gives high precision but what about its "calibration"



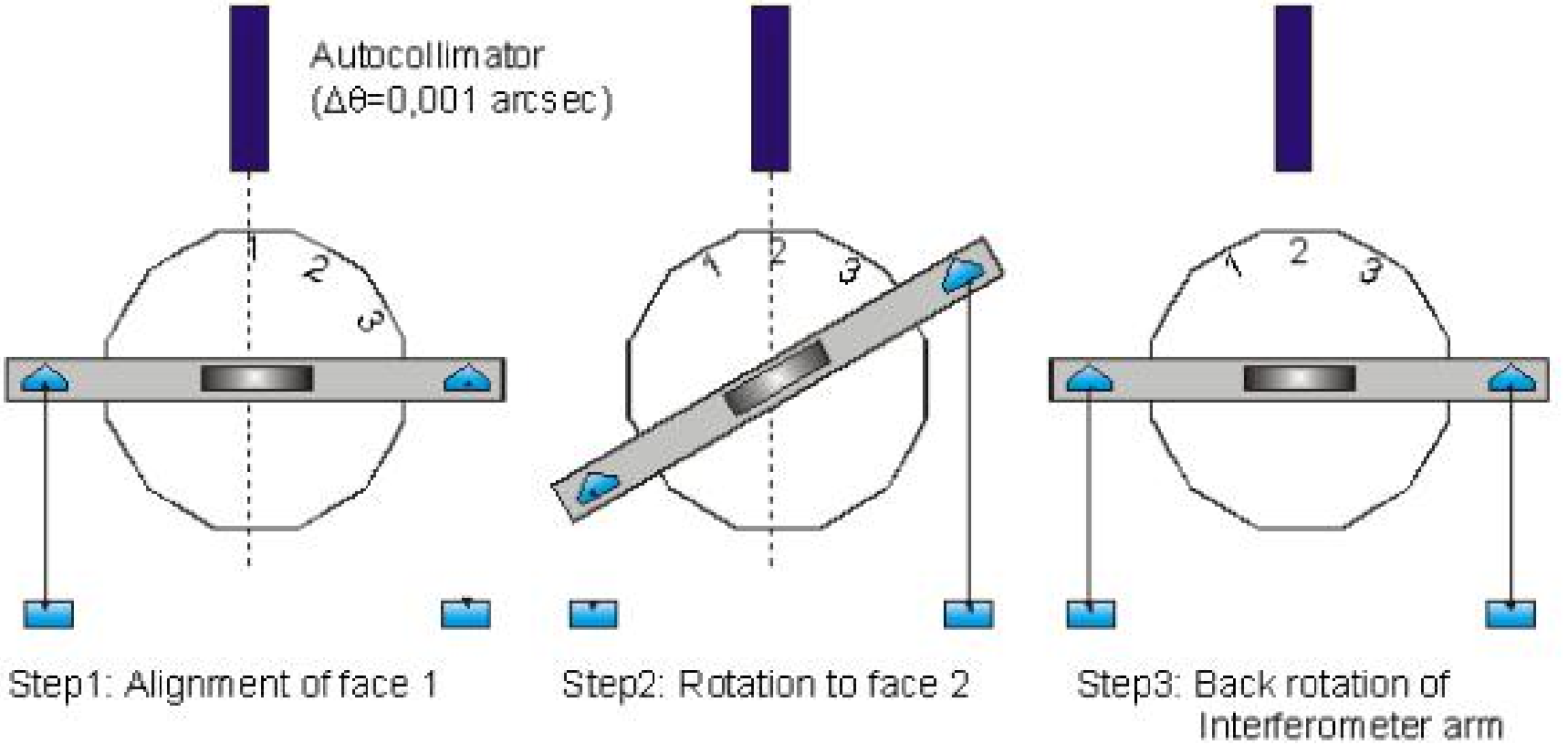
$$\tan\theta = \frac{\text{change in optical path length}}{\text{length of interferometer arm}}$$

What can we use to calibrate a precision angle device?
Is there a "Standard" for angle measurement?

See: http://www.ill.fr/YellowBook/PN3/

Absolute Measurement of 2.2Mev n-p Capture Gamma Energy

Calibrate Angle interferometer



Measure 24 interfacial angles of a precision quartz optical polygon Since they must sum to 360°, there are only 23 independent quantities. A 24 parameter fit can give the calibration constant.

See: http://www.ill.fr/YellowBook/PN3/

Determination of the Neutron Mass

λ_{np} = 5.573 409 78(99) x 10^{-13} meters

G.L Greene, et. al., Phys. Rev. Lett. 24, 819 (1986)
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

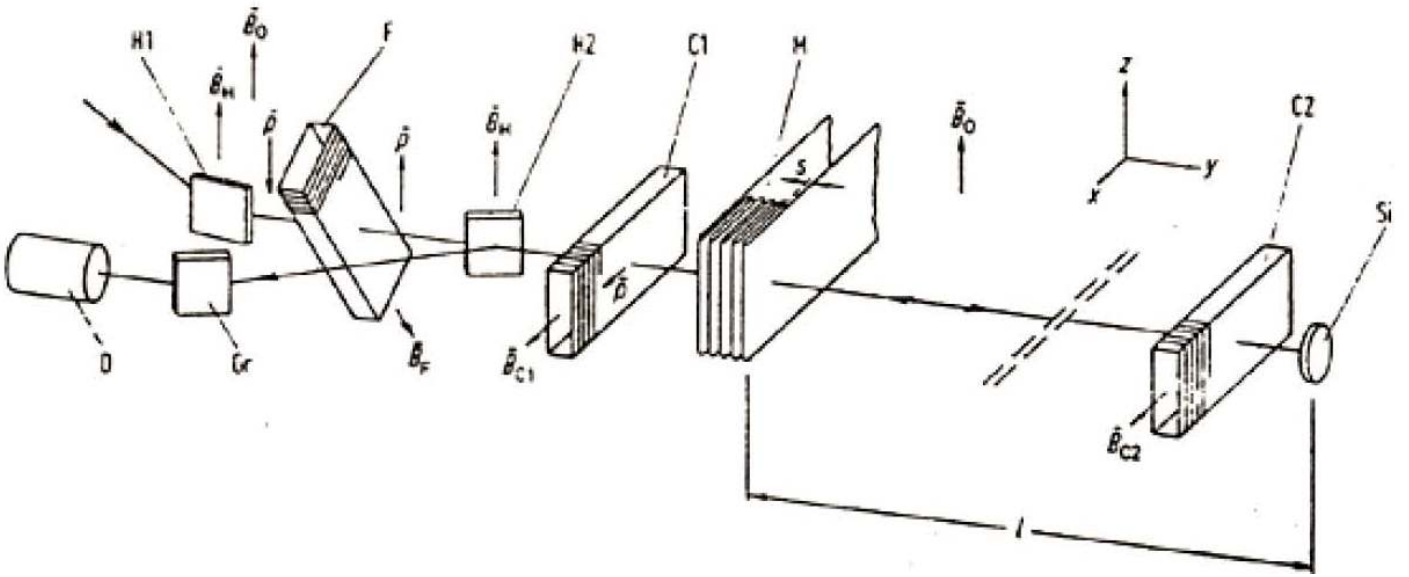
M(n) = 1.008 664 916 37(99) atomic mass units (u)

Who could possibly care about all those decimal places?

Determination of h/m

Planck Relation: $\lambda = \frac{h}{p} = \left(\frac{h}{m}\right)\frac{1}{v} \Rightarrow \frac{h}{m} = \lambda v$

A simultaneous determination of the neutron wavelength and velocity gives h/m.



$$h/m_n = 3.95603330\ (30) \times 10^{-7}\ m^2 s^{-1} \quad 80\ ppb$$

Kugler, Nistler, & Weirauch, NIM, **A284**, 143 (1969)
Kugler, Nistler, & Weirauch, PTB Ann Rep (1992)

The Fine Structure Constant from m_n and h/m_n

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

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

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

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

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

This Procedure gives a value for the fine structure constant with an error of ~40 parts per billion. This is one of the most accurate methods for the determination of α without using QED.

Comparisons of Different Determinations of α Provide Important Tests

$$\alpha = \frac{\mu_0}{c}\frac{\Omega_{NIST}}{[R_H]_{NIST}}$$

$$\alpha = \left\{\left(\mu_p'/\mu_B\right)^{-1}[\gamma_p']_{NIST}[R_H]_{NIST}^{-1}\left[2e/h\right]_{NIST}^{-1}(2R_\infty\mu_0)\right\}^{1/3}$$

$$\alpha = \left\{2cR_\infty\left(m_p/m_e\right)\left(m_n/m_p\right)\left(h/m_n\right)\right\}^{-1/2}$$

$$\alpha = F(g_e - 2)$$

$$\alpha = \left\{4R_\infty/c\left(\mu_p'/\mu_B\right)^{-1}[\gamma_p'(high)]_{NIST}V_{NIST}^2\Omega_{NIST}^{-1}\left[2e/h\right]_{NIST}^{-1}\right\}^{-1/2}$$

$$\alpha = \left\{2\sqrt{8}\left(m_p/m_e\right)R_\infty V_m(Si)V_{NIST}^2\left[M_p\mu_0c^2d_{220}(Si)\right]^{-1}\left[2e/h\right]_{NIST}^{-1}\right\}^{-1}$$

$$\alpha = \left\{3\left(1+m_e/m_\mu\right)^3\left[16R_\infty c\left(\mu_p'/\mu_B\right)q(\mu_\mu/\mu_p)\right]^{-1}\right\}^{-1/2}$$

$$\alpha = \left\{4R_\infty/c\,[\gamma_p']_{NIST}\Omega_{NIST}\left(\mu_p'/\mu_B\right)^{-1}\left[2e/h\right]_{NIST}^{-1}\right\}^{-1/2}$$

$$\alpha = \{2R_\infty\lambda_C\}^{-1/2}$$

$$\alpha = \left\{2R_\infty\left(m_p/m_e\right)\left(N_Ah/c\right)\left[M_p\cdot 10^{-3}\right]\right\}^{-1/2}$$

See: Mohr and Taylor, http://physics.nist.gov/cuu/Constants/index.html

The Neutron's Gravitational Mass

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:

$$F = m_i a$$

$$F = m_g g$$

$$\boxed{\frac{m_g}{m_i} = \frac{a}{g} = \gamma}$$

Falling Neutrons

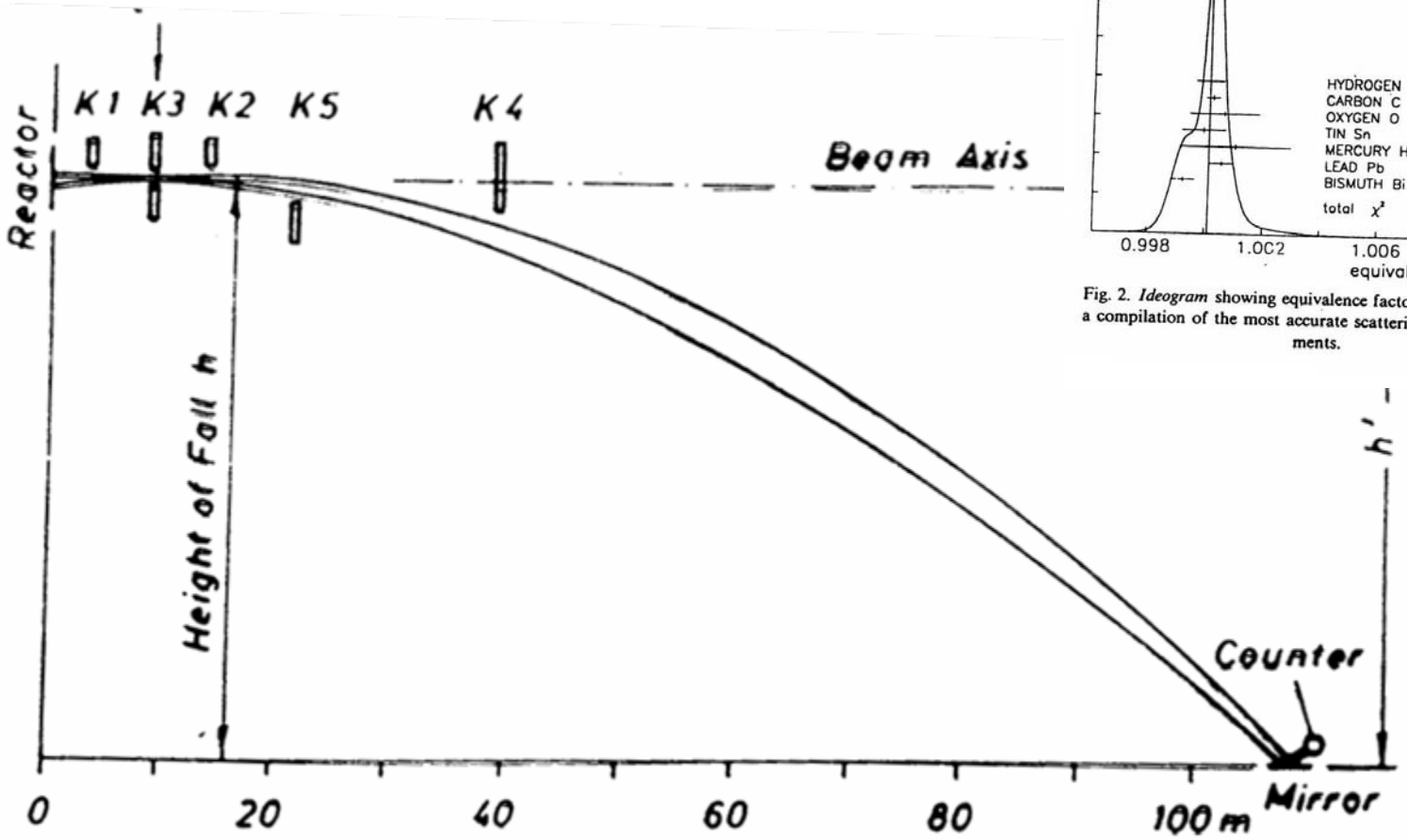


Fig. 1. Principle of the neutron-gravity refractometer

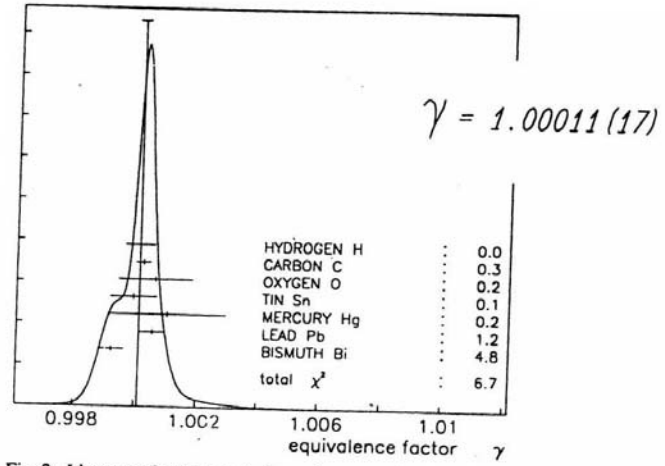


Fig. 2. *Ideogram* showing equivalence factors γ obtained from a compilation of the most accurate scattering length measurements.

