The Fundamental Properties of the Neutron II

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Some Neutron Properties

Mechanical Properties

Mass (including a test of $E = m c^2$)

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 Charge ?

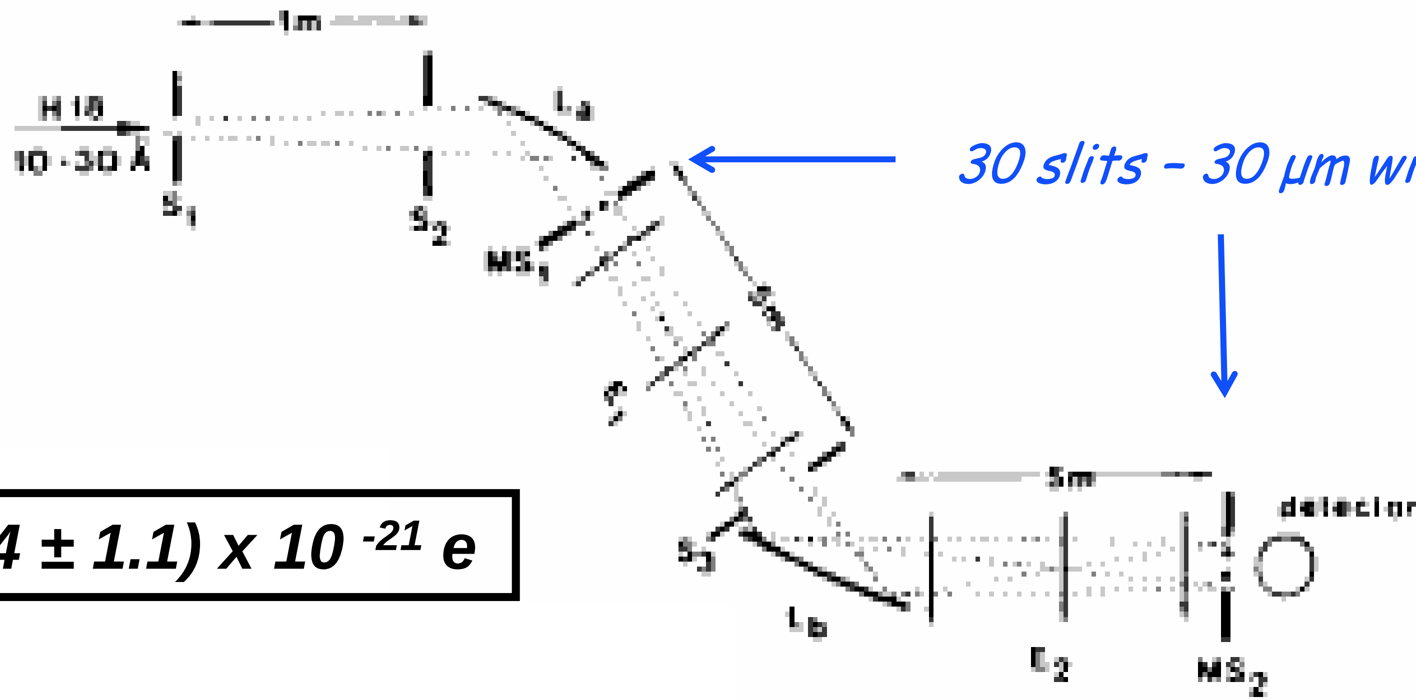
Is the Neutron "Really" Neutral?

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



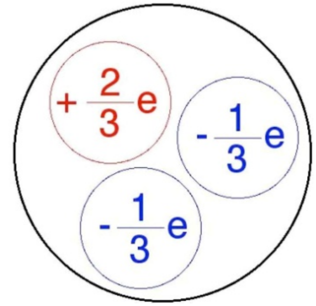
$$\boxed{Q_n = (0.4 \pm 1.1) \times 10^{-21}\ e}$$

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

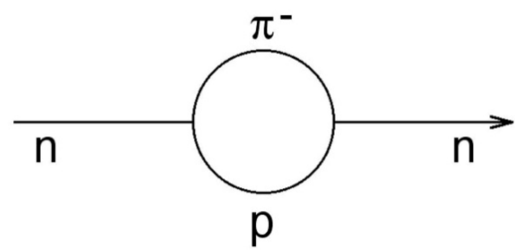
The Neutron Charge Distribution

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:

