The Fundamental Properties of the Neutron I

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NIST

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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*

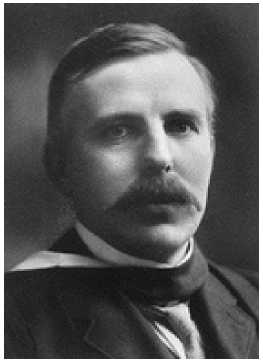
Commins and Bucksbaum, *Weak Interactions of Quarks and Leptons*

Particle Data Group, **pdg.lbl.gov**

Acknowledgements for images

Mike Snow, Fred Weitfeldt, Brad Fillipone, Jeff Nico, Paul Huffman, Scott Dewey,…

Short History Lesson



Ernest Rutherford

1920 Noting that atomic number (Z) does not correspond to atomic correspond to atomic weight, Rutherford suggests that, in suggests that, in addition to "bare" protons, the nucleus nucleus contains some tightly bound "proton- electron pairs" or electron pairs" or neutrons.

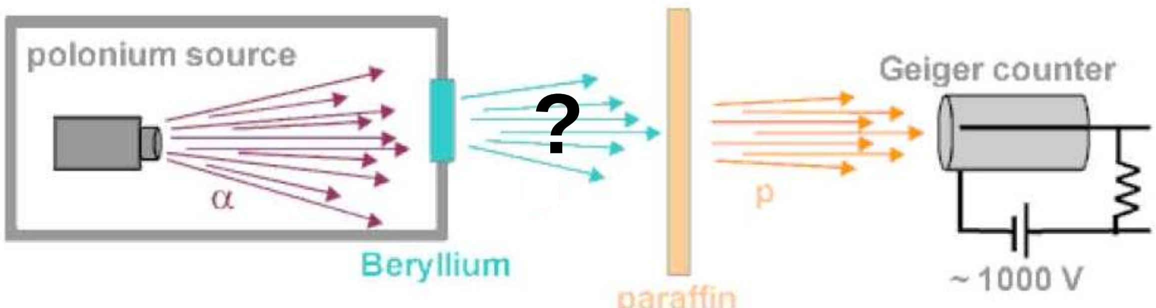
Walter Bothe

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

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

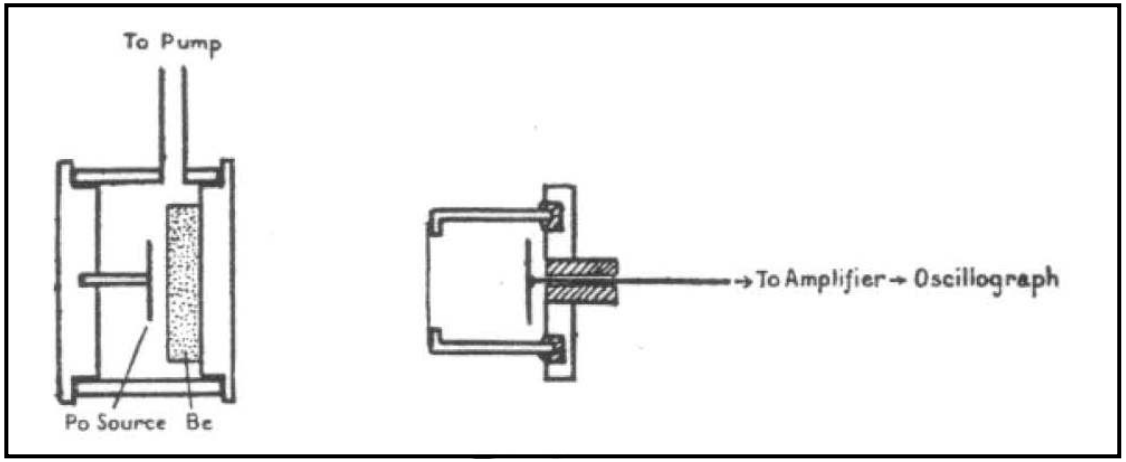
Irene Curie

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



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

James Chadwick



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

Chadwick claimed this was Rutherford's "Neutron" ***"Neutron"***

1933 Bainbridge makes precision measurements of the atomic masses ***atomic masses*** ***of the proton and the deuteron using the mass spectrograph*** ***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 ***determining the*** ***recoil energy of the protons they were able to determine*:*** ***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

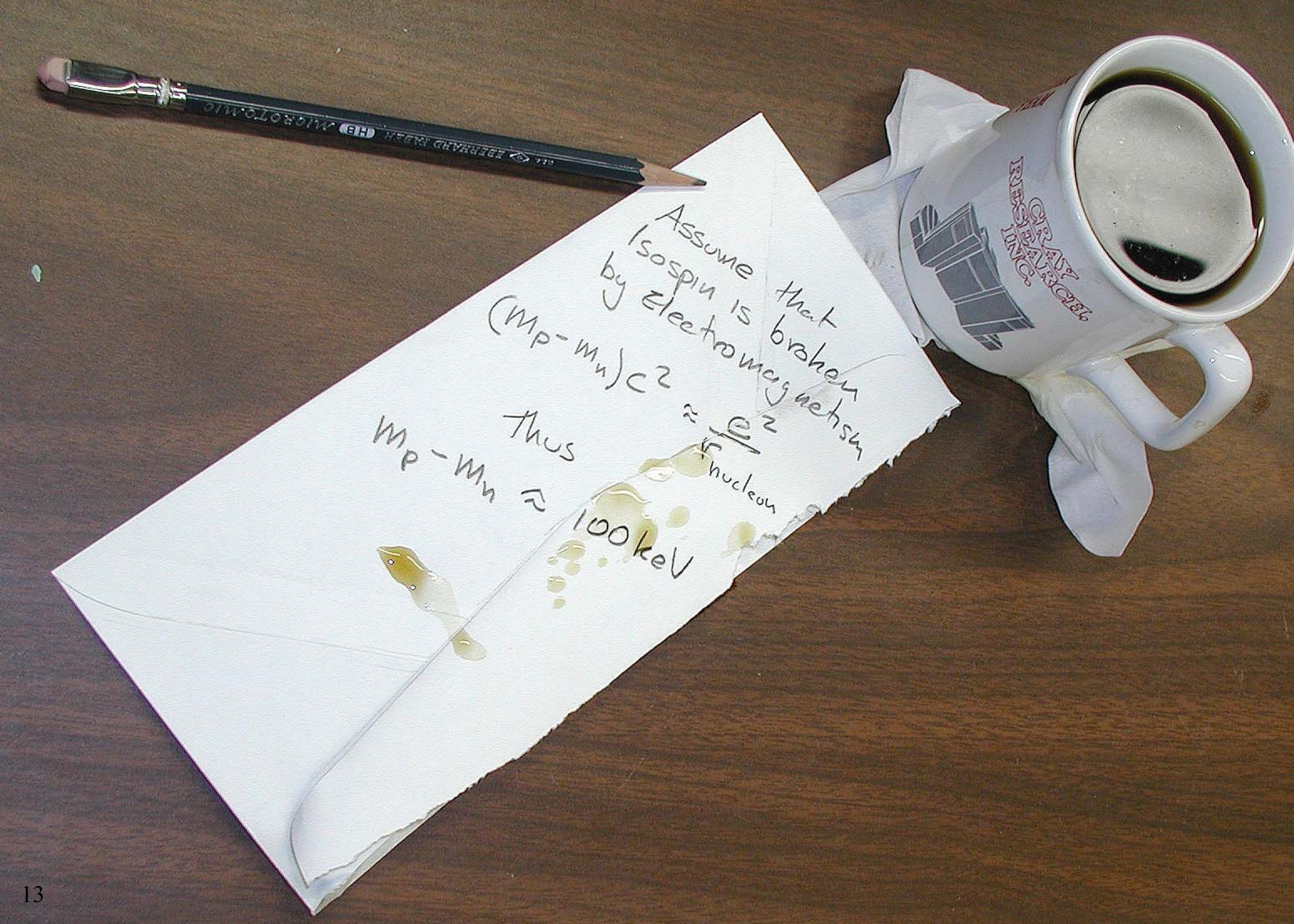
Theory of the Neutron Mass

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 Electromagnetism
$(m_p - m_n)c^2 \approx \frac{e^2}{r_{nucleon}}$
thus
$m_p - m_n \approx 100\,keV$
CRAY RESEARCH, INC.

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 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.

