The Fundamental Properties of the Neutron I

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Why Study Neutrons?

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

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

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

The neutron is well suited as a laboratory for tests of physics beyond the Standard Model.
The Neutron is complicated enough to be interesting...

But is simple enough to be understandable.
Some Useful References

Fermi, *Lecture Notes on Nuclear Physics*
Byrne, *Neutrons, Nuclei and Matter*
Golub, Lamoreaux, Richardson, *Ultracold Neutrons*
Commins and Bucksbaum, *Weak Interactions of Quarks and Leptons*
Particle Data Group, [pdg.lbl.gov](http://pdg.lbl.gov)
Acknowledgements for images

Mike Snow, Fred Weitfeldt, Brad Fillipone, Jeff Nico, Paul Huffman, Scott Dewey,...
Short History Lesson
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. 
\[ \alpha + ^9\text{Be} \rightarrow ^{12}\text{C} + n \]

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


Chadwick claimed this was Rutherford’s “Neutron”. 

“Neutron”
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*:

\[ M_n = 1.0080 \pm 0.0005 \]

**KEY OBSERVATION:** \( M_n > M_p + M_e \)

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

2. It is energetically possible for a neutron to decay to \( e^- + p^+ \)
Some Neutron Properties

**Mechanical Properties**
*Mass*
*Gravitational Mass (equivalence principle test)*
*Spin*

**Electromagnetic Properties**
*Charge (or limit on neutrality)*
*Internal Charge Distribution*
*Magnetic Dipole Moment*
*Electric Dipole Moment*

**Neutron Decay**
*Neutron Mean Lifetime*
*Correlations in Neutron Decay*
*“Exotic” Decay modes*

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

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

The quark masses are thought to be a minor contribution.

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

The current challenge is to provide a robust estimate for the neutron-proton mass difference.
Assume that isospin is broken by electromagnetic
\[(m_p - m_n) c^2 \approx \frac{e}{\hbar} \text{ nucleon}\]
Thus
\[m_p - m_n \approx 100 \text{ keV}\]
Why does the free neutron decay?

The reaction \( n \rightarrow p + e^- + \bar{\nu}_e \) proceeds because \( m_n > m_p + m_e \)

\[ m_{\text{nucleon}} = BE(\text{strong}) + BE(\text{electrostatic}) + m(\text{quarks}) \]

**Strong:**

\[ BE(\text{neutron}) = BE(\text{proton}) \]

*isospin symmetry of strong force*

**Electrostatic:**

\[ BE = \frac{1}{2} \sum_{i<j} \frac{q_i q_j}{r_{ij}} \]

\( BE(\text{proton}) = 0 \)

\( BE(\text{neutron}) \approx -160 \text{ keV} \)

**Quark masses:**

- up (~4 MeV)
- charm (1.2 GeV)
- top (175 GeV)
- down (~7 MeV)
- strange (150 MeV)
- bottom (4.2 GeV)

If \( m(\text{up}) > m(\text{down}) \) the hydrogen atom would decay by electron capture with a lifetime of <14 years!
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.*
The Neutron Spin
The Neutron has an Intrinsic Spin of $s = \frac{1}{2}$

1934 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 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 $\vec{L} = \hbar \vec{\sigma}$
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:**
\[
\hat{C} \cdot \Psi_n \Rightarrow \Psi_{\bar{n}} : \quad q \Rightarrow -q
\]

Wigner-Eckhart Theorem Implies \[ \vec{\mu} = \mu \vec{J} \text{ and } \vec{d} = d \vec{J} \]

Non-Relativistic Hamiltonian
\[
H = \vec{\mu} \cdot \vec{B} + \vec{d} \cdot \vec{E}
\]

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Non-zero \(d\) violates \(P, T,\) and \(CP\)

After B. Fillipone
Non-Elementary Particles can have EDM’s
Without Violating Parity and Time Reversal Symmetry

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

However, it would then have a degenerate ground state which is incompatible with observed nuclear shell structure.
“It is generally assumed on the basis of some suggestive theoretical symmetry arguments that nuclei and elementary particle can have no electric dipole moments. It is the purpose of this note to point out that although these theoretical arguments are valid when applied to molecular and atomic moments whose electromagnetic origin is well understood, their extension to nuclei and elementary particles rests on assumptions not yet tested.”

