

The Fundamental Properties of the Neutron

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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.

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

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

Suggested References

Dubbers, *The Neutron and its Role in Cosmology and Particle physics*

Reviews of Modern Physics, 83, 1111 (2011)

Wietfeldt, Greene, *The Neutron Lifetime*

Reviews of Modern Physics, 83, 1173 (2011)

Byrne, *Neutrons, Nuclei and Matter* (chapters 1&2)

Golub, Lamoreaux, Richardson, *Ultracold Neutrons*

Commins and Bucksbaum, *Weak Interactions of Quarks and Leptons*

Particle Data Group, pdg.lbl.gov



Fermi, *Lecture Notes on Nuclear Physics*

Acknowledgements for images

Mike Snow, Fred Wietfeldt, Brad Phillipone, Jeff Nico, Paul Huffman, Scott Dewey, Nadia Fomin, ...

Some Neutron Properties

Mechanical Properties

Mass

Gravitational Mass (equivalence principle test)

Hartmut Abele

Spin

Electromagnetic Properties

Charge (or limit on neutrality)

Internal Charge Distribution

Fred Wietfeldt

Magnetic Dipole Moment

Electric Dipole Moment

Takeyasu Ito, Florian Piegsa

Neutron Decay

Neutron Mean Lifetime

Scott Dewey, Chen-Yu Liu

Correlations in Neutron Decay

Gertrude Konrad

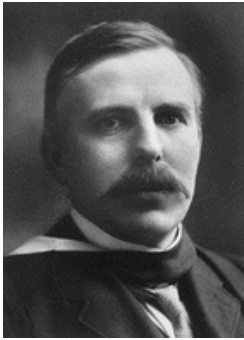
“Exotic” Decay modes

Mike Snow

Miscellaneous Quantum Numbers:

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

Short History Lesson



Ernest Rutherford

1920 Noting that atomic number (Z) does not correspond to atomic weight (A), Rutherford suggests that, in addition to “bare” protons, the nucleus contains a heavy neutral particle.

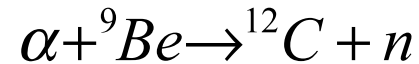
“Under some circumstances..... it may be possible for an electron to combine much more closely with the H nucleus, forming a kind of neutral doublet. Such an atom would have very novel properties. Its external field would be practically zero, and in consequence it should be able to move freely through matter...”

Bakerian Lecture, 1920



Walter Bothe

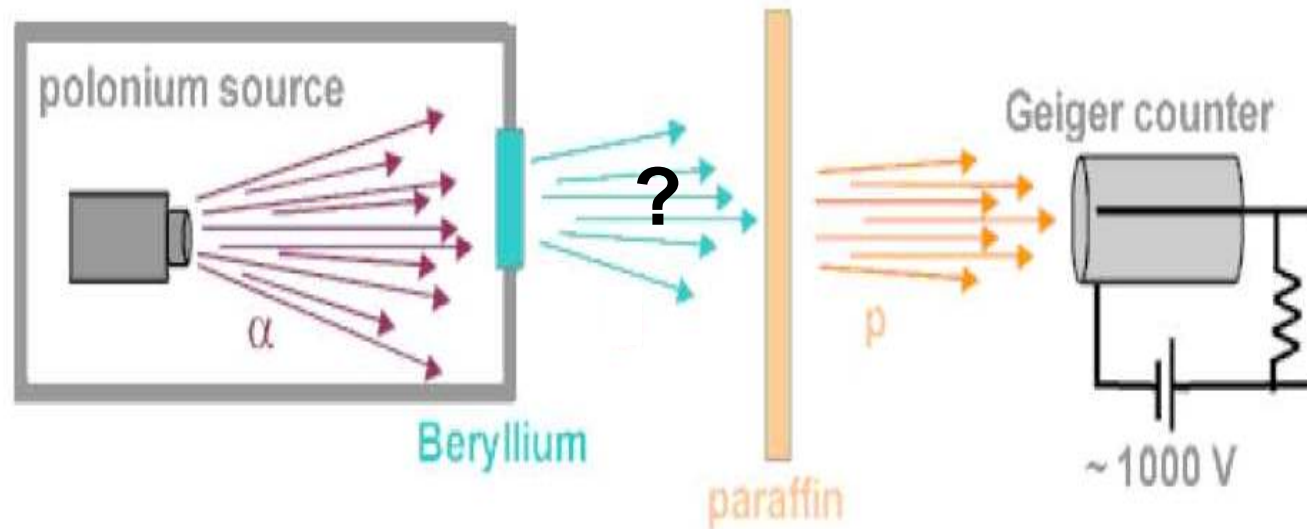
1930 Bothe and Becker discover a penetrating, neutral radiation when alpha particles hit a Be target.



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



Irene Curie



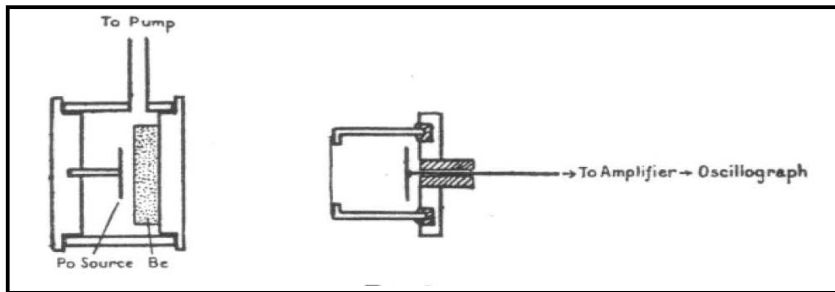


James Chadwick

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

$$M_n = 1.15 \pm 10\%$$



Chadwick claimed this was Rutherford's "Neutron"

"It is, of course, possible to suppose that the neutron may be an elementary particle... This view has little to recommend it at present."

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

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

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

Using 2.62MeV gammas from Thorium and determining the recoil energy of the protons they were able to determine*:

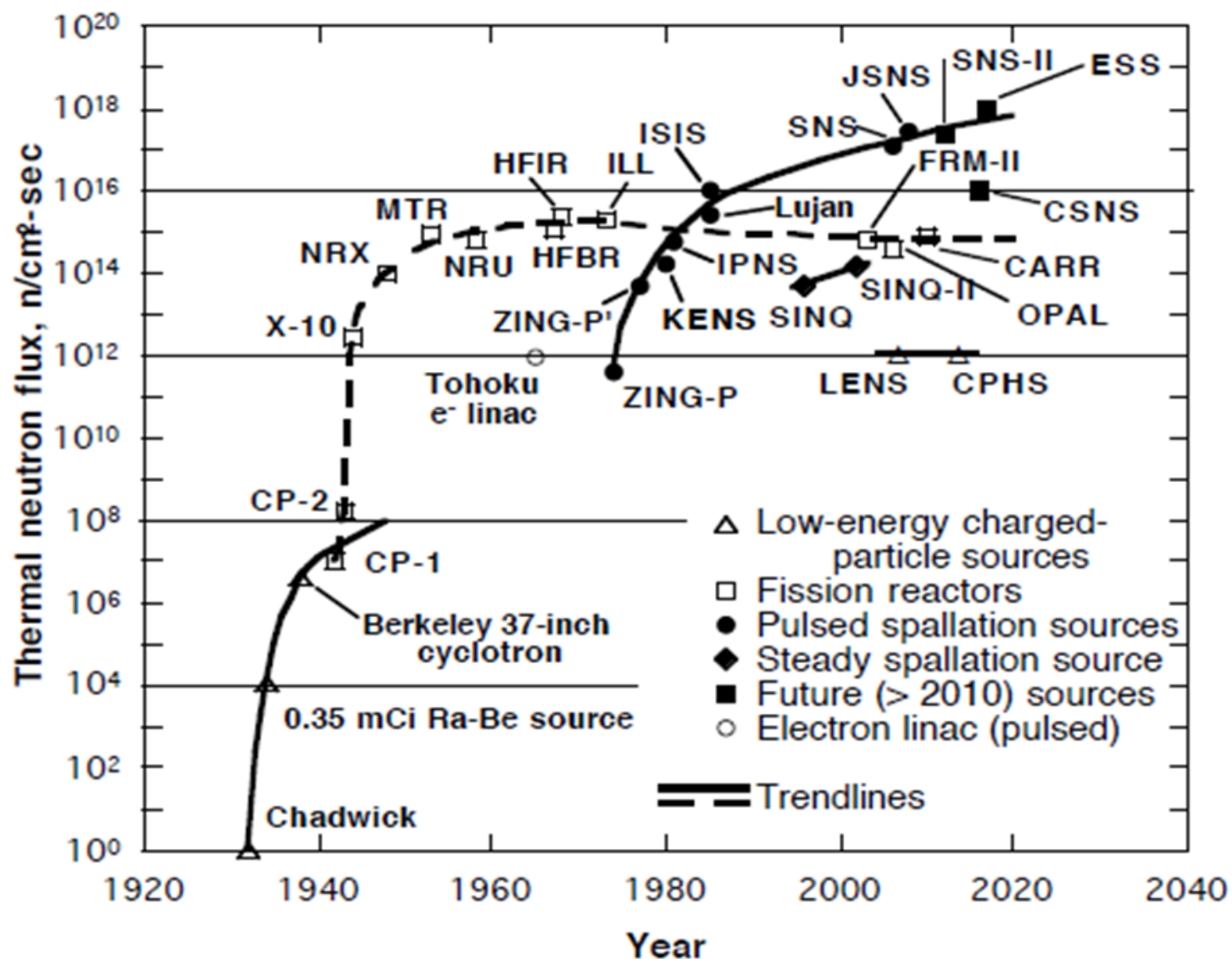
$$M_n = 1.0080 \pm 0.0005$$

$$M_n > M_p + M_e$$

*“If the neutron is definitely heavier than the hydrogen atom, then one must conclude that **a free neutron is unstable**, i.e., it can change spontaneously into a proton+electron+neutrino”*

Chadwick and Goldhaber, Nature, 134 237 (1934)

Peak Neutron Source Intensities Have Increased by Nearly 18 Orders of Magnitude Since Chadwick



Old and New Neutron Sources at Oak Ridge



Graphite Reactor



Spallation Neutron Source

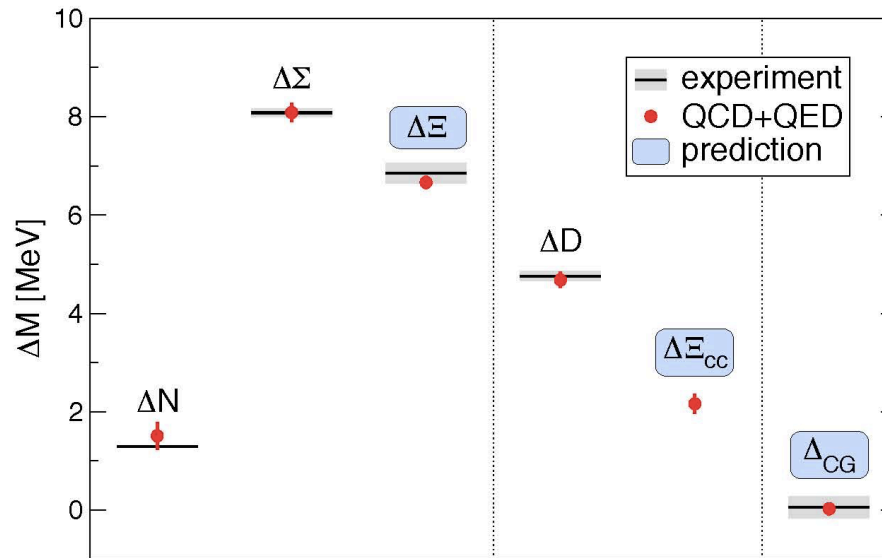
The Neutron Mass

Neutron Mass and QCD

“Ab initio calculation of the neutron-proton mass difference,”

Sz. Borsanyi, Science 27 March 2015: Vol. 347 no. 6229 pp. 1452-1455

NEW!



$$M_n - M_p = 1.51 (28) \text{ MeV}$$

$$(M_n - M_p)_{\text{exp}} = 1.293332 \text{ MeV}$$

$$\Delta M_{QCD} = 2.52 \text{ MeV}$$

$$\Delta M_{QED} = -1.00 \text{ MeV}$$

Determination of the Neutron Mass

The most accurate method for the determination of the neutron mass considers the reaction:



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

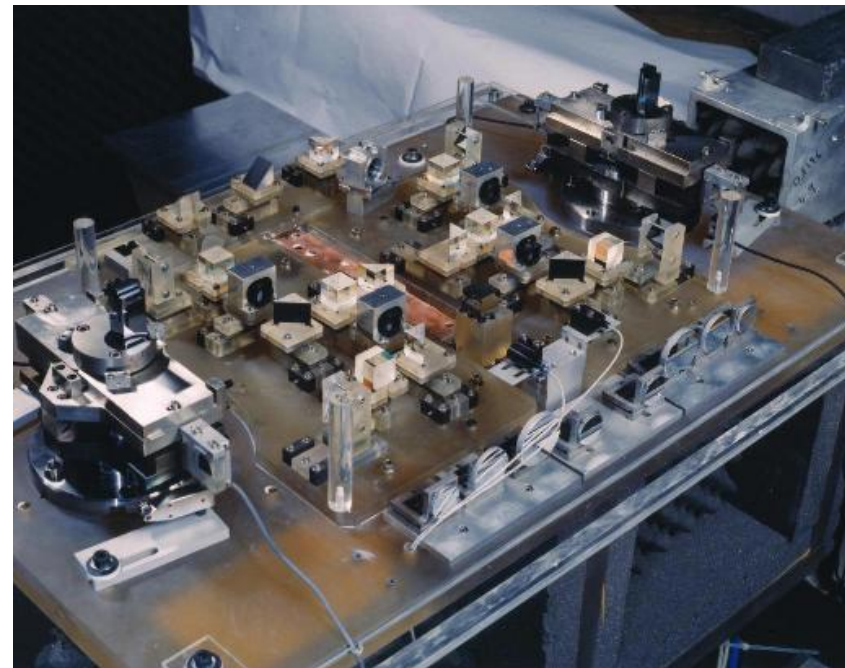
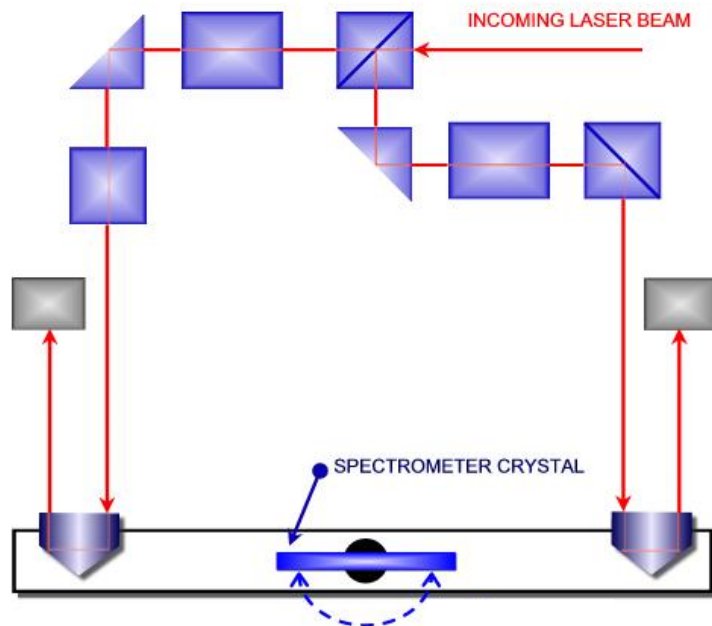
The actual experiment is the determination of the D – H mass difference in atomic mass units.

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 .