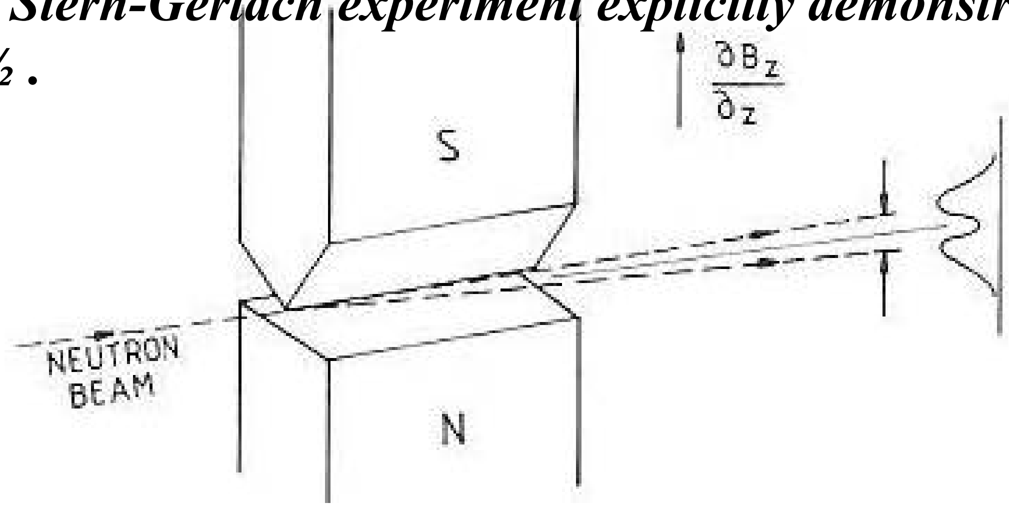
The Neutron Spin

The Neutron has an Intrinsic Spin of s=½

1934 Schwinger concludes that s=½ based on the band spectrum of
spectrum of molecular D_2 and the scattering of neutrons from ortho and
ortho and para H_2.

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

1954 Neutron Stern-Gerlach experiment explicitly demonstrates s=½ .
demonstrates s=½ .



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

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

Non-Relativistic Hamiltonian

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

C-even
P-even
T-even

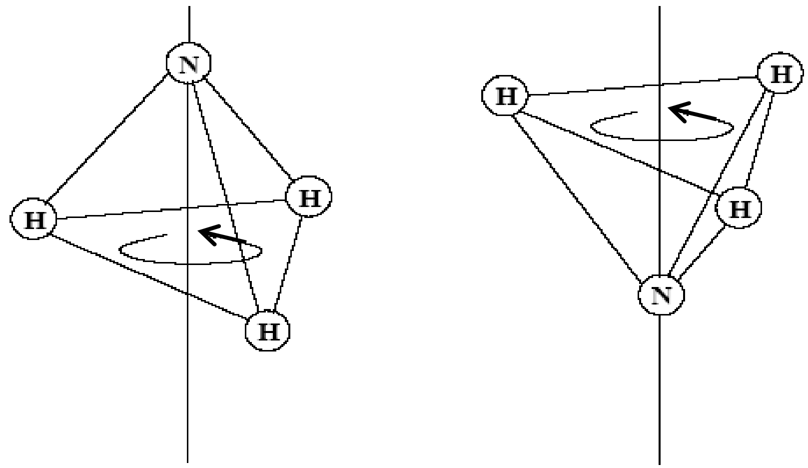
C-even
P-odd
T-odd

Non-zero d violates P,T, and CP

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

After B.Fillipone

Non-Elementary Particles can have EDM's <u>Without</u> Violating Parity and Time Reversal Symmetry

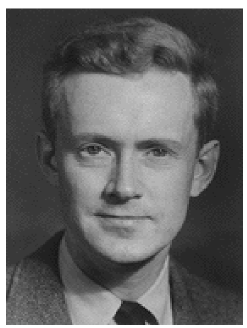


If the neutron was a composite object it could also have non-zero edm without P and T violation.

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"

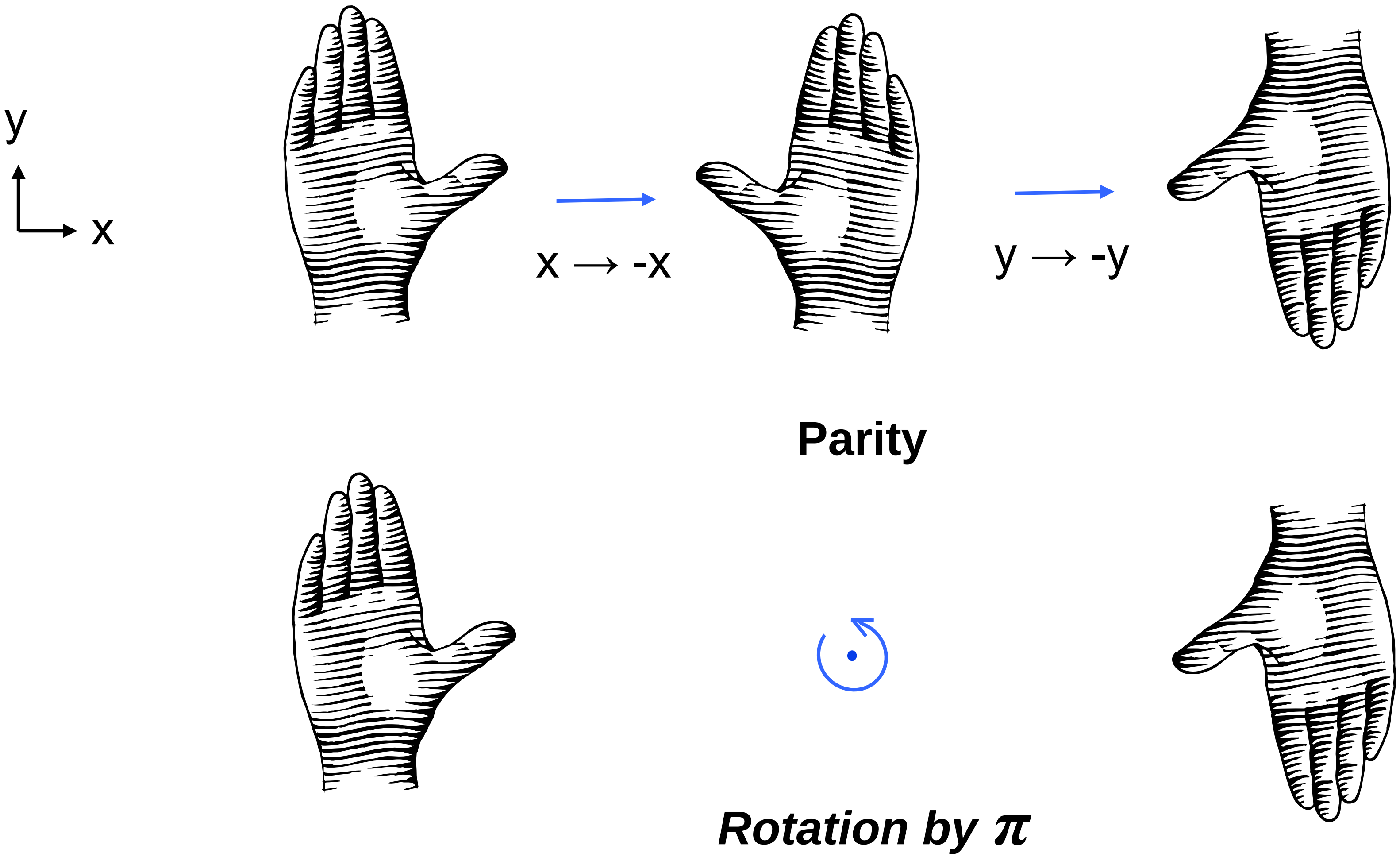
E.M.Purcell and N.F.Ramsey,
Physical Review 78, 807 (1950)



Edward Purcell

Norman Ramsey

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

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

"space-time" is not Euclidean

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

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 ($T>>1$ 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:

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

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:

