Some Neutron Properties

<u>Mechanical</u>

- ***Mass***
- ***Spin (Angular Momentum)***

<u>Electrical</u>

- ***Charge (?)***
- ***Magnetic Dipole Moment***
- ***Electric Dipole Moment***
- ***Electric Polarizabilitiy***
- ***Internal Charge Distribution***
- ***…***

<u>Nuclear</u>

- ***Lifetime***
- ***Decay Correlations***
- ***Rare Decay Modes***
- ***Intrinsic Parity (P)***
- ***Isospin (I)***
- ***Baryon Number (B)***
- ***Strangeness (S)***
- ***…***

The Neutron Mass

M(n) = 1.008 664 915 78(55) atomic mass units (u)

Important Observation:

$$m_n > m_p + m_e$$

939.565 Mev > 938.272 MeV + 0.511 MeV = 938.783 MeV

This mean that it is energetically possible for the neutron can decay via:

$$n \rightarrow p + e + \overline{\upsilon}_e$$

The beta decay of the neutron is the prototype for essentially all radioactivity

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= ma corresponds to m_i *F=GmM/r2 corresponds to* m_g

$$F = m_i a_n$$
$$m_g g = m_i a_n$$

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

Neutron "Gravitational" Mass

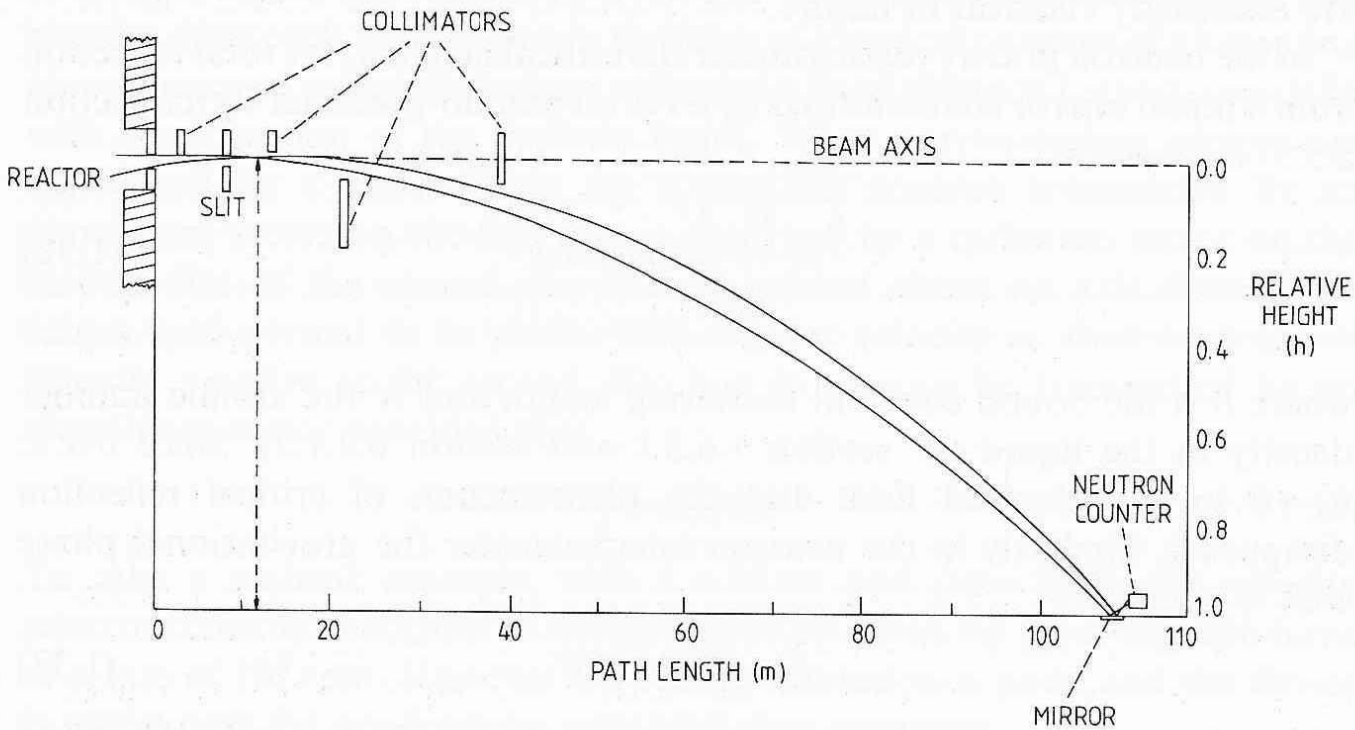


Figure 1.2. The neutron gravity refractometer designed by Koester (1965) to measure scattering lengths by determining the critical heights for reflection of neutrons from the surface of a liquid mirror. By operating with a known scattering length the instrument has been used to demonstrate the equality of the inertial and gravitational masses of the neutron.