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

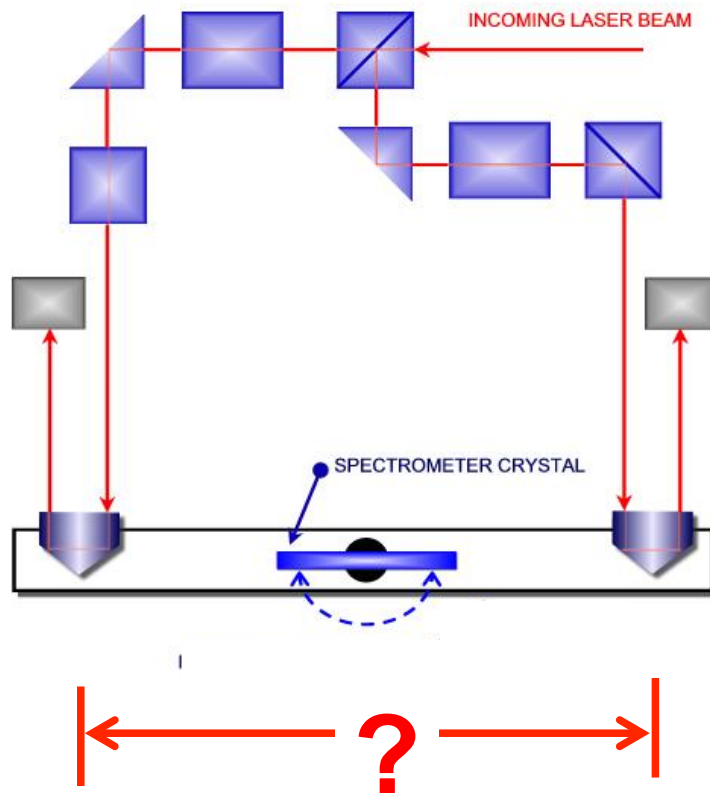
*Bragg Angle is a few milli-radian
Need nano-radian precision!*



GAMS4 at ILL

Precision vs. Accuracy

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



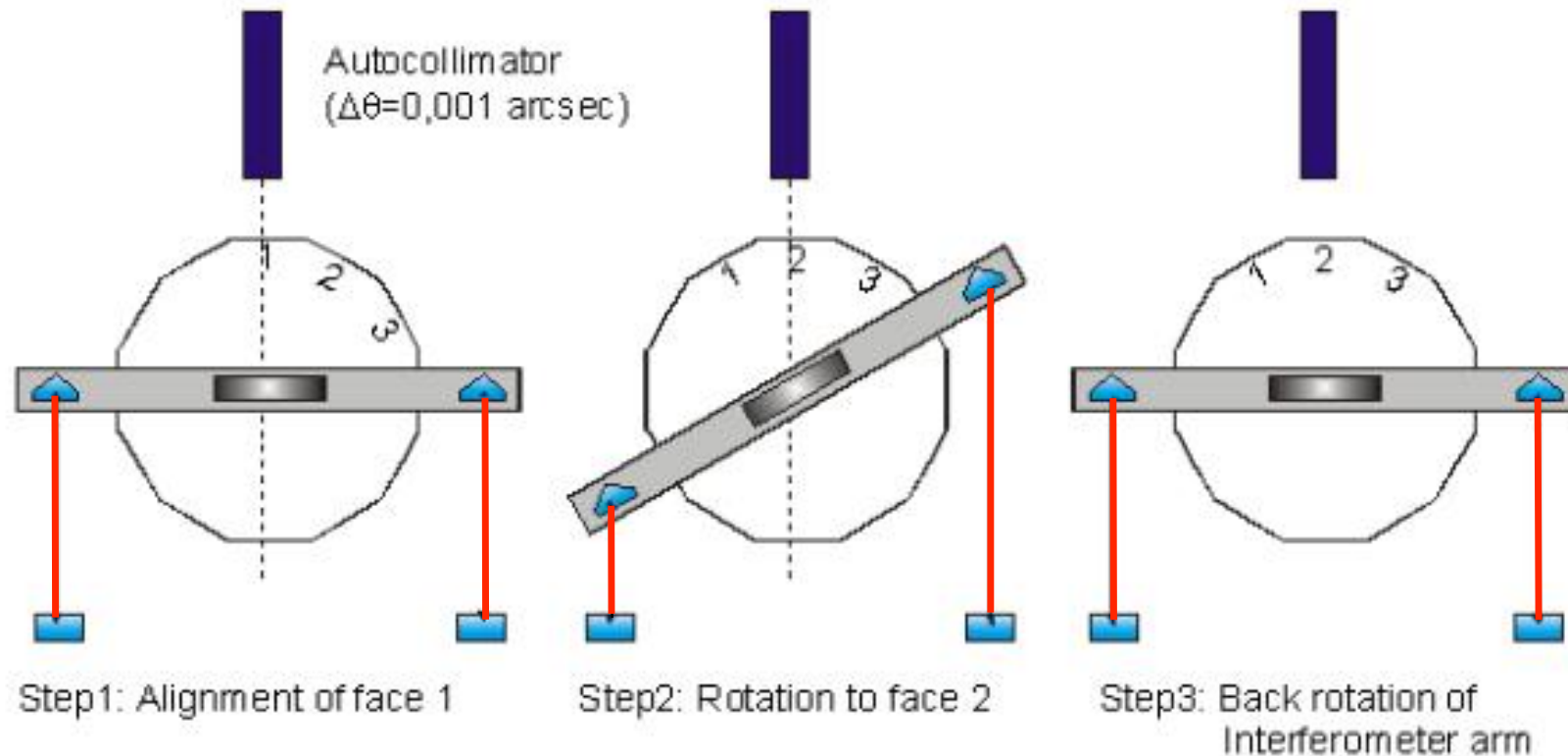
$$\tan \theta = \frac{\text{change in optical path length}}{\text{length of interferometer arm}}$$

$$1 \lambda \approx 10^{-6} \text{ radian}$$

$$1 \text{ "millifringe"} \approx 10^{-9} \text{ radian}$$

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

Calibration of 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.*

Determination of the Neutron Mass

$$\gamma_{np} = 5.573\,409\,78(99) \times 10^{-13} \text{ meters}$$

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

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

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

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

which gives

$$***M(n) = 1.008\,664\,916\,37(99) \text{ atomic mass units (u)}***$$

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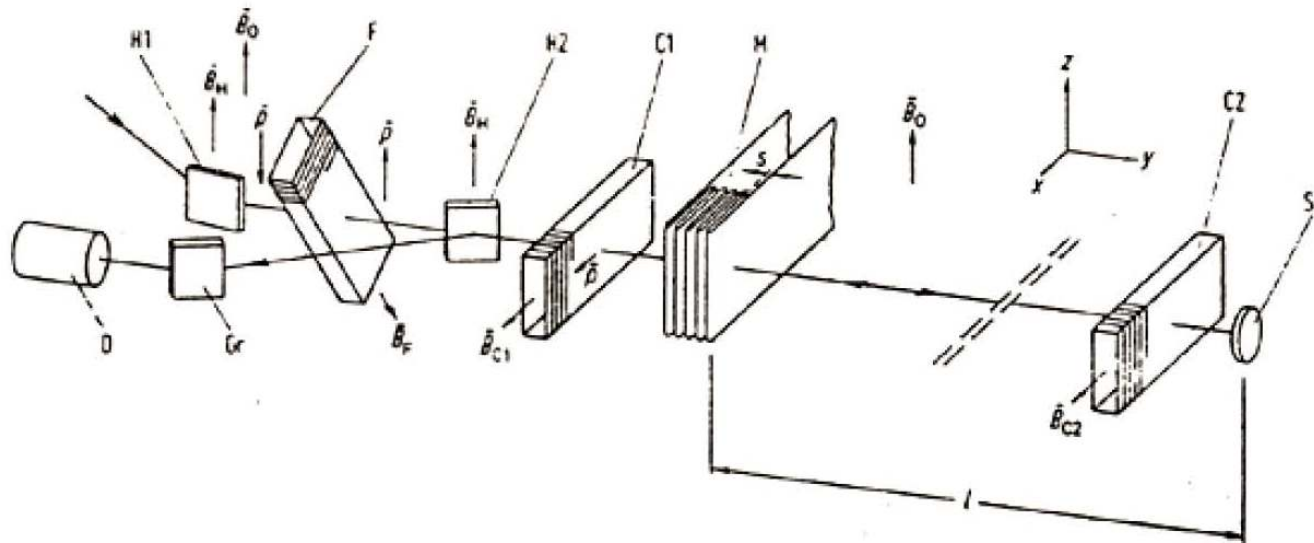
$$***M(n) = 1.008\,664\,916\,37(99) \text{ atomic mass units (u)}***$$

***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 .



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

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

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

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

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

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

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

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

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

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

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

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

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:

$$F = m_i a$$

$$F = m_g g$$

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

Falling Neutrons

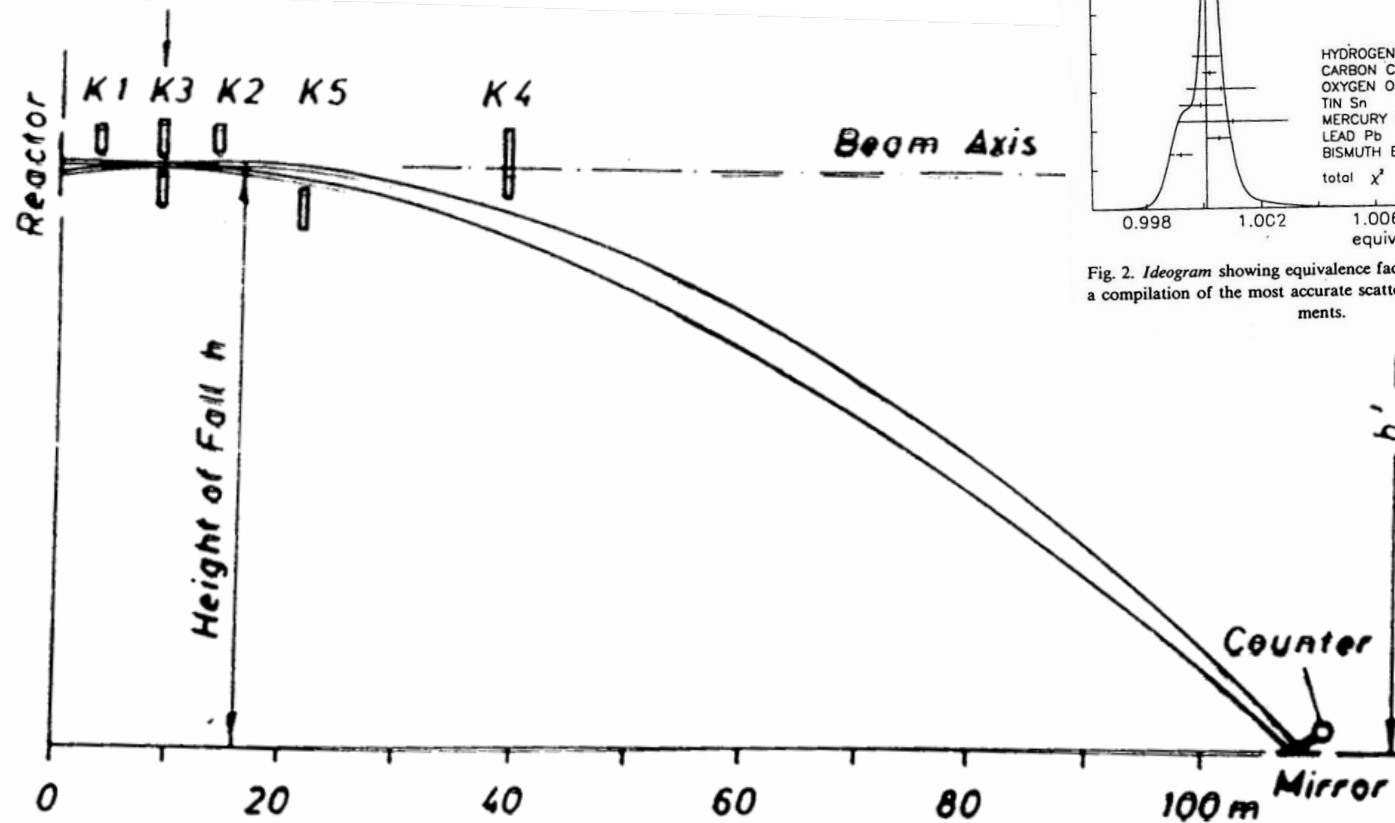


Fig. 1. Principle of the neutron-gravity refractometer

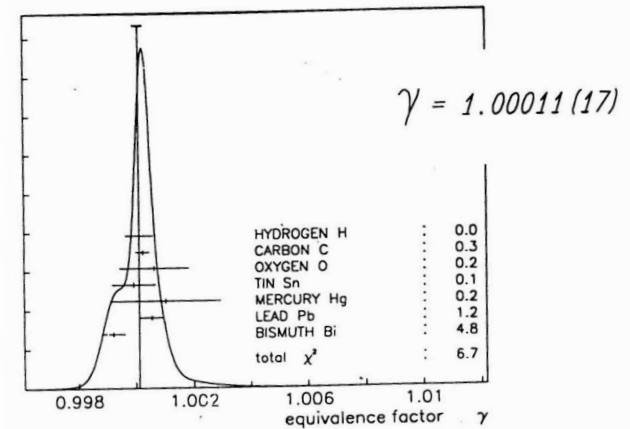
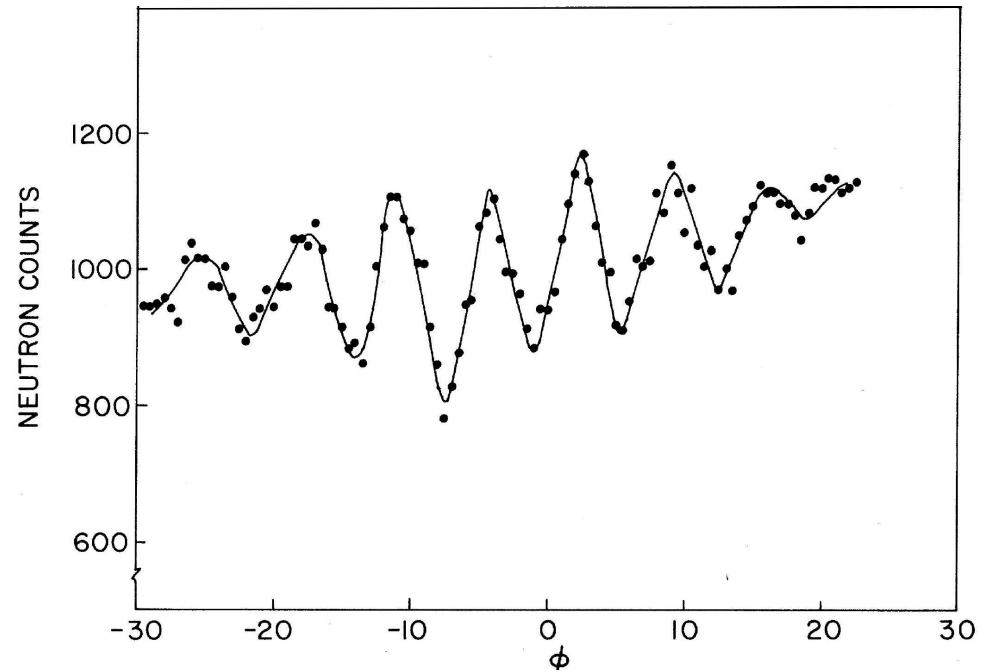
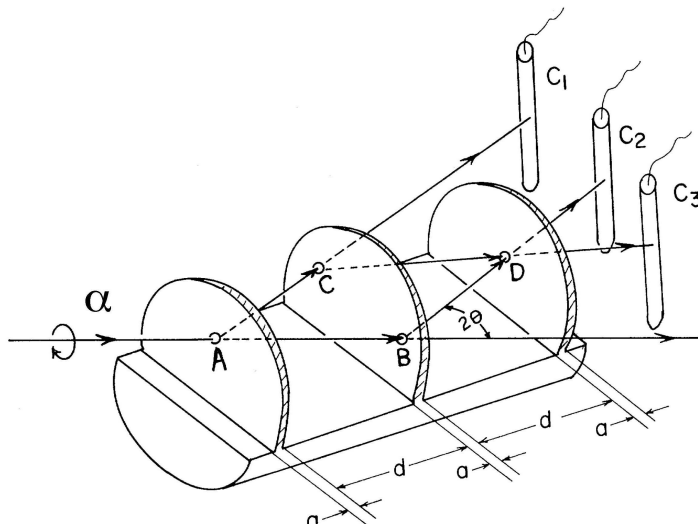


Fig. 2. Ideogram showing equivalence factors γ obtained from a compilation of the most accurate scattering length measurements.