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

Neutron Electric Scattering Form Factor

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

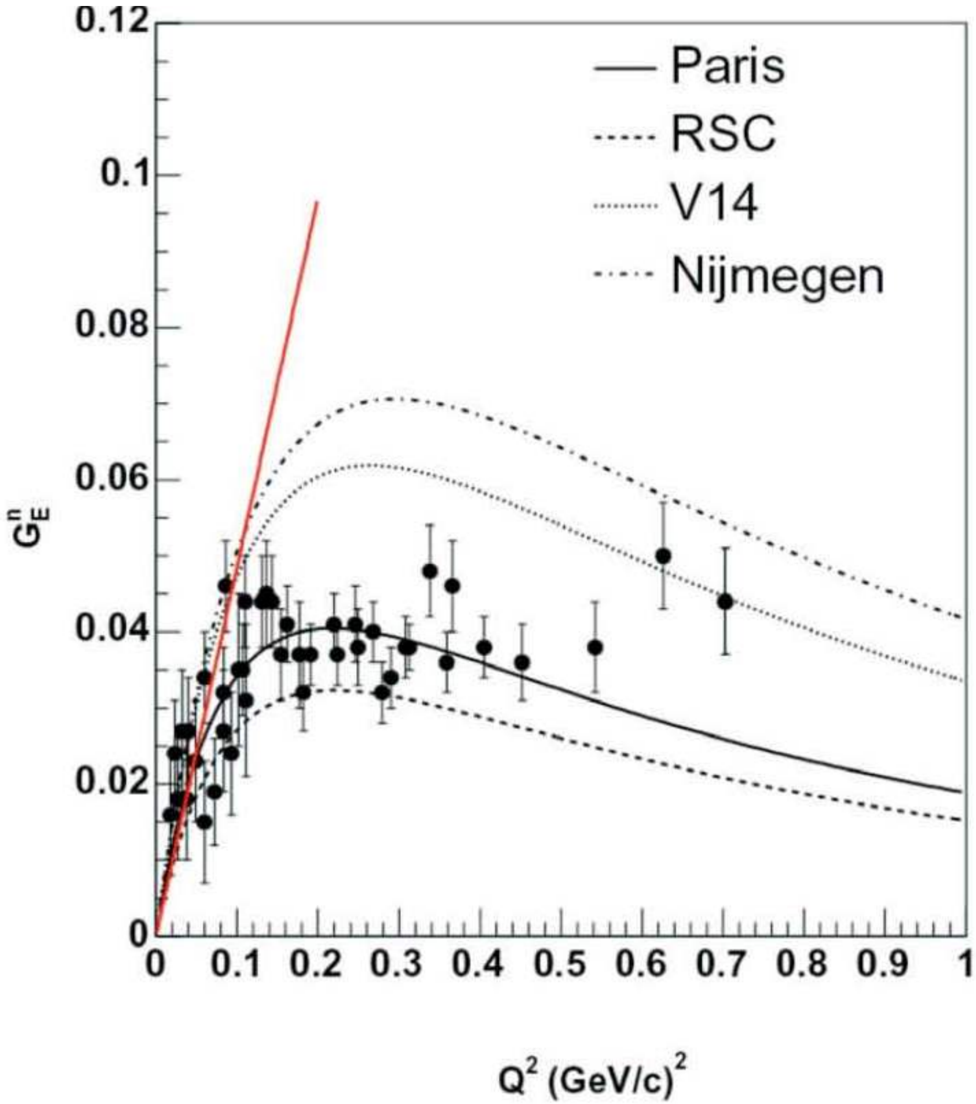
Expanding in the momentum transfer Q^2 :

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

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 $G_E^n\left(Q^2\right)$.
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]
		$-1.44\pm0.033\pm0.06$	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.

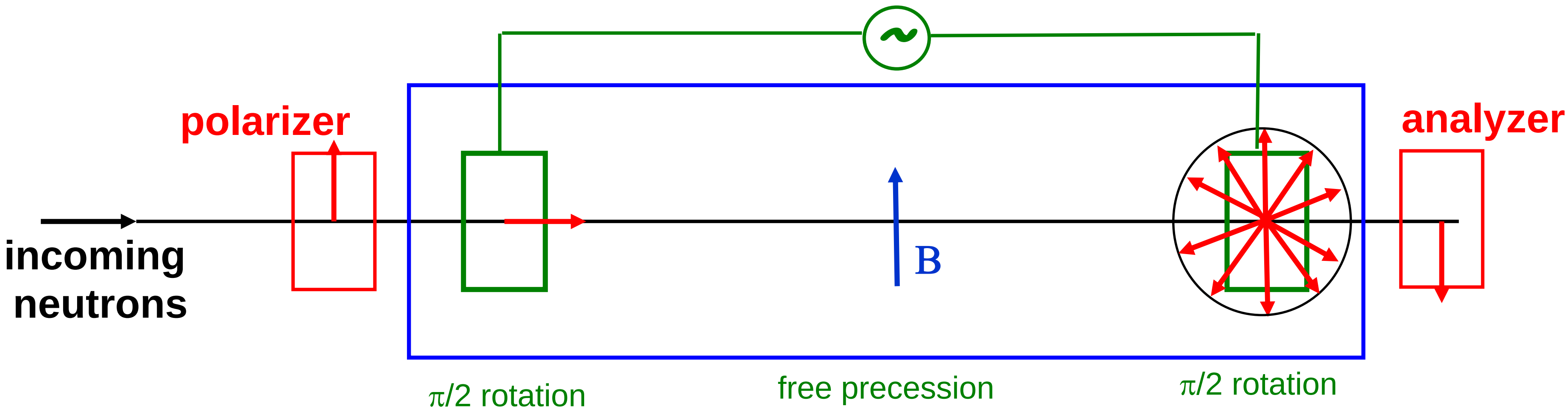
$$\mu_n = -\tfrac{1}{3}\mu_u + \tfrac{4}{3}\mu_d$$

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

3.

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

Method of Separated Oscillatory Fields



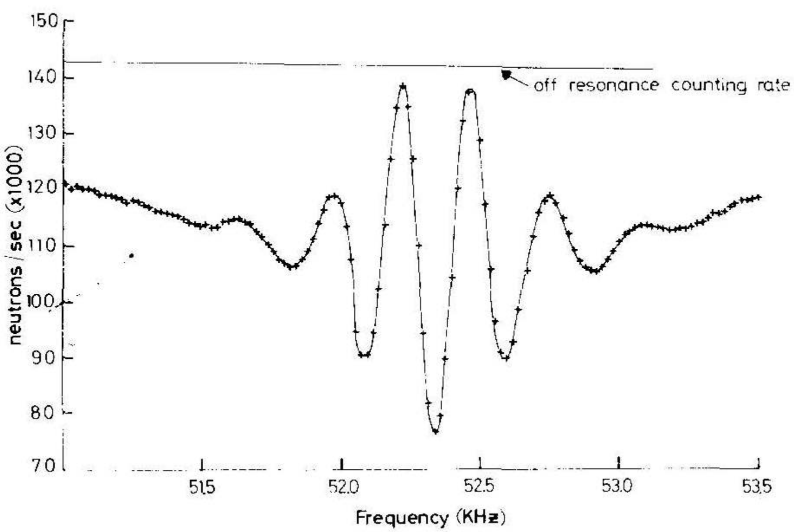
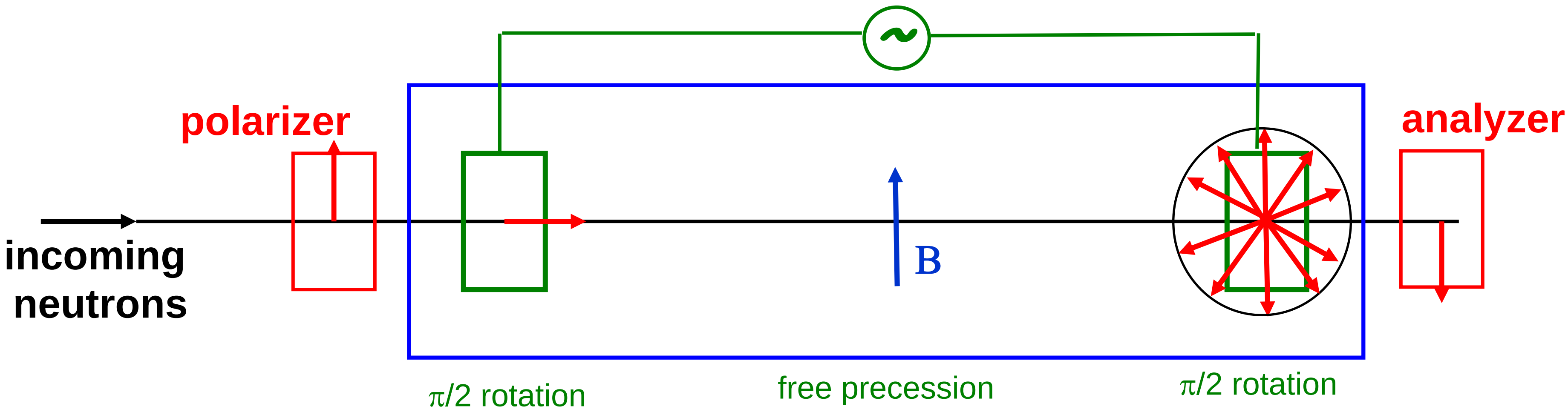


