Fundamental Neutron Physics I

Neutron Properties

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Why focus on the neutron?

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

The neutron can be used to probe Strong, Weak, EM and Gravitational phenomena.

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.

Overview of the Lectures

1. Introduction to the basic physics of the neutron as a particle

2. Overview of neutron facilities and techniques

3. Discussion of neutron beta decay

4. Survey of selected ongoing projects

This field is characterized by a great variety of experimental techniques that call upon a wide range of physics.

Some References

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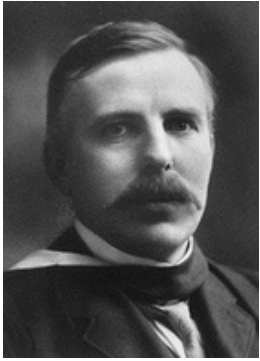Commins and Bucksbaum, *Weak Interactions of Quarks and Leptons*
Particle Data Group, **pdg.lbl.gov**

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Acknowledgements for images

Mike Snow, Fred Weitfeldt, Brad Fillipone, Jeff Nico, Paul Huffman, Sam Werner, Pieter Mumm, Scott Dewey, Chris Crawford, Harmut Abele, Yuri Kamyskov,...

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Historical Introduction

2007 is the 75th Anniversary of the Discovery of the Neutron

Ernest Rutherford

Walter Bothe

Irene Curie

1920   *Noting that atomic number (Z) does not correspond to atomic weight, Rutherford suggests that, in addition to "bare" protons, the nucleus contains some tightly bound "proton-electron pairs" or neutrons.*
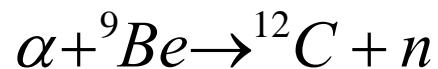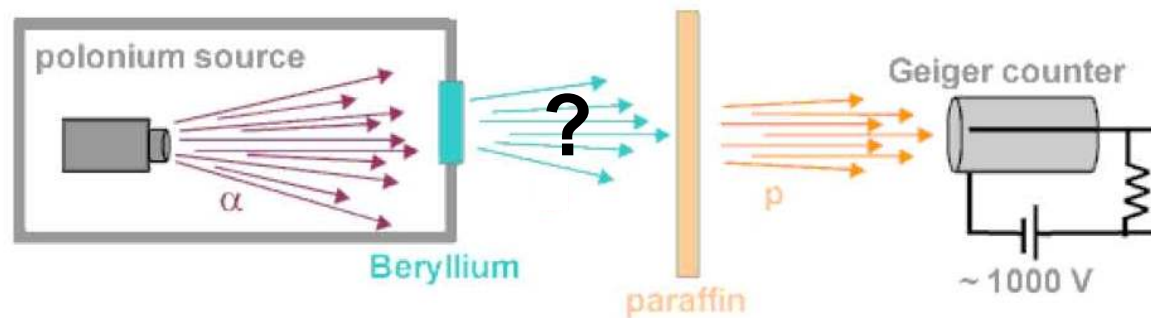
1930   *Bothe and Becker discovered a penetrating, neutral radiation when alpha particles hit a Be target.*

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

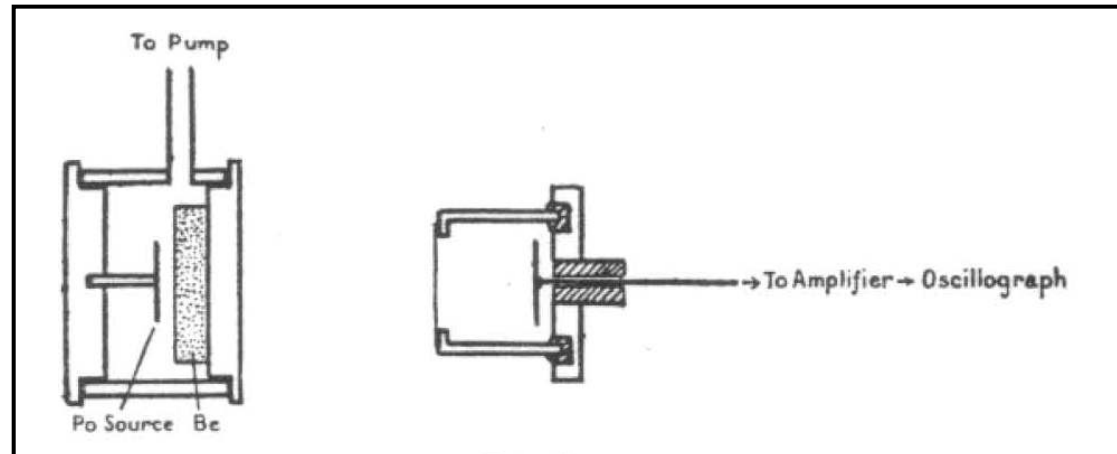$$\alpha + {}^9Be \rightarrow {}^{12}C + n$$

1932   ***Chadwick replaced the paraffin with a variety of other targets and, by measuring the recoil energies of the ejected particles was able to determine the mass of the neutral particle***

$$M = 1.15 \pm \sim 10\%$$

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

Chadwick claimed this was Rutherford's "Neutron"

James Chadwick

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

$$h\nu + {}_1D^2 \rightarrow {}_1H^2 + {}_1n^0$$
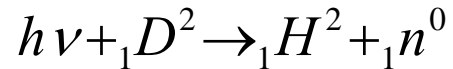
Using 2.62MeV gammas from Thorium and determining the recoil energy of the protons they we re able to determine*:

$$M_n = 1.0080 \pm 0.0005$$

➡ **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 $e + p$

*Chadwick and Goldhaber, Nature, 134 237 (1934)

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Some Neutron Properties

Mechanical Properties
Mass

Gravitational Mass (equivalence principle test)

Spin

Electromagnetic Properties
Charge (limit on neutrality)

Magnetic Dipole Moment

Electric Dipole Moment

Internal Charge Distribution

Miscellaneous Quantum Numbers:
Intrinsic Parity (P), Isospin (I), Baryon Number (B), Strangeness (S), …
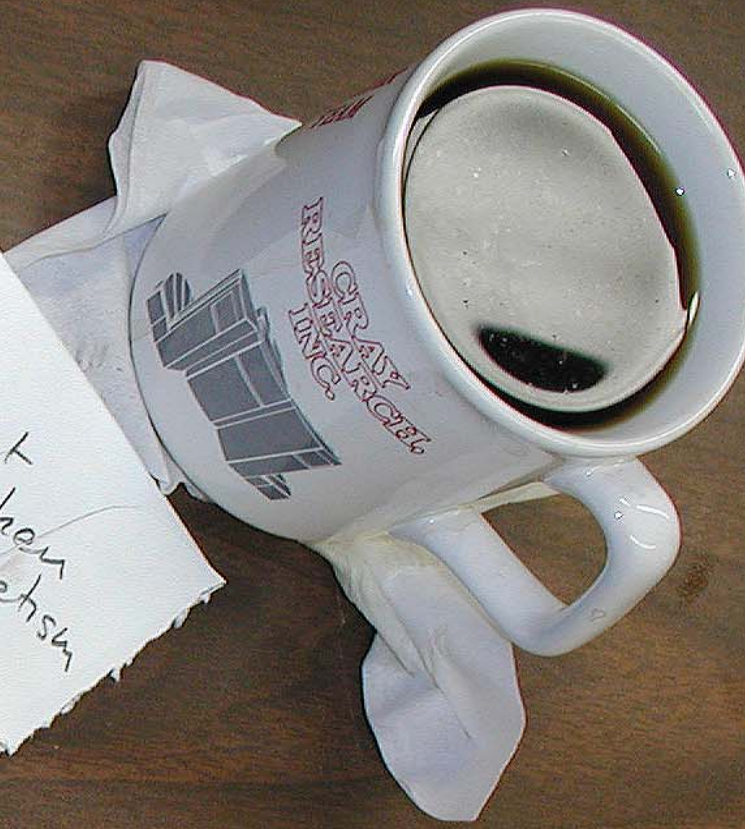
The Neutron Mass