J. W. T. Dabbs, et. al., Phys. Rev. 139, B756 (1965)
 For review see: Schmiedmayer, NIM A284, 59 (1989)

The Collela-Overhauser-Werner Experiment COW



Test of the Weak Equivalence Principle in the Quantum Limit

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

...

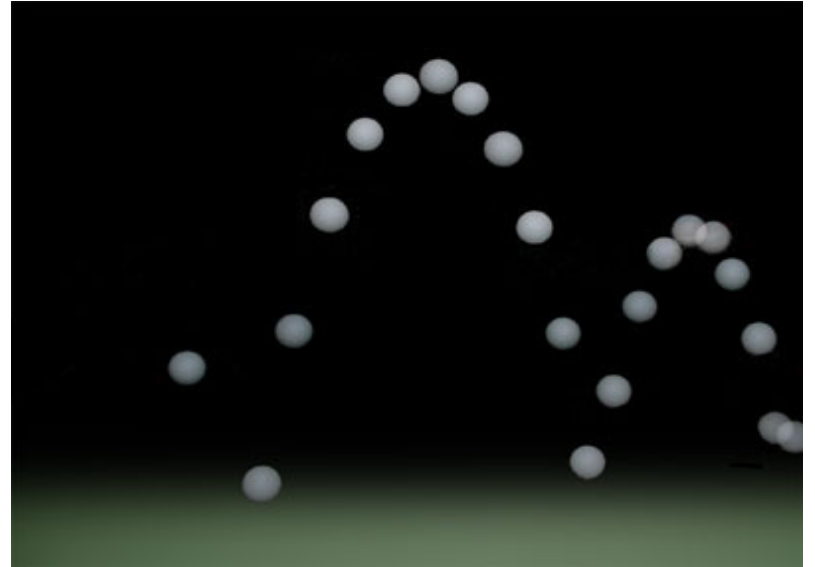
...

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

Quantum Bouncing Ball

$$V(x) = \begin{cases} 0 & \text{for } x < 0 \\ mgh & \text{for } x \geq 0 \end{cases}$$

$$-\frac{\hbar^2}{2m} \frac{\partial^2 \psi}{\partial x^2} + mgx\psi = E\psi$$



This differential equation is not soluble in terms of elementary functions.

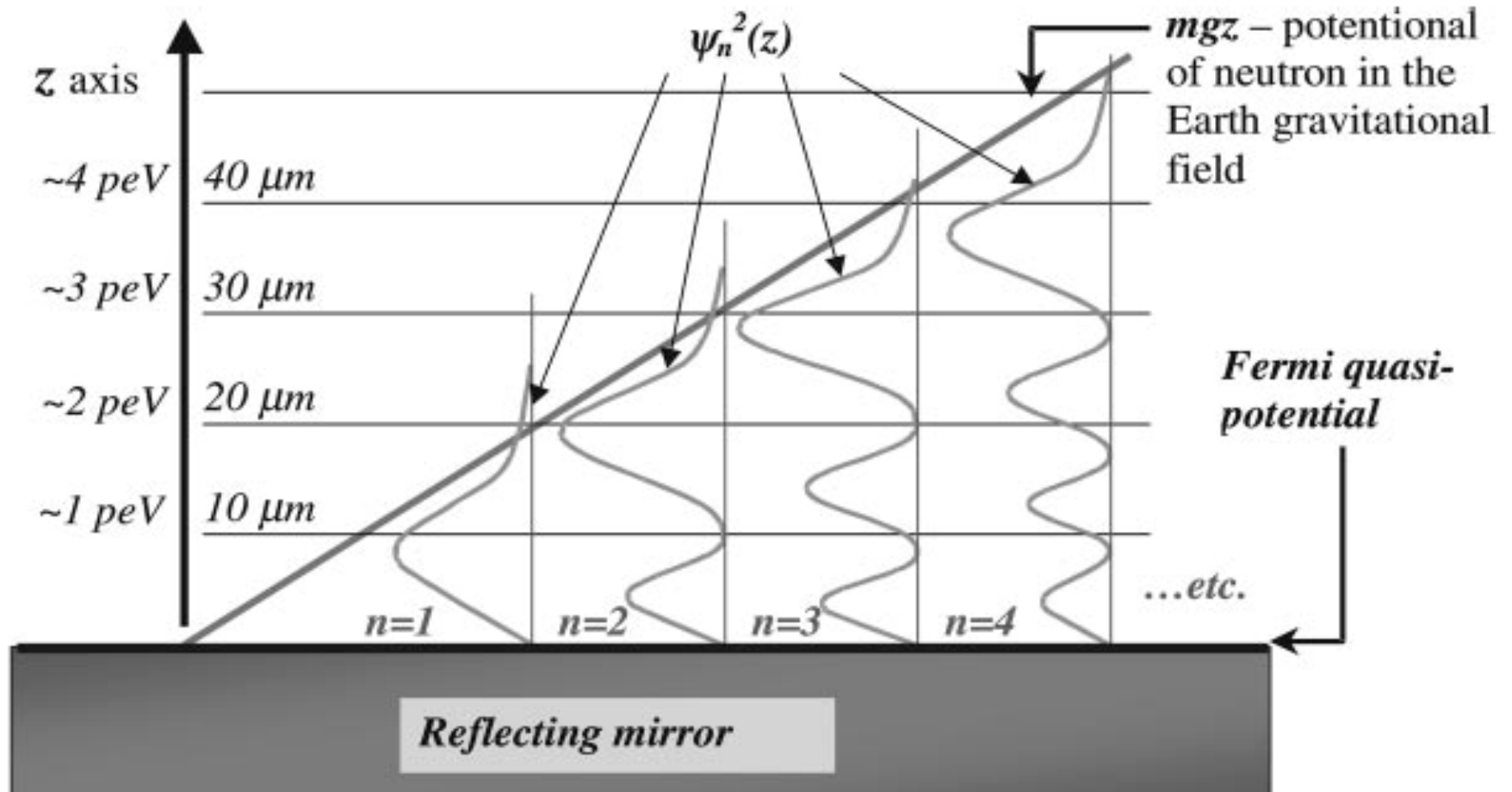
However the Airy's equation:

$$\frac{d^2 y}{dx^2} - yx = 0$$

has been extensively studied.

See Problem 8.5, Griffiths *Introduction to Quantum Mechanics*

The Quantum “Bouncing Neutron”



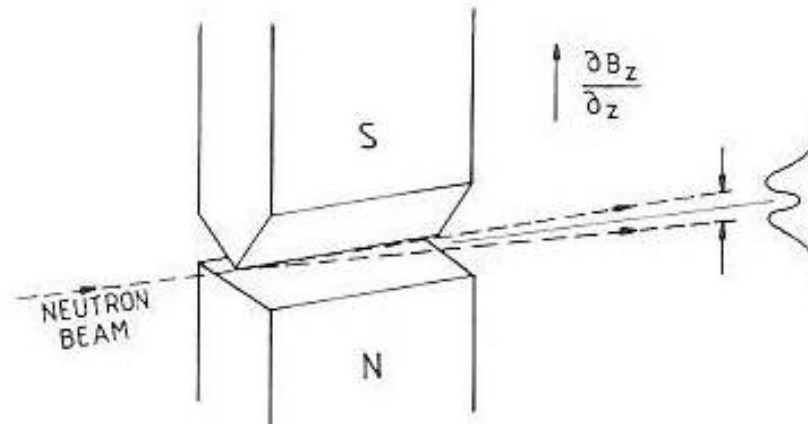
$$E_1 = 1.44 \times 10^{-12} \text{ eV}$$

*Nezvizhevsky, et al, Nucl Instrum and Meth, A440, 754 (2000)
 Nezvizhevsky, et al, Nature 415, 297 (2002)

The Neutron Spin

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

- 1934 *Molecular spectroscopy indicates that deuteron has spin 1, implying that the neutron has spin $\frac{1}{2}$ or $\frac{3}{2}$*
- 1937 *Schwinger concludes that $s=\frac{1}{2}$ 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 $s=\frac{1}{2}$.*



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

What EM properties can a Neutron Have?

Charge (or limit on neutrality)

Internal Charge Distribution

Magnetic Dipole Moment

Electric Dipole Moment

~~Magnetic Quadrupole Moment~~

...

***Spin $\frac{1}{2}$ particles can have
no moments higher than dipole***

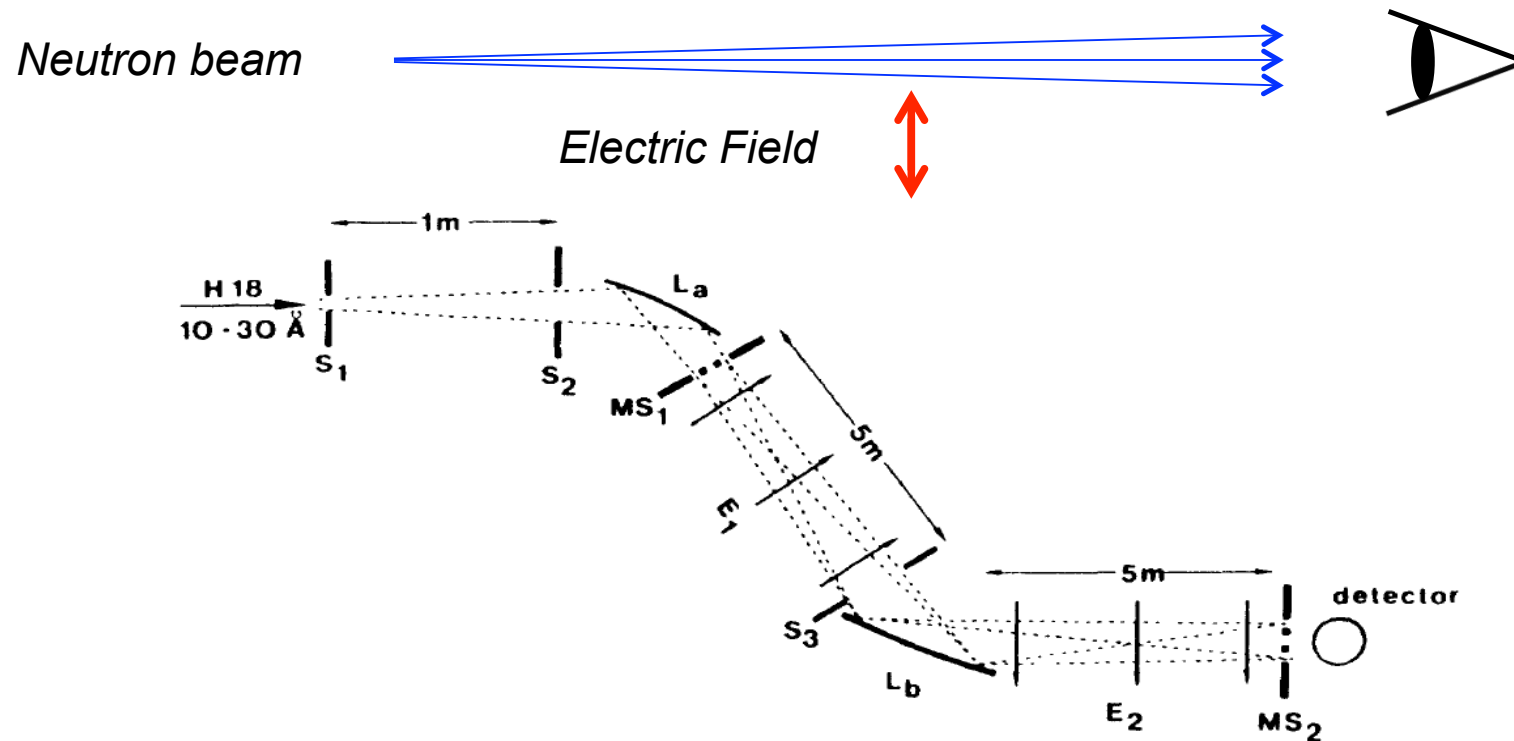
The Neutron Charge ?

The Neutron Charge ?

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)

The Neutron Appears to be Neutral



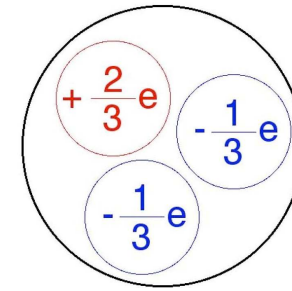
$$Q_n = (-0.4 \pm 1.1) \times 10^{-21} e$$

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

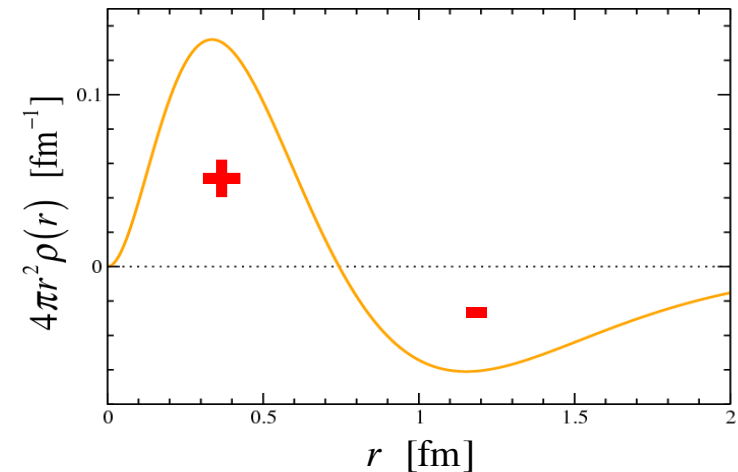
The Neutron Charge Distribution

Neutrality Does Not Imply Uniformity

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



The neutron actually has a positive core with a negative “halo”



Neutron Mean Charge Radius:

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

Neutron Electric Scattering Form Factor

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

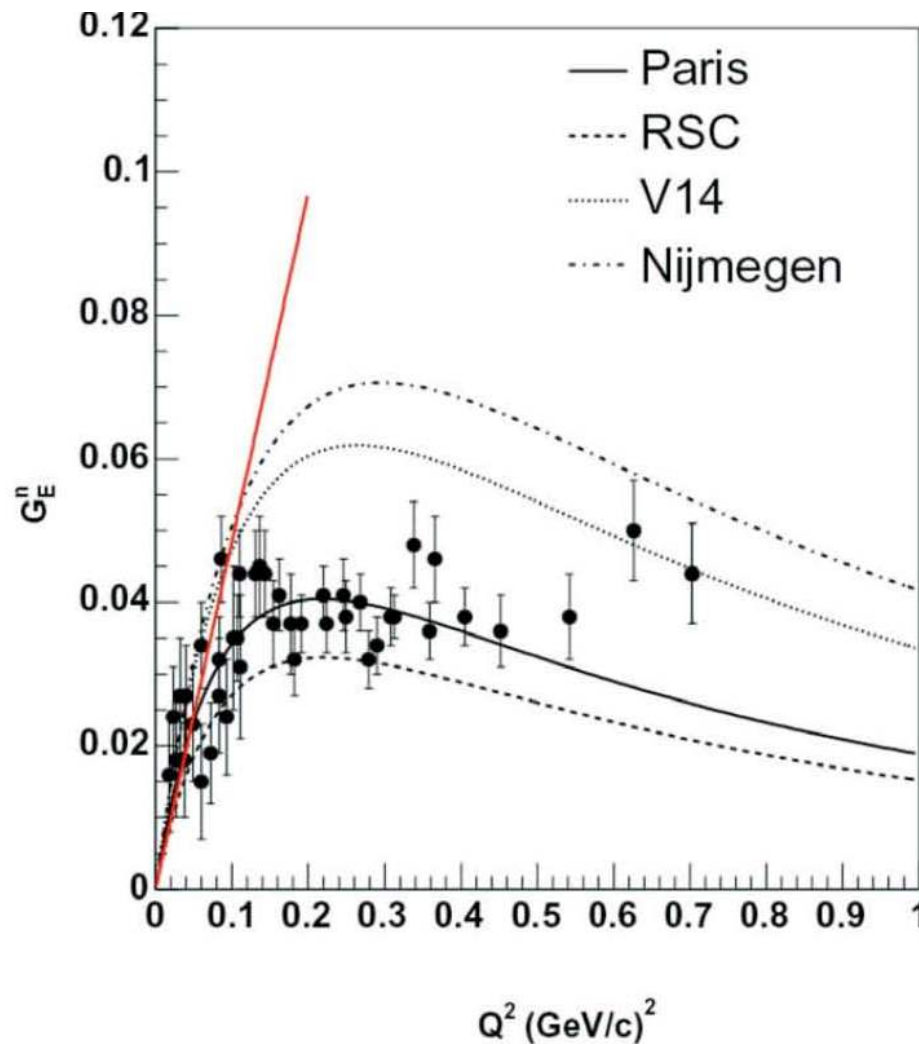
Expanding in the momentum transfer Q^2 :

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

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 $G_E^n(Q^2)$
Constrains the Slope In Electron Scattering Experiments.
(e.g. Bates, JLab, ...)*



V. Ziskin, Ph.D. thesis, 2005

Experimental Situation is in Disarray

2230

S. KOPECKY *et al.*

56

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.