Fig. 1. Neutron resonance.

Method of Separated Oscillatory Fields



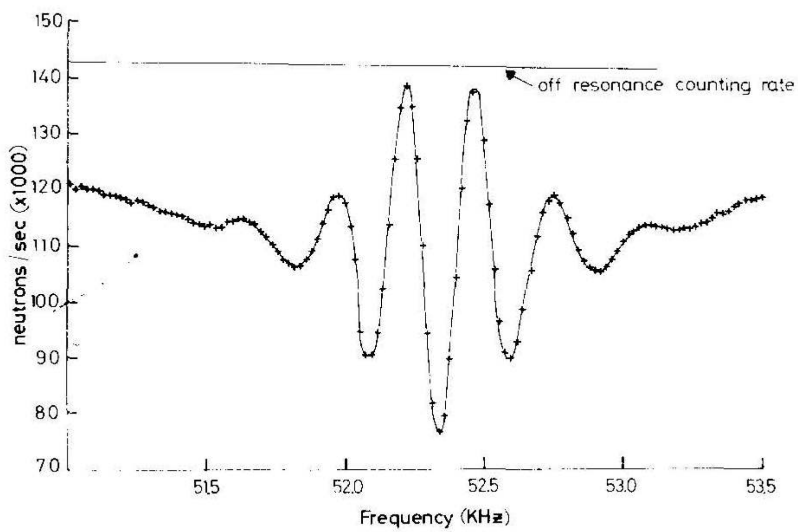


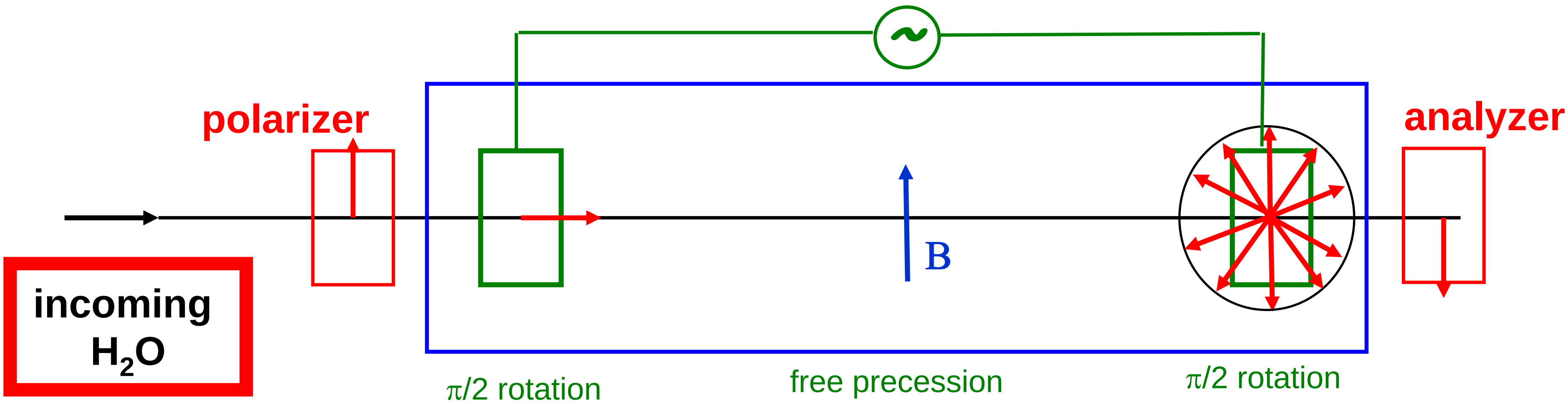
Fig. 1. Neutron resonance.

$$\omega = \overline{H}$$

How to determine $\overline{H}$?