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**.*
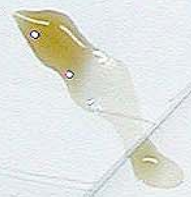
Assume that
Isospin is broken
by electromagnetism

$$(M_p - M_n)c^2 \approx \frac{e^2}{r_{nucleon}}$$

Thus

$$M_p - M_n \approx 100 \, keV$$

Determination of the Neutron Mass

The best 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/
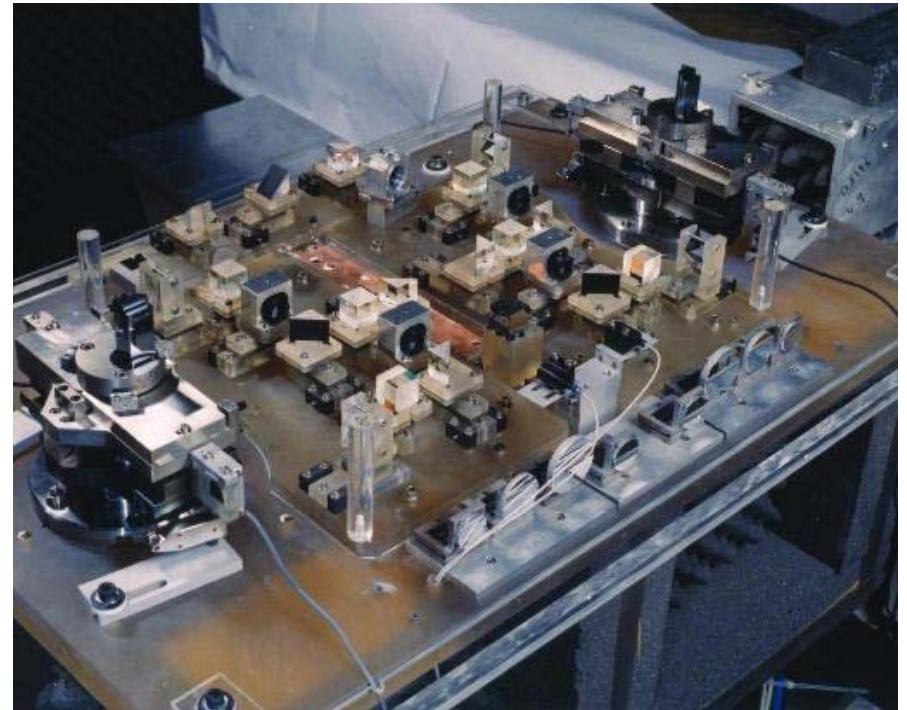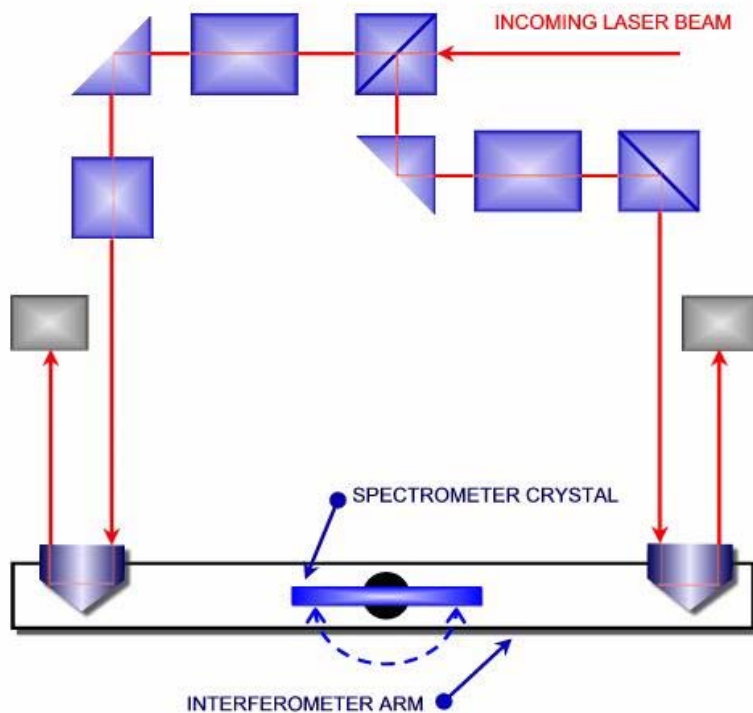
Precision vs. Accuracy