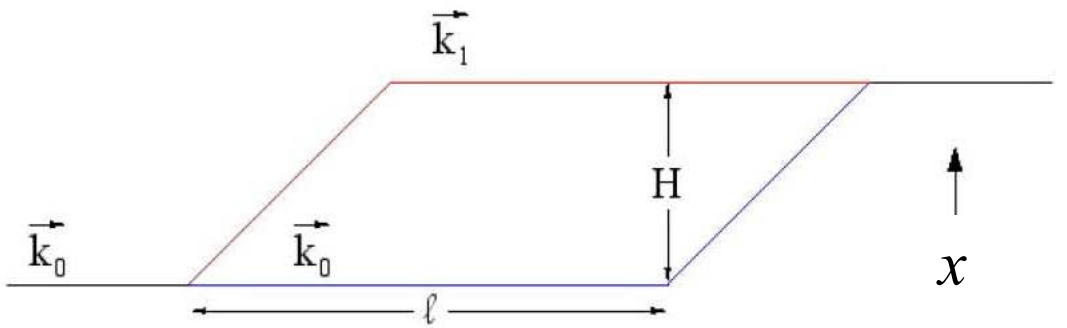
*For review see: Schmiedmayer, NIM **A284**, 59 (1989)*

Quantum Mechanical Gravitational Phase Shift

$$-\frac{\hbar^2}{2m_i}\frac{\partial^2\psi}{\partial x^2}+m_g gx\psi = E\psi$$

$m_i =$ *neutron inertial mass*

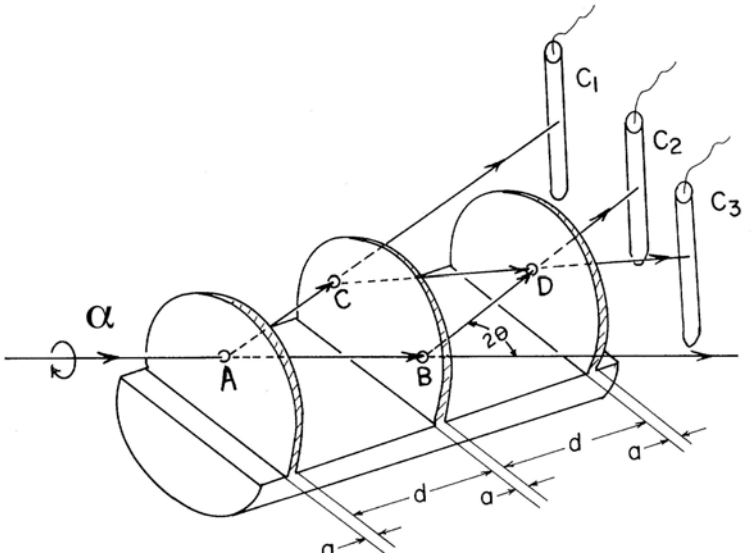
$m_g =$ *neutron gravitational mass*

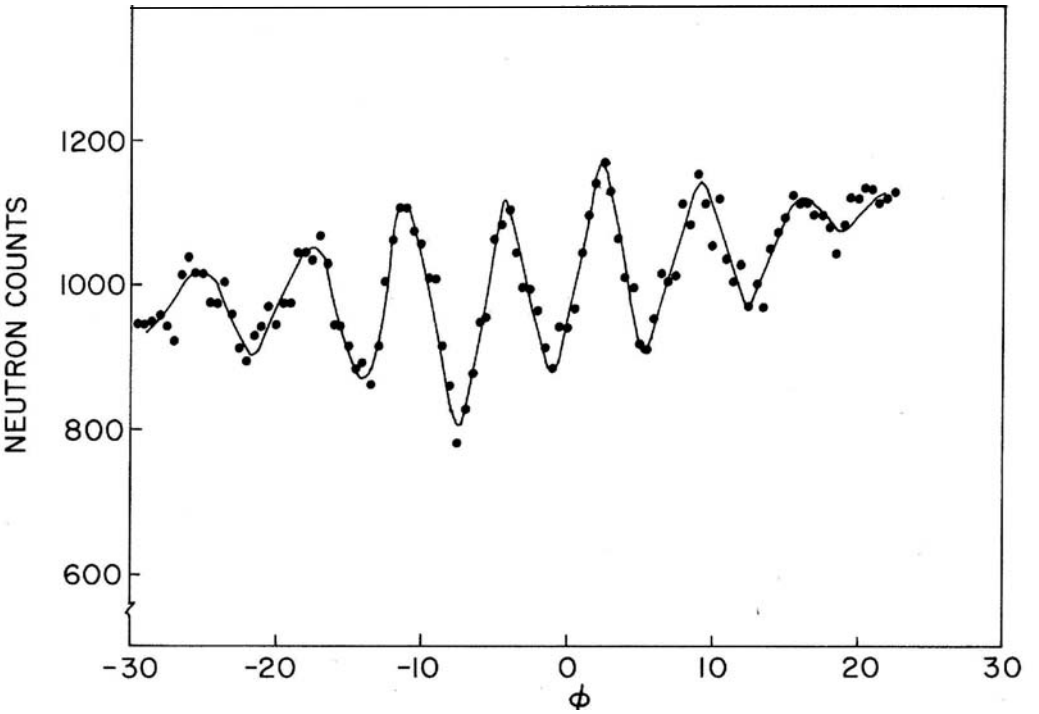


$$\Delta\phi = \frac{2\pi\lambda g A}{h^2} m_i m_g$$

A=Hl = Area of parallelogram

The Collela-Overhauser-Werner Experiment COW





Collela, Overhauser, Werner, PRL ***34****, 1472 (1975)*

…

…

Littrell, Allman, Werner, Phys Rev ***A56****, 1767 (1997)*

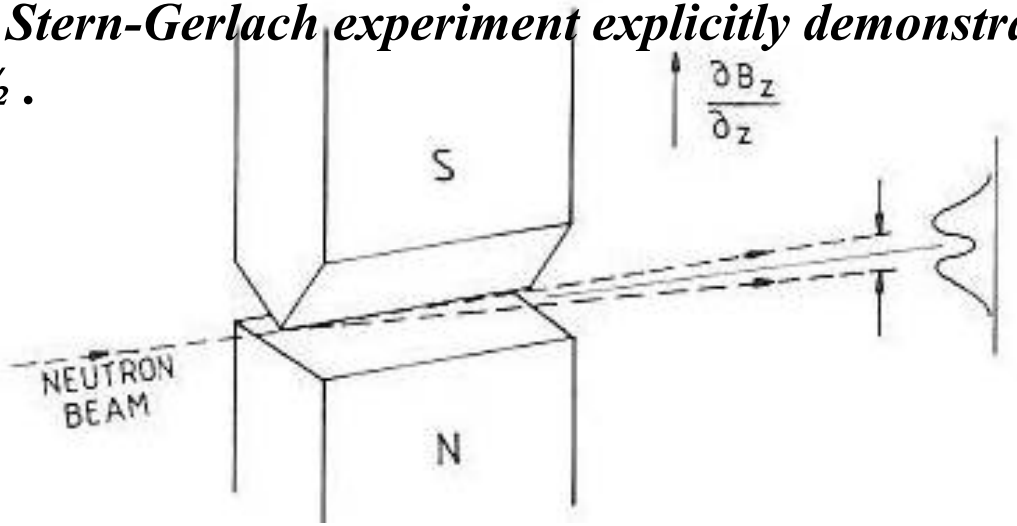
The Neutron Spin

The Neutron has an Intrinsic Spin of $s=\frac{1}{2}$

1934 Schwinger concludes that s=½ based on the band spectrum of spectrum of molecular D_2 and the scattering of neutrons from ortho and ortho and para H_2.

1949 Hughes and Burgey observe the mirror reflection of neutrons neutrons from magnetized iron. They observe 2 critical angles angles definitively showing the neutron has two magnetic sub-levels. sub-levels.

1954 Neutron Stern-Gerlach experiment explicitly demonstrates s=½ . demonstrates s=½ .



*See also Fischbach, Greene, Hughes, PRL **66**, 256 (1991) showing* $\vec{L} = \hbar\vec{\sigma}$

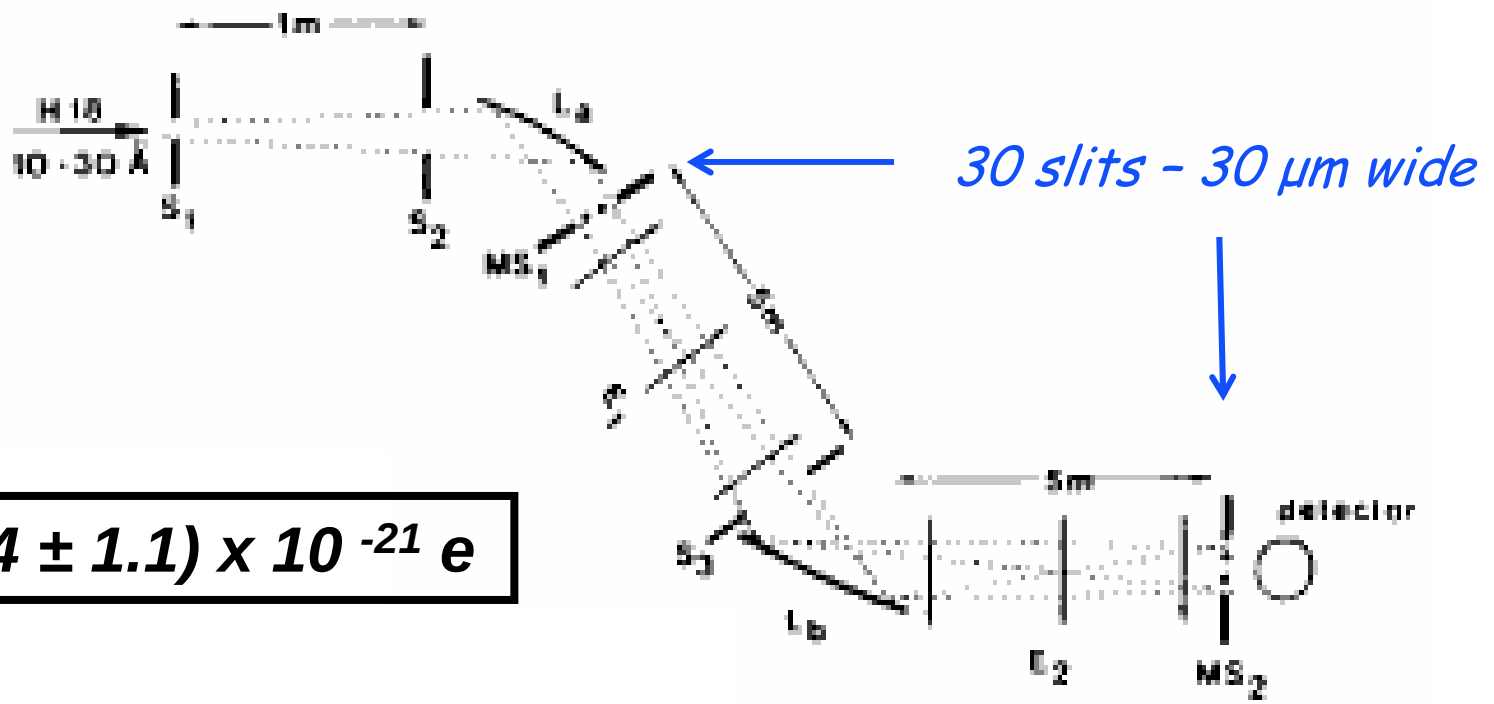
The Neutron Charge ?

Is the Neutron "Really" Neutral?

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

Einstein (1924), Blackett (1947), Bondi (1959), Chu (1987)

Experiment uses focusing device in strong electric field



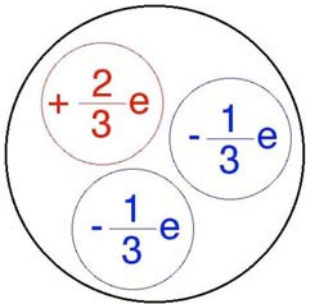
$$Q_n = (0.4 \pm 1.1) \times 10^{-21}\ e$$

Baumann et al, Phys. Rev. D **37**, 3107 (1988)

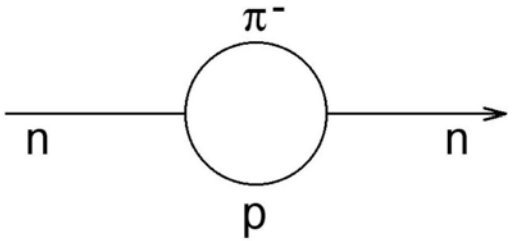
The Neutron Charge Distribution

Neutrality Does Not Imply Uniformity

The neutron is a composite structure of charged quarks which may be distributed non uniformly within the neutron.



Fermi & Marshall suggested that the neutron should have a positive "core" and a negative "skin" due to virtual pion emission



Neutron Mean Charge Radius:

$$\left\langle r_n^2 \right\rangle = \int \rho(r) r^2 dr^3$$

Neutron Electric Scattering Form Factor

The Fourier transform of the neutron charge density $G_E^n\left(Q^2\right)$ is accessible from electron scattering.