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

Calibration of Magnetic Field Using Flowing Water



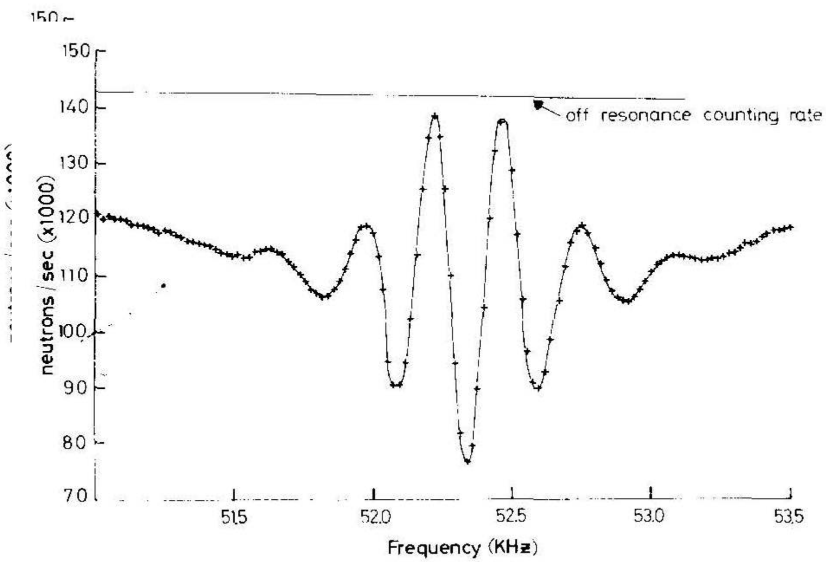


Fig. 1. Neutron resonance.

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

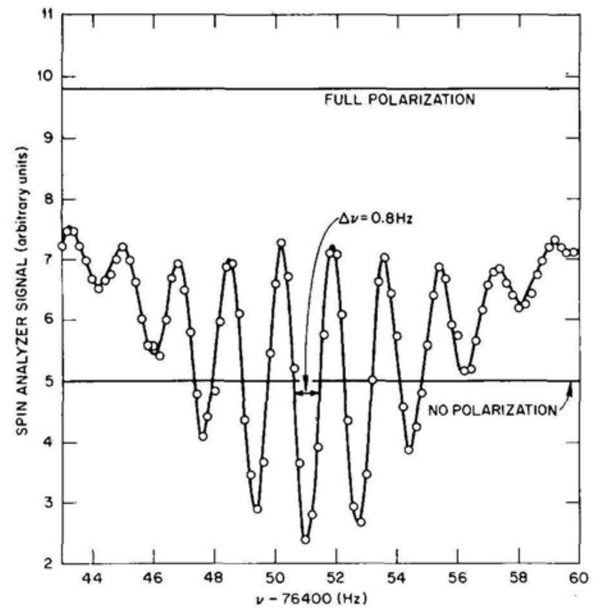


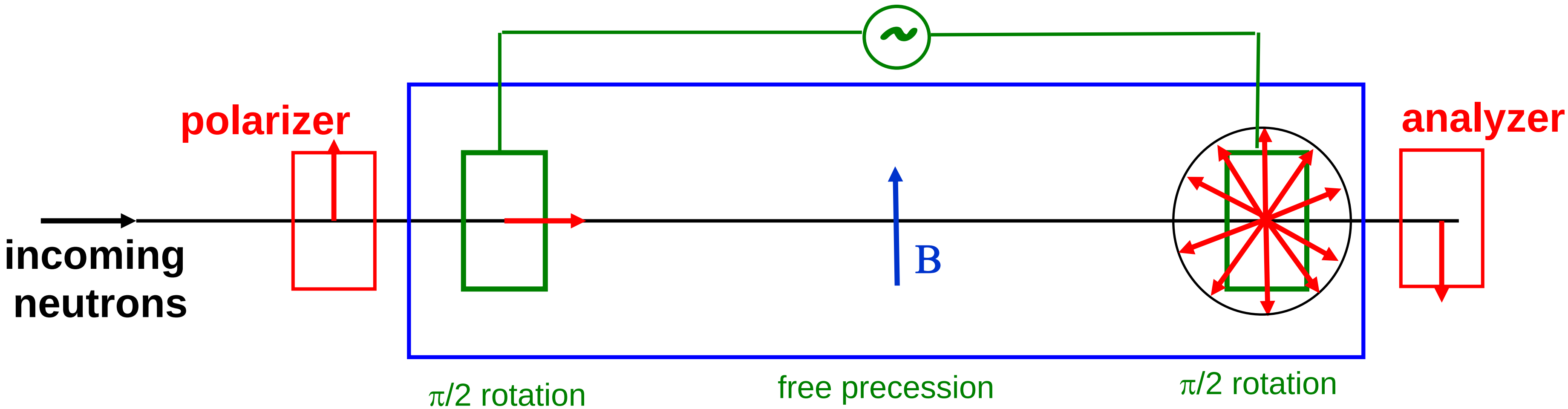
Fig. 2. Proton resonance.

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

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?

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

experiment

vs.

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

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.

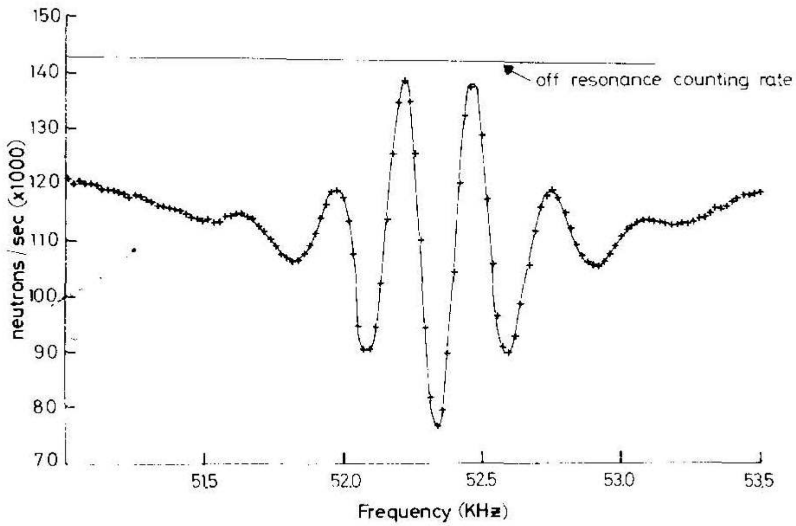
The spin structure of the nucleon is one of the outstanding problems at the interface between nuclear and particle physics.