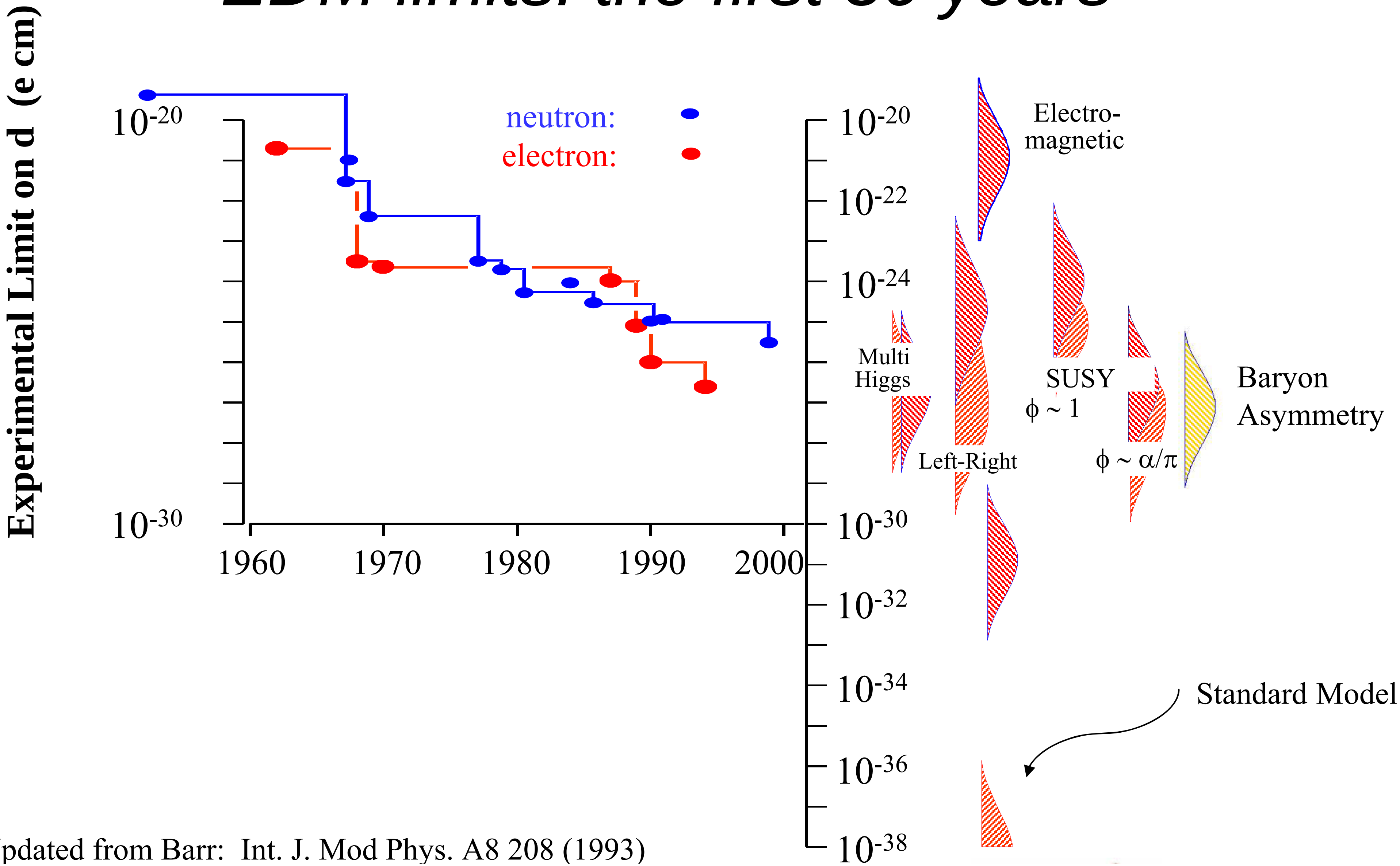
Can the T violation needed to generate the matter- antimatter asymmetry when the universe was 10^6 s old be related to an observable quantity today?

- *If the matter-antimatter 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)*

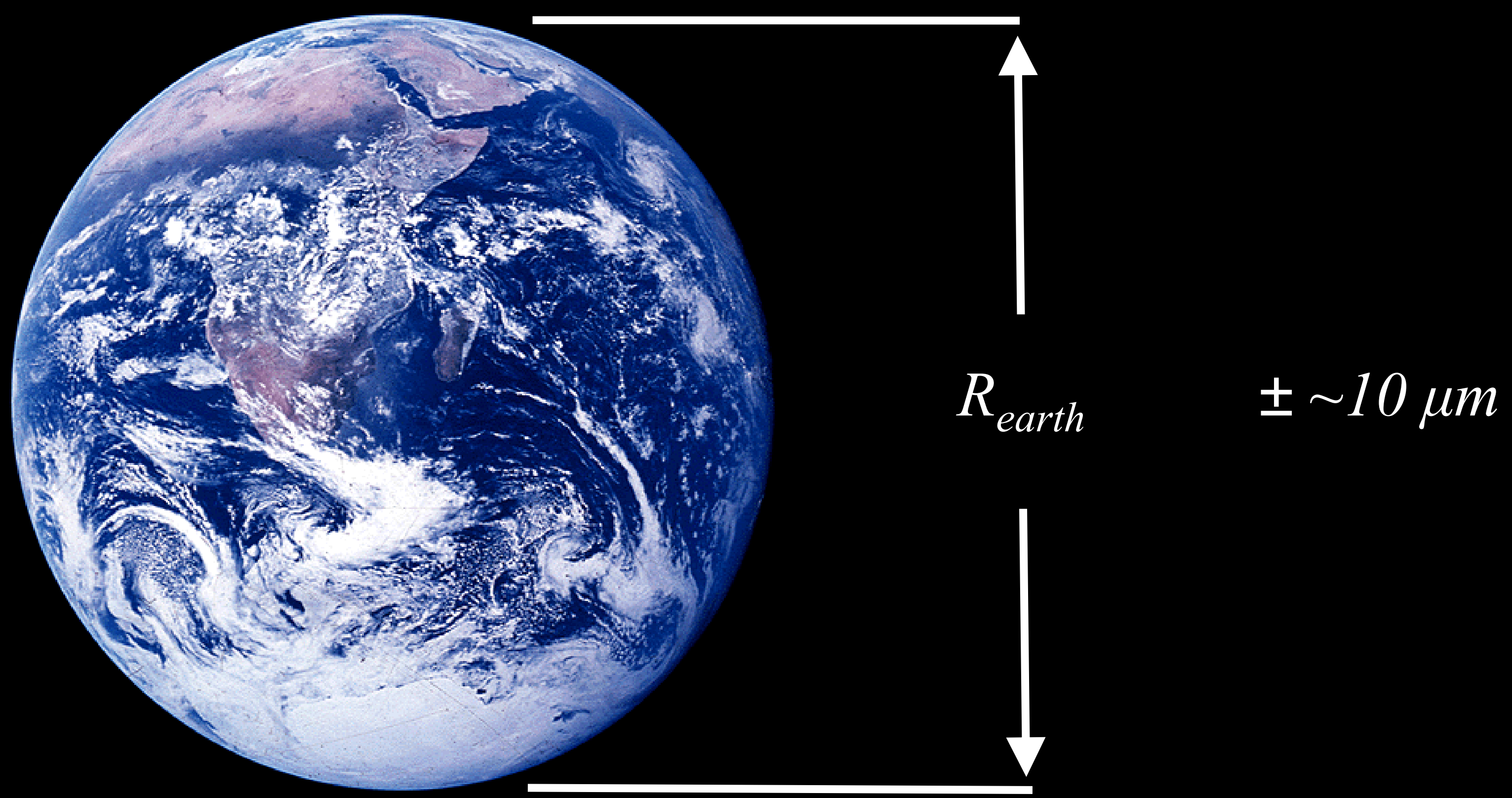
- ***The next 2 orders of magnitude will be very interesting.***

EDM limits: the first 50 years

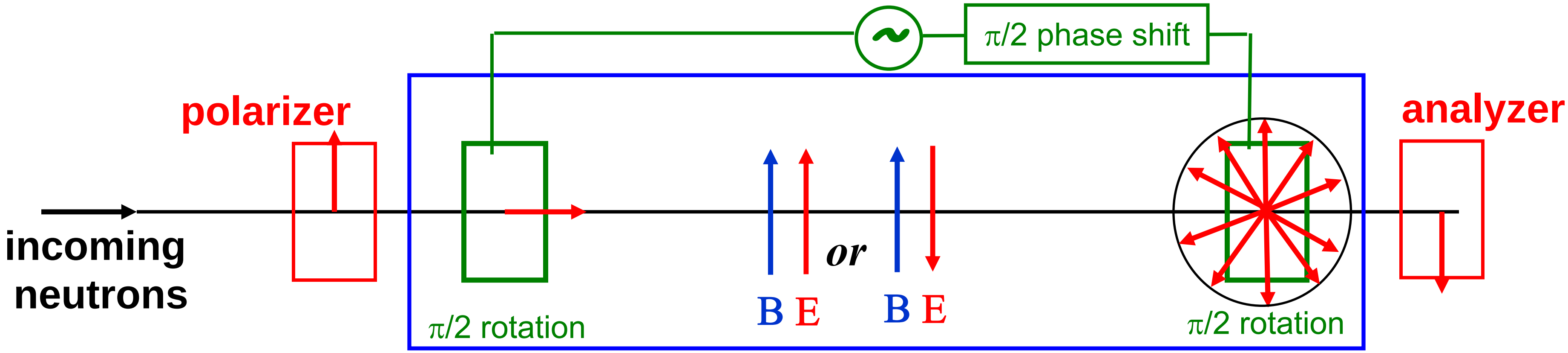


Updated from Barr: Int. J. Mod Phys. A8 208 (1993)