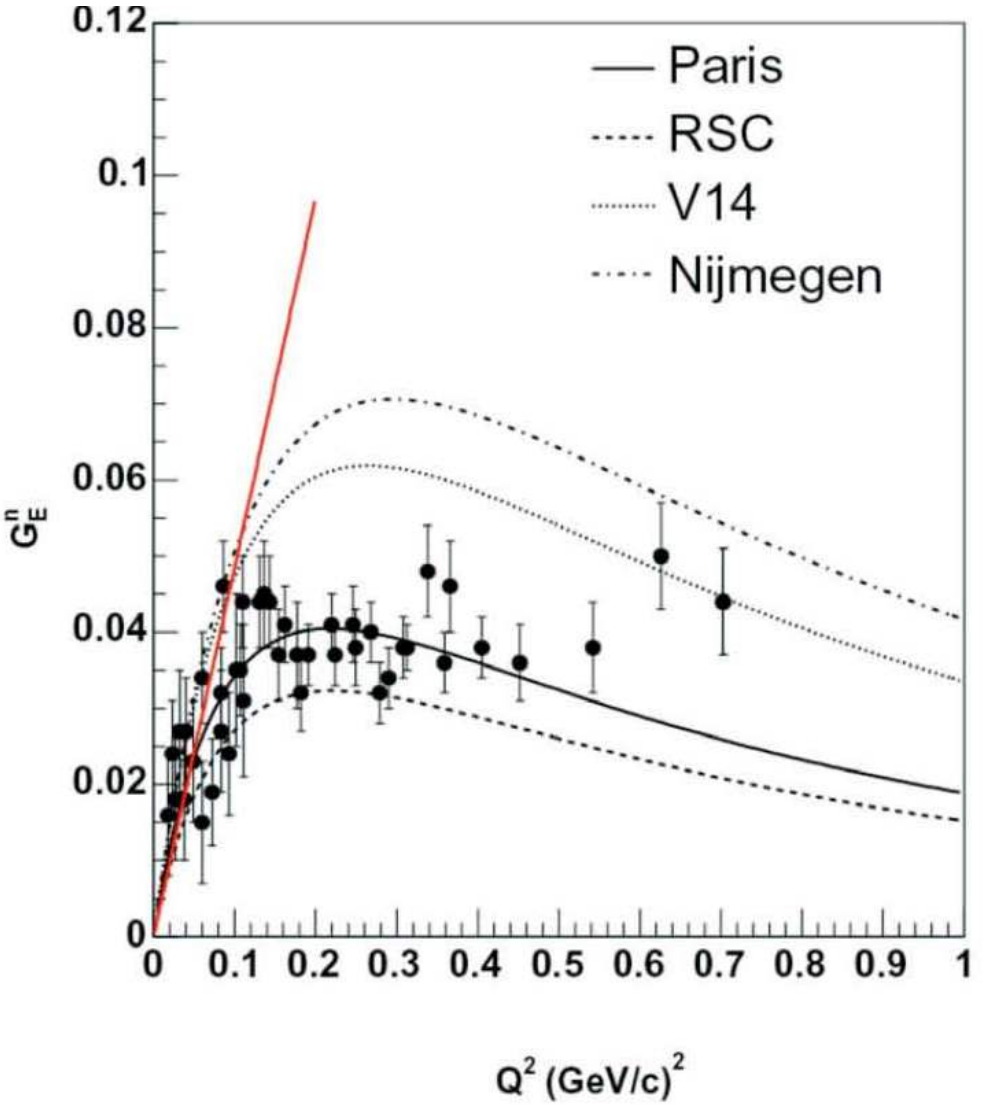
Expanding in the momentum transfer Q^2 :

$$G_E^n\left(Q^2\right) = q_n - \frac{1}{6}\left\langle r_n^2 \right\rangle Q^2$$

In the limit of low Q^2 :

$$\left\langle r_n^2 \right\rangle = -6\frac{d}{dQ^2} G_E^n\left(Q^2\right)\Big|_{Q^2=0}$$

The Mean Square Neutron Charge Radius $G_E^n(Q^2)$.
Constrains the Slope In Electron Scattering Experiments.
(e.g. Bates, JLab,…)



V. Ziskin, Ph.D. thesis, 2005

Experimental Situation is in Disarray

TABLE I. Experimental results of b_{ne} in units of 10^{-3} fm.

Experiment	Target	Result	Reference
Angular scattering	Ar	-0.1 ± 1.8	1947 [7] Fermi
Transmission	Bi	-1.9 ± 0.4	1951 [8] Havens
Angular scattering	Kr, Xe	-1.5 ± 0.4	1952 [9] Hamermesh
Mirror reflection	Bi/O	-1.39 ± 0.13	1953 [10] Hughes
Angular scattering	Kr, Xe	-1.4 ± 0.3	1956 [11] Crouch
Crystal spectrometer transmission	Bi	-1.56 ± 0.05	1959 [2] Melkonian
		-1.49 ± 0.05	1976 in Ref. [15]
		$-1.44\pm0.033\pm0.06$	1997 this work
Angular scattering	Ne, Ar, Kr, Xe	-1.34 ± 0.03	1966 [12] Krohn
Angular scattering	Ne, Ar, Kr, Xe	-1.30 ± 0.03	1973 [13] Krohn
Single crystal scattering	^{186}W	-1.60 ± 0.05	1975 [14] Alexandrov
Filter-transmission, mirror reflection	Pb	-1.364 ± 0.025	1976 [15] Koester
Filter-transmission, mirror reflection	Bi	-1.393 ± 0.025	1976 [15] Koester
n-TOF transmission, mirror reflection Ref. [17]	Bi	-1.55 ± 0.11	1986 [16] Alexandrov
Filter-transmission, mirror reflection	Pb, Bi	-1.32 ± 0.04	1986 [17] Koester
n-TOF transmission	thorogenic ^{208}Pb	$-1.31\pm0.03\pm0.04$	1995 [1] Kopecky
		$-1.33\pm0.027\pm0.03$	1997 this work
Filter-transmission, mirror reflection	Pb-isotopes, Bi	-1.32 ± 0.03	1995 [5] Koester
Garching-Argonne compilation	[12,13,15,17]	-1.31 ± 0.03	1986 [3] Sears
Dubna compilation	[14,16]	-1.59 ± 0.04	1989 [19] Alexandrov
Foldy approximation, b_F		-1.468	1952 [18] Foldy

A new approach using neutron interferometry is underway at NIST. This will be discussed in a later lecture.

The Neutron Magnetic Moment

"Naive" Quark Model

Static SU(6) Model:

1. *Baryons wavefunctions are quark color singlets with correct symmetry*

2. *Baryon magnetic moments arise solely from the static sum of the quark moments*

3. *Individual quark moments are proportional to quark charges (i.e. $\mu_u = -2\mu_d$)*

1.

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

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

2.

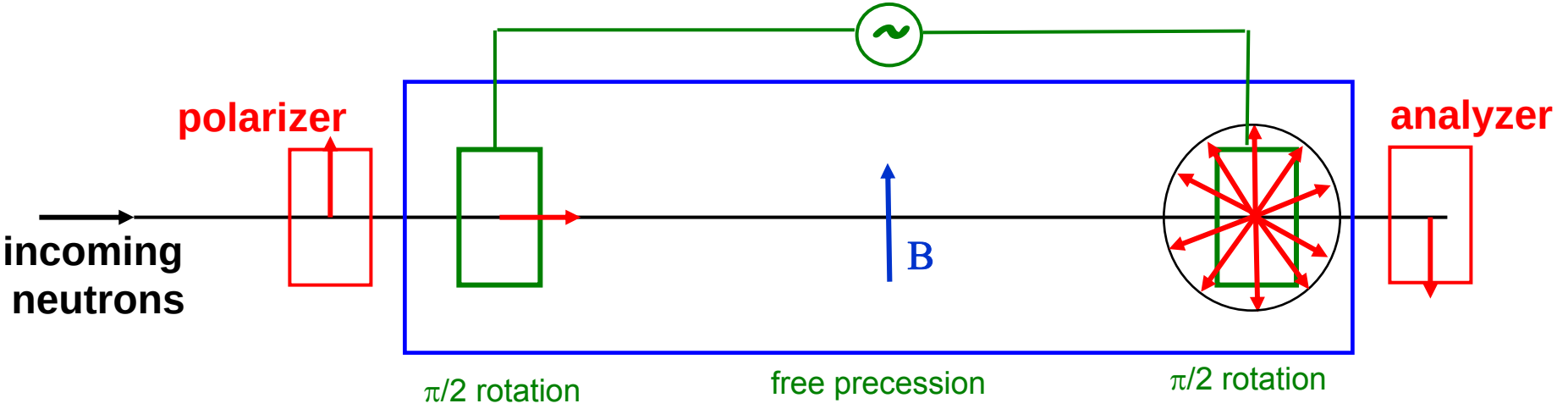
$$\mu_n = -\tfrac{1}{3}\mu_u + \tfrac{4}{3}\mu_d$$

$$\mu_p = -\tfrac{1}{3}\mu_d + \tfrac{4}{3}\mu_u$$

3.

$$\boxed{\frac{\mu_n}{\mu_p} = -\frac{2}{3}}$$

Method of Separated Oscillatory Fields



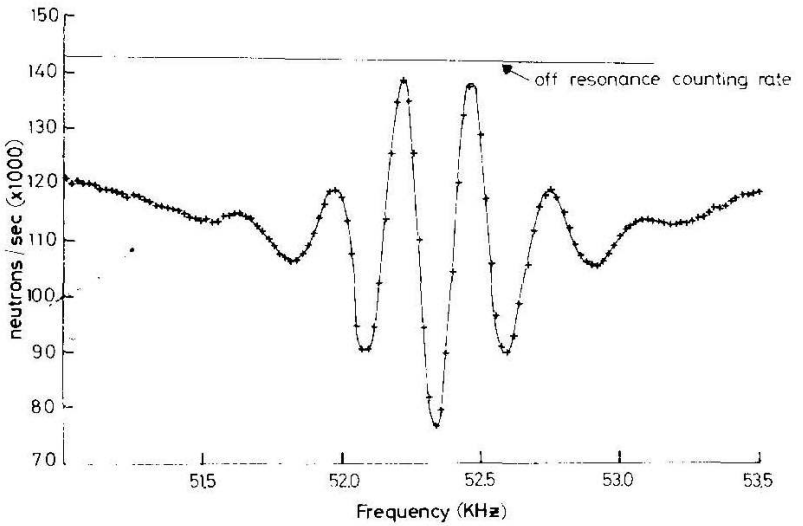
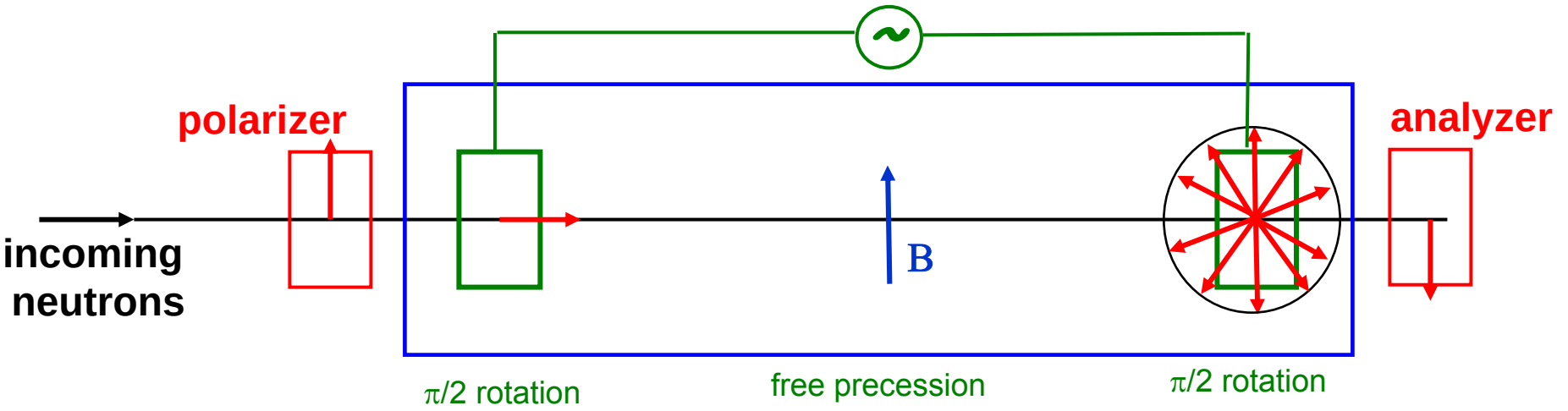


Fig. 1. Neutron resonance.

Method of Separated Oscillatory Fields



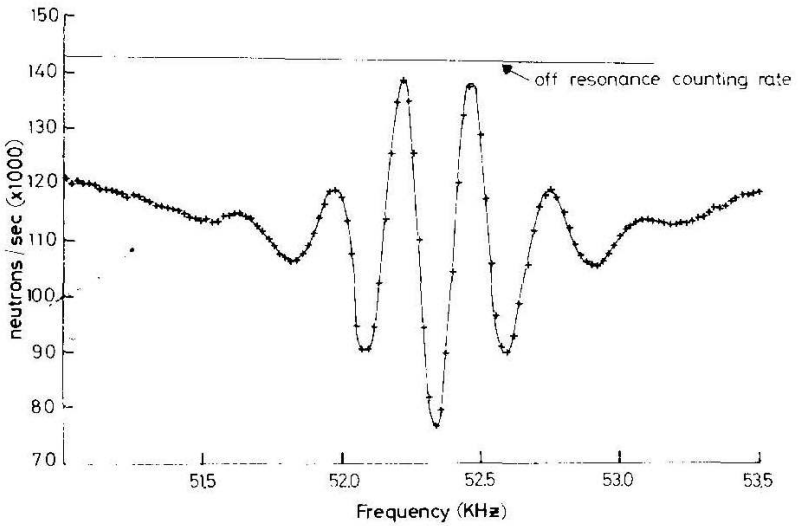


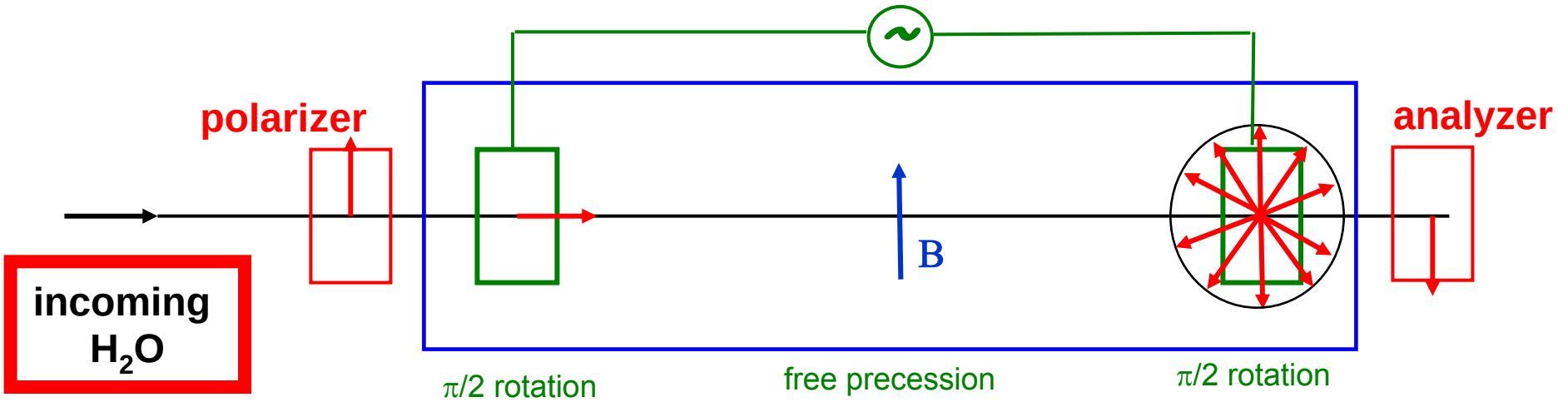
Fig. 1. Neutron resonance.

$$\omega = \bar{H}$$

How to determine $\bar{H}$?