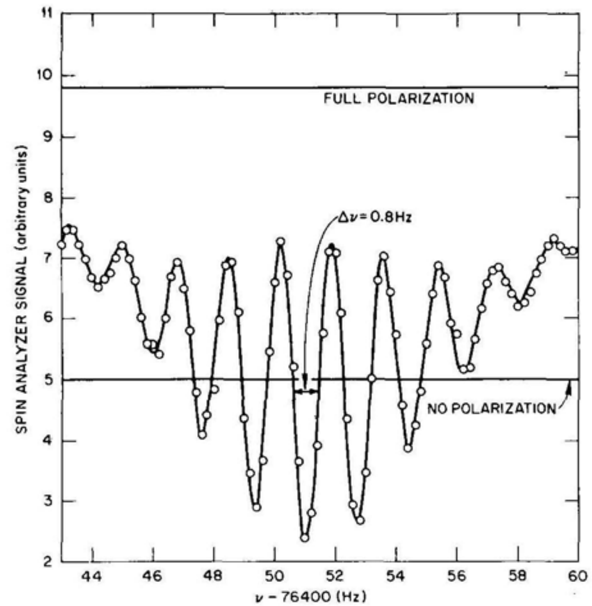
Over the past 20 years more than 1000 theoretical papers have been published and major experiments have been carried out at practically all major accelerator laboratories.

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 Mass

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

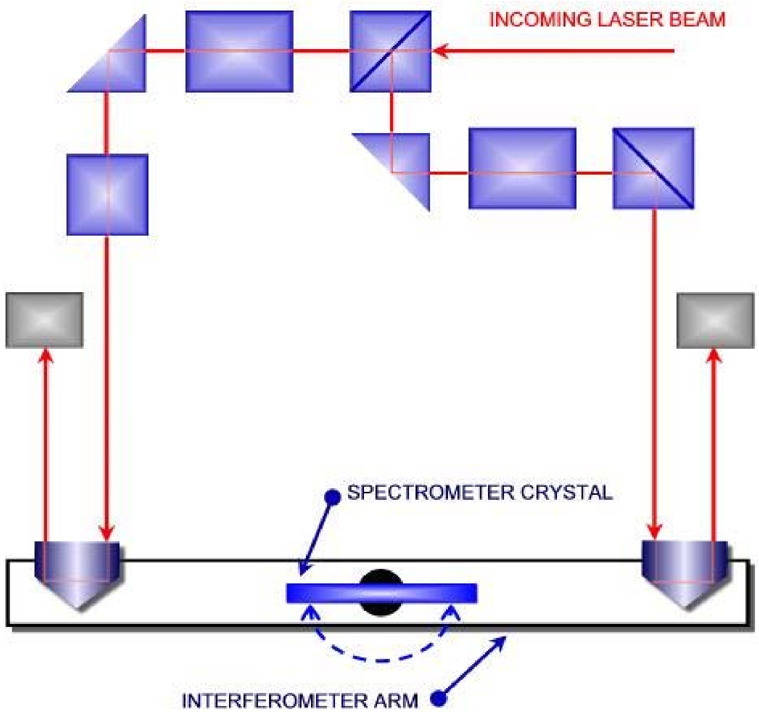
The actual experiment is the determination of the D – H mass difference in atomic mass units.

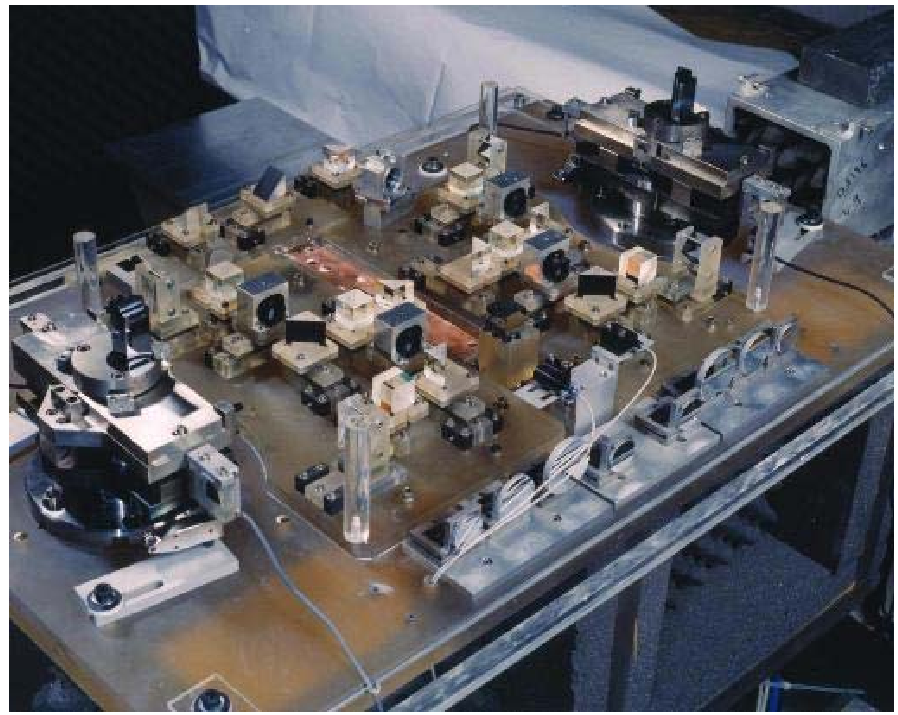
Absolute Measurement of 2.2Mev n-p Capture Gamma Energy

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!