$$\frac{m_g}{m_i} = 1.00011(17)$$

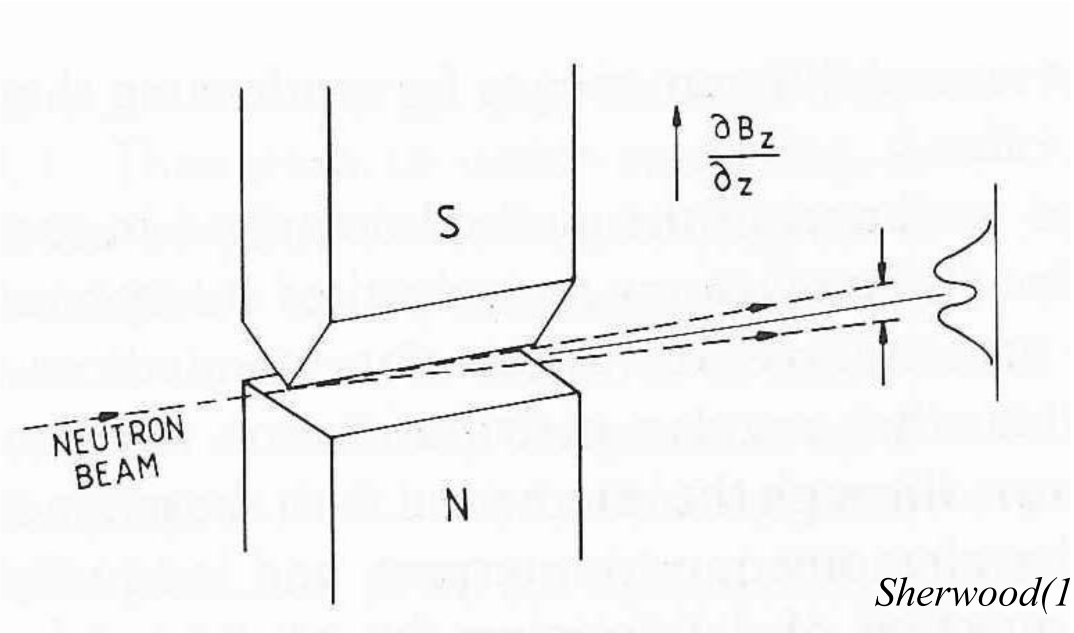
The Neutron Spin (Angular Momentum)

A detailed analysis of the scattering of neutrons from ortho and para-hydrogen can be used to determine that the neutron has s=½ (Schwinger 1937)

A more explicit demonstration uses the fact that the neutron has finite magnetic moment and thus will feel a force in an in homogeneous magnetic field of:

$$\boldsymbol{F} = -\nabla(\boldsymbol{\mu} \cdot \boldsymbol{B})$$

This force leads to a deflection in a Stern-Gerlach Apparatus:



Sherwood(1954),, Barkan (1968),…

The Neutron Charge - Is it "REALLY" Neutral

From time to time, the absolute 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 is the only neutral fundamental particle on which a precision test of neutrality has been made.

The Experiment: Use "BRUTE FORCE" – That is, measure the deflection of a neutron beam in a transverse electric field.

Neutron Velocity	*200 m/s*
Flight Path	*10 m*
Electric Field	*60 kV/m*
Deflection Sensitivity	*~1 nm*

Result: $Q_n = -0.4 \pm 1.1 \times 10^{-21}\ e$

The neutrality of the neutron combined with the measured equality of the electron and proton charge (from the neutrality of atoms) provides a precise test of the neutrality of the neutrino and/or charge conservation in the weak interaction,

Electrical and Magnetic Moments of the Neutron

Since the neutron has an internal charge distribution, it can in principle have various E-M moments (i.e. monopole, dipole, quadropole, hexadecapole,…):

Scalar Moment:

Electric	*This is just the total charge*
Magnetic	*This would be a magnetic monopole*