Angle Interferometer gives high precision but what about its "calibration"
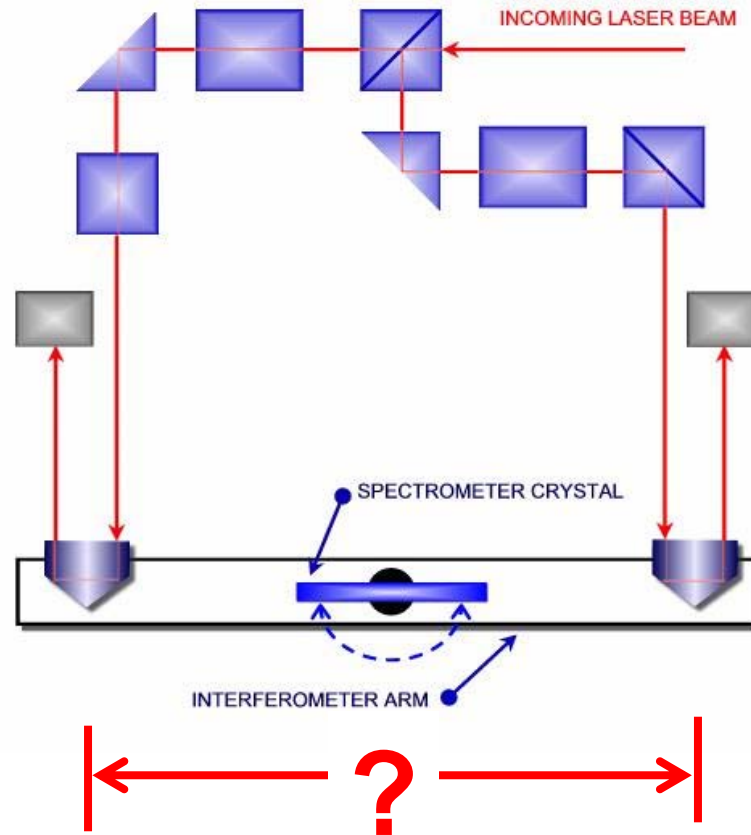
What can we use to calibrate a precision angle device?
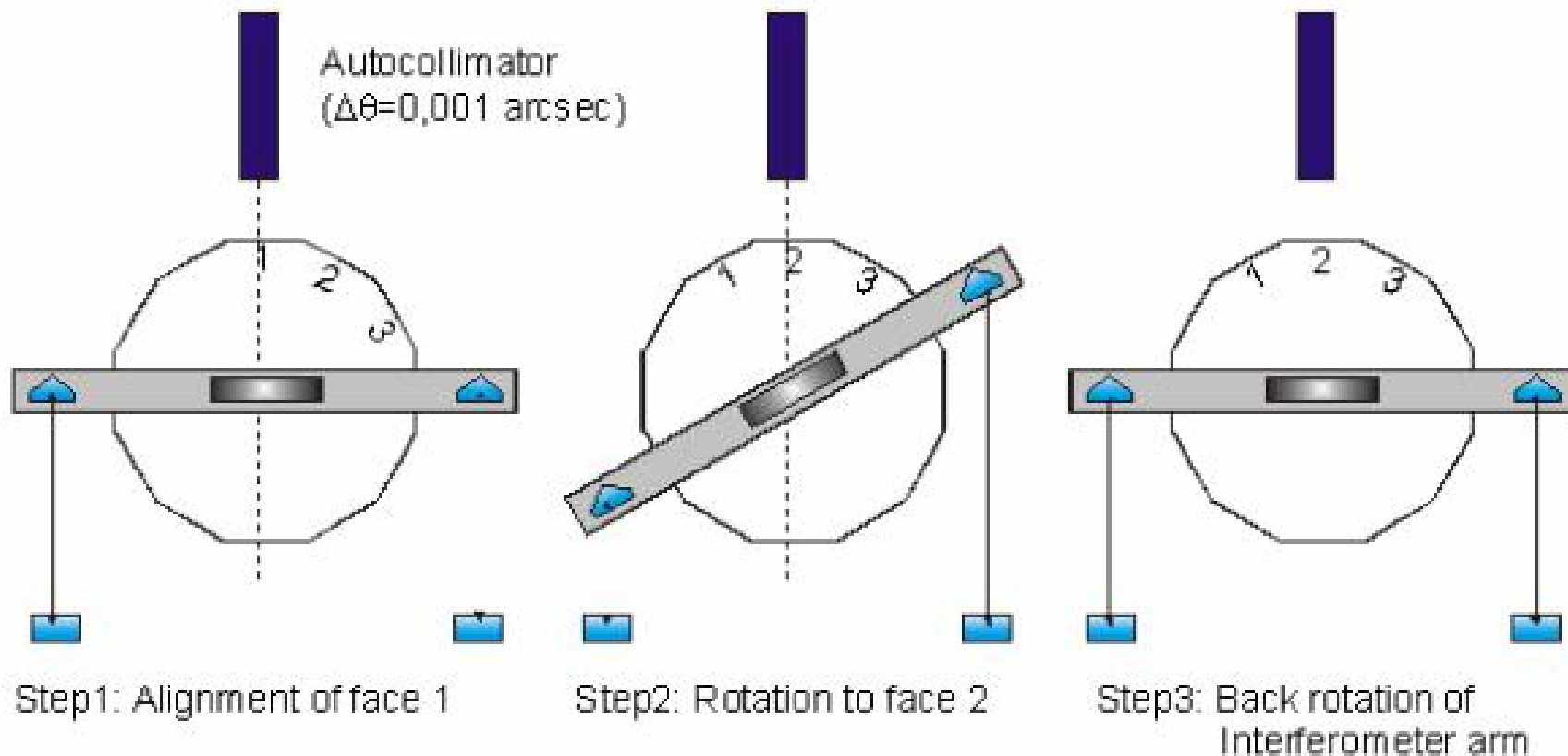Is there a "Standard" for angle measurement?

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

The NIST Standard for the Kilogram:

What is the NIST Standard for angles?

Absolute Measurement of 2.2Mev n-p Capture Gamma Energy

Step 3: Calibrate Angle interferometer

Autocollimator
($\Delta\theta = 0.001$ arcsec)

Step1: Alignment of face 1

Step2: Rotation to face 2

Step3: Back rotation of Interferometer arm

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.

Greene NNPSS July 2007

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

Determination of the Neutron Mass

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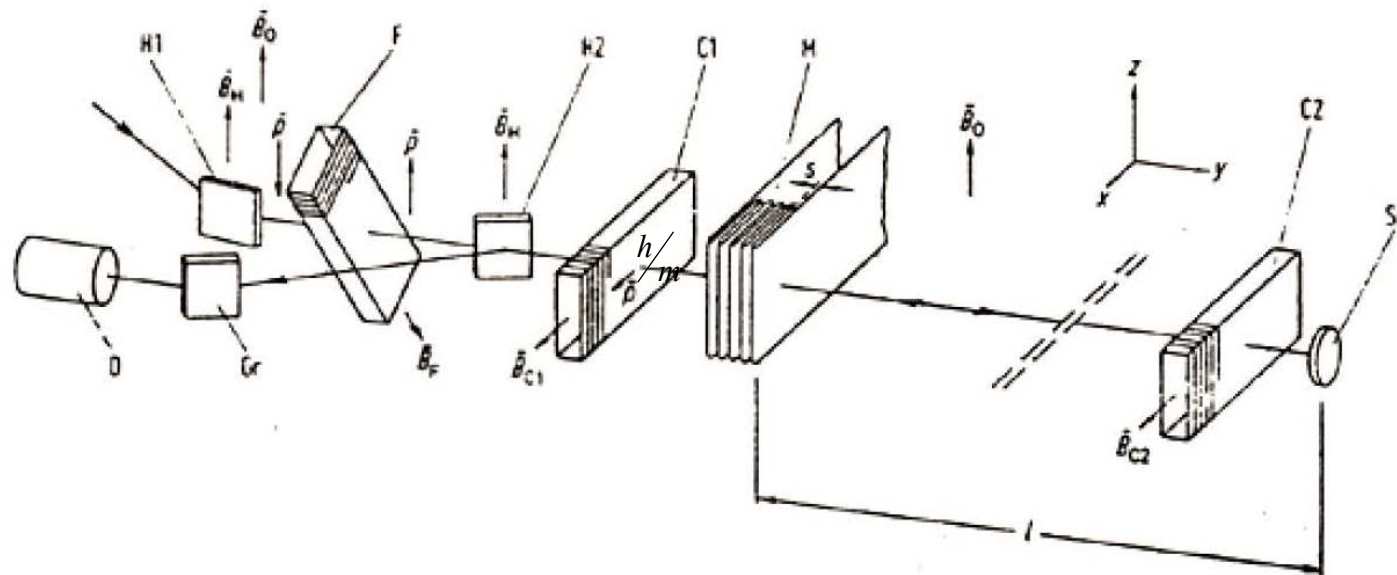
which gives

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

Determination of h/m

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

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

$$h/m_n = 3.95603330\ (30)\ x\ 10^{-7}\ m^2s^{-1} \quad 80\ ppb$$
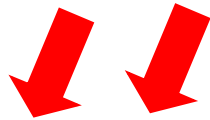
Kugler, Nistler, & Weirauch, NIM, **A284**, 143 (1969)

Kugler, Nistler, & Weirauch, PTB Ann Rep (1992)

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The Fine Structure Constant from m_n and h/m_n

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

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

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

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

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

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 QED.