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.

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

2.

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

3.

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

Measuring the Neutron Magnetic Moment

Method of Separated Oscillatory Fields

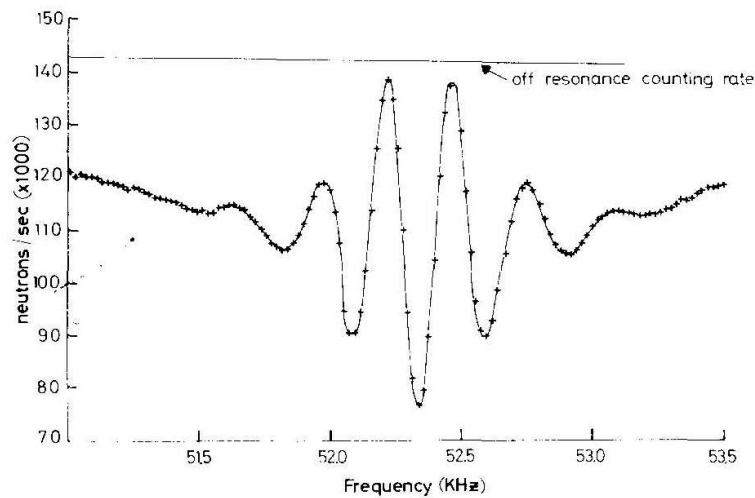
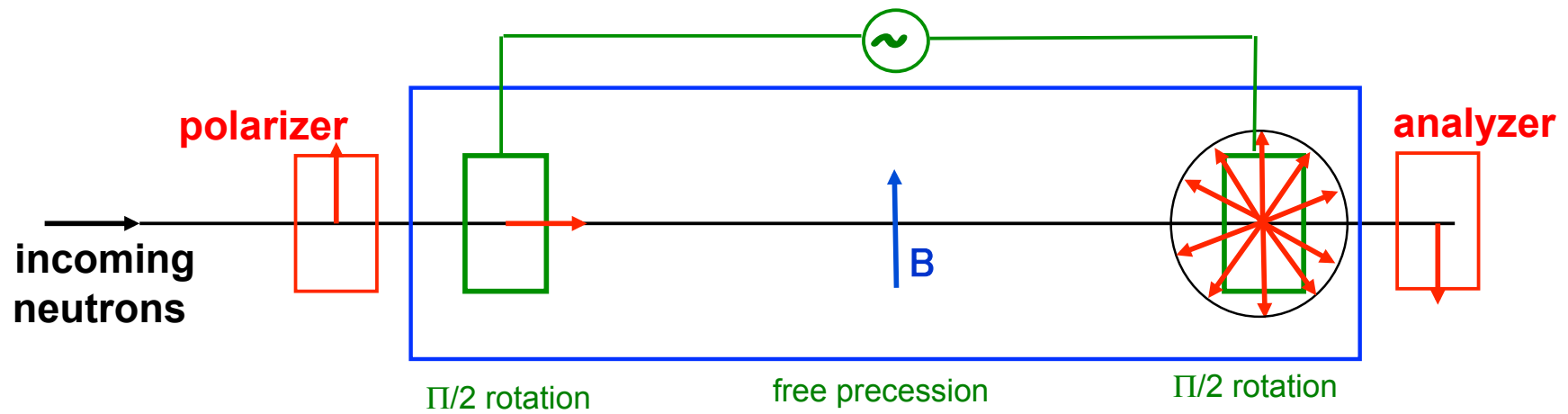


Fig. 1. Neutron resonance.

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

How to determine \bar{H} ?

Calibration of Magnetic Field Using Flowing Water

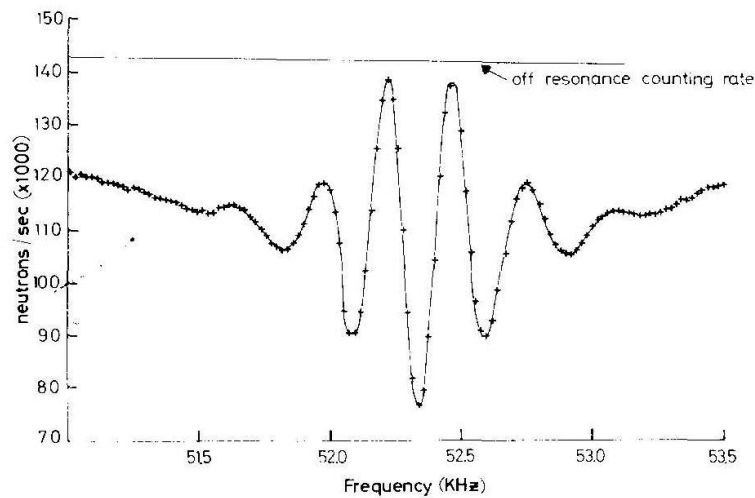
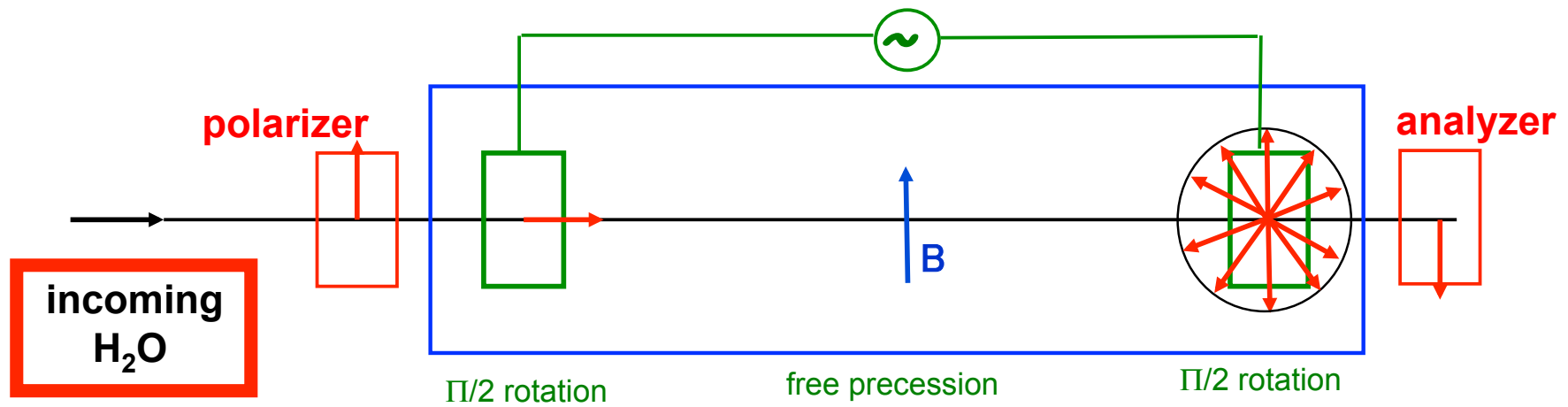


Fig. 1. Neutron resonance.

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

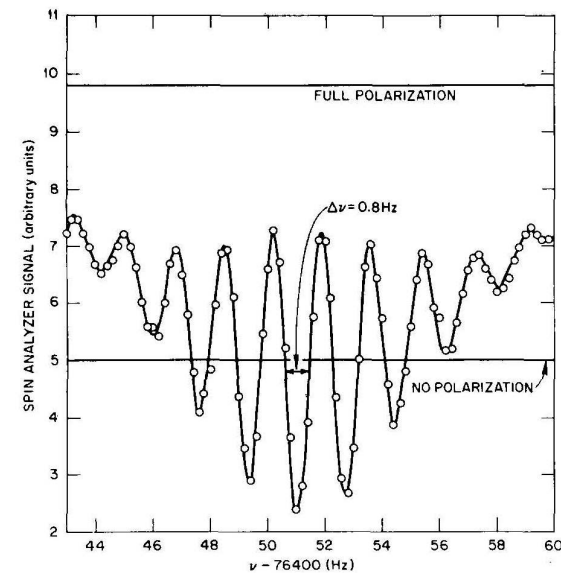
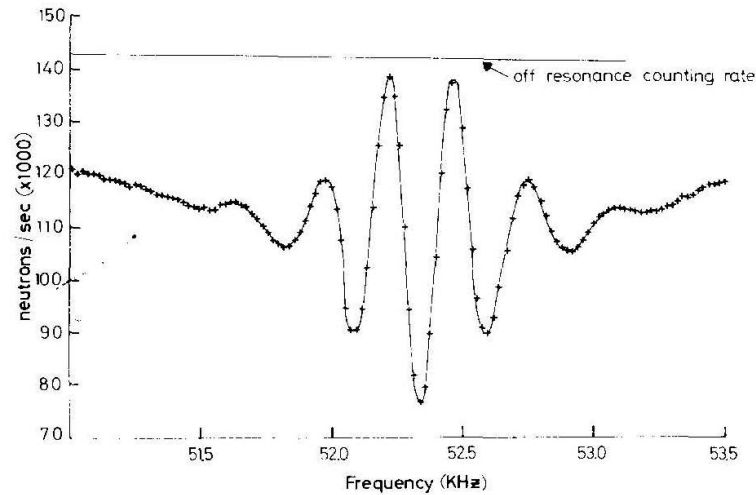


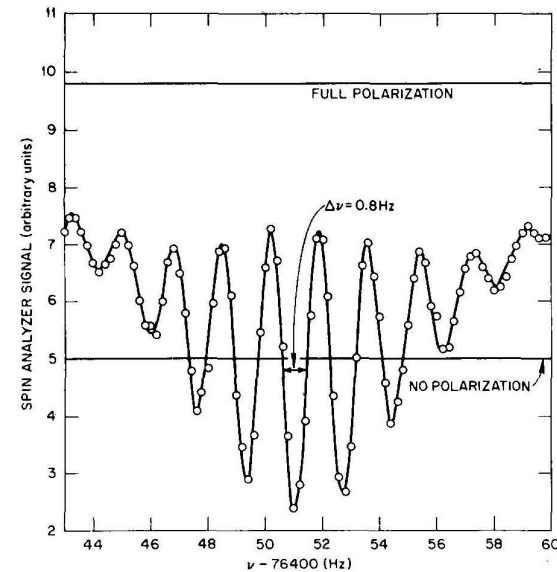
Fig. 2. Proton resonance.

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

Sensitivity of the Ramsey Method



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



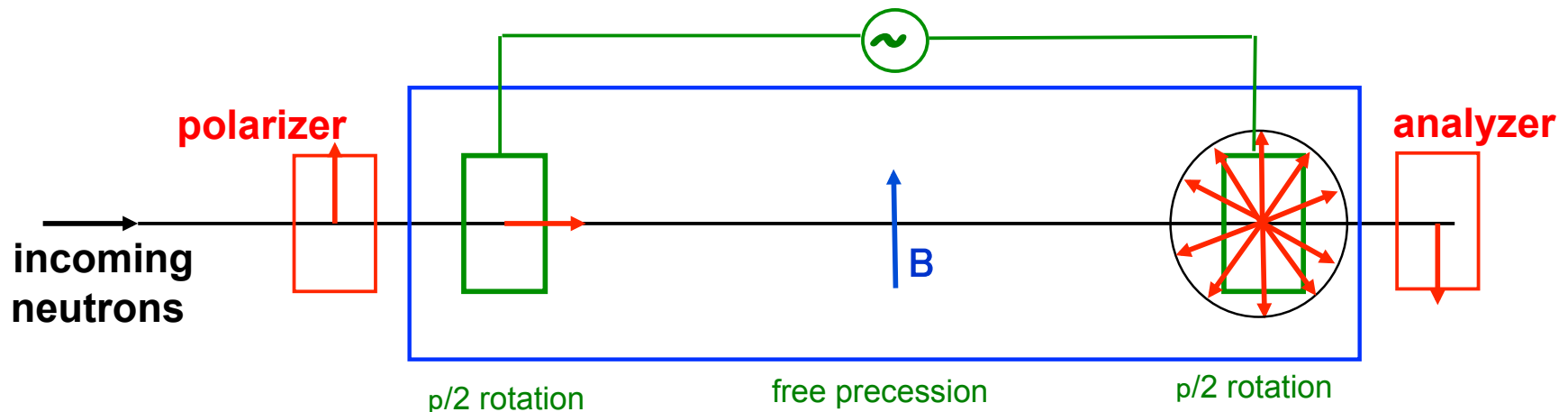
$$\Delta\omega_{proton} = 0.8Hz$$

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 $\times 100$ m/s. The water velocity was a few m/s.

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 than 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 ^3He indicate that only 20-30% of the nucleon spin comes from the intrinsic spin of the quarks.

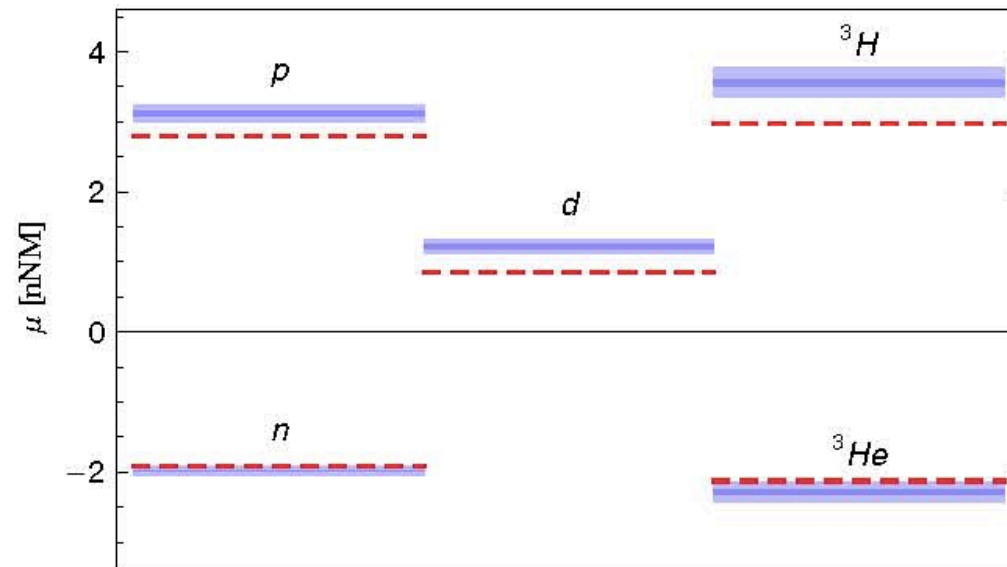
The spin structure of the nucleon is one of the outstanding problems at the interface between nuclear and particle physics.

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.