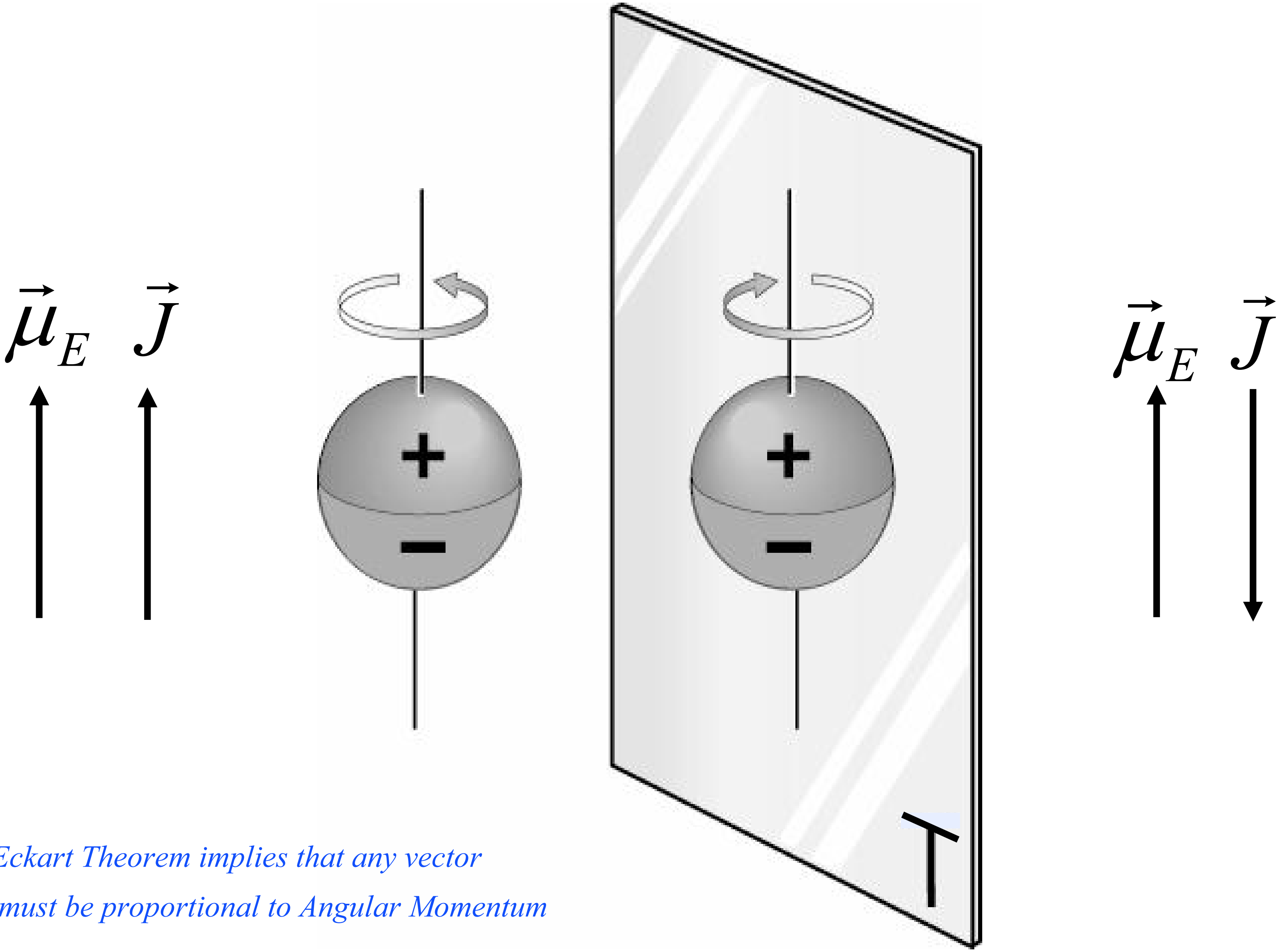
Vector Moments:

Magnetic	*This is the usual "magnetic" dipole moment*
Electric	*An electric dipole moment would result from a small displacement of the net + and net - charges*

~~*Higher Moments:*~~

Higher moments (quadropole and above are strictly forbidden by the Wigner-Eckhart theorem. Basically this say that a spin ½ system is not "complicated" enough to exhibit static moments higher than a dipole.

An Electric Dipole Moment Violates T Non-Invariance



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

The Neutron EDM, Time Reversal, and the Cosmic Matter / Anti-Matter Asymmetry

Observation: The Universe is made entirely of Matter. There is essentially NO Antimatter out. There are occasional positrons,…but there are NO anti-matter galaxies, antimatter stars,…

Question: Why?

Conjecture:

- *In the early phases of the Big Bang ($t \leq 10^{-6}$ s), there was a perfect symmetry between matter and antimatter.*
- *At about $t \approx 10^{-6}$ s, when quarks coalesced into hadrons (p,n,…) a "Baryon number" violating process made a very slight imbalance in the amount of matter and antimatter.*
- *As the temperature of the universe dropped all the antimatter annihilated leaving a tiny amount of matter and a lots of photons. These photons are still around (highly red-shifted) in the form of the Cosmic Microwave Background (CMB). The ratio of matter to CMB photons is about 10^{-10}.*
- *This process can only occur if there is T violation!*

The same T violating process that leads to a matter/antimatter asymmetry will also lead to a neutron edm. Observation/Measurement of an EDM can provide a fundamental test of the physics of the Big Bang!