Comparisons of Different Determinations of α Provide Important Tests

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

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

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

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

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

$$\alpha = \left\{ 2\sqrt{8} \left(m_p \middle/ m_e \right) R_\infty V_m(Si) V_{NIST}^2 [M_p \mu_0 c^2 d_{220}(Si)]^{-1} \left[2e \middle/ h \right]_{NIST}^{-1} \right\}^{-1}$$

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

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

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

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

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:

$$F_n = m_i \, a_n$$

$$m_g \, g = m_i \, a_n$$

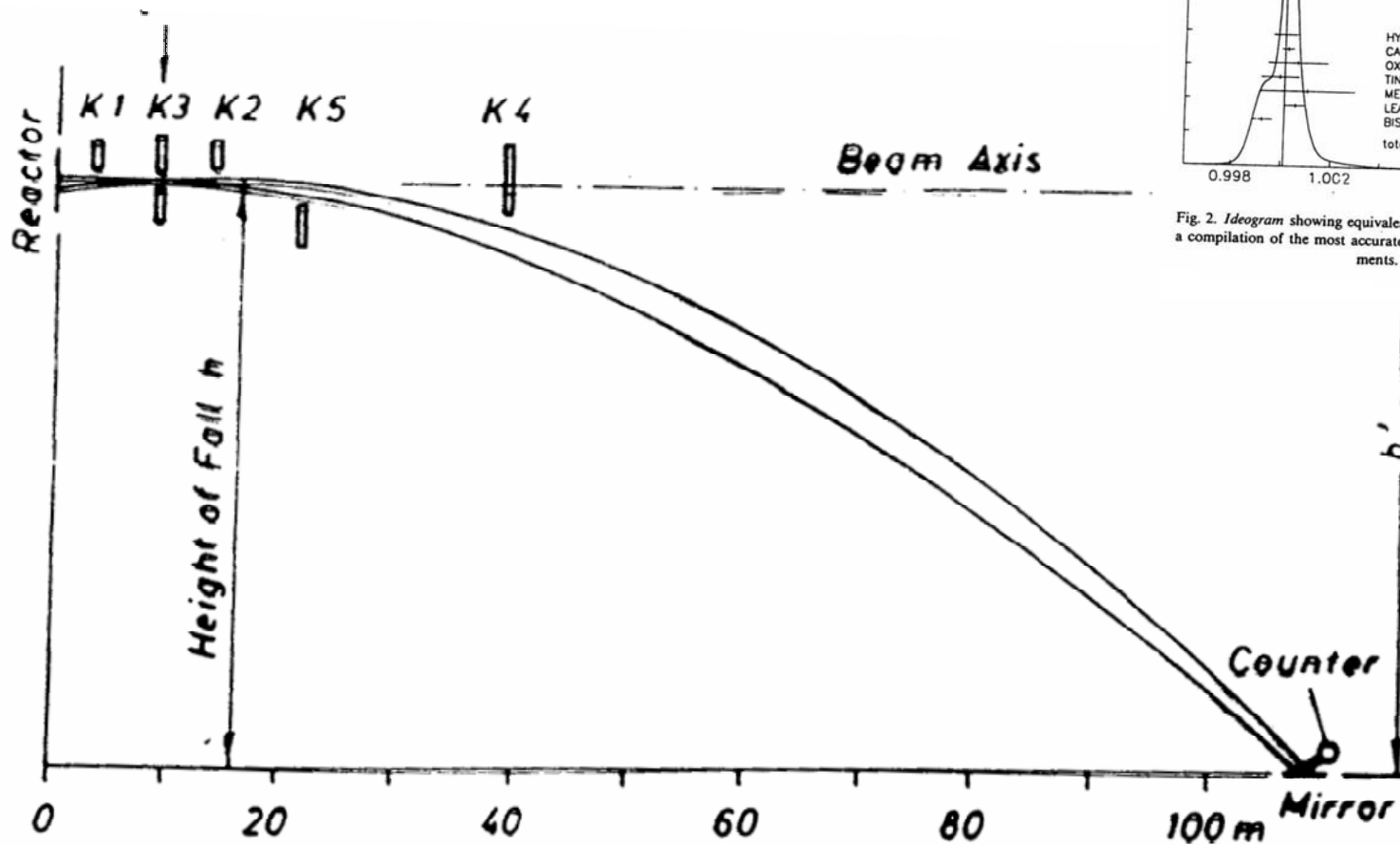$$m_g \, / \, m_i = a_n \, / g \equiv \gamma$$

Falling Neutrons

γ = 1.00011 (17)

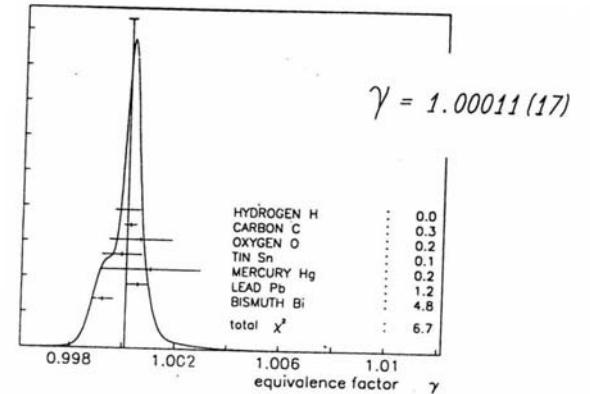|	
HYDROGEN H	0.0
CARBON C	0.3
OXYGEN O	0.2
TIN Sn	0.1
MERCURY Hg	0.2
LEAD Pb	1.2
BISMUTH Bi	4.8
total χ^2	6.7

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

Fig. 1. Principle of the neutron-gravity refractometer

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

More on this in Lecture IV

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 molecular D_2 and the scattering of neutrons from ortho and para H_2.*