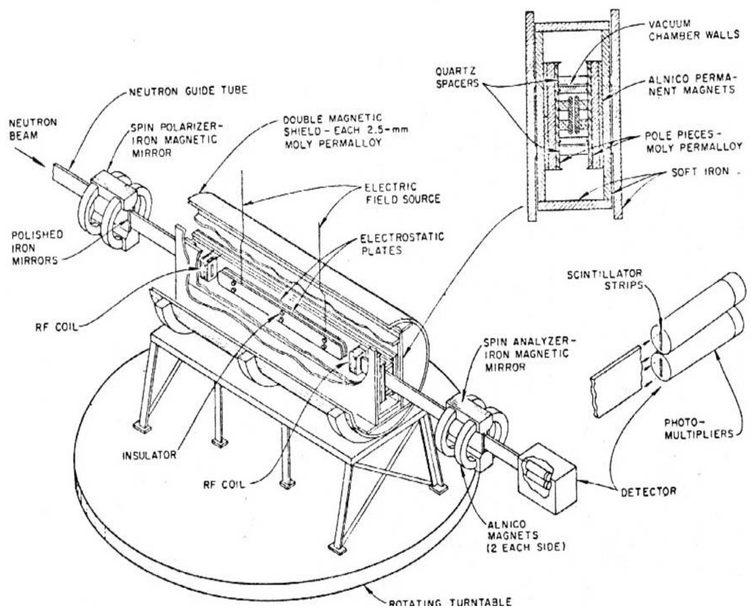
If a neutron were blown up to the size of the earth, the current limit on its EDM would correspond to a displacement of + and – electron charge by ~10 μm

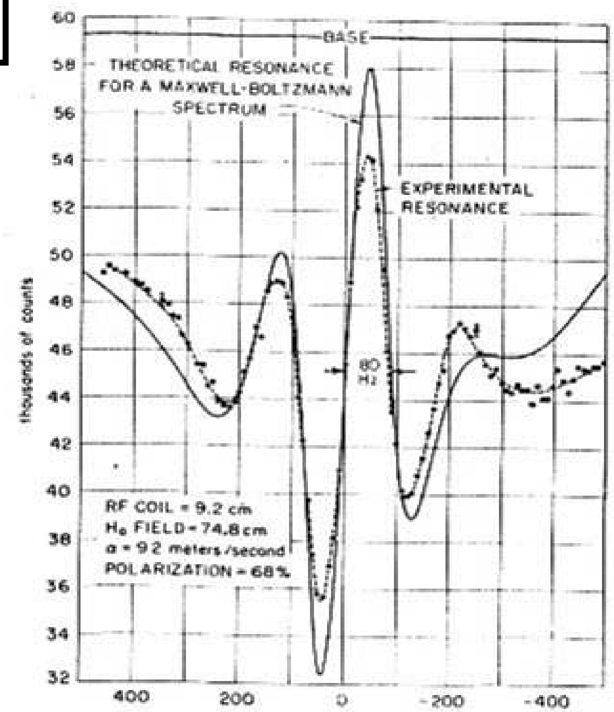


Neutron Beam EDM Experiment



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





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

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

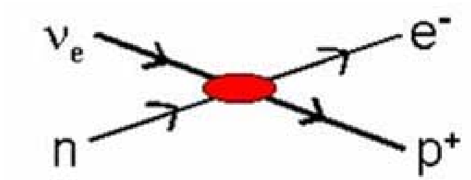
Neutron Decay

Wolfgang Pauli

Enrico Fermi

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

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



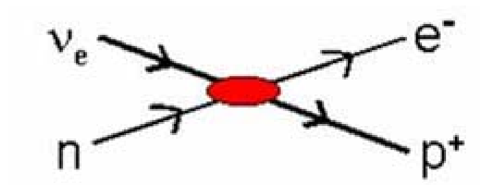
1935 The β decay of the neutron is predicted by Chadwick and Chadwick and Goldhaber based on their observation that $M_n>M_p+M_e$ observation that $M_n>M_p+M_e$.

Based on their ΔM, the neutron lifetime is estimated at ~½ hr. estimated at ~½ hr.

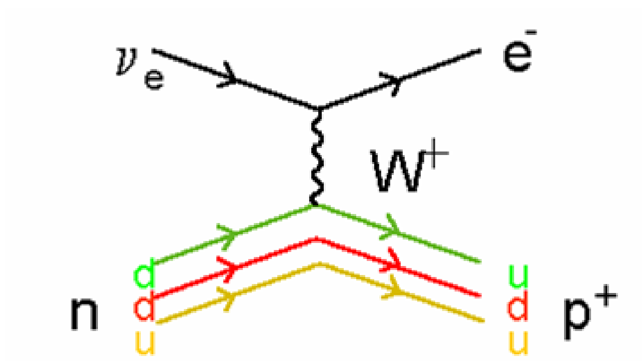
1948 Snell and Miller observe neutron decay at Oak Ridge Ridge

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

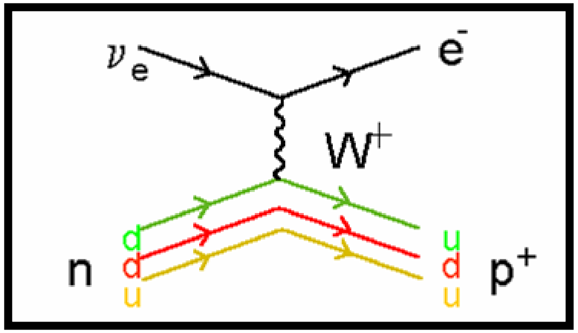
Fermi's View of Neutron Decay:



Modern View of Neutron Decay:

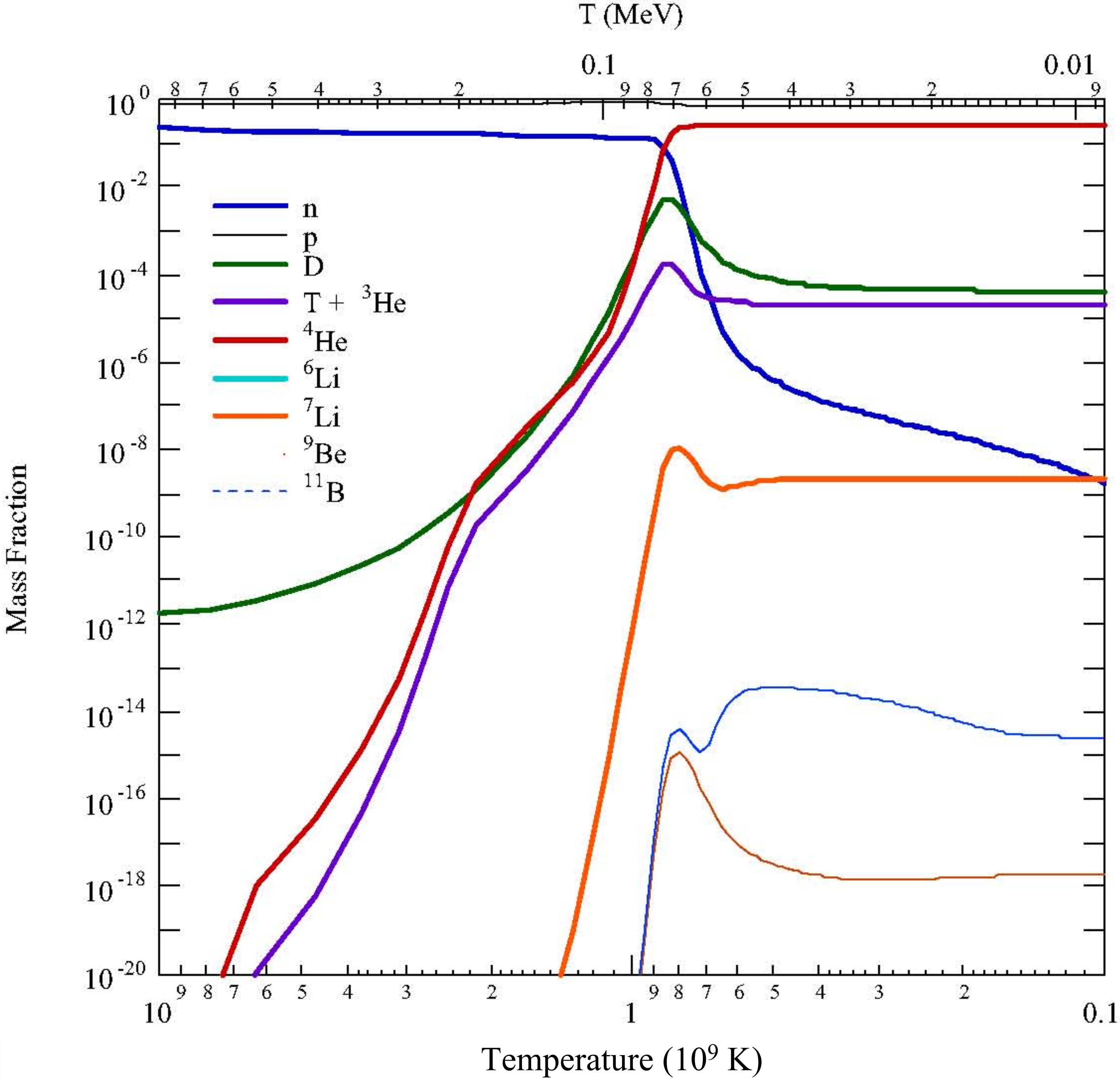


Processes with the same Feynman Diagram as Neutron Decay



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

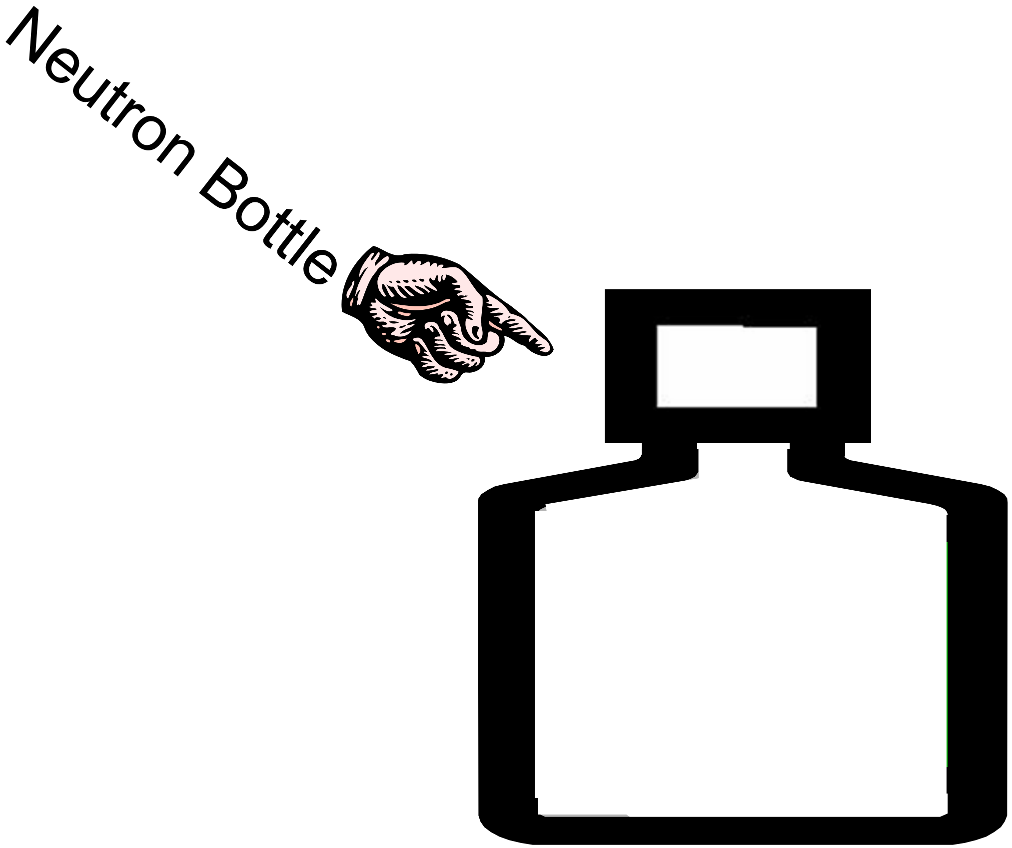
After D. Dubbers



T (MeV)
0.1
0.01
Mass Fraction
n
p
D
T + ^{3}He
^{4}He
^{6}Li
^{7}Li
^{9}Be
^{11}B
Temperature (10^9 K)

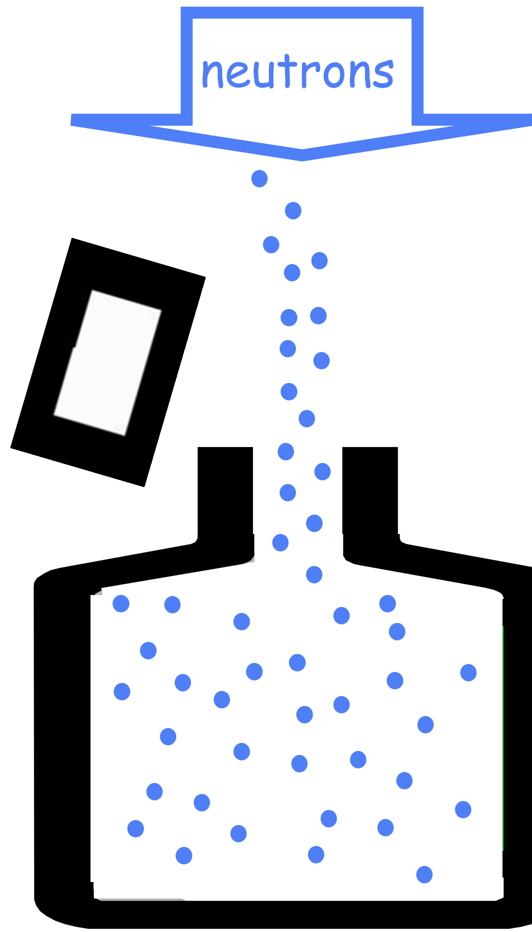
Measuring the Neutron Lifetime

Step 1. Get One Neutron "Bottle"



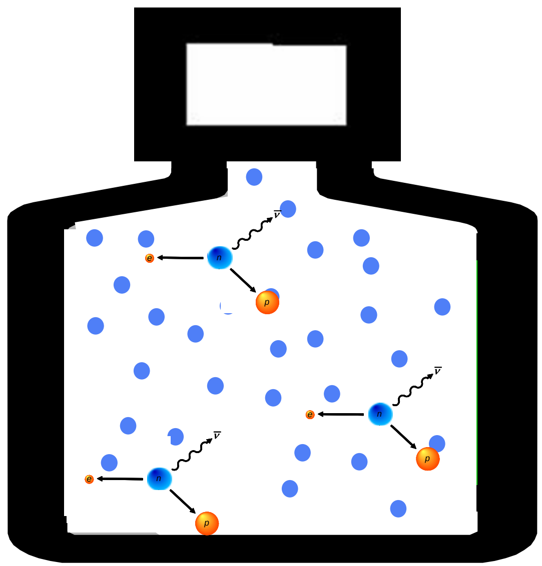
Measuring the Neutron Lifetime

Step 1. Fill Neutron "Bottle"