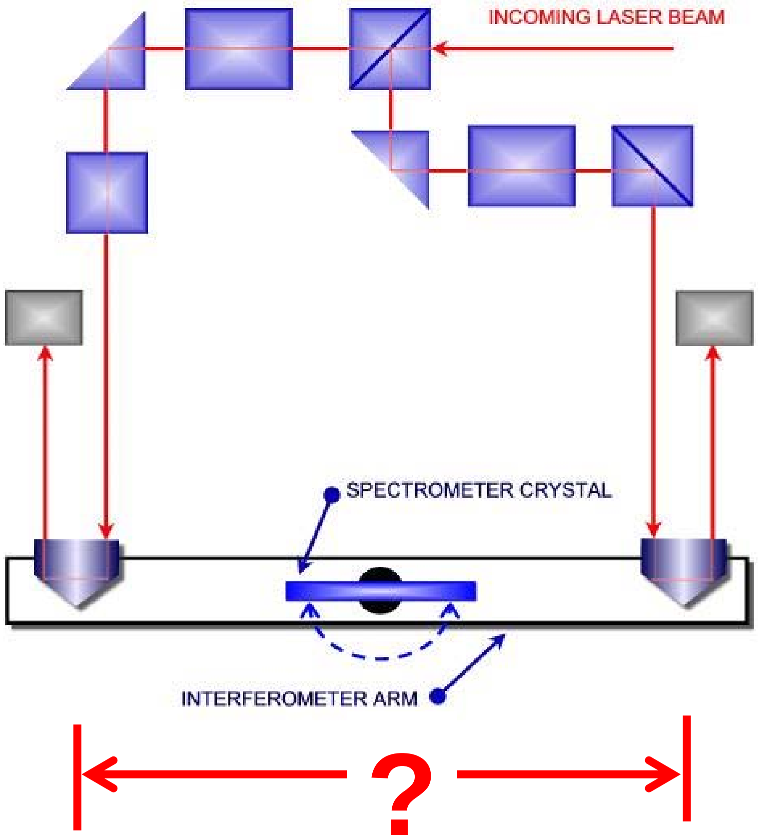




See: http://www.ill.fr/YellowBook/PN3/

Precision vs. Accuracy

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



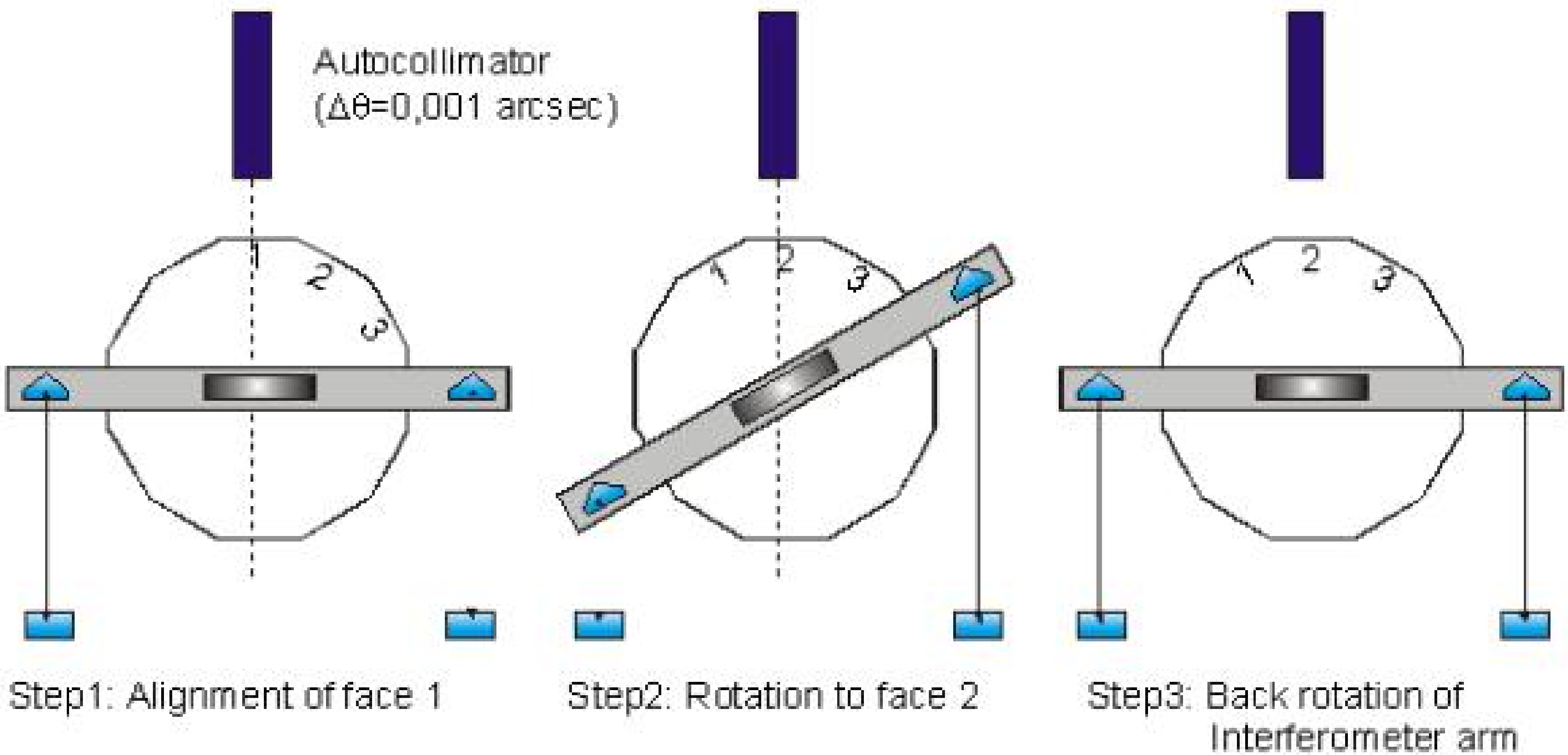
$$\tan\theta = \frac{\text{change in optical path length}}{\text{length of interferometer arm}}$$