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

1954   *Neutron Stern-Gerlach experiment explicitly demonstrates s=½ .*
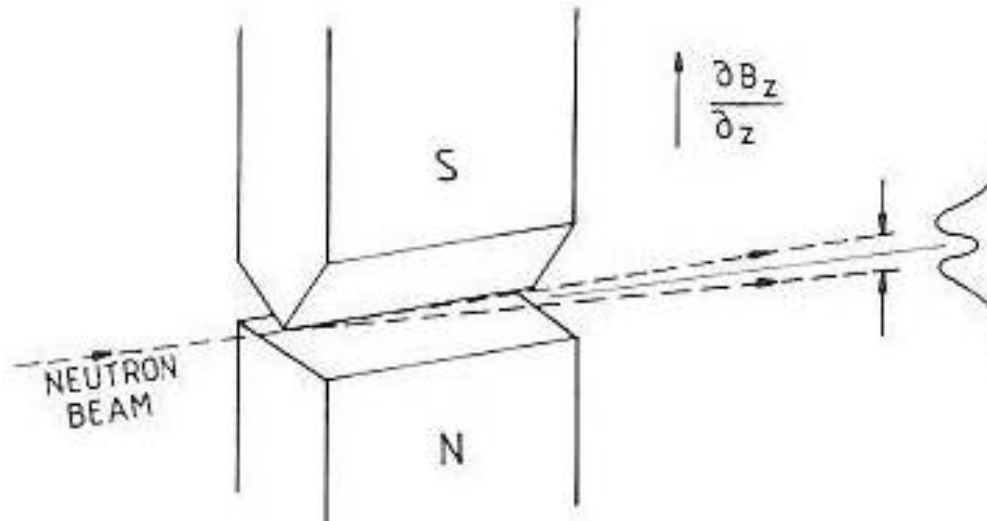
*See also Fischbach, Greene, Hughes, PRL **66**, 256 (1991) showing $\vec{L} = \hbar\vec{s}$*
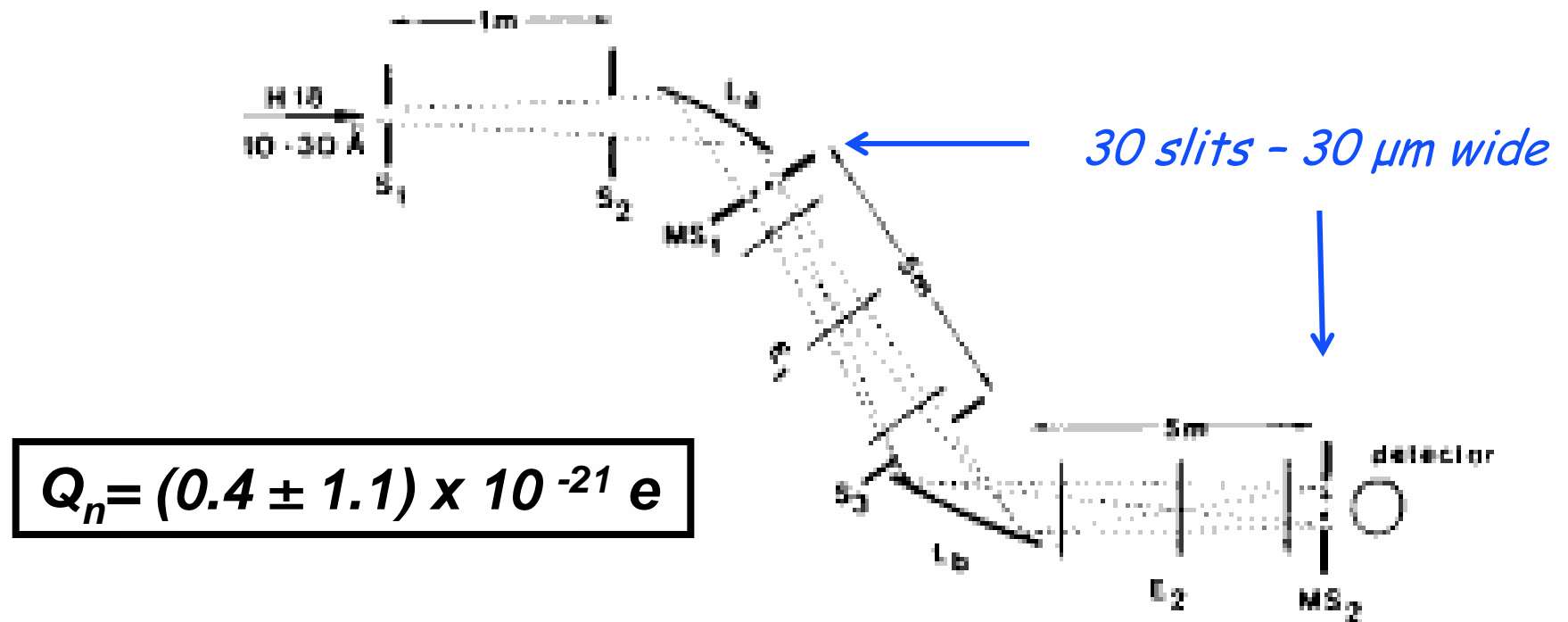
The Neutron Charge ?

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)

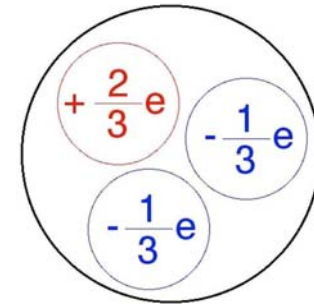**Experiment uses focusing device in strong electric field**

30 slits – 30 µm wide

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

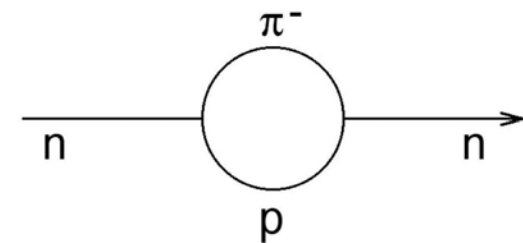Baumann et al, Phys. Rev. D **37**, 3107 (1988)

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 $G_E^n(Q^2)$ is accessible from electron scattering.
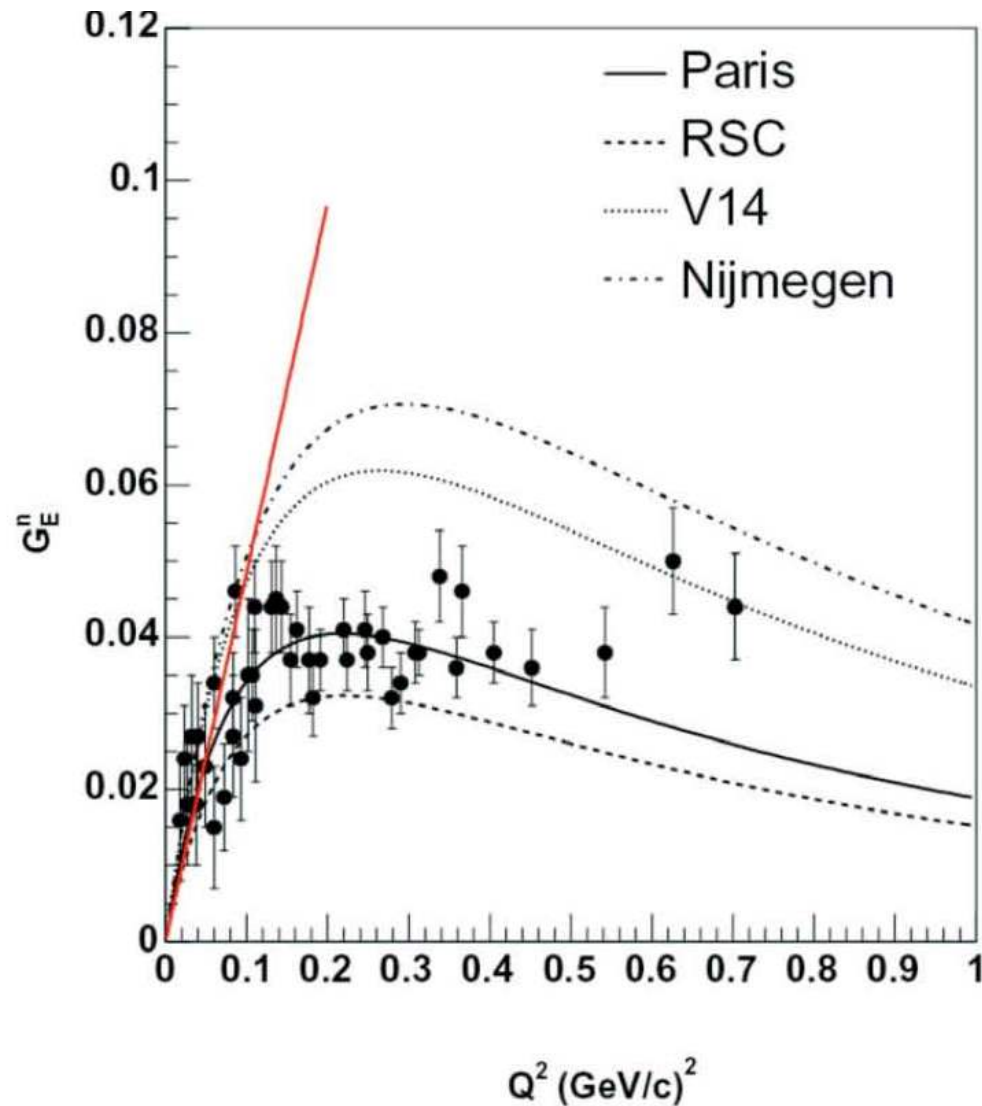
Expanding in the momentum transfer Q^2 :