*G. L. Greene, et. al. Physics Letters, **71B**, 297 (1977)*

Calibration of Magnetic Field Using Flowing Water



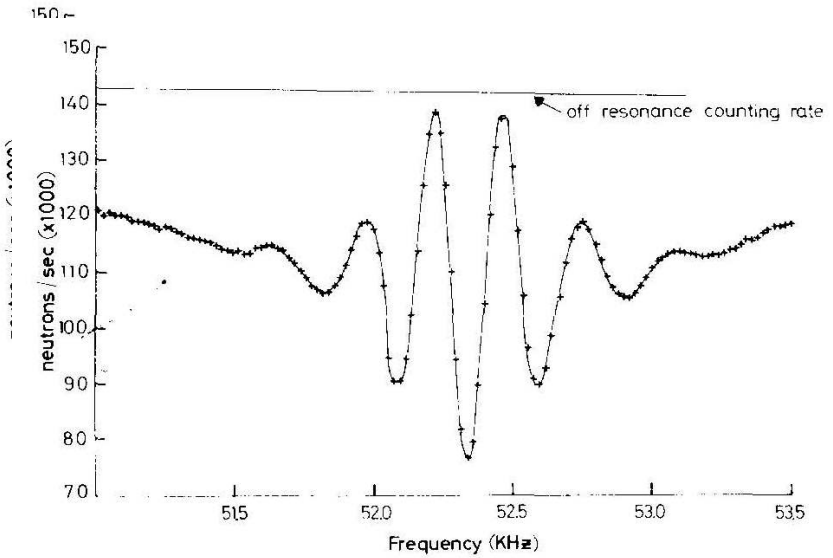


Fig. 1. Neutron resonance.

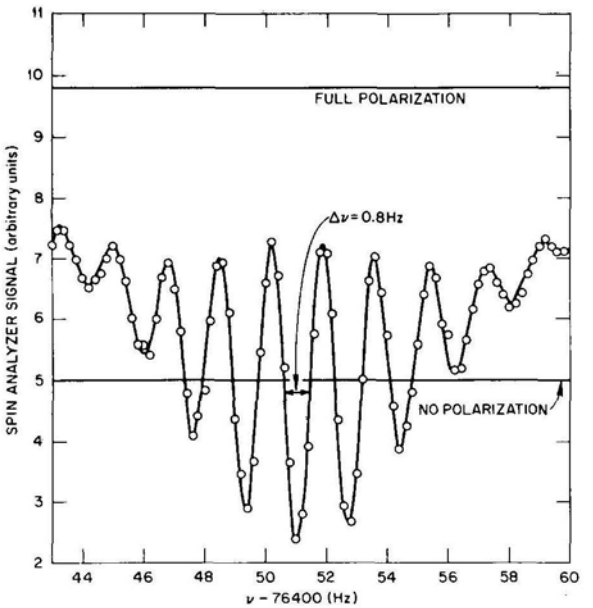


Fig. 2. Proton resonance.

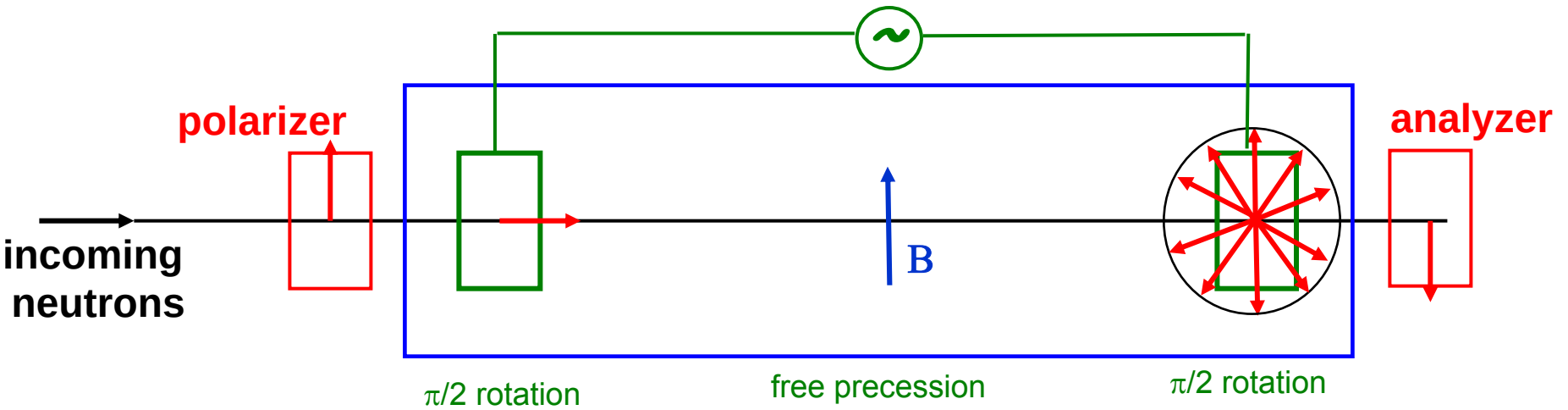
$$\frac{\mu_n}{\mu_p} = -0.68497935(17)$$

*G. L. Greene, et. al. Physics Letters, **71B**, 297 (1977)*

Sign of the Neutron Magnetic Moment

Strictly speaking, the Ramsey method, using separated oscillatory fields, is only sensitive to the absolute value of the magnetic moment

$$\left|\frac{\mu_n}{\mu_p}\right| = 0.68497935(17)$$



Solution: Use Rotating Fields Rather that Oscillating Fields

$$\mu_n < 0$$

E. H. Rogers and H.H. Staub, Phys Rev ***74****, 1025 (1948)*

WHY IS THE AGREEMENT SO GOOD?

$$\frac{\mu_n}{\mu_p} = -0.68497935(17)$$ experiment

vs.

$$\frac{\mu_n}{\mu_p} = -0.67$$ theory

Polarized electron, proton, and muon scattering experiments on H, D and ^{3}He indicate that only 20-30% of the nucleon spin comes from the intrinsic spin of the quarks.

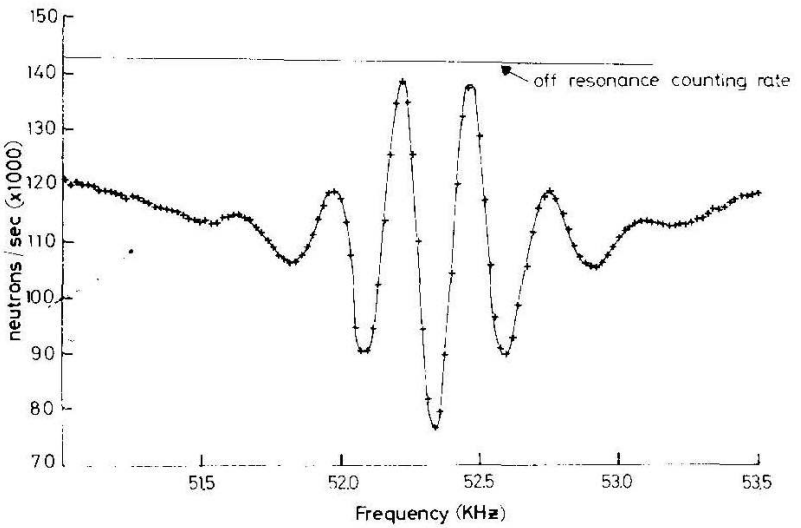
The spin structure of the nucleon is one of the outstanding problems at the interface between nuclear and particle physics.

Over the past 20 years more than 1000 theoretical papers have been published and major experiments have been carried out at practically all major accelerator laboratories.

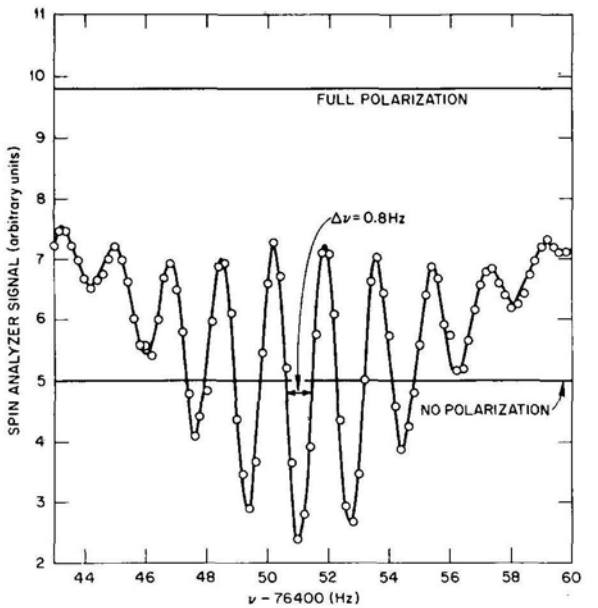
The work is ongoing…

See S. Bass, Science, 315, 1672 (2007) for a brief review and references

Sensitivity of the Ramsey Method



$$\Delta\omega_{neutron} = 150Hz$$



$$\Delta\omega_{proton} = 0.8Hz$$

In General, the sensitivity of any frequency measurement will be inversely proportional to the coherence time. For the Ramsey Method the linewidth is $\Delta\omega = 1/2T$. In the neutron magnetic moment experiment the neutron velocity was a few x100 m/s. The water velocity was a few m/s.

The Neutron Electric Dipole Moment

Discrete Symmetries

Parity: $\hat{P}\cdot\Psi(x,y,z)\Rightarrow\Psi(-x,-y,-z)$

Time Reversal: $\hat{T}\cdot\Psi(t)\Rightarrow\Psi(-t)$

Charge Conjugation: $\hat{C}\cdot\Psi_n\Rightarrow\Psi_{\bar{n}}\ \therefore\ q\Rightarrow -q$

Wigner-Eckhart Theorem Implies $\vec{\mu}=\mu\vec{J}$ *and* $\vec{d}=d\vec{J}$

Non-Relativistic Hamiltonian

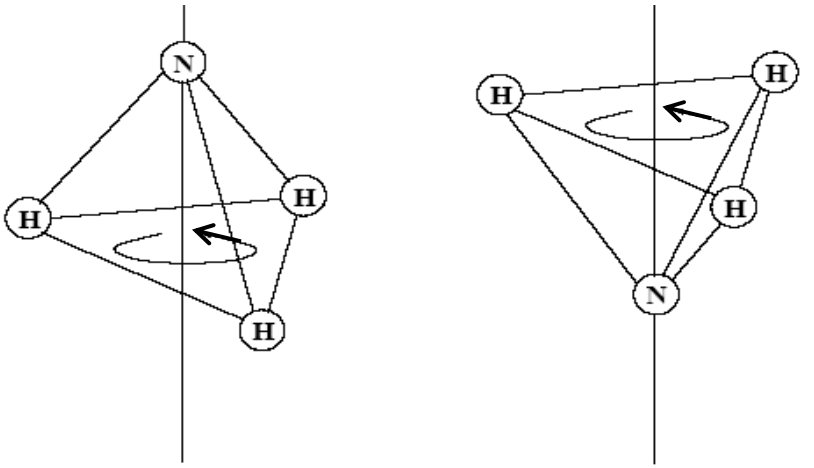
$$H=\underbrace{\vec{\mu}\cdot\vec{B}}_{\substack{\text{C-even}\\ \text{P-even}\\ \text{T-even}}}+\underbrace{\vec{d}\cdot\vec{E}}_{\substack{\text{C-even}\\ \text{P-odd}\\ \text{T-odd}}}$$

Non-zero d violates P,T, and CP

	C	P	T
$\vec{J}$	+	+	-
$\vec{\mu}$	-	+	-
$\vec{d}$	-	+	-
$\vec{B}$	-	+	-
$\vec{E}$	-	-	+

After B.Fillipone

Non-Elementary Particles can have EDM's
<u>Without</u> Violating Parity and Time Reversal Symmetry

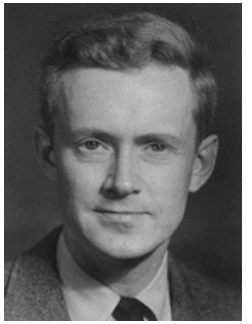


If the neutron was a composite object it could also have non-zero edm without P and T violation.

However, it would then have a degenerate ground state which is incompatible with observed nuclear shell structure.

"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"

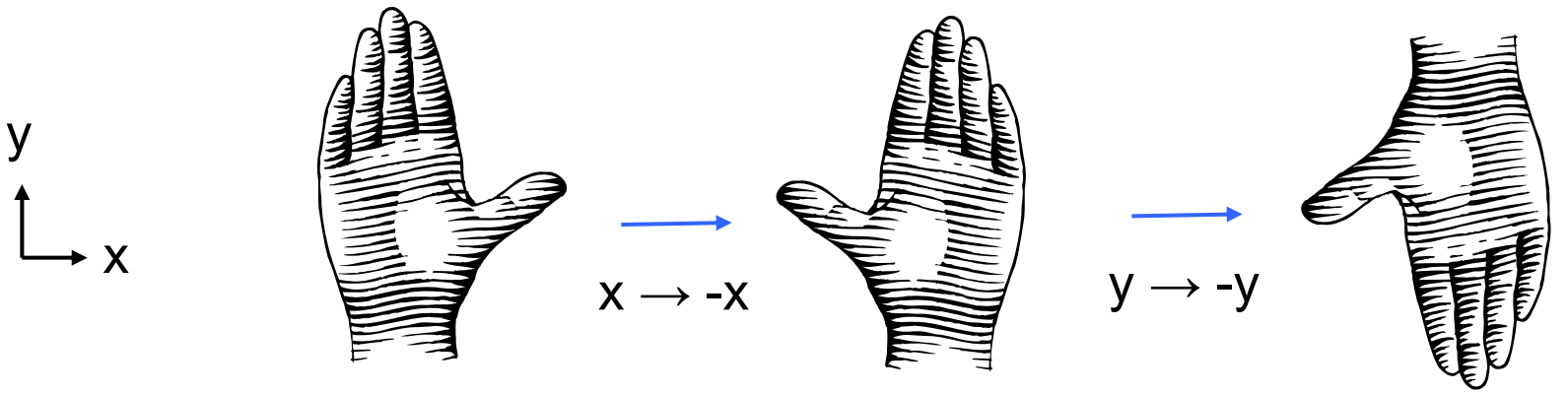
E.M.Purcell and N.F.Ramsey,
Physical Review 78, 807 (1950)



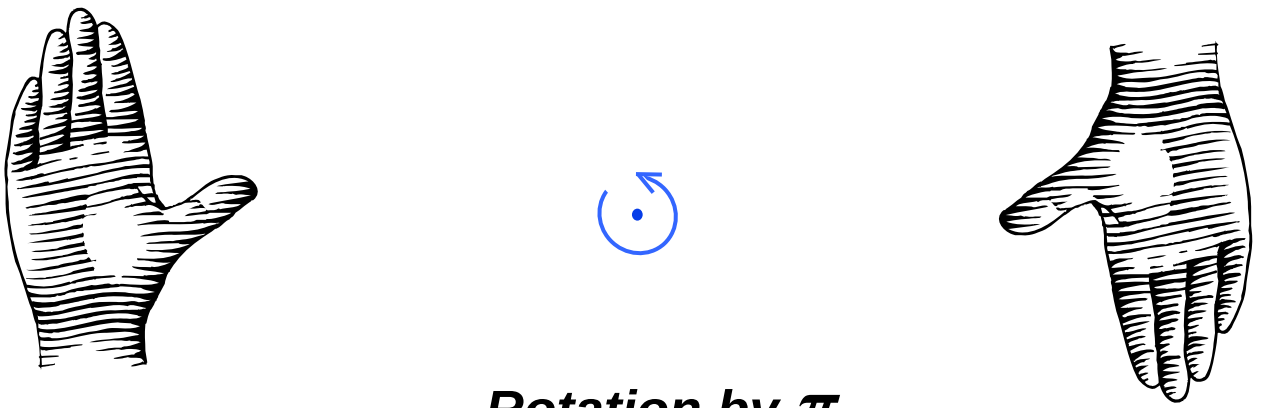
Edward Purcell

Norman Ramsey

Parity in 2 Dimensions



Parity



Rotation by π

In a Euclidean space of even dimension,

Parity = Rotation

Question: What about "space-time" Isn't it an an even dimensioned manifold

$$(x, y, z, ct) \xrightarrow{PT} (-x, -y, -z, -ct)$$

"space-time" is not Euclidean

$$ds^2 = dx^2 + dy^2 + dz^2 - c^2dt^2$$

Combined action of CPT is equivalent to a rotation in Minkowski space and is therefore a "real" symmetry.