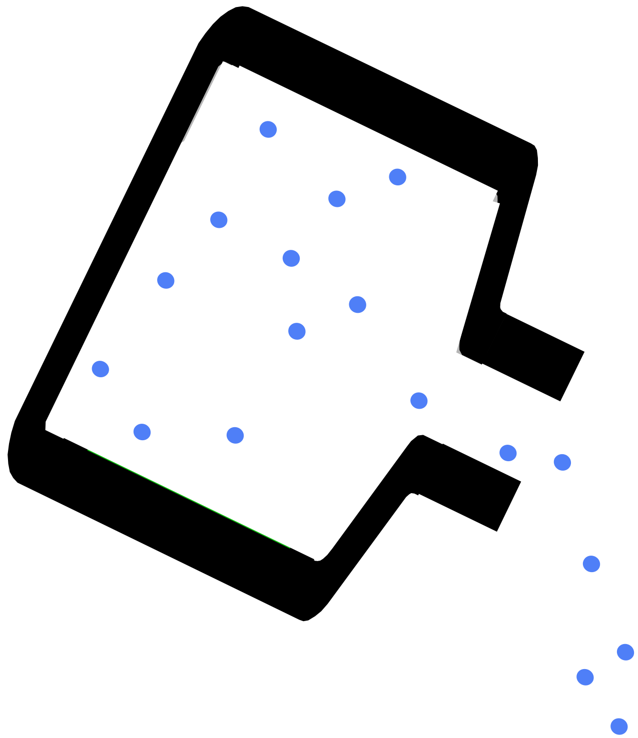
Measuring the Neutron Lifetime

Step 3. Let neutron decays for time $t \sim \tau_n$



Measuring the Neutron Lifetime

Step 4. Pour neutrons out and count



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

Some Neutron Bottles

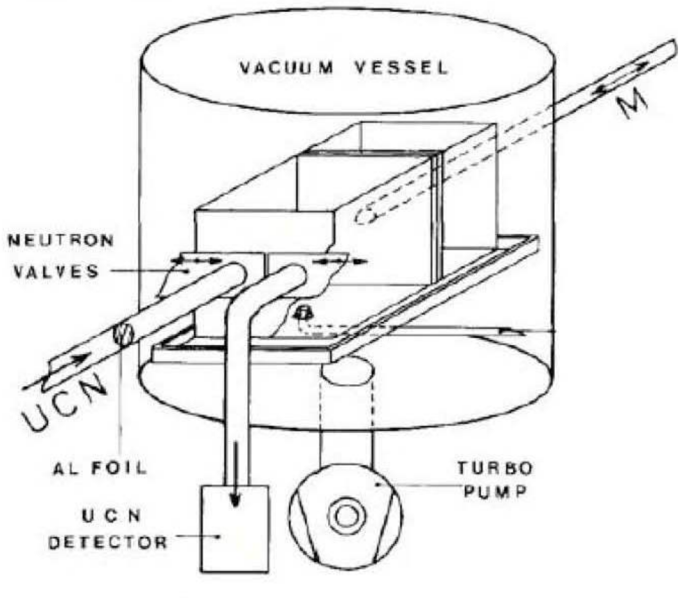
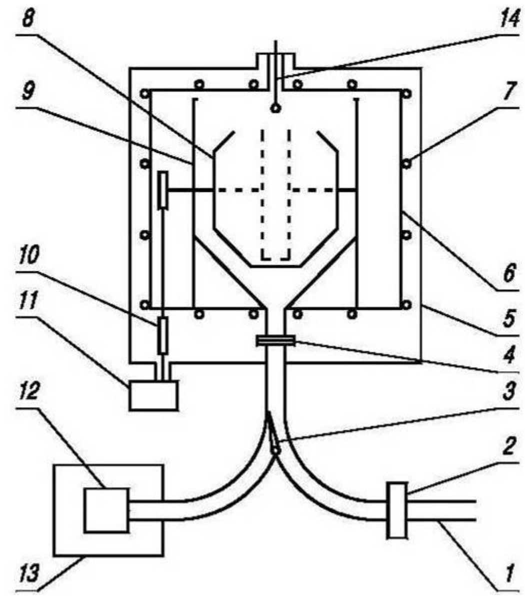
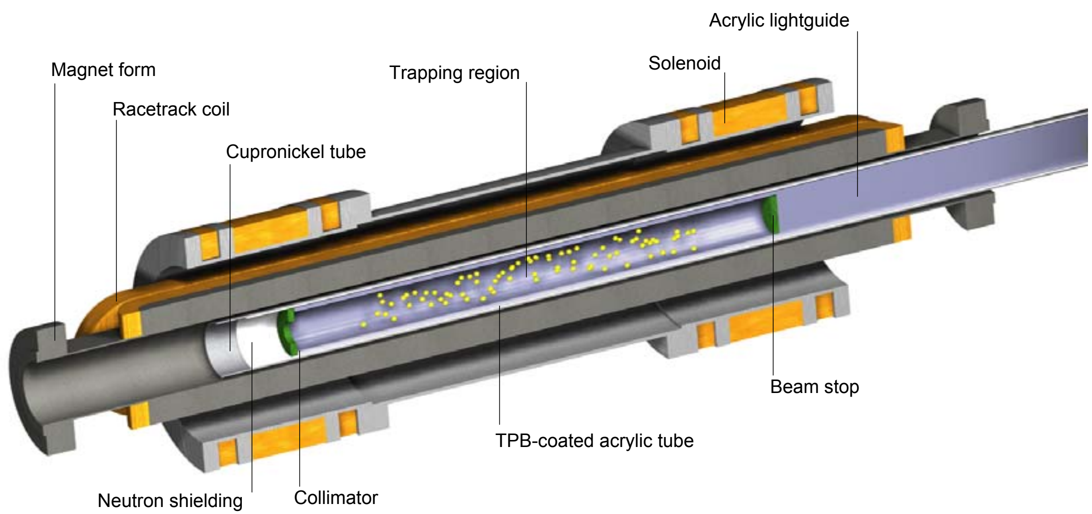


FIG. 1. Sketch of the apparatus.

Mampe et al, *PRL* ***63*** *(1989)*



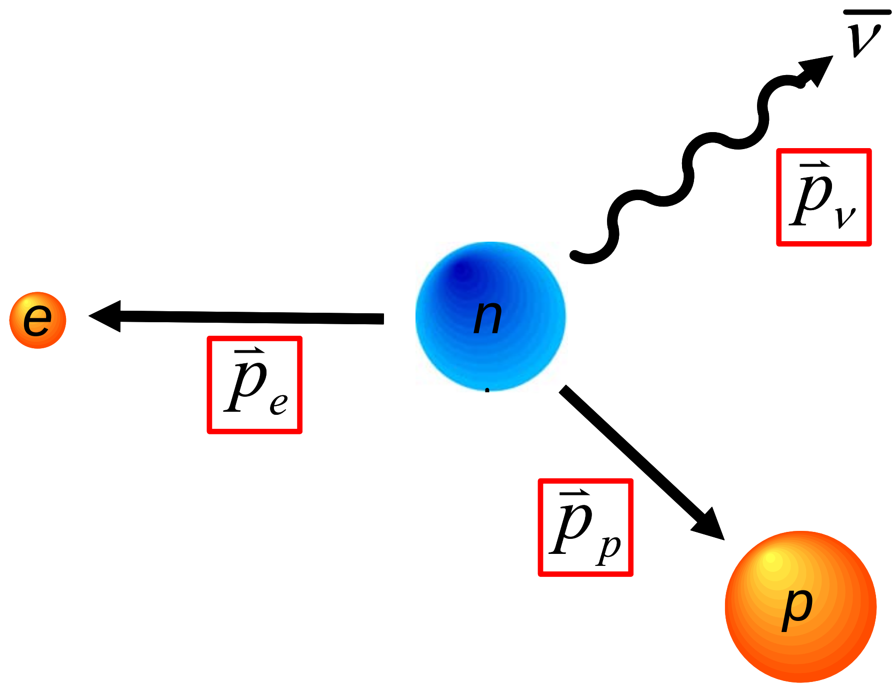
Serebrov et al, Phys Lett B605 (2005)



Huffman, et al, Nature, 403 (2000)

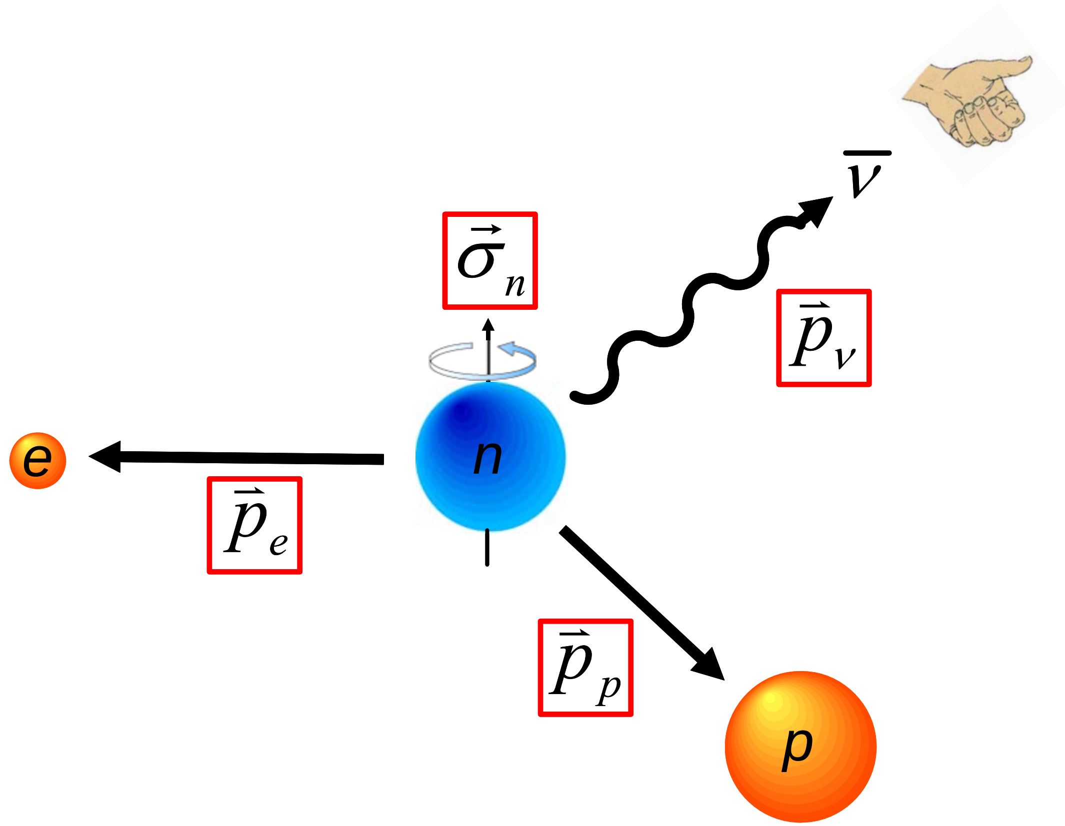
Phenomenology of Neutron Beta Decay

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.