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

In the limit of low Q^2 :

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

The Mean Square Neutron Charge Radius $G_E^n\left(Q^2\right)$.
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]
		$-1.44 \pm 0.033 \pm 0.06$	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	$-1.31 \pm 0.03 \pm 0.04$	1995 [1] Kopecky
		$-1.33 \pm 0.027 \pm 0.03$	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.

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

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Method of Separated Oscillatory Fields

polarizer   **analyzer**

incoming neutrons

B

π/2 rotation   free precession   π/2 rotation
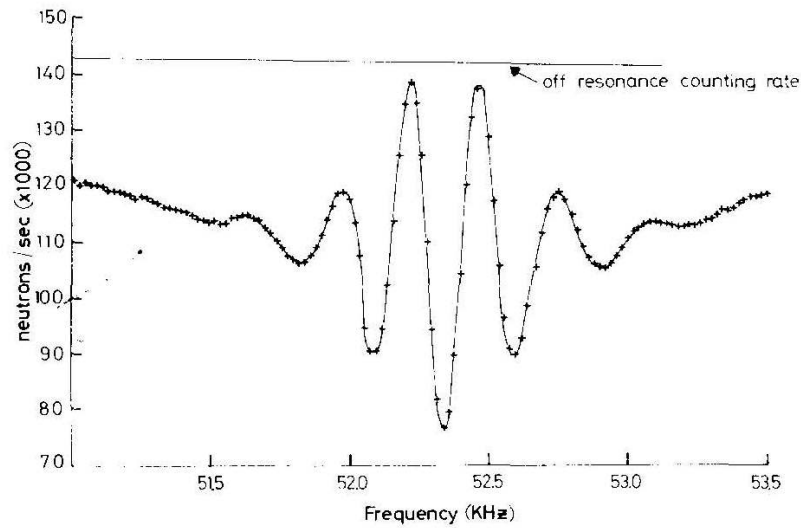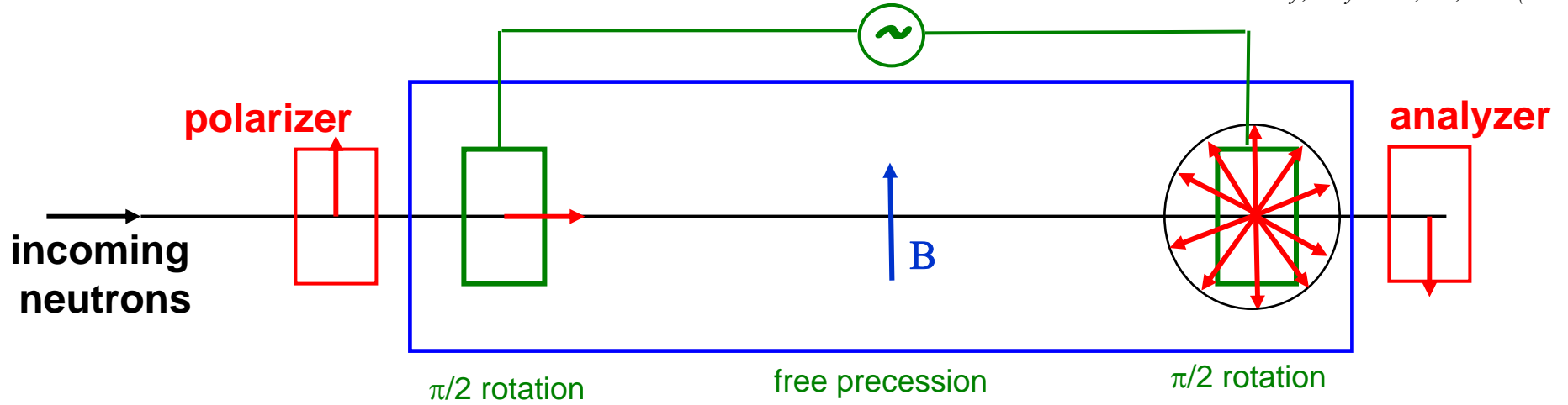
Fig. 1. Neutron resonance.

$$\frac{\mu_n}{\mu_p} = -0.68497935(17)$$
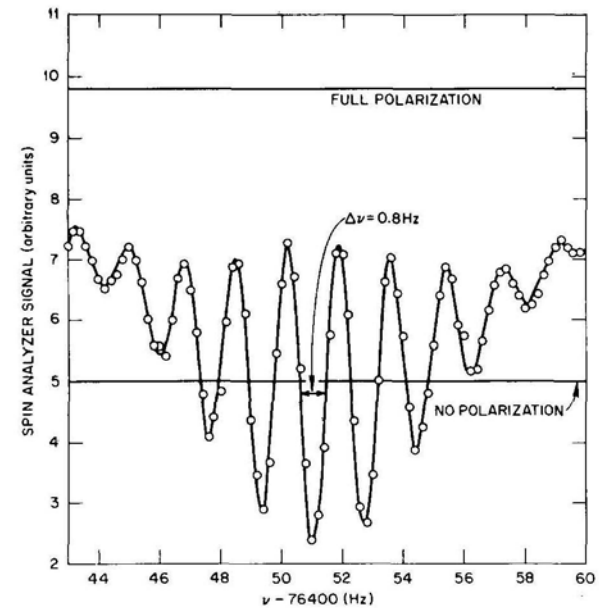
Fig. 2. Proton resonance.