Schwinger's "Strong" Rotation

CPT Conservation is quite compelling -

Any Local, Lorentz Invariant Field Theory Must Conserve CPT

The Cosmic Baryon Asymmetry and the n EDM

The Baryon Asymmetry "Problem"

There is an extremely strong symmetry between Matter and Antimatter.

Why then, is there essentially NO Anti-Matter in the cosmos?

Generating a Matter-Antimatter Asymmetry

A. D. Sakharov, JETP Lett. **5**, *24 (1967).*

1. *Very early in the Big Bang ($t<10^{-6}$ s), matter and antimatter (i.e. p & $\overline{p}$) were in thermal equilibrium (T>>1 GeV). There was exact balance between matter and antimatter.*

2. *At some point, there was a symmetry breaking process that led to a small imbalance between the number of Baryons and Anti-Baryons…i.e a few more Baryons.*

3. *When the Universe cooled to below T~1GeV, All the anti-baryons annihilated leaving a few baryons and lots of high-energy annihilation photons.*

4. *The photons are still around! They have been highly red shifted by subsequent expansion and are now microwaves as the Cosmic Microwave Background.*

In this scenario, the total "apparent" matter-antimatter asymmetry is really very tiny… given by ratio of Baryons to CMB photons:

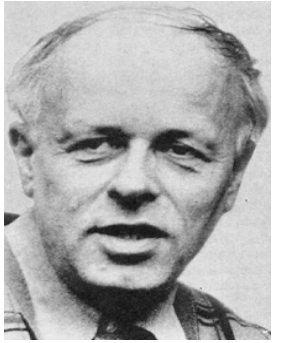
$$\frac{n_{Baryon}}{n_{\gamma}} \approx 10^{-10}$$

Requirements for the Sakharov Process

1. *The process must violate Baryon Number Conservation*

2. *There must be a period of Non-Thermal Equilibrium*

3. *There must be a process that violates Time Reversal Non-Invariance --- "T-violation"*



A. Sakharov

Question:

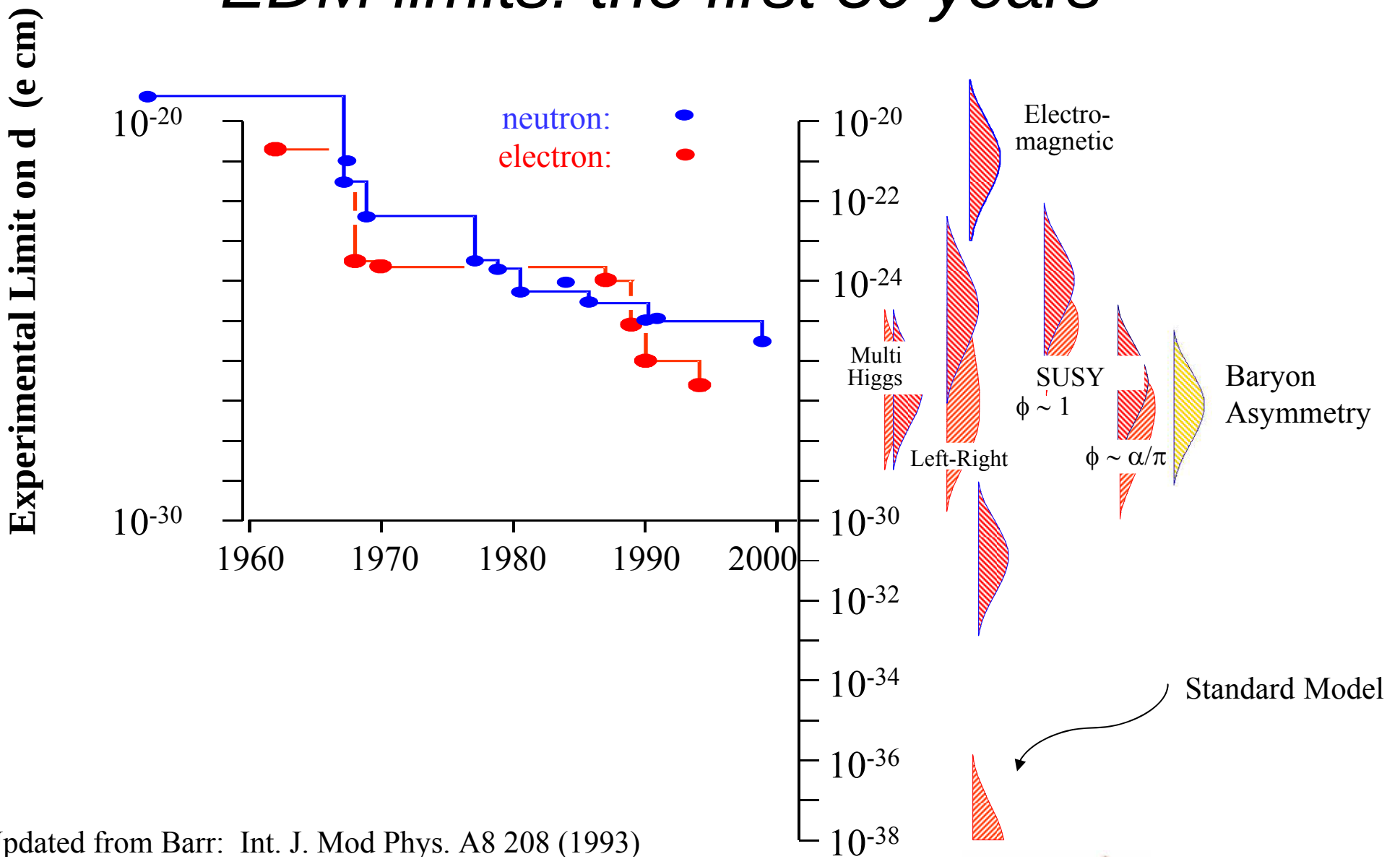
Can the T violation needed to generate the matter- antimatter asymmetry when the universe was 10^6 s old be related to an observable quantity today?

- *If the matter-antimatter asymmetry is generated by a T-violating process during the big bang, the same process would generate a neutron edm <u>at some level</u>.*

- *The observed magnitude of the matter antimatter asymmetry appears to imply a neutron edm with a magnitude approximately equal to the current experimental limit (~10^{-26} e-cm)*

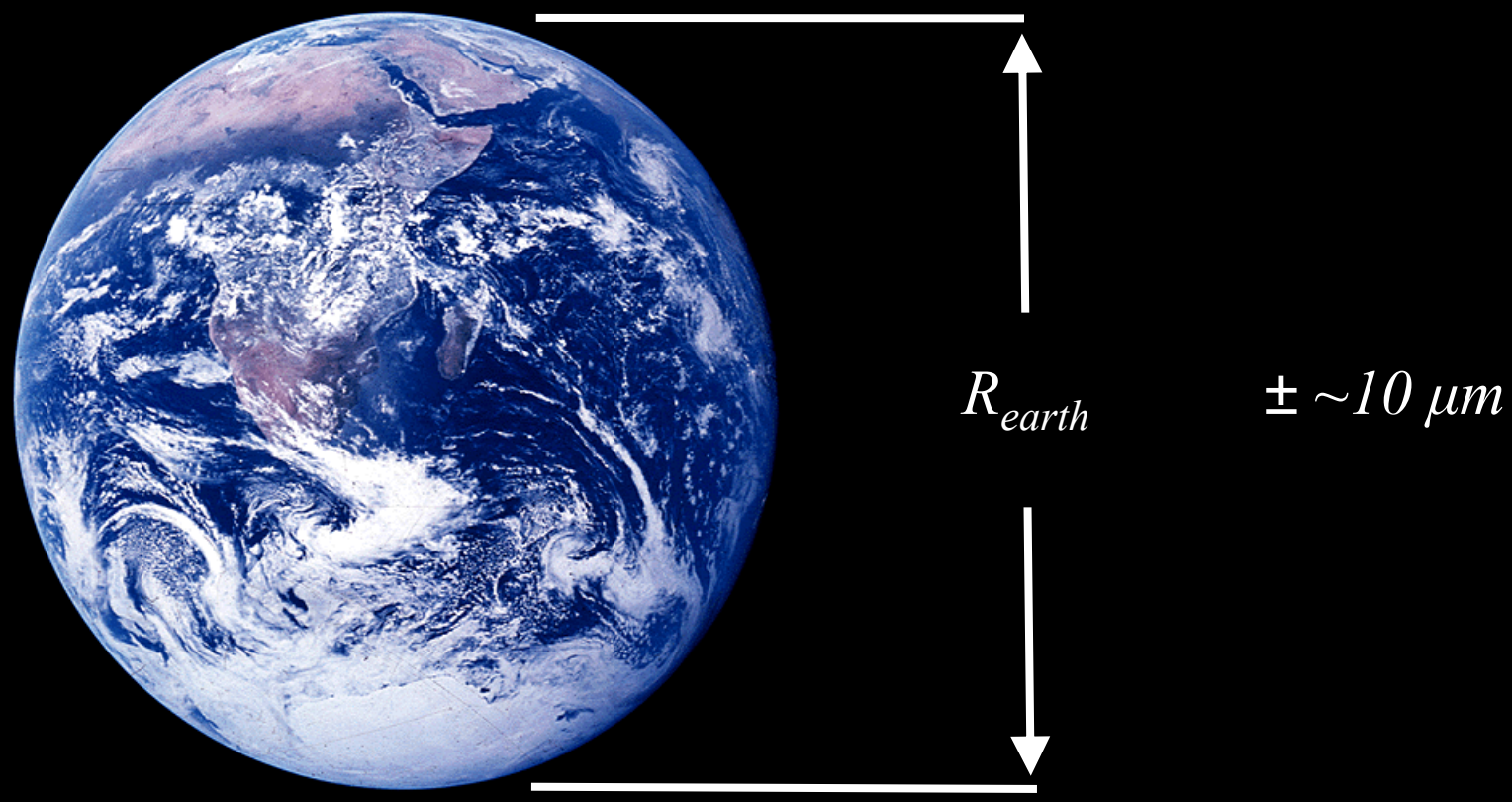
- ***The next 2 orders of magnitude will be very interesting.***

EDM limits: the first 50 years

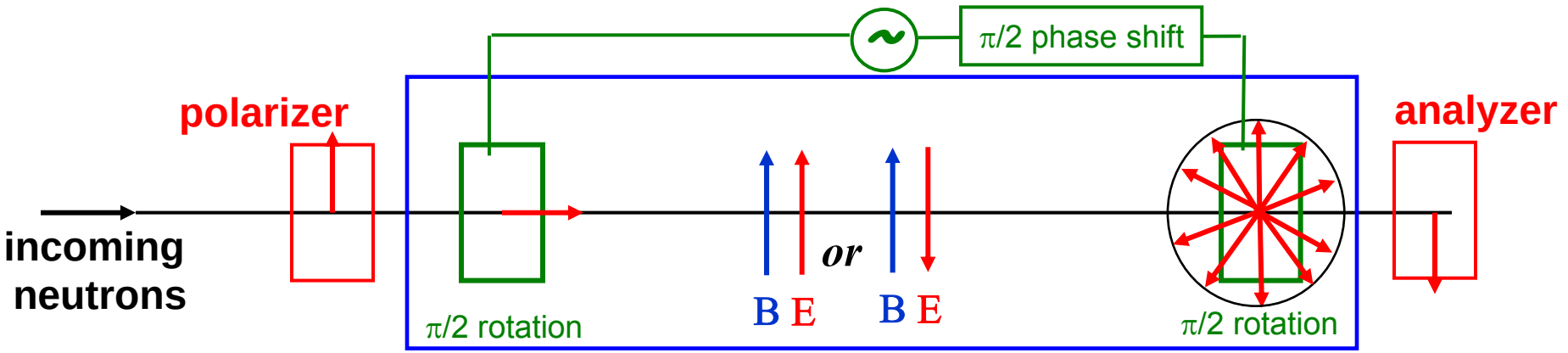


Updated from Barr: Int. J. Mod Phys. A8 208 (1993)

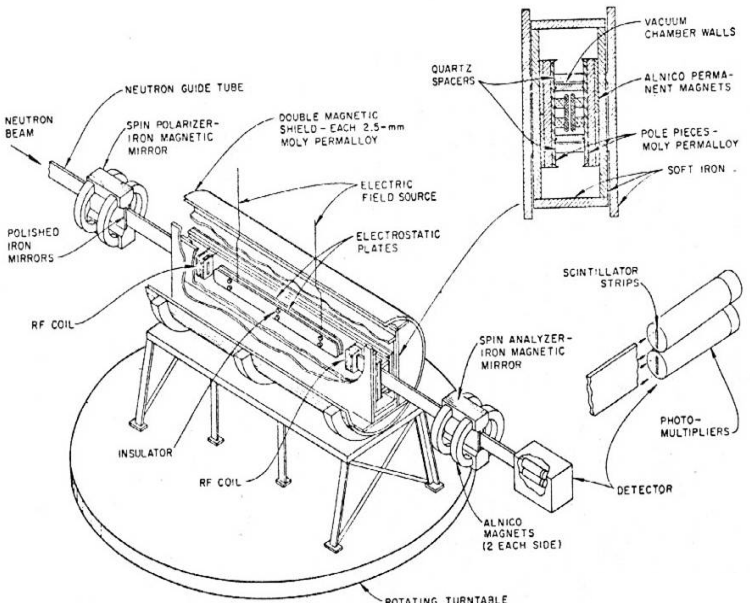
If a neutron were blown up to the size of the earth, the current limit on its EDM would correspond to a displacement of + and – electron charge by ~10 μm