Other Electromagnetic Properties

- *The total charge of the neutron is zero but since the neutron has finite size (~1 fm), this charge could have a radial distribution:*

In fact, this is the case and this distribution gives a very small neutron-electron interaction. There can also be a distribution of magnetism.

- *Because the neutron is a composite structure, that is held together by non-electromagnetic forces it is, in principle "polarizable." That is, the application of a strong electric or magnetic field will "induce" a dipole moment. This gives rise to a potential of the form:*

$$V = -\frac{1}{2}\alpha E^2 - \frac{1}{2}\beta B^2$$

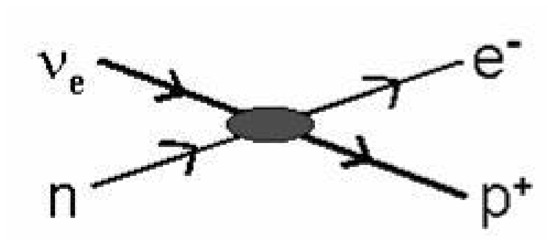
The electric polarizability has been measured and is an important quantity for the testing of certain nuclear theories.

Introduction to Neutron Decay

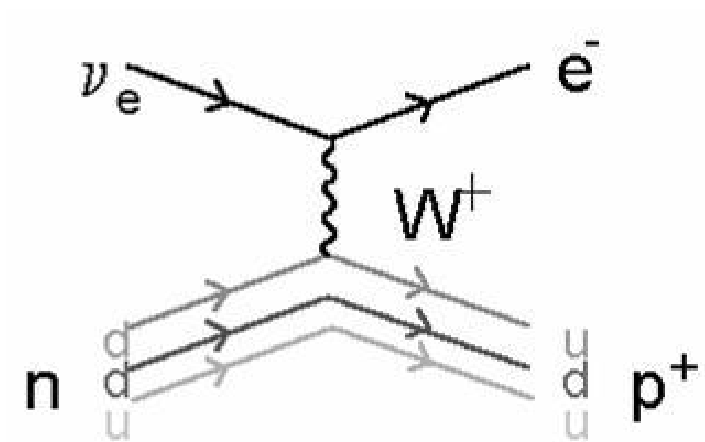
$$n \rightarrow p^{+} + e^{-} + \overline{\nu}_{e}$$

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

Neutron decay is best viewed as an interaction:



Actually, it is the quarks within the neutron that are interacting



Theoretical Implications the Neutron Beta-Decay Lifetime

Cosmology:

The neutron lifetime sets the time scale over which nucleosynthesis occurs during the Big-Bang. The comparison of the neutron lifetime, the cosmological He/H (or D/H) ratio, and the number of neutrino species provides a prediction for the Universal Baryon Density. This is a critical component of the "Dark Matter Problem."

Astrophysics:

The reaction which provides the dominant source of energy in the Sun (pp fusion) is governed by the same matrix element as neutron decay. The neutron lifetime is a key parameter of the solar models which are involved in the "Solar Neutrino Problem"

Particle Physics:

A comparison between the neutron lifetime and neutron decay correlations provides a unique test of the standard model, as well as providing an insight into the origin of parity violation.

Some of the reactions in Big Bang Nucleosynthesis

$$n \rightarrow p + e + \overline{\nu}$$

$$p + n \rightarrow d + \gamma$$

$$p + D \rightarrow {}^{3}He + \gamma$$

$$D + D \rightarrow {}^{3}He + n$$

$$D + D \rightarrow T + p$$

$$D + T \rightarrow {}^{4}He + n$$

$$D + {}^{3}He \rightarrow He + p$$

$${}^{3}He + {}^{3}He \rightarrow {}^{4}He + 2p$$

….

..

The "Time Scale" for Big Bang Nucleosynthesis is Given by the Neutron Lifetime

If τ_n were much smaller (seconds instead of minutes), there would be no neutrons left when the universe was cool enough for nuclei –

THE UNIVERSE BE ALL HYDROGEN

If τ_n were much larger (say hours instead of minutes), there would be no significant decrease in the number of neutrons when the neutrinos decouple ($t \approx 1$ s)-

THE UNIVERSE BE ~2/3 He, ~1/3 H

IN EITHER CASE, THE SUBSEQUENT EVOLUTION OF THE UNIVERSE WOULD BE VERY DIFFERENT !