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

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: $\hat{C} \cdot \Psi_n \Rightarrow \Psi_{\bar{n}}$

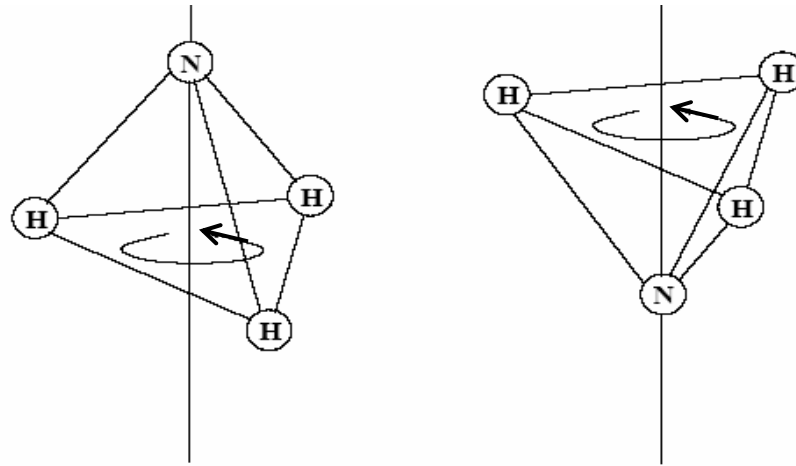Wigner-Eckhart Theorem Implies $\quad \vec{\mu} = \mu \dfrac{\vec{J}}{J} \quad$ and $\quad \vec{d} = d \dfrac{\vec{J}}{J}$

Non-Relativistic Hamiltonian

$$H = \vec{\mu} \cdot \vec{B} + \vec{d} \cdot \vec{E}$$

$\vec{\mu} \cdot \vec{B}$: C-even, P-even, T-even

$\vec{d} \cdot \vec{E}$: C-even, P-odd, T-odd

Non-zero d violates P,T, and CP

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

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.

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)
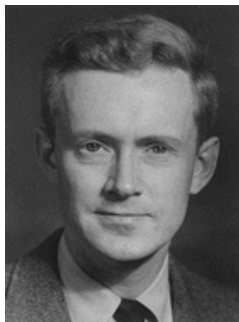
Edward Purcell   Norman Ramsey

A Short History of Symmetry Violation

1863 (94 BP)   *Pasteur notes parity "violation" in organic molecules*

1950 (7 BP)   *Purcell and Ramsey suggest that parity violation must be subject to experimental confirmation*
(Ramsey gets 50-1 odds from Feynman)

1951 (6 BP)   *First experiment specifically designed to look for a parity violation (neutron EDM at ORNL)*

1956 (1 BP)   *Lee and Yang propose parity violation in weak interactions to explain the "Tau-Theta" problem and suggest specific experiments.*

1957   *Wu, Ambler, et. al. and Garwin, et. al., Conclusively demonstrate that parity is violated in the weak interaction*

Landau suggests that CP is the "Real" symmetry

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A Short History of Symmetry Violation (con't)

1964   Christianson, et. al., demonstrate that CP is violated in K-decay

It is quickly realized that only symmetry which has really solid theoretical basis is the combined action of CPT

Parity in 2 Dimensions
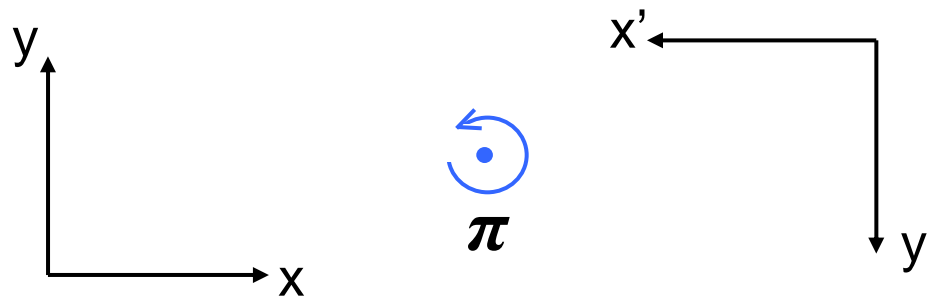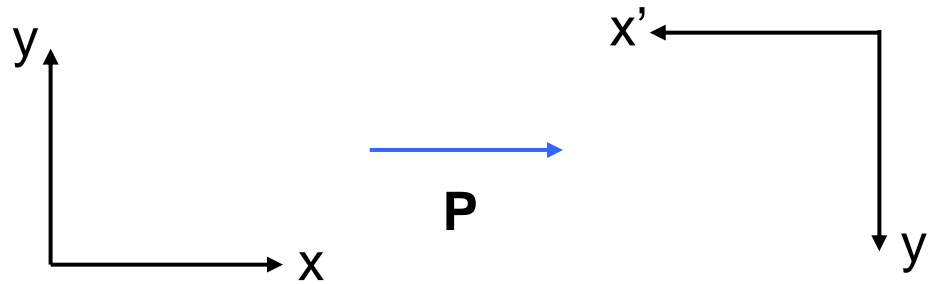
In a Euclidean space of even dimension,
Parity = Rotation

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

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

"space-time" is not Euclidean

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

- 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 Baryon Asymmetry "Problem" and the n EDM

There is an extremely strong symmetry
between Matter and Antimatter.