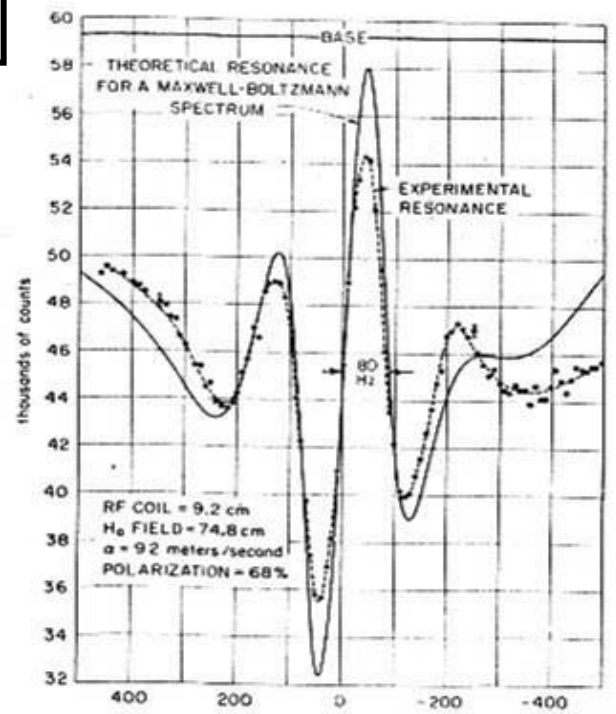


Neutron Beam EDM Experiment



$$\omega = \frac{2\mu_n B}{\hbar} \pm \frac{2d_n E}{\hbar}$$





Dress et al. Phys. Rep. **43**, 410 (1978)

EDM Statistical Sensitivity

$$\sigma_{edm} \propto \frac{1}{ET\sqrt{N_n}}$$

E = *Applied Electric Field*

T = *Observation Time* ($\Delta\omega \approx T^{-1}$)

N_n = *Number of neutrons observed*

EDM Statistical Sensitivity

$$\sigma_{edm} \propto \frac{1}{ET\sqrt{N_n}}$$

E = *Applied Electric Field*

T = *Observation Time* ($\Delta\omega \approx T^{-1}$)

N_n = *Number of neutrons observed*

Observation Time in Beam Experiment was ~ 3 ms

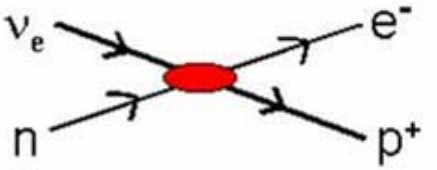
Neutron Decay

Wolfgang Pauli

Enrico Fermi

1930 Pauli proposes the "neutrino" to explain apparent energy apparent energy and angular momentum non-conservation in beta conservation in beta decay

1934 Fermi takes the neutrino idea seriously and develops his develops his theory of beta decay



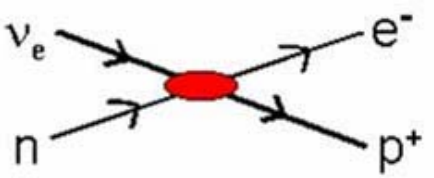
1935 The β decay of the neutron is predicted by Chadwick and Chadwick and Goldhaber based on their observation that $M_n > M_p + M_e$ observation that $M_n > M_p + M_e$.

Based on their ΔM, the neutron lifetime is estimated at ~½ hr. estimated at ~½ hr.

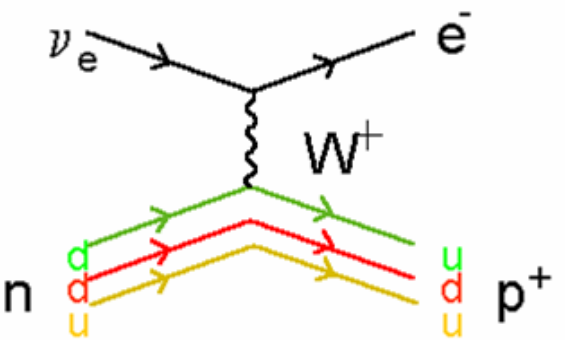
1948 Snell and Miller observe neutron decay at Oak Ridge Ridge

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

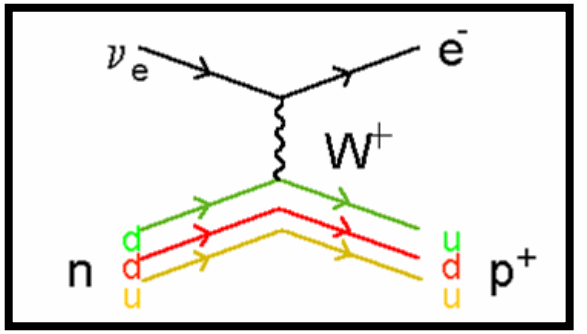
Fermi's View of Neutron Decay:



Modern View of Neutron Decay:



Processes with the same Feynman Diagram as Neutron Decay



Primordial element formation $\quad n + e^+ \longleftrightarrow p + \bar{\nu}_e$

$$p + e^- \longleftrightarrow n + \nu_e$$

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

Solar cycle $\quad p + p \longrightarrow {}^2H + e^+ + \nu_e$

$$p + p + e^- \longrightarrow {}^2H + \nu_e \quad \text{etc.}$$

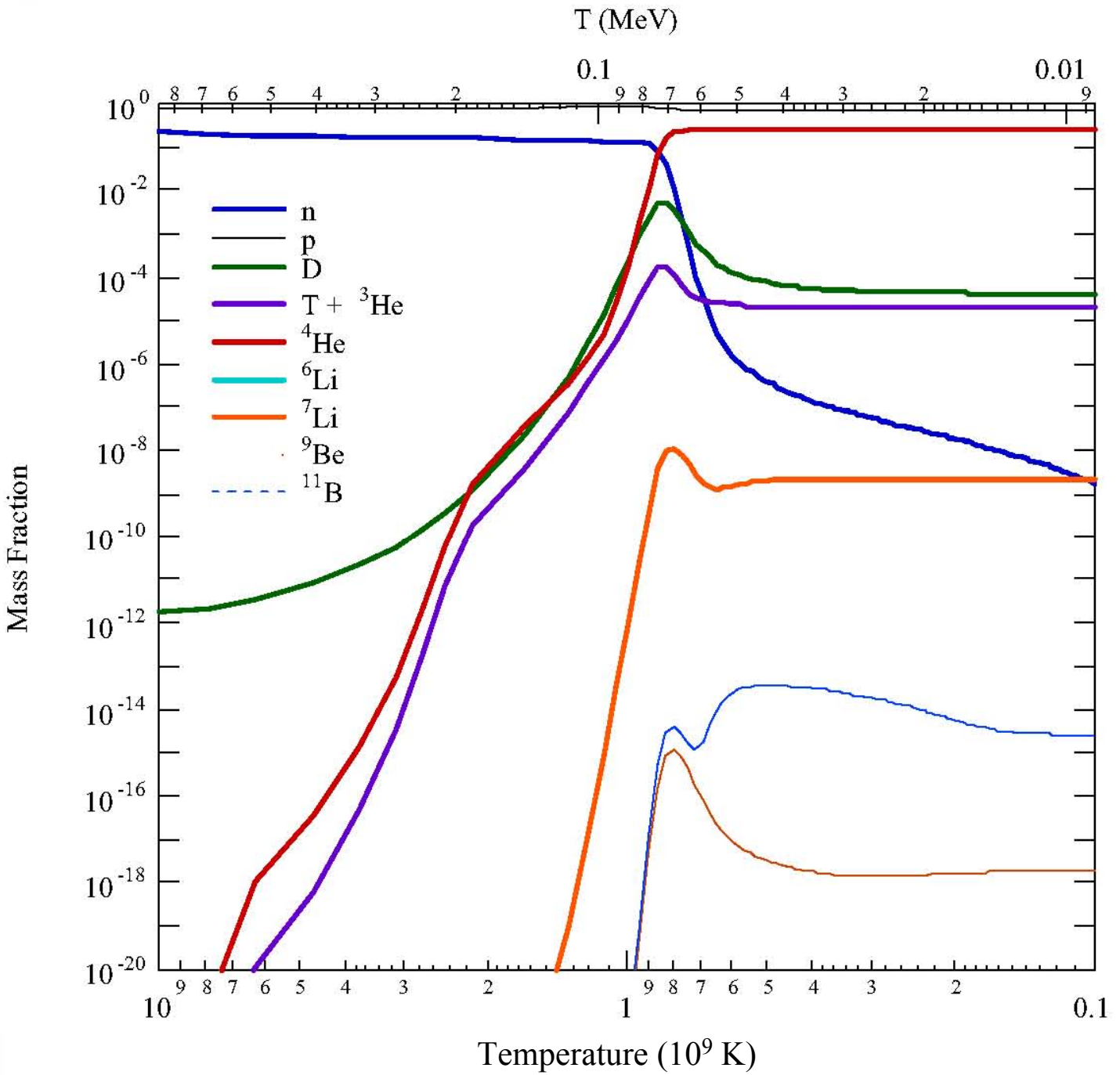
Neutron star formation $\quad p + e^- \longrightarrow n + \nu_e$

Pion decay $\quad \pi^- \longrightarrow \pi^0 + e^- + \bar{\nu}_e$

Neutrino detectors $\quad \nu_e + p \longrightarrow e^+ + n$

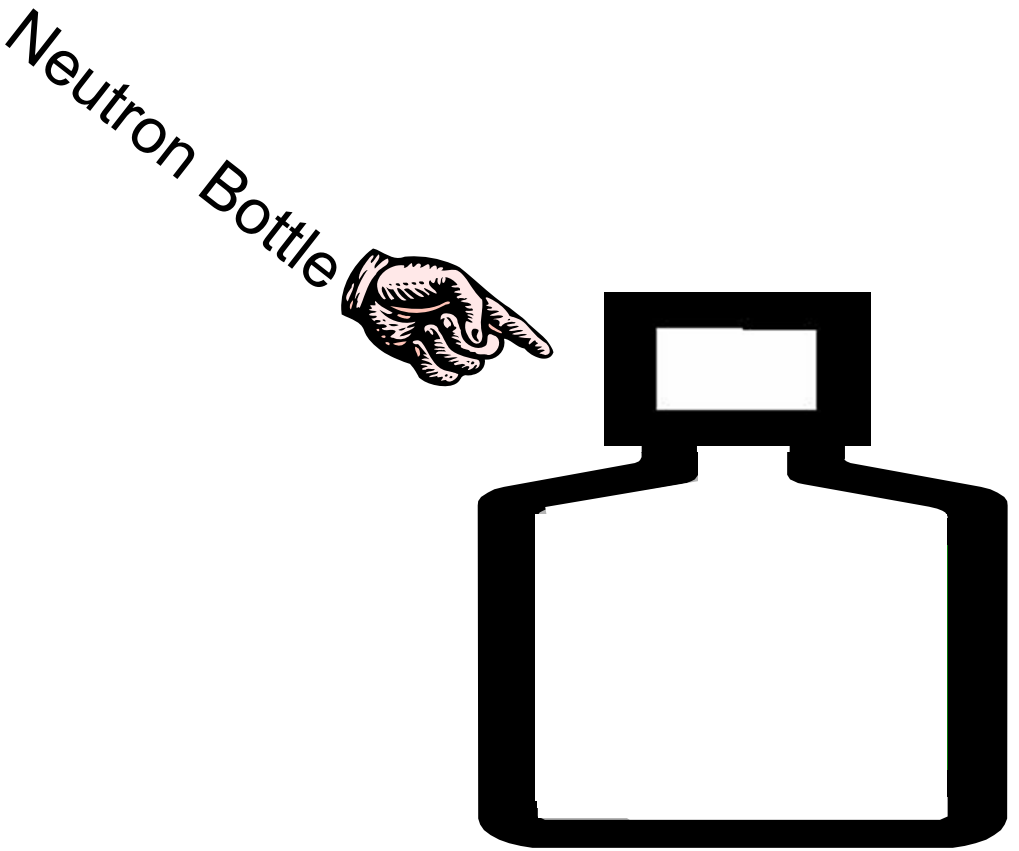
Neutrino forward scattering $\quad \nu_e + n \longrightarrow e^- + p \quad \text{etc.}$

After D. Dubbers


T (MeV)
0.1
0.01
Mass Fraction
n
p
D
T + ^{3}He
^{4}He
^{6}Li
^{7}Li
^{9}Be
^{11}B
Temperature (10^9 K)

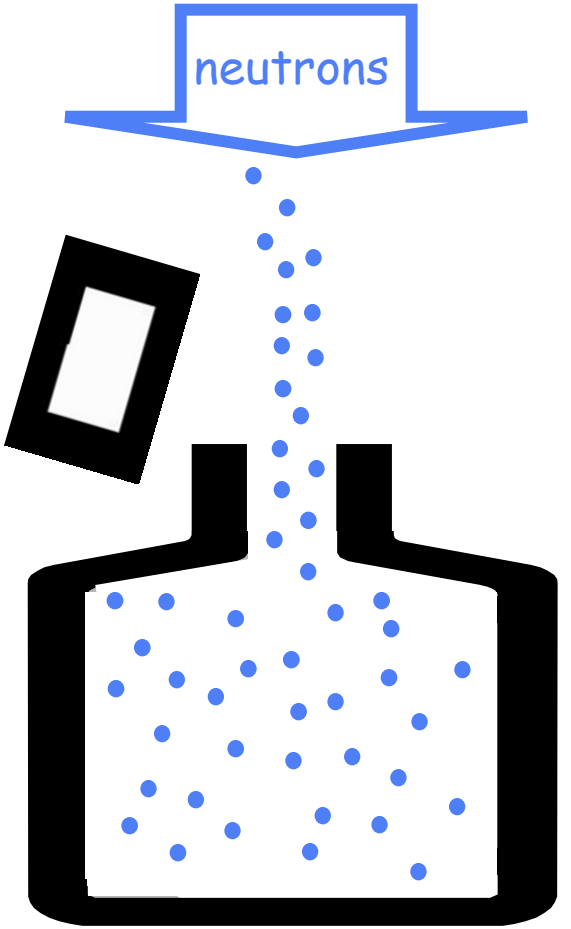
Measuring the Neutron Lifetime

Step 1. Get One Neutron "Bottle"