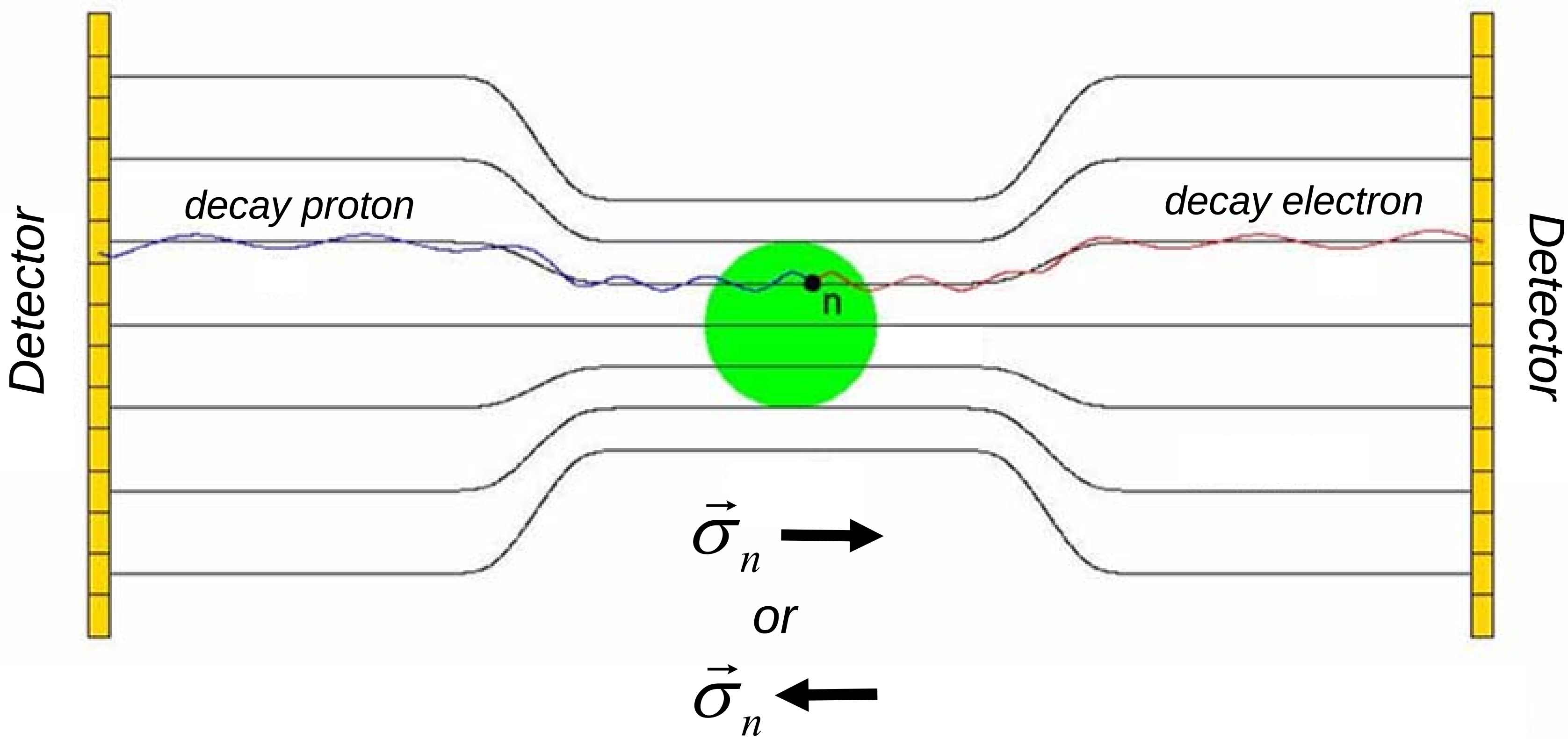
Correlations in Neutron Decay

Parity violation implies a rich phenomenology in neutron decay.

$$dW \propto \frac{1}{\tau_n} F(E_e)\left[1 + a\frac{\mathbf{p}_e \cdot \mathbf{p}_\upsilon}{E_e \cdot E_\upsilon} + A\frac{\sigma_n \cdot \mathbf{p}_e}{E_e} + B\frac{\sigma_n \cdot \mathbf{p}_\upsilon}{E_\upsilon} + \ldots\right]$$

Much more about this in subsequent lectures

General Scheme of n-Beta Correlation Experiments



“Exotic” Neutron Decay

Exotic Neutron Decay

Allowed by the Standard Model:

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

"radiative decay"

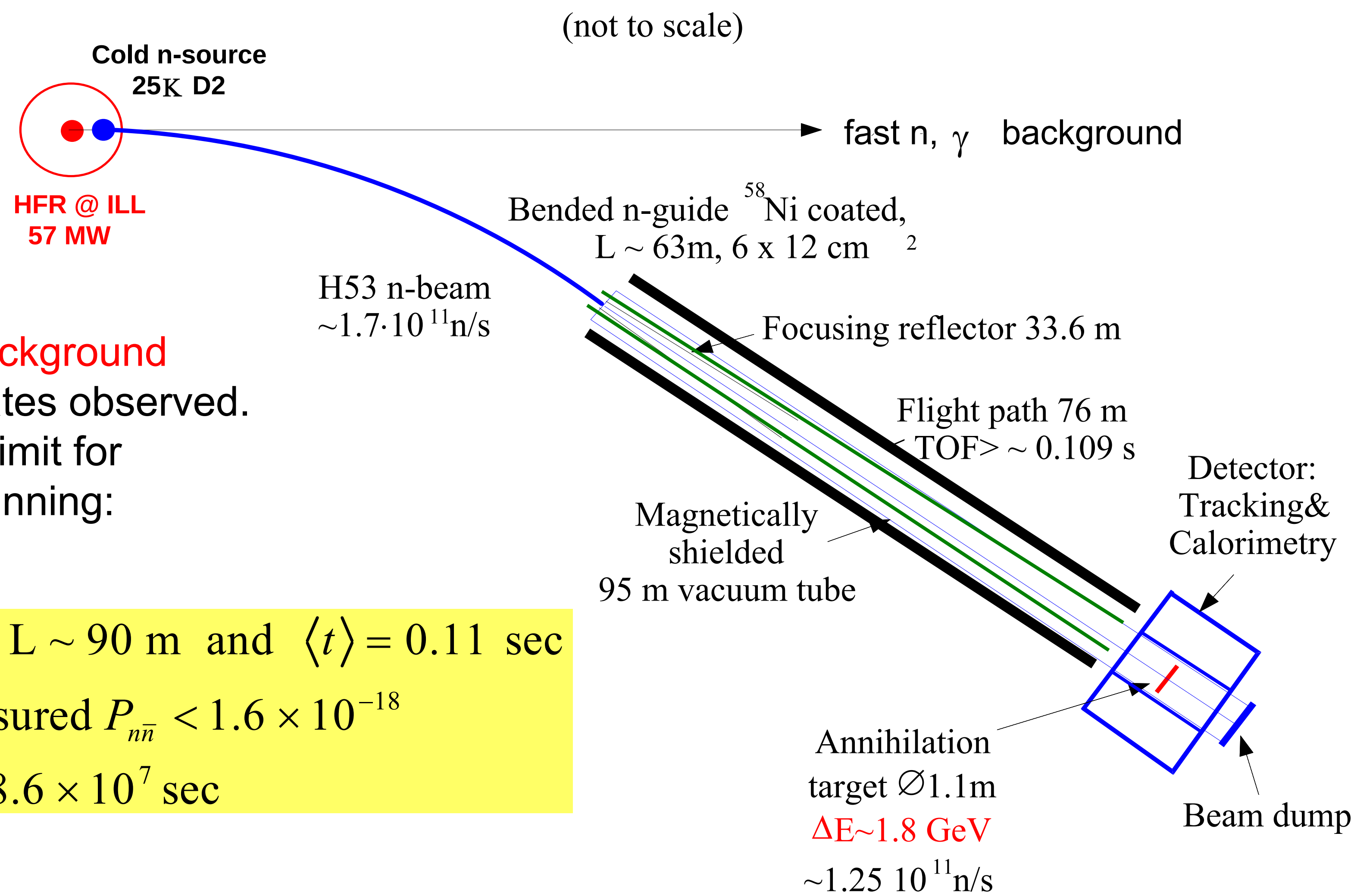
$$n \rightarrow {}^{1}H_{0} + \overline{\nu}$$

Forbidden by the Standard Model:

$$n \rightarrow \overline{n}$$

"n-nbar oscillation" (ΔB=2)

N-Nbar search at the Institute Laue Langevin



No GeV background

No candidates observed.