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

NEW! Neutron Magnetic Moment and QCD

“Magnetic Moments of Light Nuclei from Lattice Quantum Chromodynamics, S. R. Beane, PRL 113, 252001 (2014)



$$\mu_n = -1.981(19) \text{ NM}$$

$$\mu_p = 3.119(72) \text{ NM}$$

$$\mu_{n,\text{exp}} = -1.9130427(05) \text{ NM}$$

$$\mu_{p,\text{exp}} = 2.792847356(23) \text{ NM}$$

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:

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

$$\vec{\mu} = \mu \vec{J}$$

$$\vec{d} = d \vec{J}$$

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

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

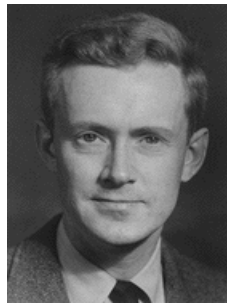
After B. Fillipone

A Short History of Symmetry Violation

1863 (94 BP) Pasteur notes parity “violation” in organic molecules

“It is generally assumed on the basis of some suggestive theoretical symmetry arguments that nuclei and elementary particles 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

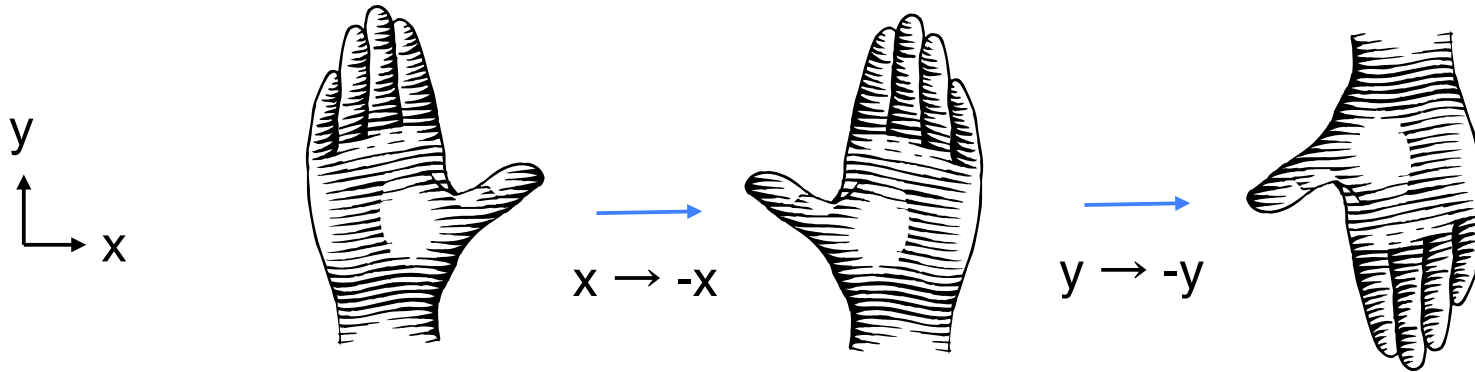
- 1863 (94 BP) Pasteur notes parity “violation” in organic molecules*
- 1950 (7 BP) Purcell and Ramsey suggest that parity violation must be
subject to experimental confirmation
(Ramsey gets 50-1 odds against from Feynman)*
- 1951 (6 BP) First experiment specifically designed to look for a parity
violation (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
(Feynman pays up)*
- Landau suggests that CP is the “Real” symmetry*

A Short History of Symmetry Violation (con't)

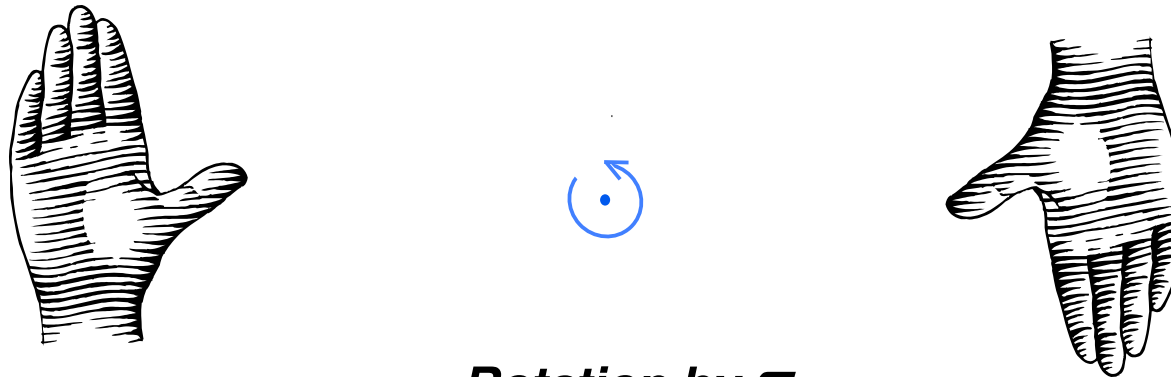
1964 Christianson, et. al., demonstrate that CP is violated in K-decay

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

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

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 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).

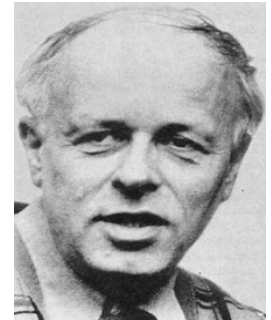
1. Very early in the Big Bang ($t < 10^{-6}$ s), matter and antimatter (i.e. p & \bar{p}) were in thermal equilibrium ($T \gg 1$ GeV). There was exact balance between matter and antimatter.
2. At some point, there was a symmetry breaking process that led to a small imbalance between the number of Baryons and Anti-Baryons... i.e. a few more Baryons.
3. When the Universe cooled to below $T \sim 1$ GeV, 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:

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

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

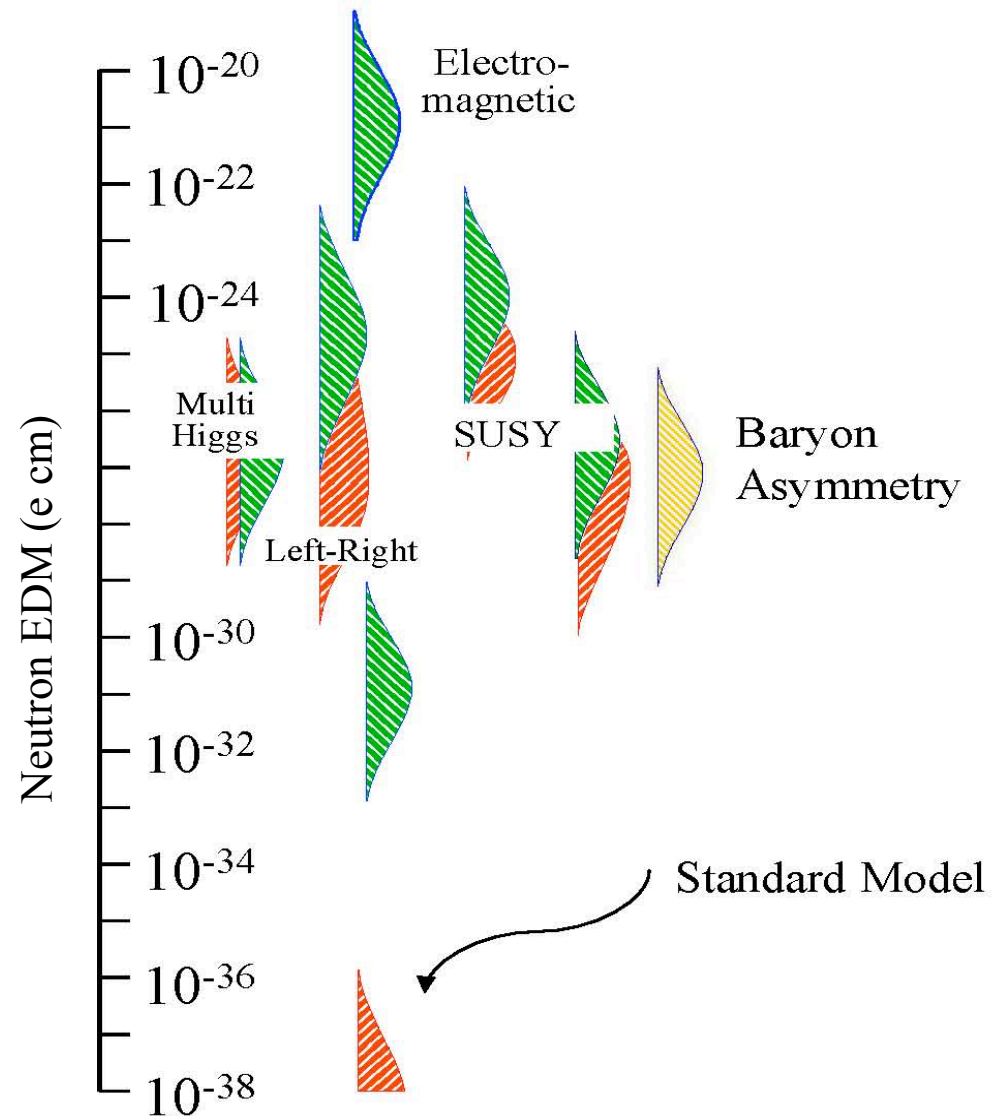
Question:

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?

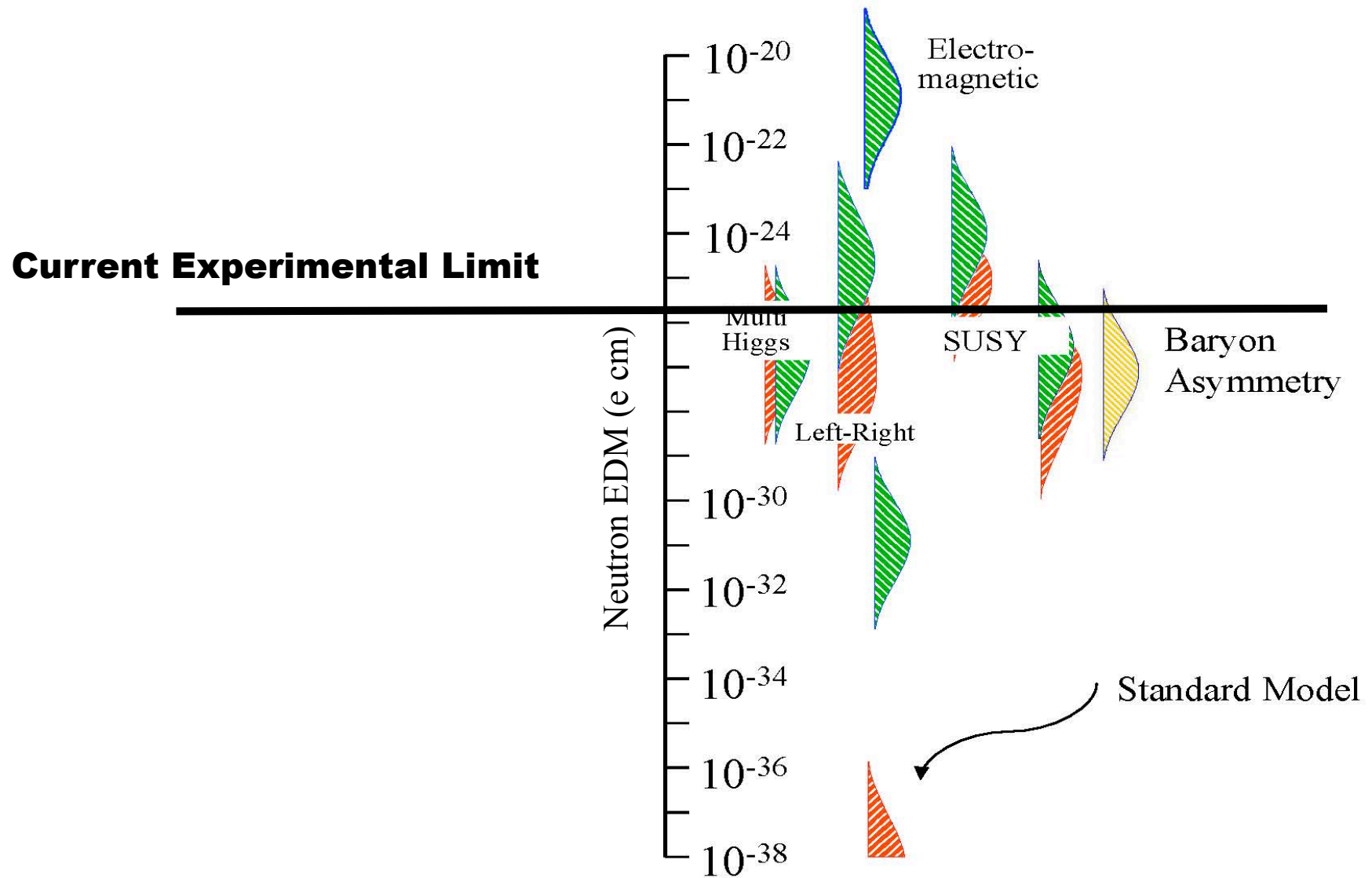
Many theories predict a non-zero neutron EDM

T-violation is allowed in the Standard Model.

However...it is not enough to explain the cosmic baryon asymmetry.

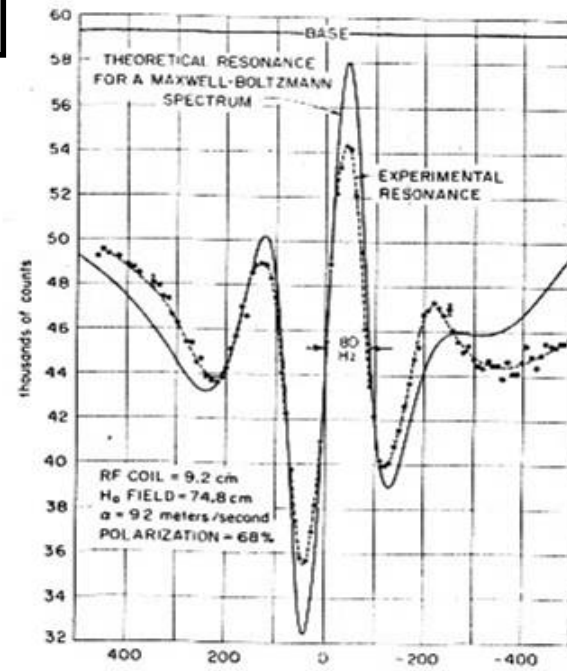
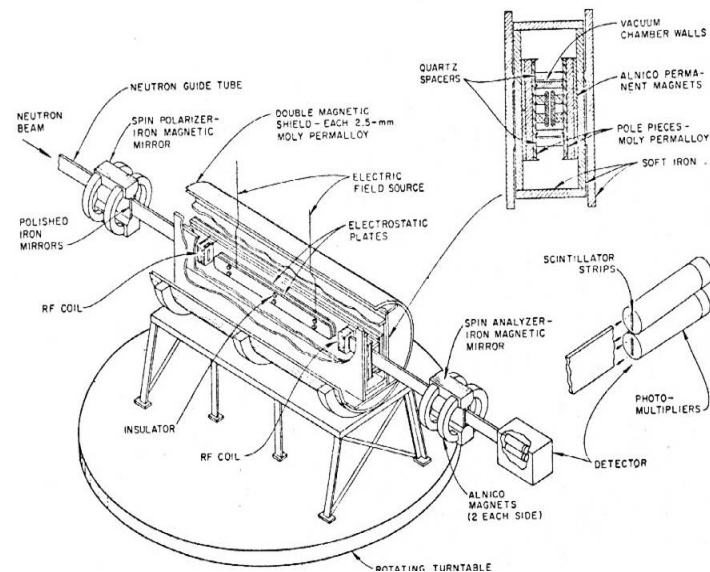
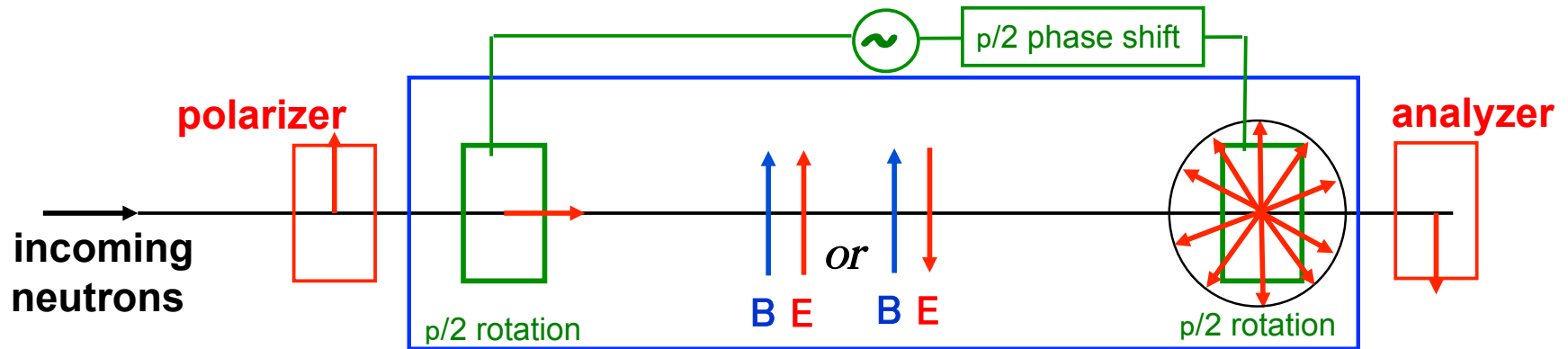