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

<u>*Generating a Matter-Antimatter Asymmetry*</u>

*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 & $\bar{p}$) 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
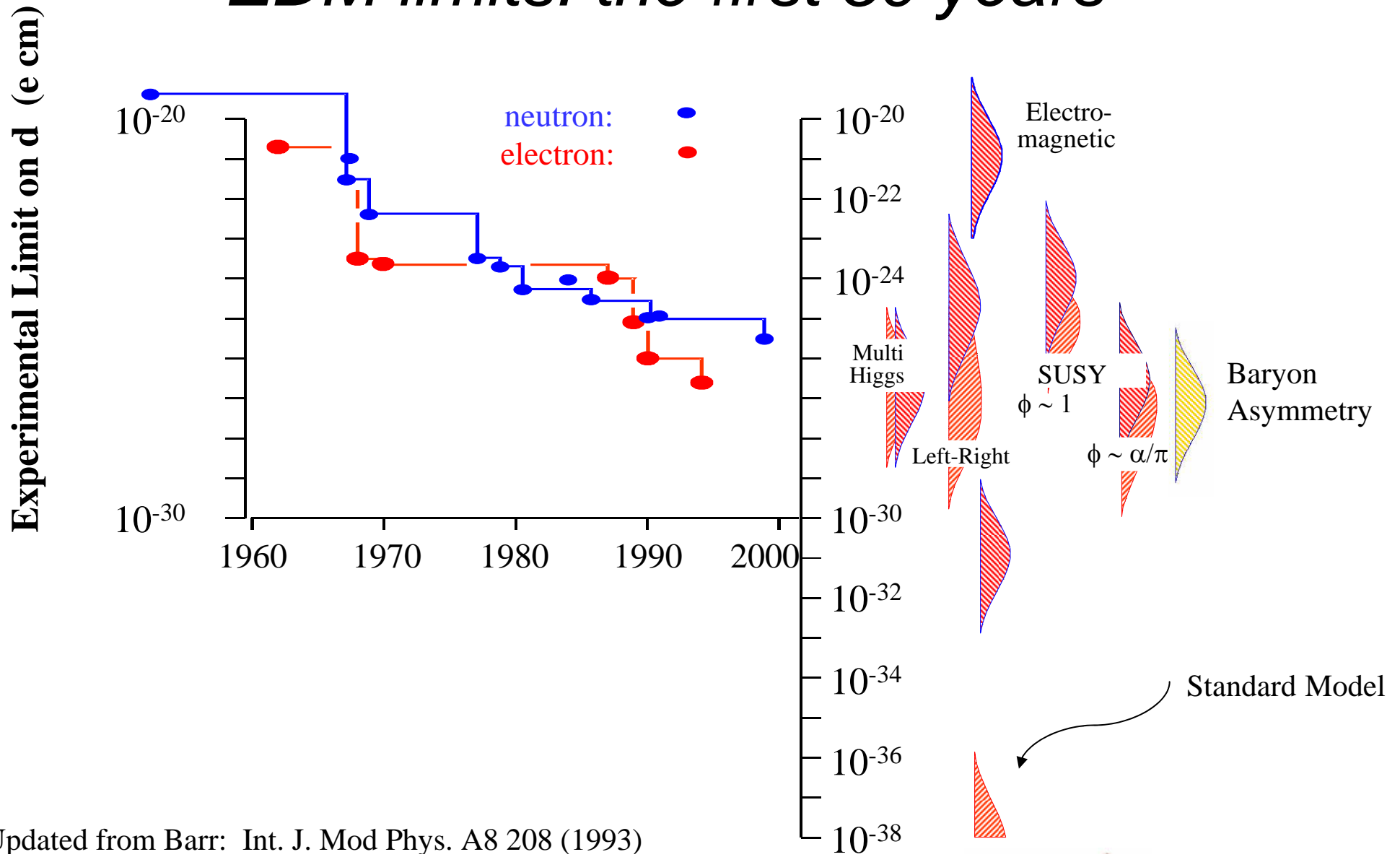   Time Reversal Non-Invariance --- "T-violation"
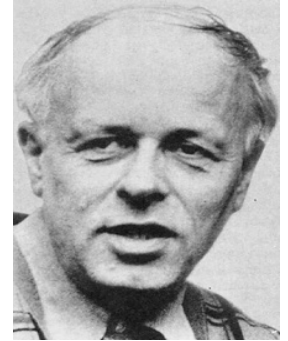
A. Sakharov

Question:

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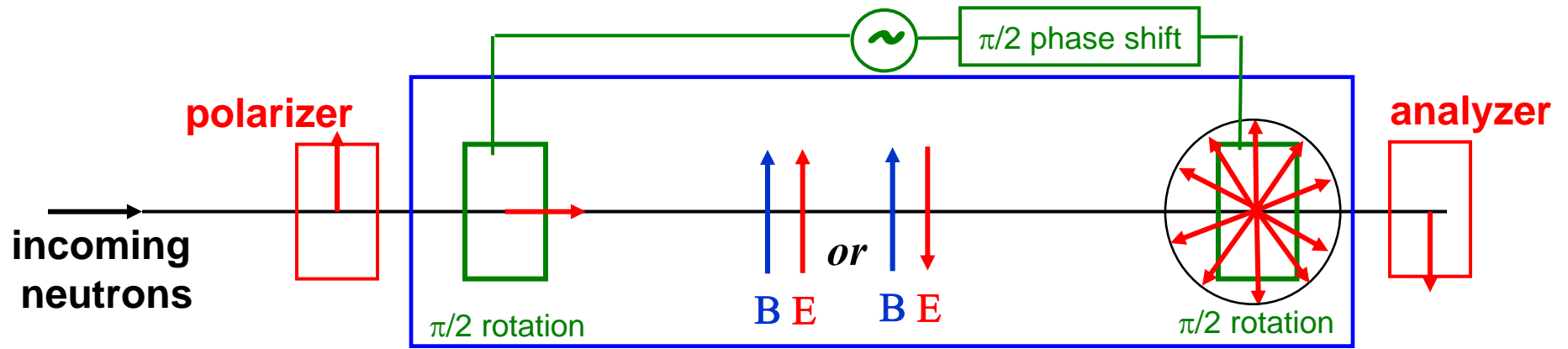*10^6 s old be related to an observable quantity today?*

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

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

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

EDM limits: the first 50 years

Experimental Limit on d (e cm)

neutron:
electron:

Electro-magnetic

Multi Higgs

Left-Right

SUSY
$\phi \sim 1$

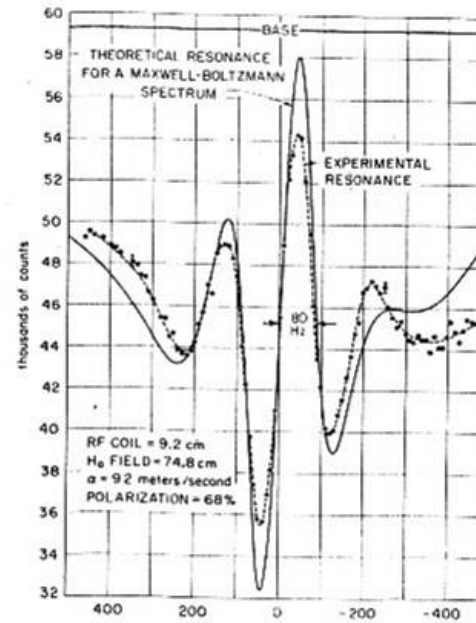$\phi \sim \alpha/\pi$
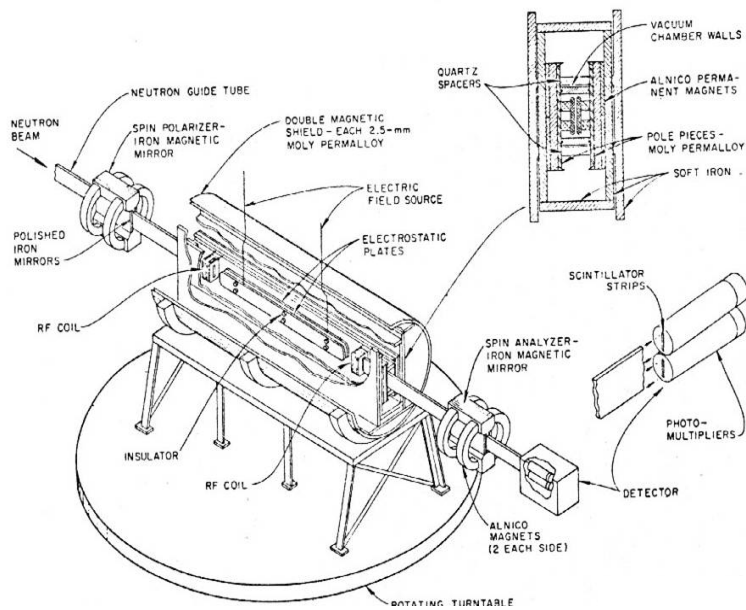
Baryon Asymmetry

Standard Model

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

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

More on this in Lecture IV