Measured limit for

a year of running:

with L ~ 90 m and $\langle t \rangle = 0.11$ sec

measured $P_{n\bar{n}} < 1.6 \times 10^{-18}$

$\tau > 8.6 \times 10^{7}$ sec

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

Slide courtesy Mike Snow

Exotic Neutron Decay

Allowed by the Standard Model:

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

"radiative decay"

$$n \rightarrow {}^{1}H_{0} + \overline{\nu}$$

Forbidden by the Standard Model:

$$n \rightarrow \overline{n}$$

"n-nbar oscillation" (ΔB=2)

Forbidden by Common Sense ??

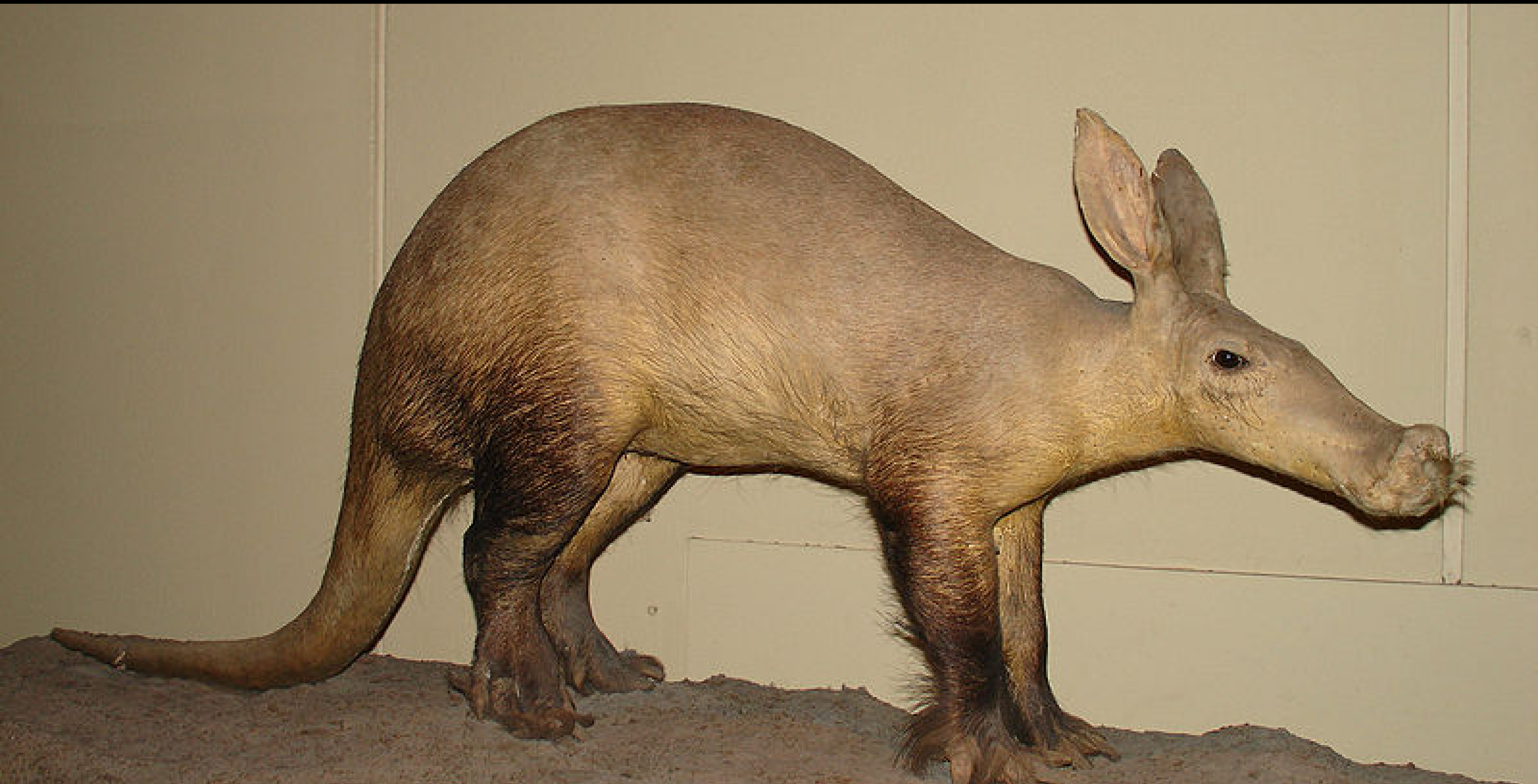
$$n \rightarrow \reflectbox{n}$$

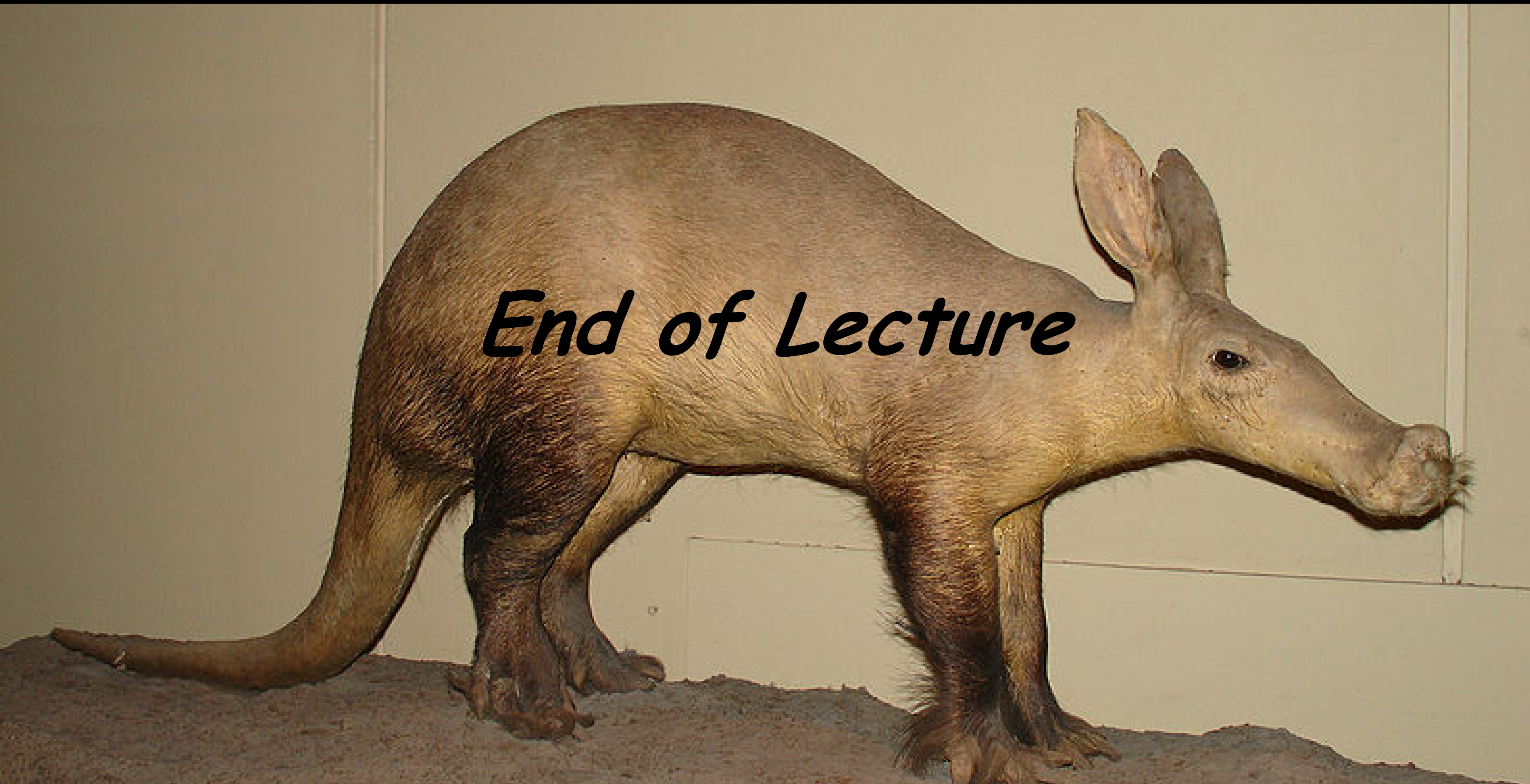
neutron – "mirror neutron" oscillation

Warning:

Just because something is "forbidden" by "common sense" does not mean it is not so!

Also Forbidden by Common Sense




End of Lecture