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

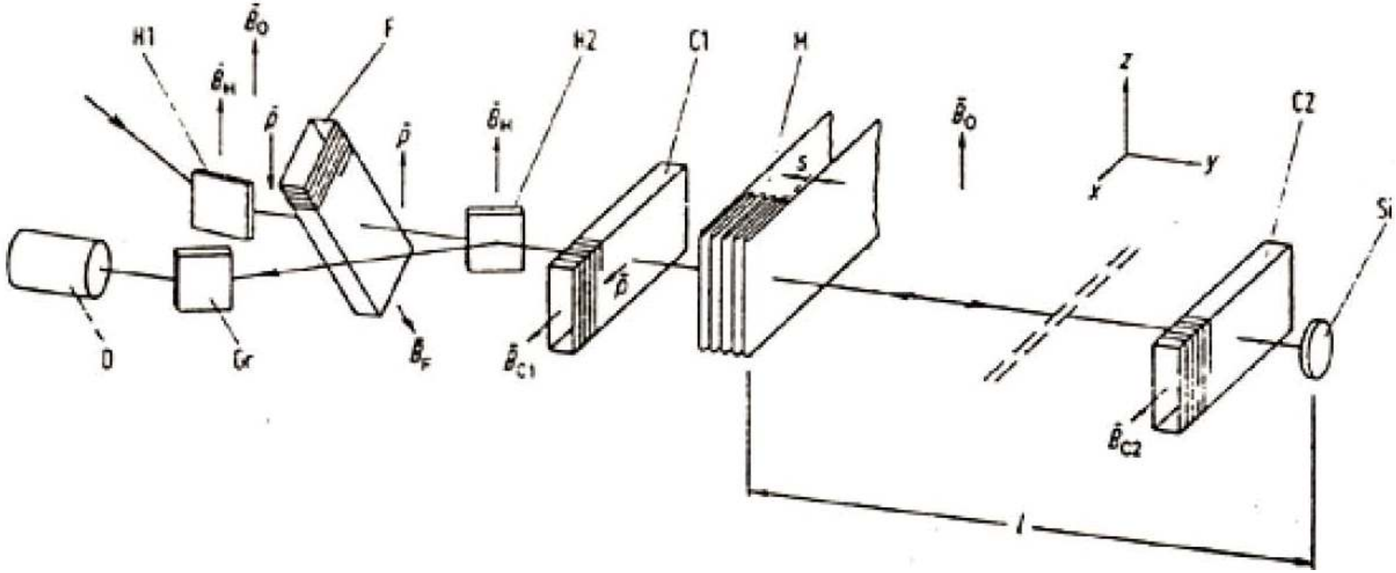
M(n) = 1.008 664 916 37(99) atomic mass units (u)

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

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

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

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

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

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

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

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

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

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

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

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

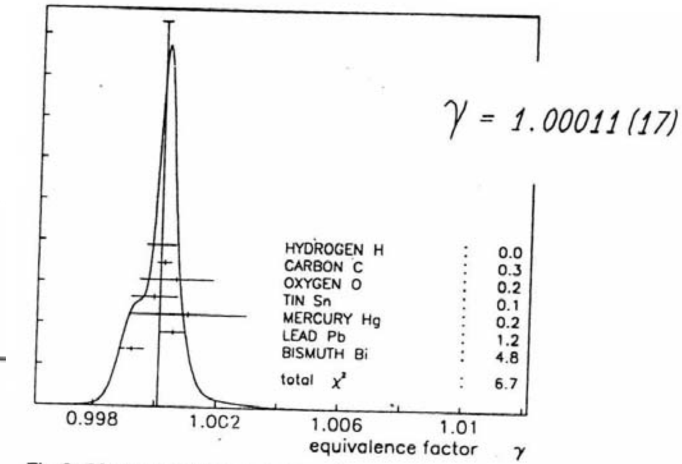


Fig. 2. *Ideogram* showing equivalence factors γ obtained from a compilation of the most accurate scattering length measurements.