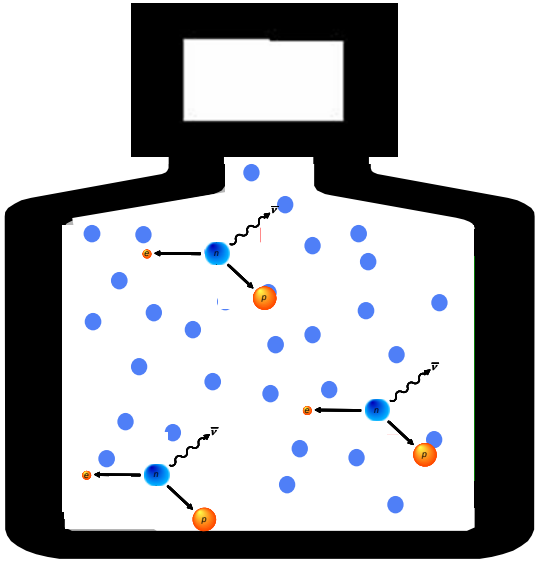
Measuring the Neutron Lifetime

Step 1. Fill Neutron "Bottle"



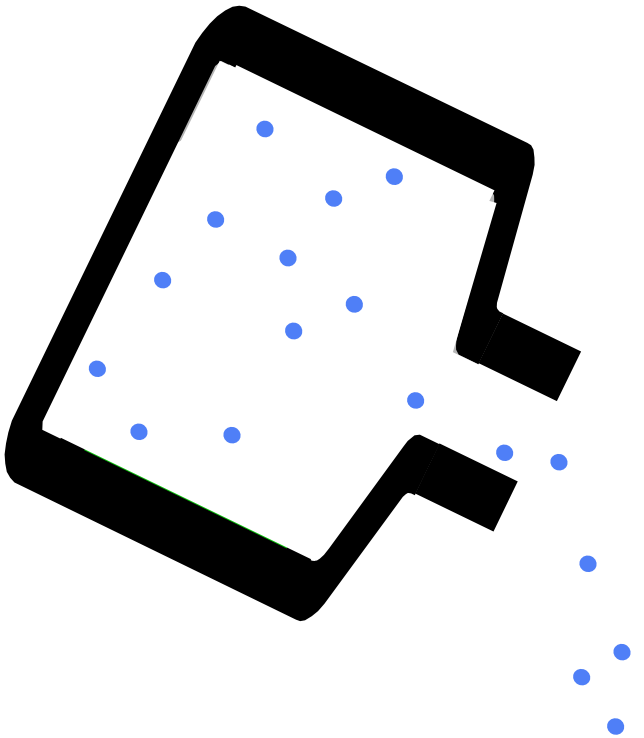
Measuring the Neutron Lifetime

Step 3. Let neutron decays for time $t \sim \tau_n$



Measuring the Neutron Lifetime

Step 4. Pour neutrons out and count



$$N(t) = N(0)e^{-t/\tau_n}$$

Some Neutron Bottles

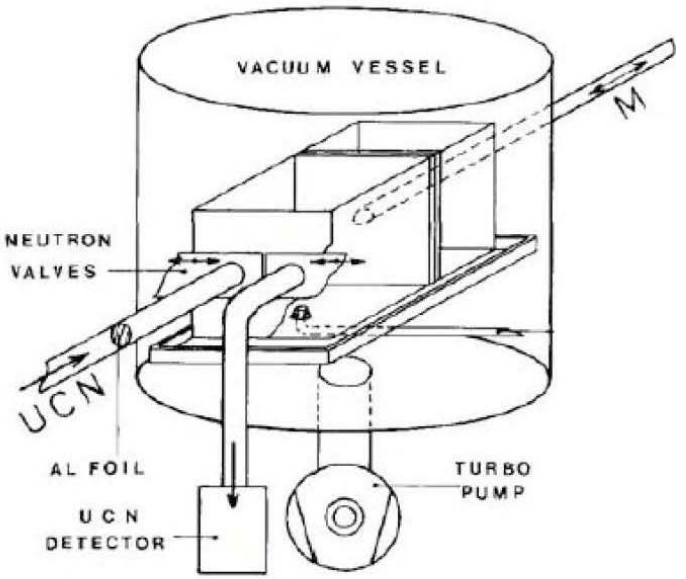
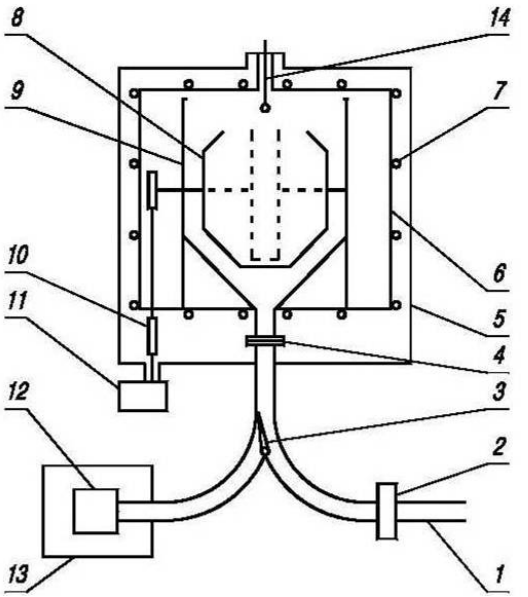
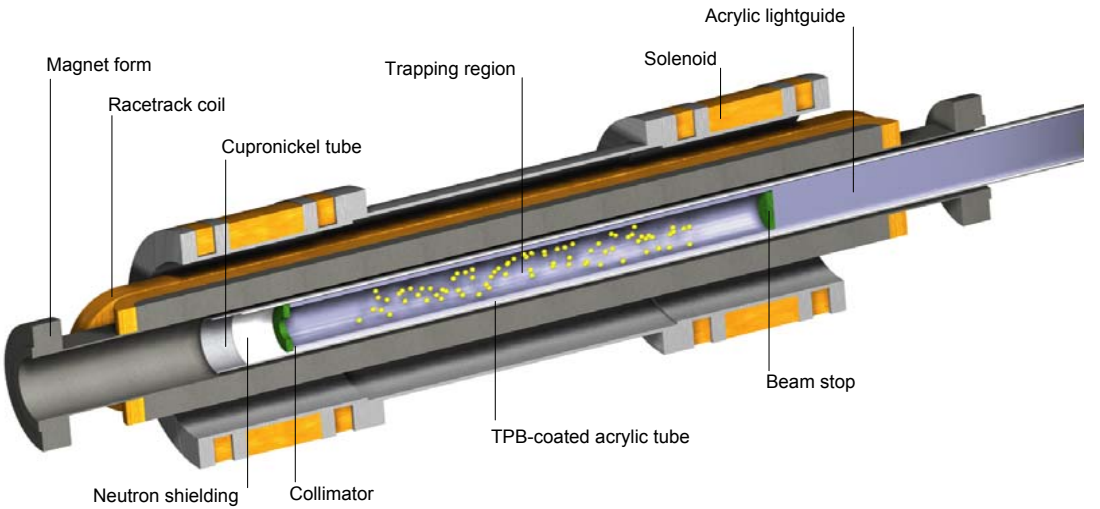


FIG. 1. Sketch of the apparatus.

Mampe et al, *PRL* ***63*** *(1989)*



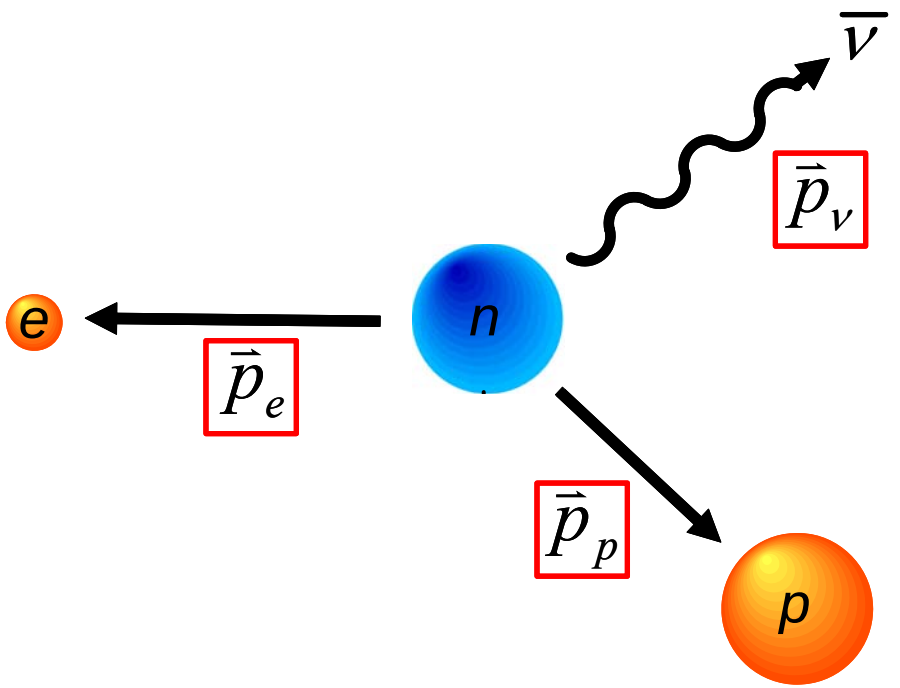
Serebrov et al, Phys Lett B605 (2005)



Huffman, et al, Nature, 403 (2000)

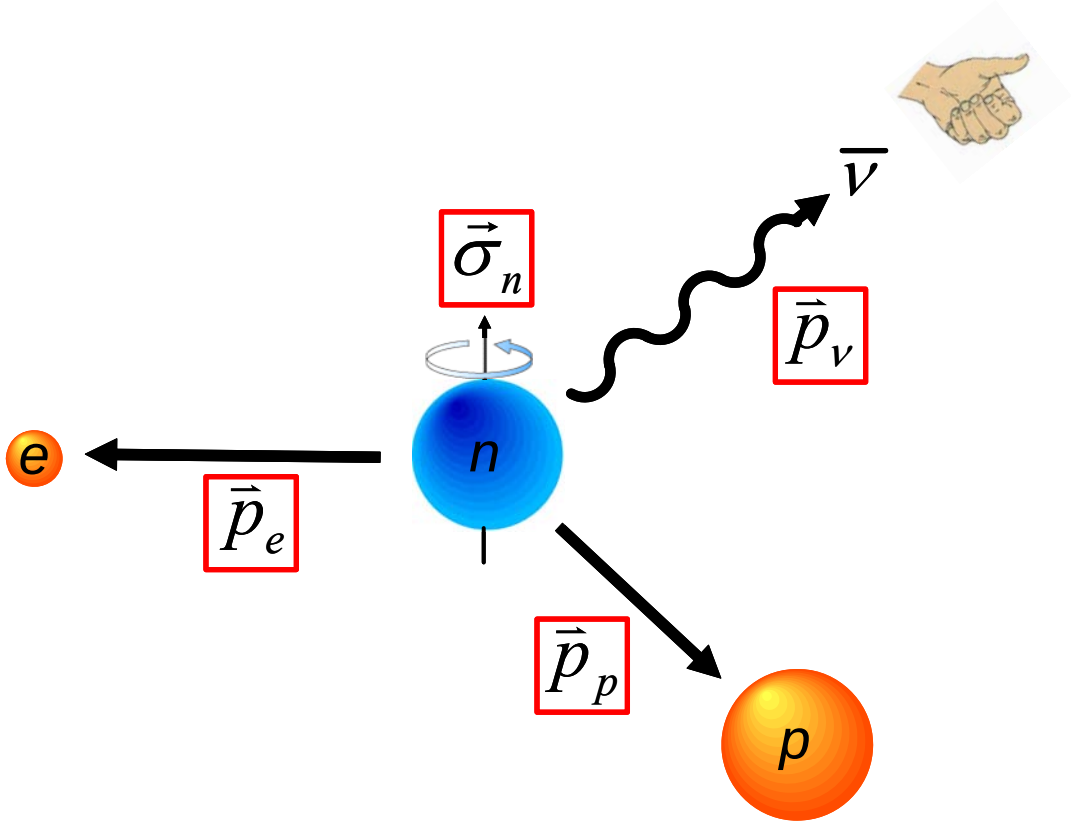
Phenomenology of Neutron Beta Decay

Momentum Must Be Conserved!



Phenomenology of Neutron Beta Decay

Momentum Must Be Conserved!



V-A says that neutrinos are purely "Left-Handed" with

$$\vec{\sigma} \cdot \vec{p} = -1$$

Conservation of linear and angular momentum implies that there are strong correlations between the initial neutron spin and decay particle momenta.

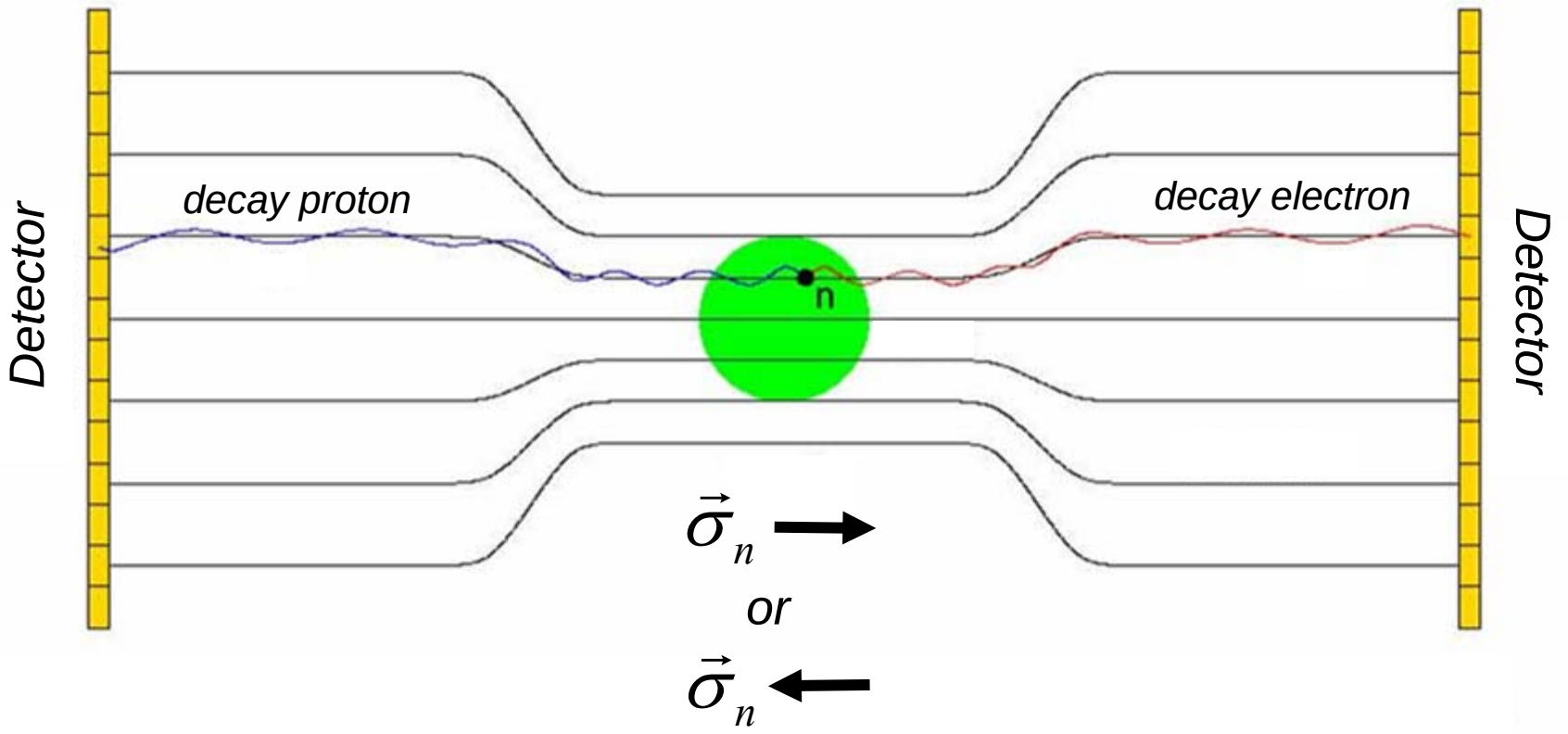
Correlations in Neutron Decay

Parity violation implies a rich phenomenology in neutron decay.