E.M. Purcell and N.F. Ramsey,
Physical Review 78, 807 (1950)
Parity in 2 Dimensions

In a Euclidean space of even dimension,

Parity = Rotation
Question: What about “space-time”
Isn’t it 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
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 ($T>>1$ 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”

Question:

Can the T violation needed to generate the matter-antimatter asymmetry when the universe was $10^6$ s old be related to an observable quantity today?
If the matter-antimatter asymmetry is generated by a $T$-violating process during the big bang, the same process would generate a neutron edm 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.
If a neutron were blown up to the size of the earth, the current limit on its EDM would correspond to a displacement of + and - electron charge by \( \pm 10 \, \mu m \)
Neutron Beam EDM Experiment

Incoming neutrons

π/2 rotation

Polarizer

or

B E

or

B E

π/2 phase shift

Analyzer

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

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
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.

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 $\Delta M$, the neutron lifetime is estimated at $\sim \frac{1}{2}$ hr.

1948    Snell and Miller observe neutron decay at Oak Ridge.
$n \rightarrow p^+ + e^- + \bar{\nu}_e$

**Fermi’s View of Neutron Decay:**

**Modern View of Neutron Decay:**
Processes with the same Feynman Diagram as Neutron Decay

Primordial element formation

\[ n + e^+ \leftrightarrow p + \nu_e \]
\[ p + e^- \leftrightarrow n + \nu_e \]
\[ n \rightarrow p + e^- + \bar{\nu}_e \]

Solar cycle

\[ p + p \rightarrow {}^2H + e^+ + \nu_e \]
\[ p + p + e^- \rightarrow {}^2H + \nu_e \quad \text{etc.} \]

Neutron star formation

\[ p + e^- \rightarrow n + \nu_e \]

Pion decay

\[ \pi^- \rightarrow \pi^0 + e^- + \bar{\nu}_e \]

Neutrino detectors

\[ \nu_e + p \rightarrow e^+ + n \]

Neutrino forward scattering

\[ \nu_e + n \rightarrow e^- + p \quad \text{etc.} \]

After D. Dubbers
Temperature (10^{9} K)
Measuring the Neutron Lifetime

Step 1. Get One Neutron “Bottle”
Measuring the Neutron Lifetime

Step 1. Fill Neutron “Bottle”
**Measuring the Neutron Lifetime**

**Step 3.** Let neutron decays for time $t \sim T_n$
Measuring the Neutron Lifetime

Step 4. Pour neutrons out and count

\[ N(t) = N(0)e^{-t/\tau_n} \]
Some Neutron Bottles

Mampe et al, PRL 63 (1989)

Serebrov et al, Phys Lett B605 (2005)

Phenomenology of Neutron Beta Decay

Momentum Must Be Conserved!
**Phenomenology of Neutron Beta Decay**

*Momentum Must Be Conserved!*

V-A says that neutrinos are purely “Left-Handed” with
\[ \vec{\sigma} \cdot \vec{p} = -1 \]

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

Parity violation implies a rich phenomenology in neutron decay.

\[ dW \propto \frac{1}{\tau_n} F(E_e) \left[ 1 + a \frac{p_e \cdot p_\nu}{E_e \cdot E_\nu} + A \frac{\sigma_n \cdot p_e}{E_e} + B \frac{\sigma_n \cdot p_\nu}{E_\nu} + \ldots \right] \]

Much more about this in subsequent lectures
General Scheme of $n$-Beta Correlation Experiments

decay proton

decay electron

$\vec{\sigma}_n$ →

or

$\vec{\sigma}_n$ ←
“Exotic” Neutron Decay
Exotic Neutron Decay

**Allowed by the Standard Model:**

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

“radiative decay”

\[ n \rightarrow ^1H_0 + \bar{\nu} \]

**Forbidden by the Standard Model:**

\[ n \rightarrow \bar{n} \]  

“n-nbar oscillation” (\(\Delta B=2\))
No GeV background
No candidates observed.
Measured limit for a year of running:

with \( L \sim 90 \text{ m} \) and \( \langle t \rangle = 0.11 \text{ sec} \)
measured \( P_{n\bar{n}} < 1.6 \times 10^{-18} \)
\( \tau > 8.6 \times 10^7 \text{ sec} \)

Exotic Neutron Decay

Allowed by the Standard Model:

\[ n \rightarrow p^+ + e^- + \bar{\nu} + \gamma \]  
\[ n \rightarrow {^1H}_0 + \bar{\nu} \]  

"radiative decay"

Forbidden by the Standard Model:

\[ n \rightarrow \bar{n} \]  

"n-nbar oscillation" (\( \Delta B=2 \))

Forbidden by Common Sense ??

\[ n \rightarrow \Omega \]  

neutron – “mirror neutron” oscillation
Warning:

Just because something is “forbidden” by “common sense” does not mean it is not so!
Also Forbidden by Common Sense
End of Lecture