Many theories predict a non-zero neutron EDM



Measuring the Neutron Electric Dipole Moment

Neutron Beam EDM Experiment



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

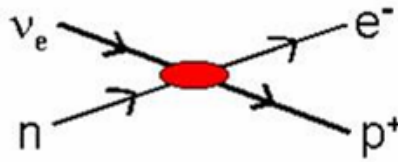
Neutron Decay and Lifetime



Wolfgang Pauli

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

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



Enrico Fermi

1935 *The β decay of the neutron is predicted by Chadwick and Goldhaber based on their observation that $M_n > M_p + M_e$. Based on their ΔM , the neutron lifetime is estimated at $\sim \frac{1}{2}$ hr.*

1948 *Snell and Miller observe neutron decay at Oak Ridge*

1951 *Robson makes the first “measurement” of the neutron lifetime*

Fermi's Bottle - A Great Idea that Didn't Work

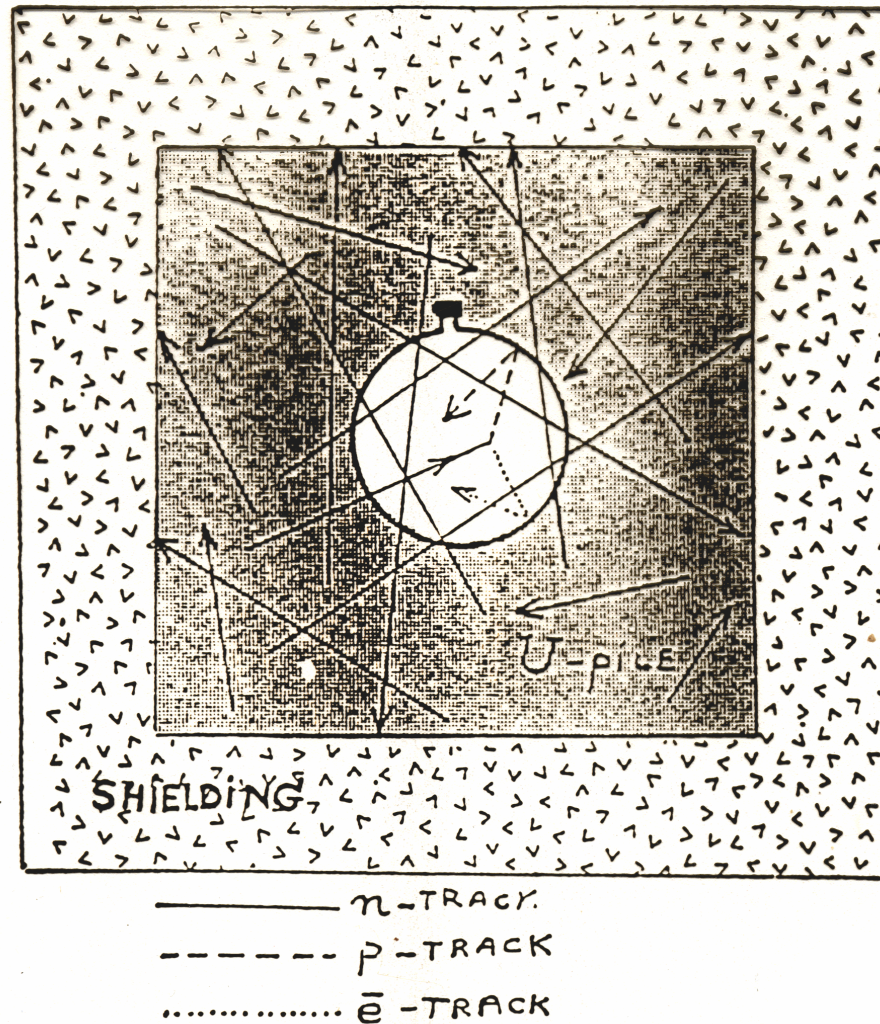
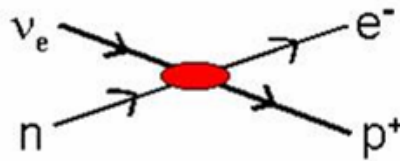


Fig. 29. Fermi's bottle in a uranium pile, designed to measure the neutron's mean life.

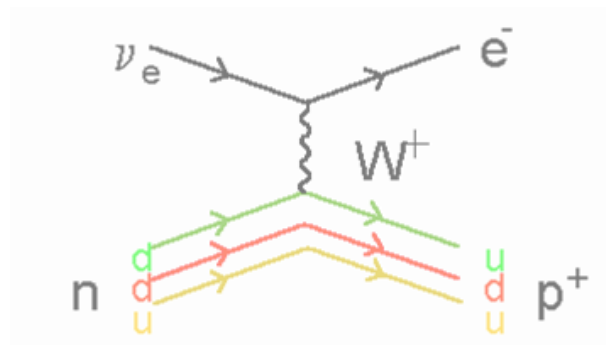
George Gamow, *Thirty Years That Shook Physics*, (1966)

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

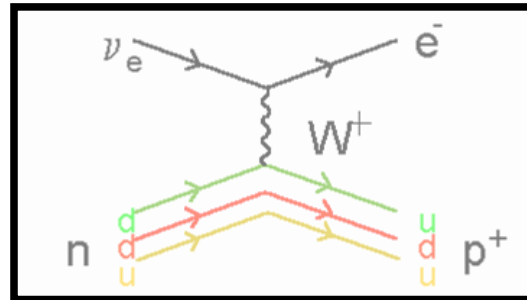
Fermi's View of Neutron Decay:



Modern View of Neutron Decay:



Processes with the same Feynman Diagram as Neutron Decay



Primordial element formation	$n + e^+ \longleftrightarrow p + \bar{\nu}_e$ $p + e^- \longleftrightarrow n + \nu_e$ $n \longrightarrow p + e^- + \bar{\nu}_e$
Solar cycle	$p + p \longrightarrow {}^2\text{H} + e^+ + \nu_e$ $p + p + e^- \longrightarrow {}^2\text{H} + \nu_e \text{ etc.}$
Neutron star formation	$p + e^- \longrightarrow n + \nu_e$
Pion decay	$\pi^- \longrightarrow \pi^0 + e^- + \bar{\nu}_e$
Neutrino detectors	$\nu_e + p \longrightarrow e^+ + n$
Neutrino forward scattering	$\nu_e + n \longrightarrow e^- + p \text{ etc.}$