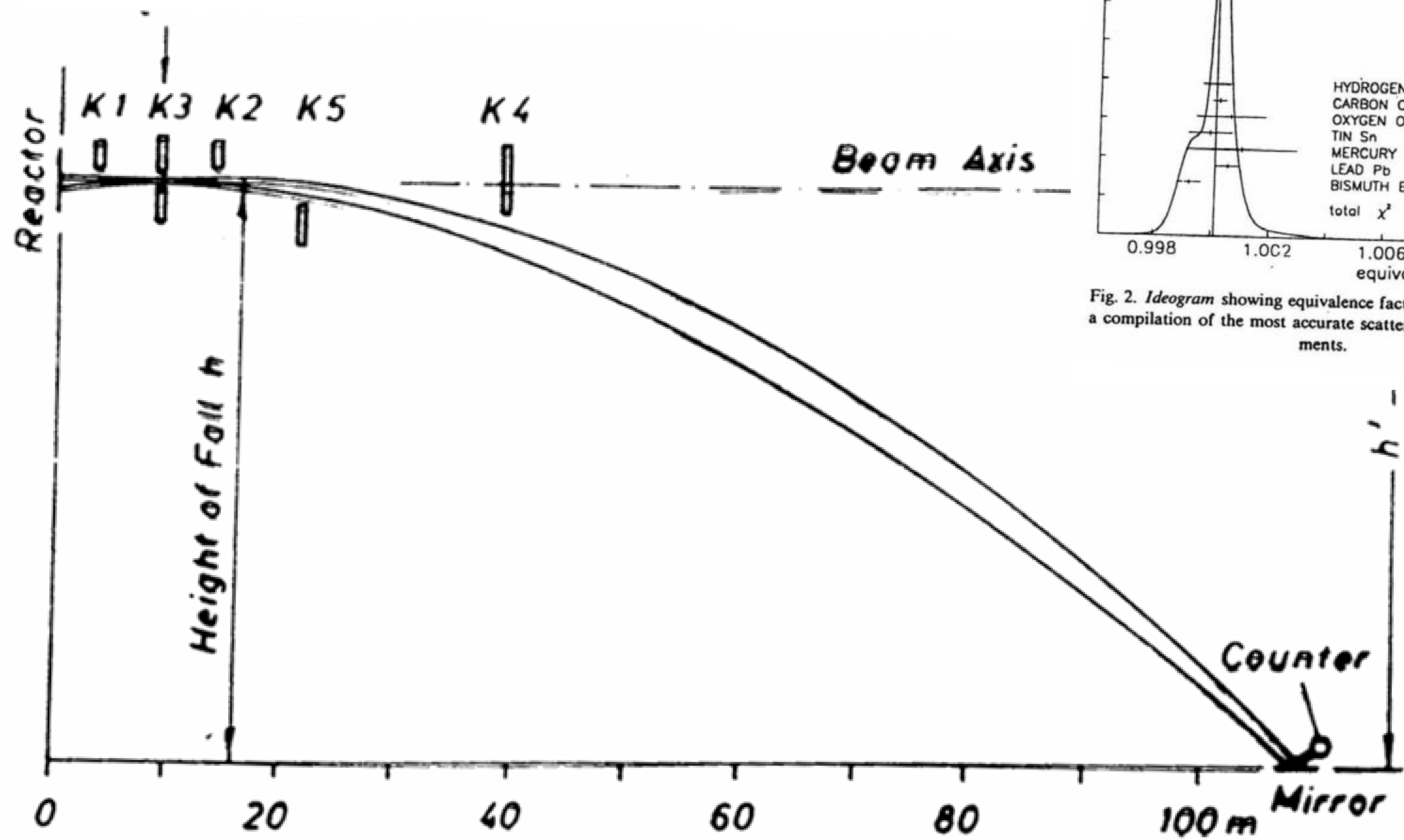


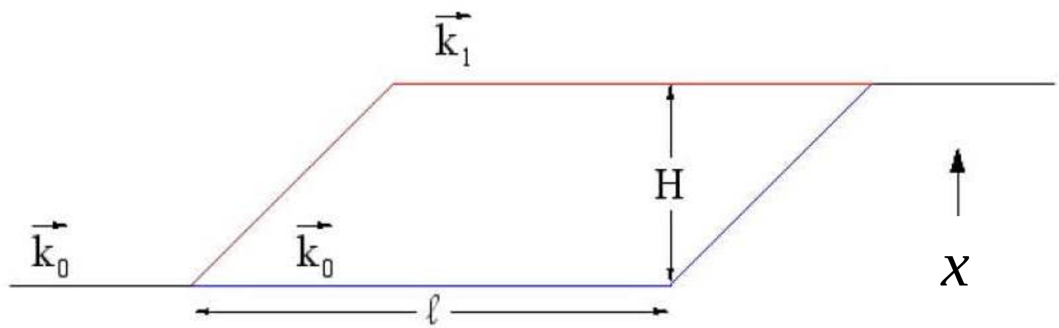
Fig. 1. Principle of the neutron-gravity refractometer

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

Quantum Mechanical Gravitational Phase Shift

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

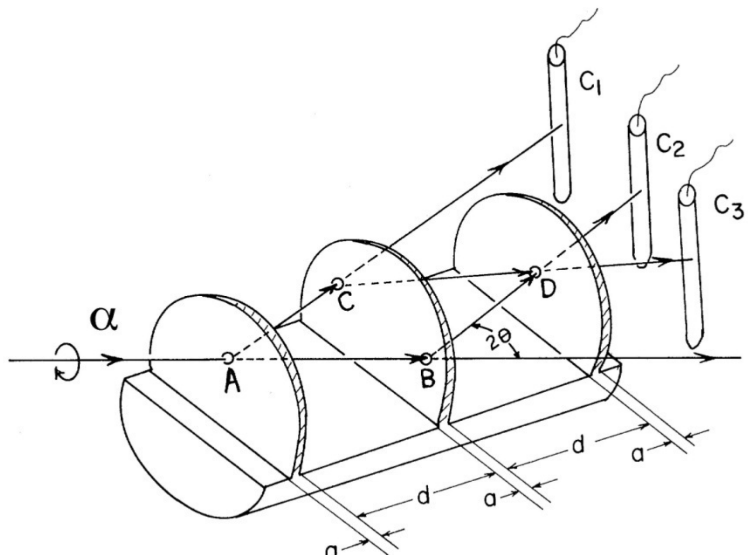
m_i = neutron inertial mass
m_g = neutron gravitational mass

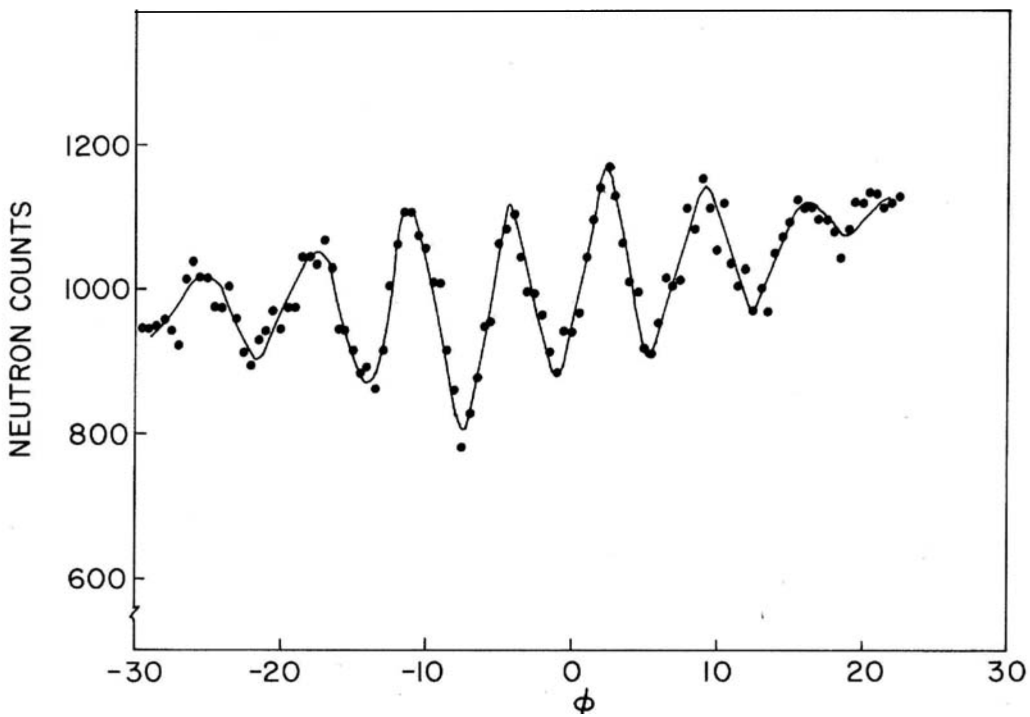


$$\Delta\phi = \frac{2\pi\lambda g A}{h^2} m_i m_g$$

A=Hl = Area of parallelogram

The Collela-Overhauser-Werner Experiment COW





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

…

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