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

Much more about this in subsequent lectures

General Scheme of n-Beta Correlation Experiments



“Exotic” Neutron Decay

Exotic Neutron Decay

Allowed by the Standard Model:

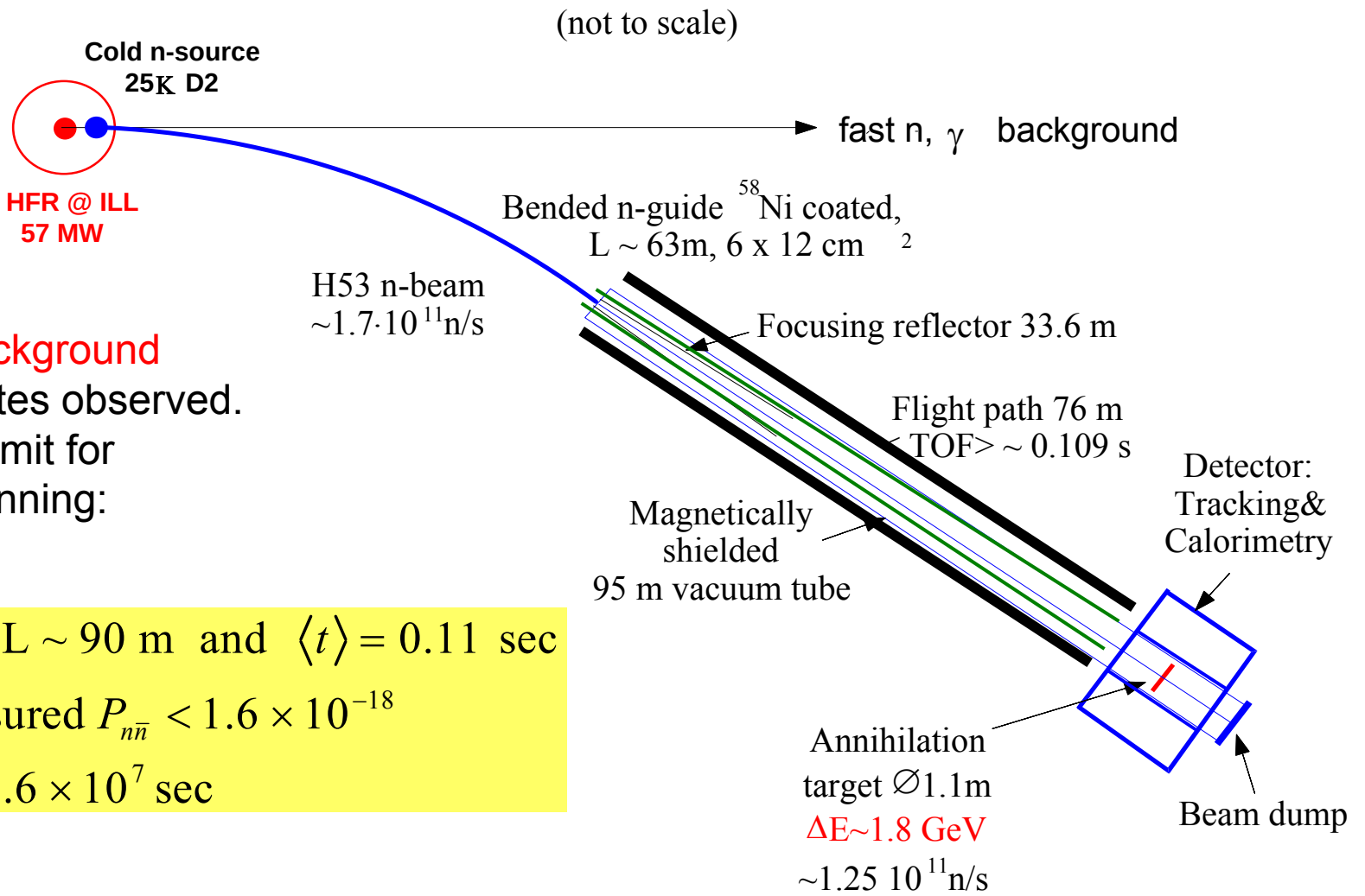
$$n \rightarrow p^{+} + e^{-} + \bar{\nu} + \gamma$$ *"radiative decay"*

$$n \rightarrow {}^{1}H_{0} + \bar{\nu}$$

Forbidden by the Standard Model:

$$n \rightarrow \bar{n}$$ *"n-nbar oscillation" (ΔB=2)*

N-Nbar search at the Institute Laue Langevin



No GeV background

No candidates observed.
Measured limit for
a year of running:

with L ~ 90 m and $\langle t \rangle = 0.11$ sec

measured $P_{n\bar{n}} < 1.6 \times 10^{-18}$

$\tau > 8.6 \times 10^{7}$ sec

Baldo-Ceolin M. et al., Z. Phys. C63,409 (1994).

Slide courtesy Mike Snow

Exotic Neutron Decay

Allowed by the Standard Model:

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

"radiative decay"

$$n \rightarrow {}^{1}H_{0} + \bar{\nu}$$

Forbidden by the Standard Model:

$$n \rightarrow \bar{n}$$

"n-nbar oscillation" (ΔB=2)

Forbidden by Common Sense ??

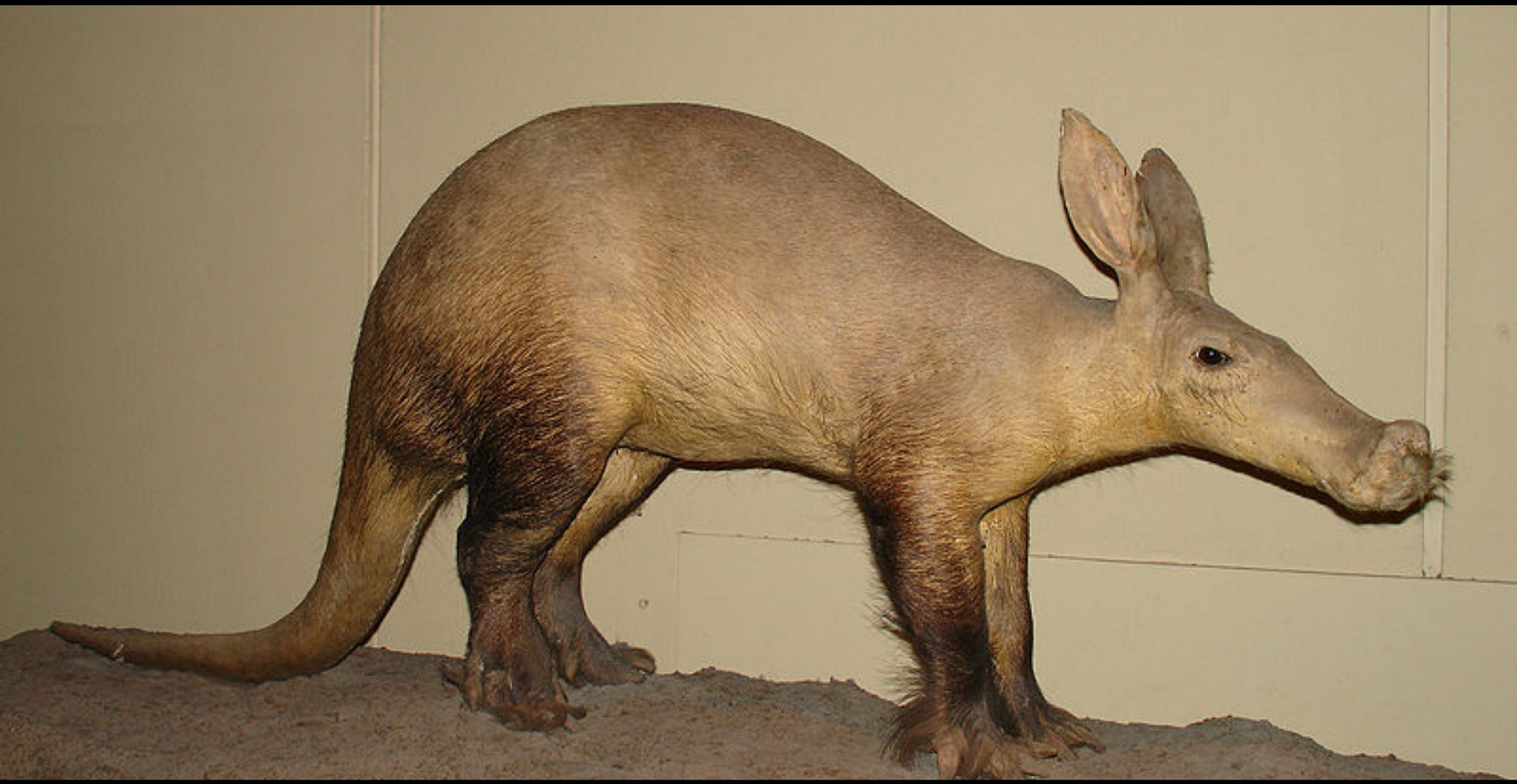
$$n \rightarrow \mathfrak{n}$$

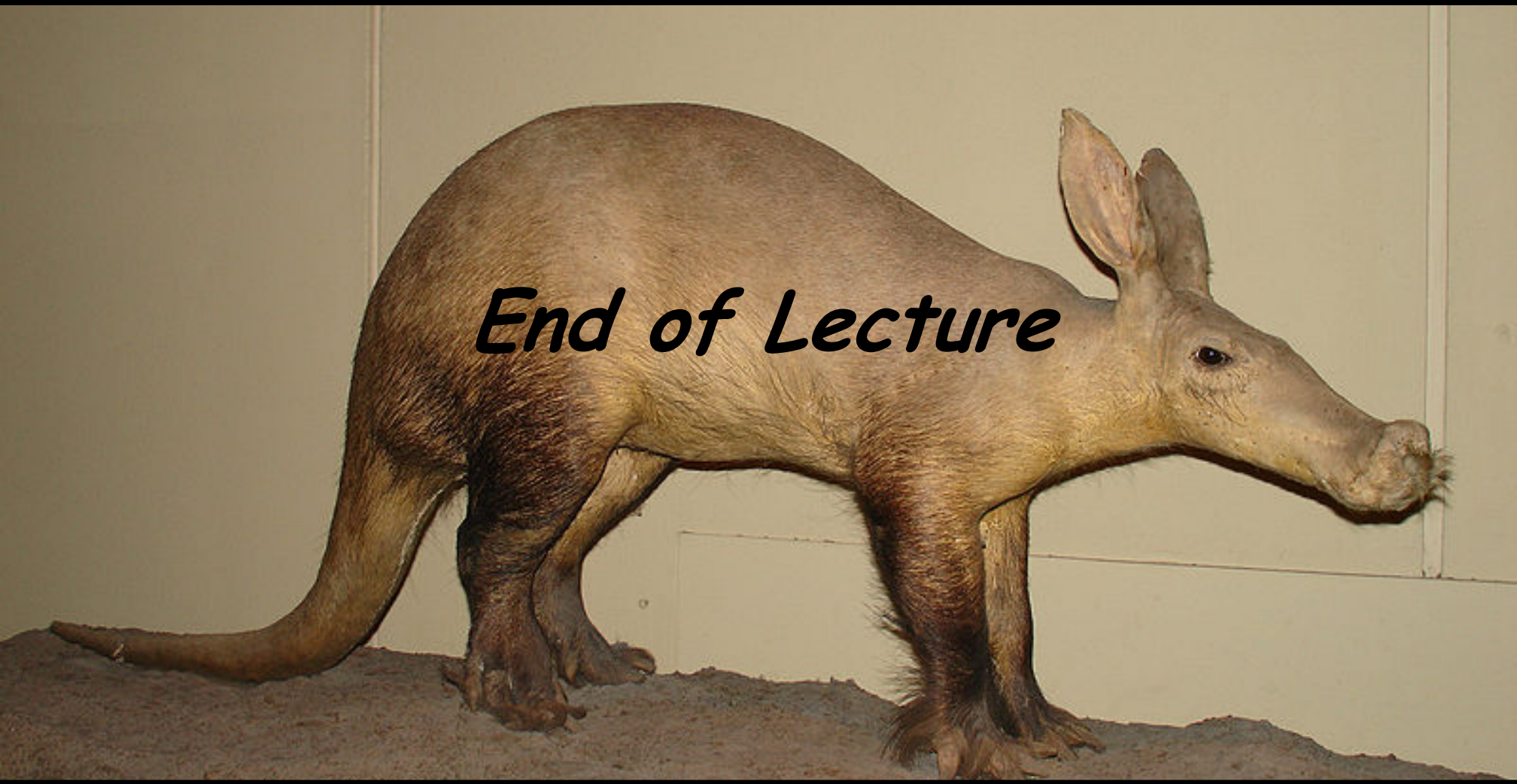
neutron – "mirror neutron" oscillation

Warning:

Just because something is "forbidden" by "common sense" does not mean it is not so!

Also Forbidden by Common Sense




End of Lecture