The Neutron Lifetime and the Big-Bang

Important Reactions in Big Bang Nucleosynthesis

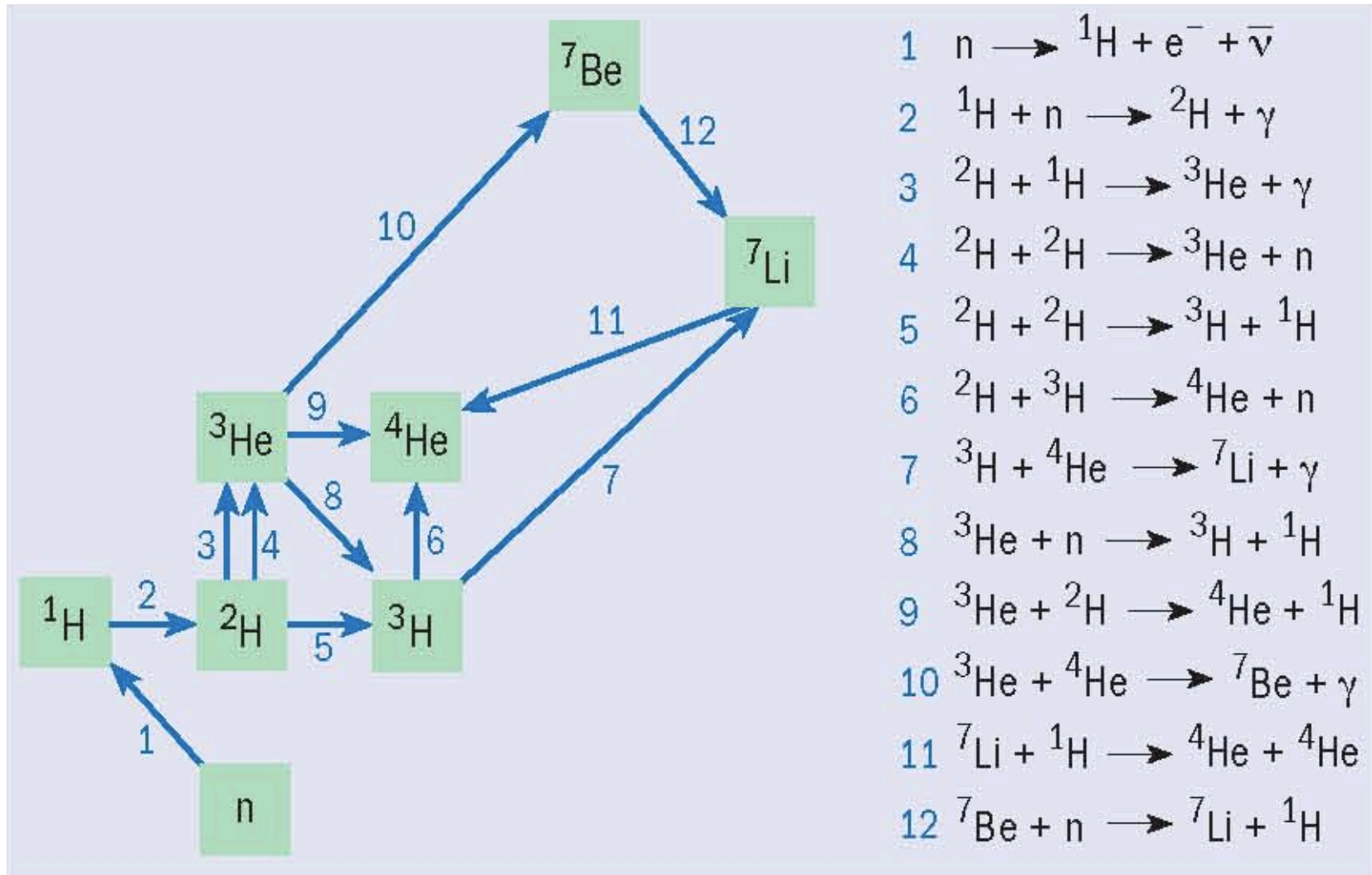


Image courtesy Ken Nollet

Important Reactions in Big Bang Nucleosynthesis

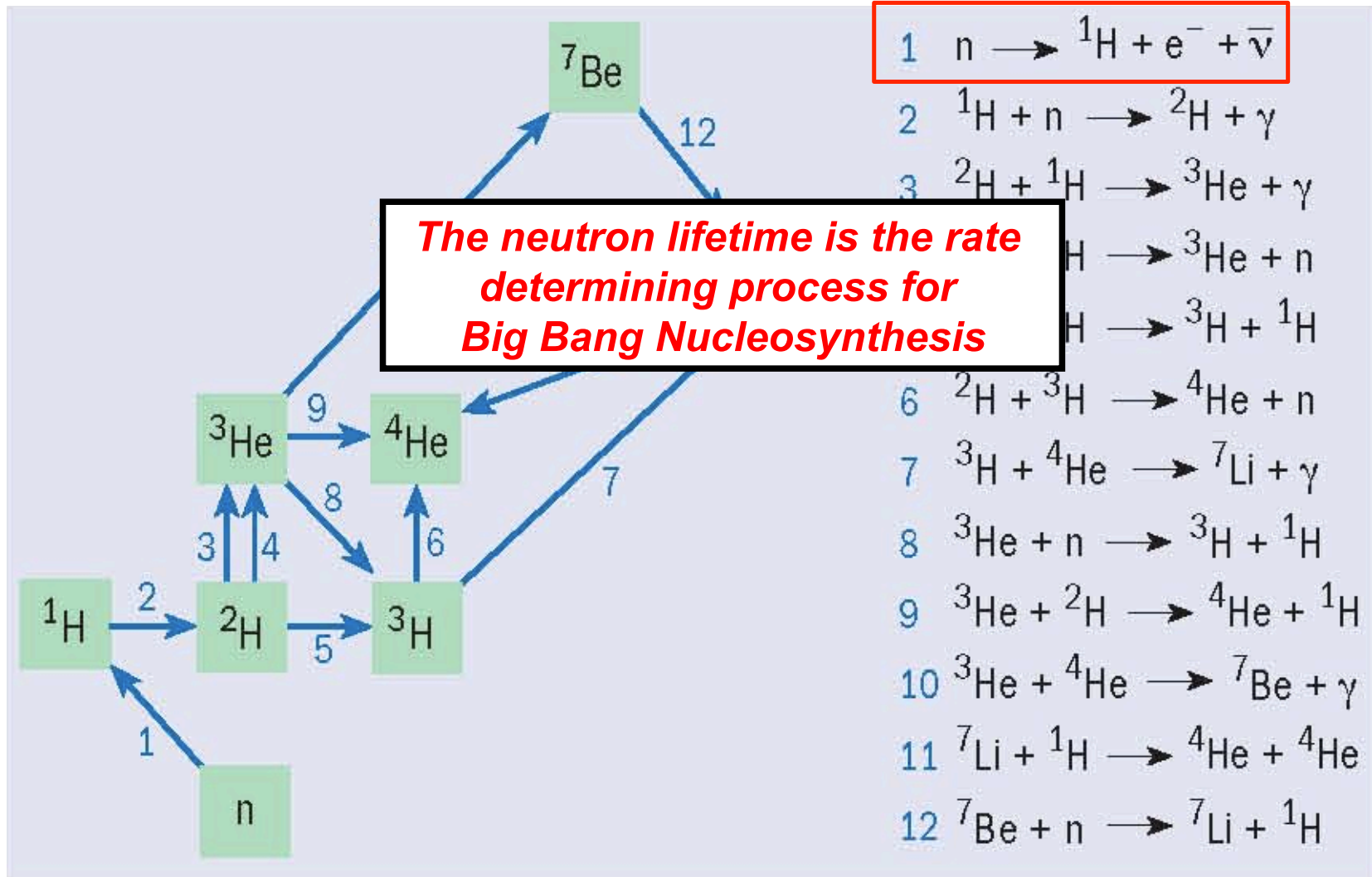


Image courtesy Ken Nollet

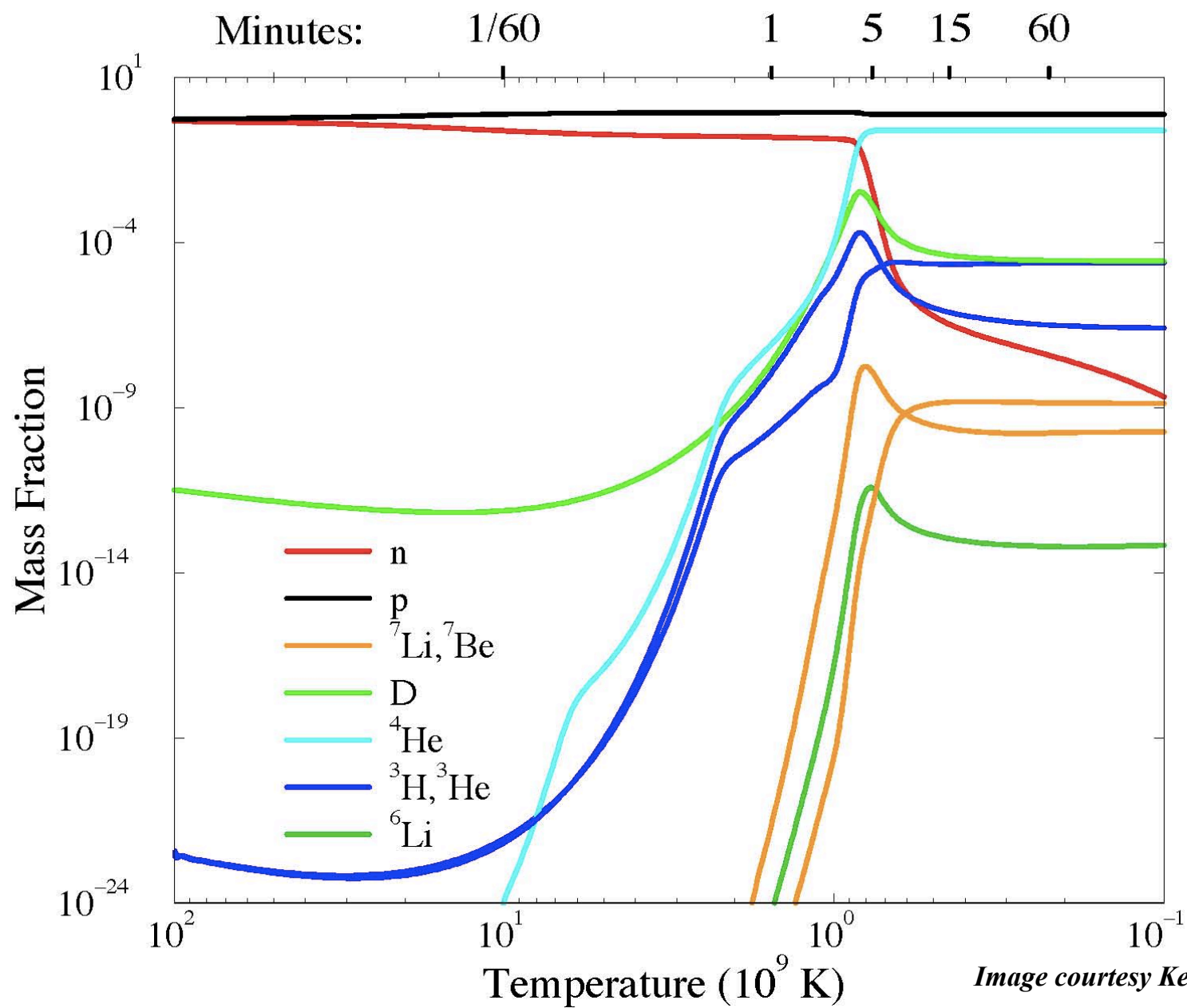


Image courtesy Ken Nollet

The Cosmic He/H Ratio Depends upon three quantities:

1) The Cooling rate of the Universe

Given by the heat capacity of the Universe

Determined mainly by the number of “light particles” ($m \leq 1 \text{ MeV}$)

Includes photons, electrons (positrons), neutrinos (x3)

2) The Rate at which Neutrons are decaying

The neutron lifetime

3) The rate at which nuclear interactions occur

*Determined by the the logarithm of the density of nucleons (baryons)**

**Because of expansion, the “absolute” baryon density is decreasing with time so the density is scaled as the ratio of matter to photons.*

The Parameters of Big Bang Nucleosynthesis

$$Y_p = 0.264 + 0.023 \log \eta_{10} + 0.018 (\tau_n - 10.28)$$

Cosmic Helium Abundance

Cosmic Baryon Density

Neutron Lifetime in Minutes

The Parameters of Big Bang Nucleosynthesis

$$Y_p = 0.264 + 0.023 \log \eta_{10} + 0.018 (\tau_n - 10.28)$$

Cosmic Helium Abundance

Cosmic Baryon Density

Neutron Lifetime in Minutes

*Y_p is the most accurate prediction in ALL of astrophysics.
Accuracy is limited by knowledge of neutron lifetime.*

We can "invert" this line of reasoning. If we measure the Helium Abundance and the Neutron Lifetime, we can determine the density of "ordinary" matter in the universe.

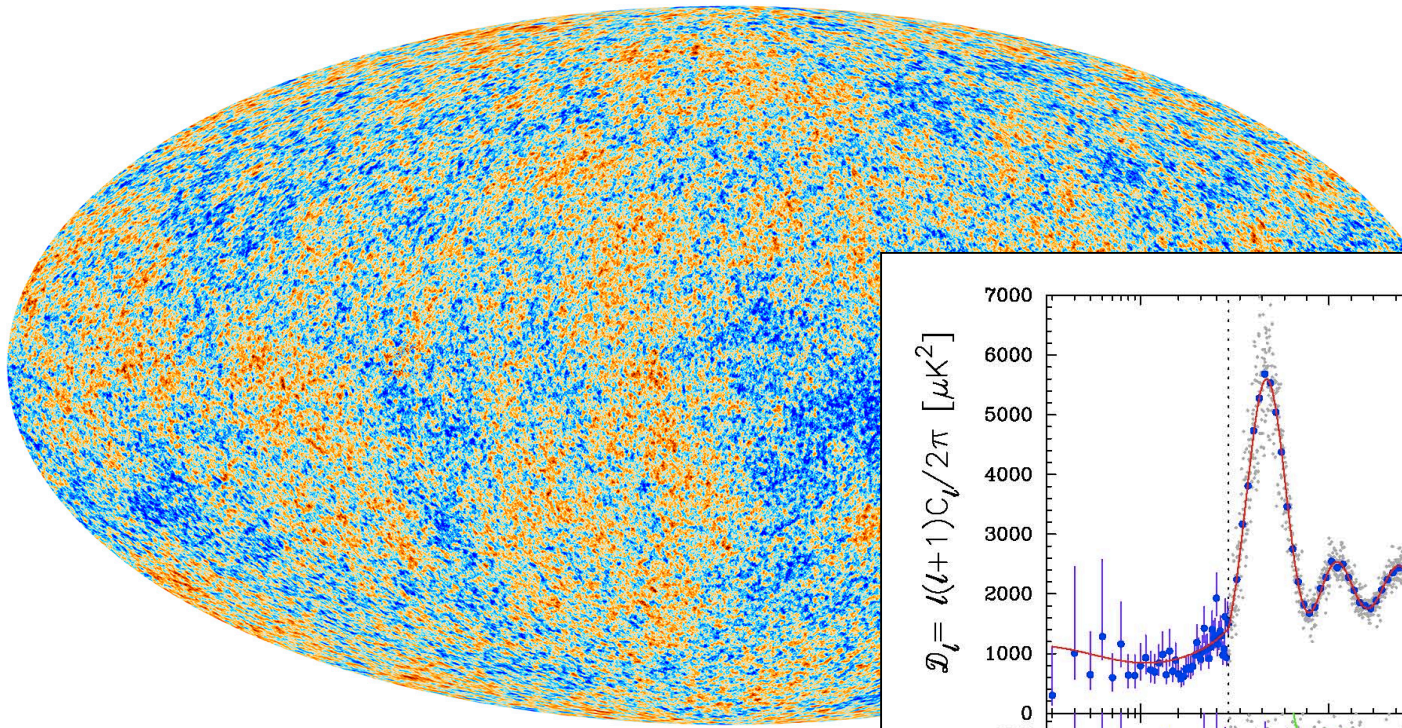
$$\log \eta_{10} = [0.264 - Y_p + 0.018(\tau_n - 10.28)] / 0.023$$

Cosmic Baryon Density

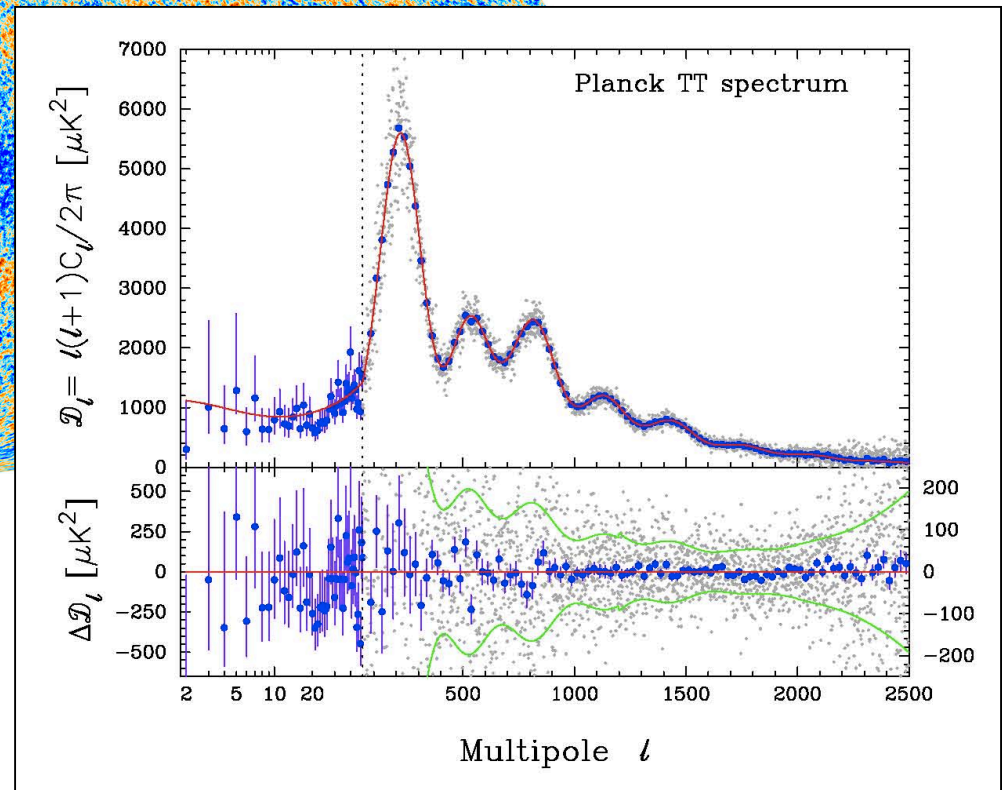
Cosmic Helium Abundance

Neutron Lifetime in Minutes

Cosmic Microwave Background – Results from Planck



Planck Collaboration 2013



$$He/H \text{ ratio } (Y_p) = 0.24771 \pm 0.00014$$

A Brief Digression on the Mass of the Universe

From Big Bang Nucleosynthesis, we conclude that, averaged over the entire universe today, after expansion, there are a few protons per cubic meter.

$$\log \eta_{10} = [0.264 - Y_P + 0.018(\tau_n - 10.28)] / 0.023$$

Cosmic Baryon Density

Cosmic Helium Abundance

Neutron Lifetime in Minutes

A Brief Digression on the Mass of the Universe

From Big Bang Nucleosynthesis, we conclude that, averaged over the entire universe today, after expansion, there are a few protons per cubic meter.

Is this a lot, or this it a little?

A Brief Digression on the Mass of the Universe

From Big Bang Nucleosynthesis, we conclude that, averaged over the entire universe today, after expansion, there are a few protons per cubic meter.

Is this a lot, or this it a little?

Compared with What?

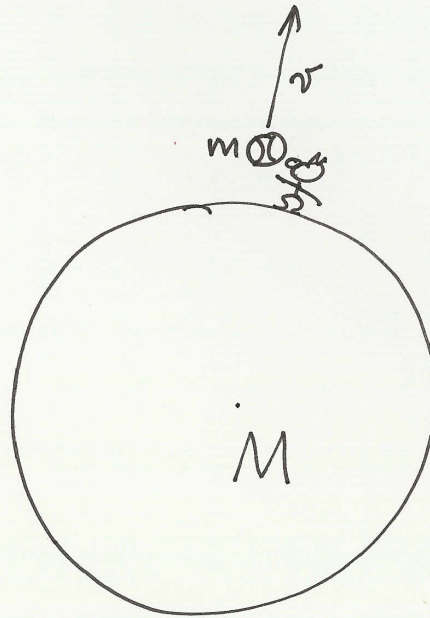
A Scale for the Density of the Universe

- *From red-shift observations we know that the Universe is in a state of (nearly) uniform expansion.*
- *If the density of the Universe is sufficiently high, this expansion will come to a stop and a universal collapse will ensue.*
- *If the density of the Universe is sufficiently low, it will expand forever.*
- *The critical density of the universe is given by the Hubble constant H , and the Gravitational constant G*

- *We define:*
$$\rho_{critical} = \frac{3}{8\pi} \frac{H^2}{G}$$

$$\Omega = \rho / \rho_{critical}$$

ESCAPE VELOCITY

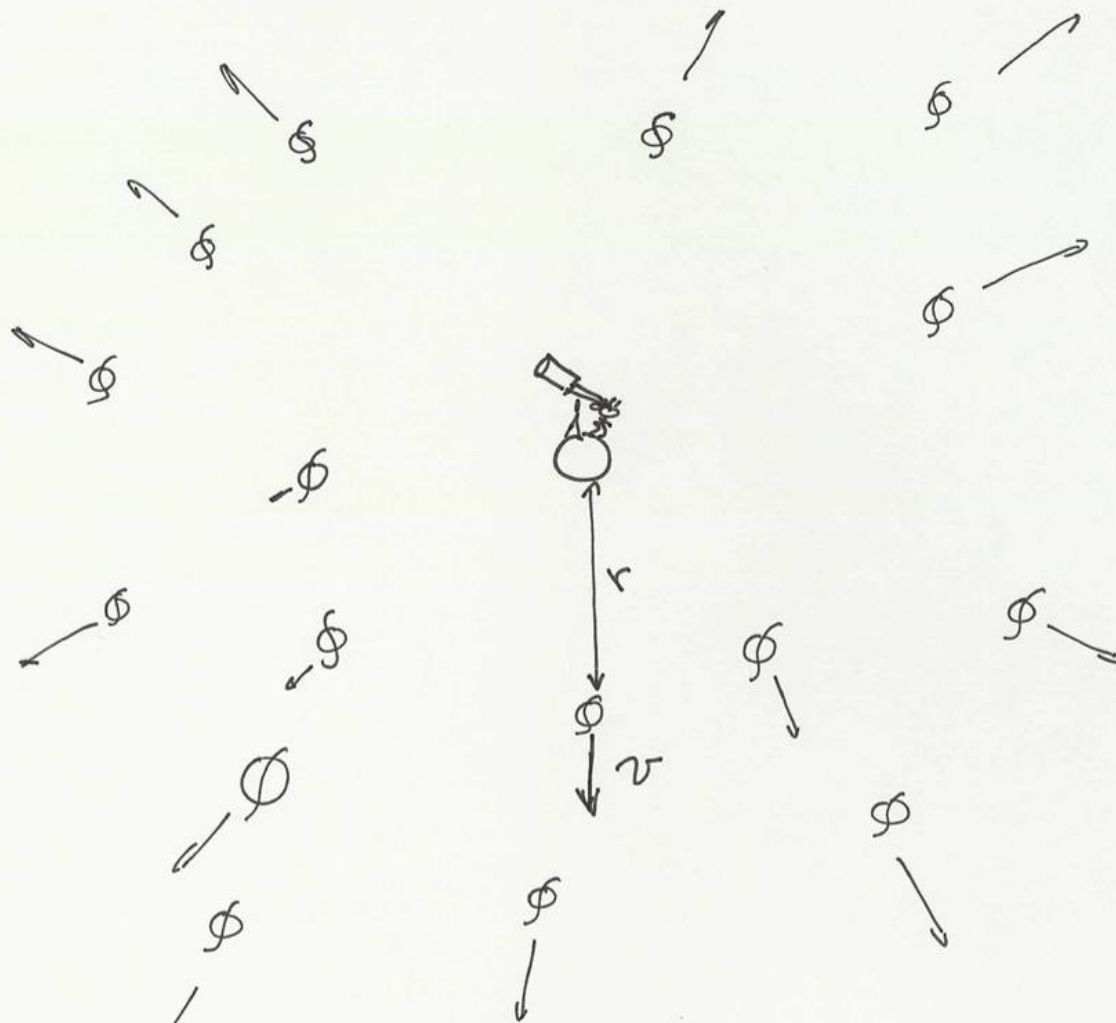


if $\frac{1}{2}mv^2 > \frac{GmM}{r}$ ball escapes

if $\frac{1}{2}mv^2 < \frac{GmM}{r}$ ball returns

$$v_{\text{escape}} = \sqrt{\frac{2GM}{r}}$$

HUBBLES LAW



$$v = Hr$$

$$M = \frac{4}{3} \pi r^3 \rho$$

$$v_{\text{escape}} = \sqrt{\frac{8\pi G \rho r^3}{3r}}$$

Define ρ_{critical} by

$$Hr = \sqrt{\frac{8\pi G \rho_{\text{crit}} r^2}{3}}$$

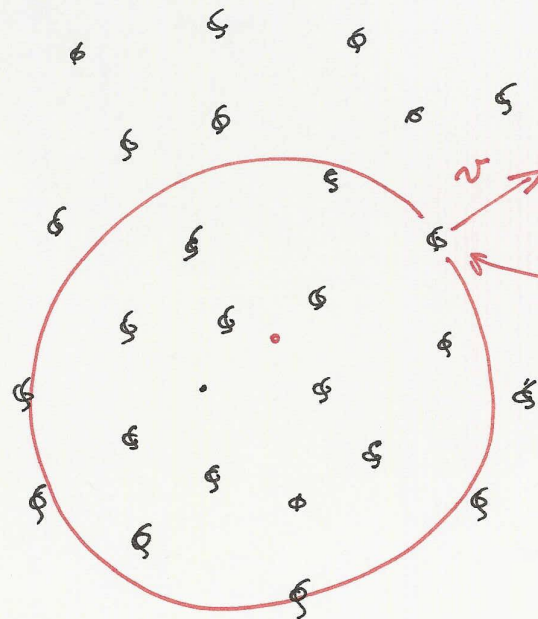
$$H^2 = \frac{8\pi}{3} G \rho_{\text{crit}}$$

$$\rho_{\text{crit}} = \frac{3}{8\pi} \frac{H^2}{G}$$

$$\Omega \equiv \frac{\rho}{\rho_{\text{crit}}}$$

If $\Omega < 1$ universe expands forever

If $\Omega > 1$ universe collapses in finite time



$$v = Hr$$

Will this Galaxy
continue to move
away

density of universe

Neutron Summer School

Laboratory Exercise

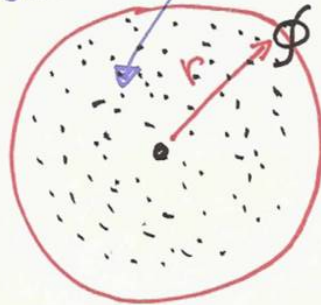
*Carry out a cosmological observation that
sets an experimental upper limit on Ω .*

Important Cosmological Observation-

The Universe is Still Here!

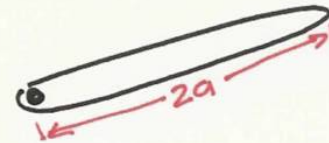
Assume that $\rho > \rho_{\text{crit}}$ ($\Omega > 1$) and that expansion has just about stopped.

M constant



With respect to earth, distant galaxies are in highly eccentric Keplerian Orbits

$$T = \frac{2\pi a^{3/2}}{\sqrt{GM}} = \frac{\pi r^{3/2}}{\sqrt{2GM}}$$



$$\underline{\underline{r = 2a}}$$

In a length of time equal to the age of the universe ($t_{\text{universe}} \approx \frac{1}{H}$), the distant galaxy will have not quite complete $\frac{1}{2}$ of a full orbit

$$\frac{2}{H} < T = \frac{\pi r^{3/2}}{\sqrt{2GM}}$$

$$\frac{2}{H} < \frac{\pi r^{3/2}}{\sqrt{\Omega r^3 H^2}}$$

$$\Omega < \frac{\pi^2}{2^2}$$

$$\boxed{\Omega < 2.5}$$

$$M = \frac{4}{3}\pi r^3 \Omega \rho_{\text{crit}}$$

$$M = \frac{1}{2} \Omega \frac{r^3 H^2}{G}$$

A Lower Limit for Ω

By simply counting the number of visible stars and galaxies we find

$$0.005 \leq \Omega_{\text{total}}$$

From extremely simple reasoning we have:

$$0.005 \leq \Omega_{\text{total}} \leq 2.5$$

Ω is NOT necessarily constant over time

If $\Omega > 1$ at any time, Then Ω will continue to grow larger with time.

If $\Omega < 1$ at any time, Then Ω will tend toward zero with time.

Only if $\Omega = 1$ EXACTLY, will it stay constant for all time

We observe that Ω is NOW not too far from 1 ($0.01 < \Omega < 2.5$). Thus:

Ω was EXTREMELY close to 1 early in the big bang ($|\Omega - 1| \leq 10^{-16}$)

This raises the “Fine Tuning” question:

If Ω is very nearly equal to 1, is it exactly 1?

For a many compelling reasons (“fine tuning”, inflation, microwave background,...), We strongly believe that

$$\Omega_{\text{Total}} = 1 \text{ Exactly!}$$

Measuring the Neutron Lifetime

Two Approaches to Measuring a Lifetime

1. Observation time is longer than (or comparable to) the lifetime.

STEP 1: Determine $N(0)$ number unstable nuclei in a sample at $t=0$, and

STEP 2: Determine $N(t)$ number unstable nuclei in a sample at $t=t$.

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

Bottle Method

2. Observation time is much shorter than the lifetime.

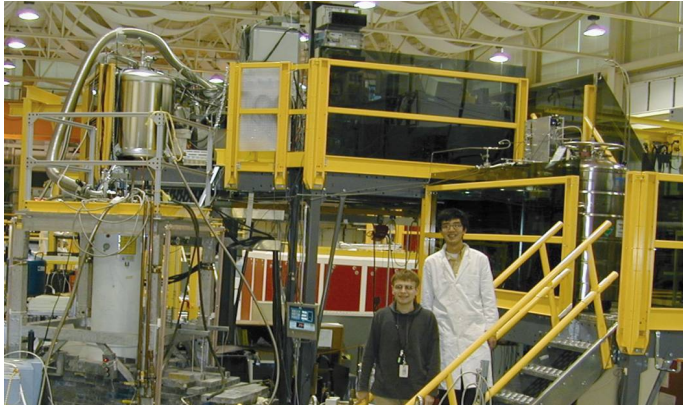
STEP 1: Determine N , the number of unstable nuclei in a sample, and

STEP 2: Determine the rate of decays \dot{N} .

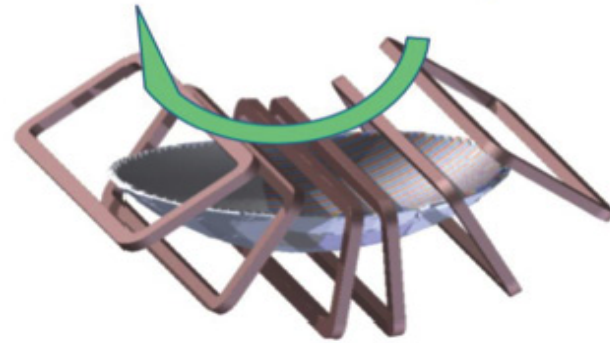
$$\dot{N} = \frac{N}{\tau}$$

Beam Method

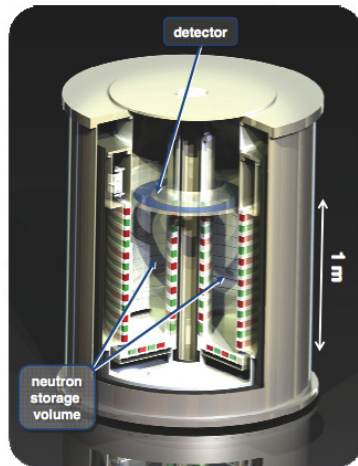
Some Neutron Bottles



**NIST
Superfluid He Bottle**



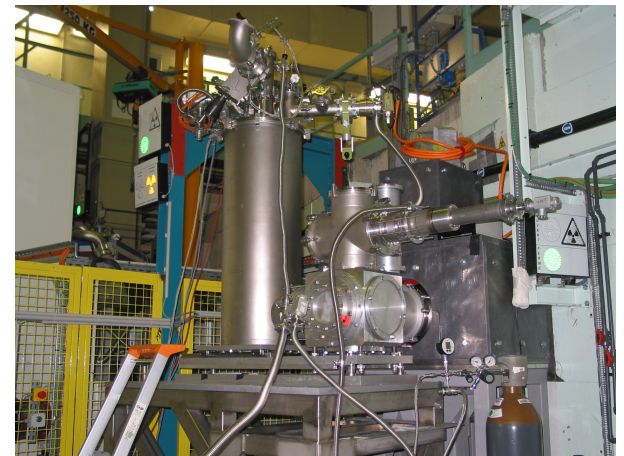
**UCN τ , Los Alamos
Magnetic Bottle**



**PENELOPE, Munich
Magnetic Bottle**

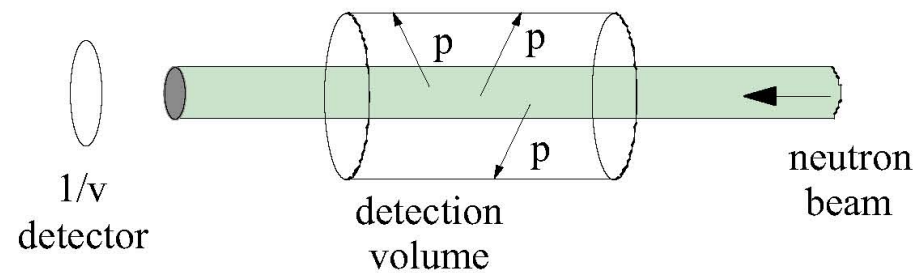


**“Big” Gravitational Trap, St. Petersburg
Material Bottle**



**HOPE, Grenoble
Magnetic Bottle**

The Neutron Lifetime: In-Beam Method



$$\text{neutron decay rate } \Gamma = \frac{N}{\tau}$$

$$\text{so } \tau = \frac{\phi V_{\text{det}}}{v \Gamma}$$

- Need to measure:
1. decay rate Γ
 2. effective decay volume V_{det}
 3. neutron flux weighted by inverse velocity

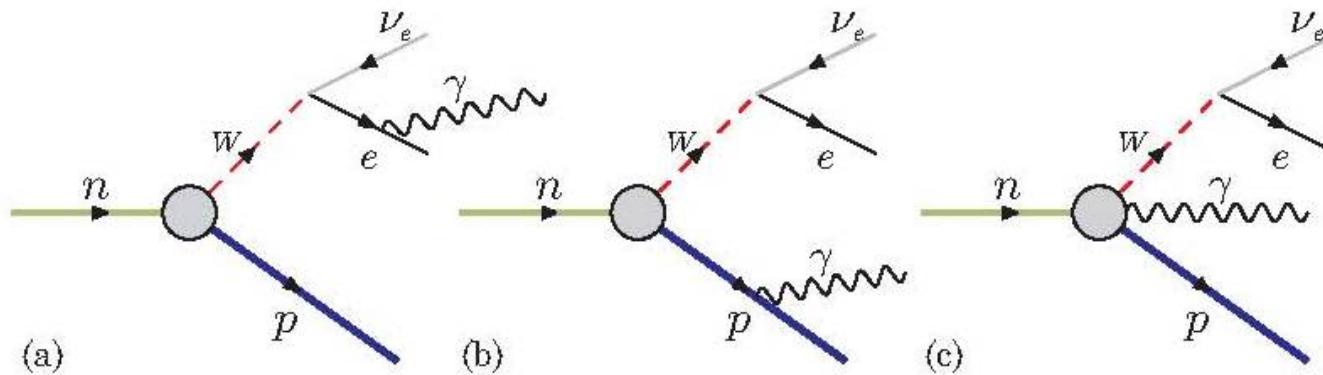
“Exotic” Neutron Decay

Exotic Neutron Decay

Allowed by the Standard Model:

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

***There Are Several Ways in Which a Photon
is Emitted During Neutron Decay***



***Neutron “Radiative Decay” is predicted
by the Standard Model***

Exotic Neutron Decay

Allowed by the Standard Model:

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

$$n \rightarrow {}^1\text{H}_0 + \bar{\nu} \quad \text{"bound state decay"}$$

Exotic Neutron Decay

Allowed by the Standard Model:

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

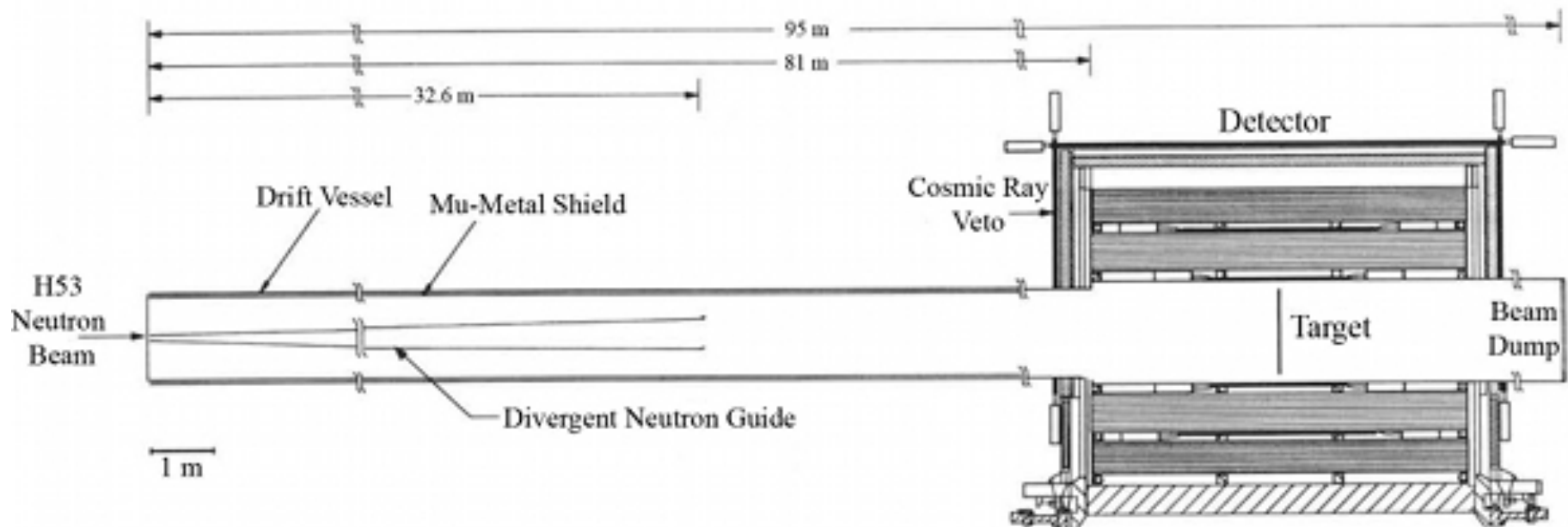
$$n \rightarrow {}^1\text{H}_0 + \bar{\nu} \quad \text{"bound state decay"}$$

Forbidden by the Standard Model:

$$n \rightarrow \bar{n} \quad \text{"n-nbar oscillation" } (\Delta B=2)$$

Search for Neutron-Antineutron Oscillation

Baryon Number Violation $\Delta B=2$



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