The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization

IAEA International Atomic Energy Agency

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Summer School on Particle Physics

6 - 17 June 2011

Neutrino Physics - I

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Neutrino Physics
Past, "Present" and Future
"Puzzle Solving"

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ICTP Lecture #2

Trieste, Italy

June, 2011

BROOKHAVEN NATIONAL LABORATORY

OUTLINE

1.) ***Early History*** (1931- 1973) the first 40+ years
2.) ***Weak Neutral Currents***: $SU(2)_L x U(1)_Y$ confirmation

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3.) ***Neutrino Oscillations***: Reactor, Solar, Atmospheric…
4.) ***Neutrino Masses, Mixing, Matter & Moments***
5.) ***Leptogenesis***: Matter-Antimatter Asymmetry (Universe)
6.) ***Neutrinoless Double Beta Decay*** (Dirac vs Majorana)

7.) ***Leptonic CP Violation*** (neutrino vs antineutrino)
Requirements~300kton H_2O, 1-2MW protons,
8.) ***Future Neutrino Physics*** ➔ **Muon Collider**
9.) ***Outlook & Speculation***

TALKS IN MEMORY OF MAURICE GOLDHABER
April 18, 1911 – May 11, 2011

1934 Student of Chadwick (m_n>m_p major implications)

1957 Measured ν_e chirality! *left-handedl

Started Modern Searches for:

Neutrinoless Double Beta Decay

Proton Decay

Observed Neutrinos from Supernova 1987a …

Director of Brookhaven National Lab (1961-1973)

Member of National Academy of Sciences

President of American Physical Society

National Medal of Science, Wolf Prize, Bonner Prize, Fermi Award

…..

May 2011 Physics Today Article on Neutrino Helicity

the Bulletin

BROOKHAVEN NATIONAL LABORATORY

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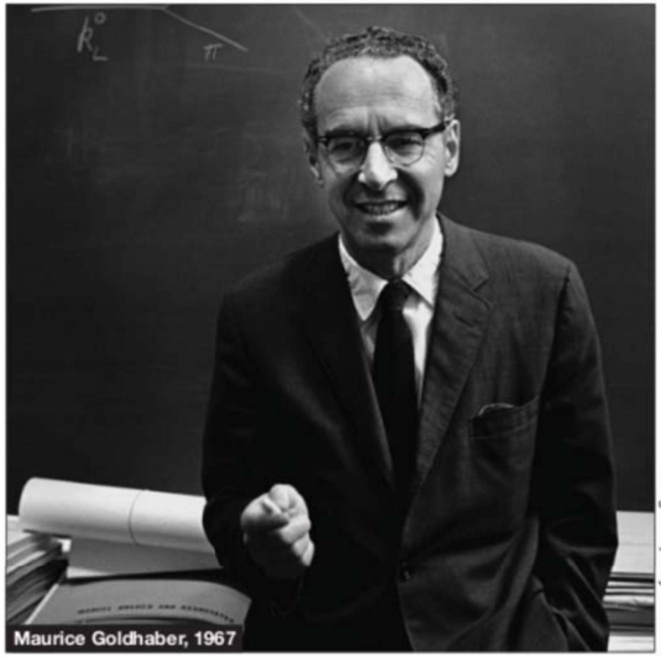
Former BNL Director Maurice Goldhaber Turns 100

On Monday, April 18, BNL will celebrate the 100th birthday of Distinguished Scientist Emeritus Maurice Goldhaber, a highly honored physicist and former BNL Director whose long and extremely productive career has won him many awards, including the Tom W. Bonner Prize in Nuclear Physics in 1971, the J. Robert Oppenheimer Memorial Prize in 1982, the National Medal of Science in 1983, the Wolf Prize in Physics in 1991, and the Enrico Fermi Award in 1999.

Born in Austria, Goldhaber earned his Ph.D. in physics at the University of Cambridge in 1936. Two years earlier, in 1934, with James Chadwick from the Cavendish Laboratory at Cambridge, he had been the first to measure accurately the mass of the subatomic particle known as the neutron, showing that it was not a compound of a proton and an electron as was believed at the time, but a new particle.



Maurice Goldhaber, 1967

Doug Humphrey 10-338-67

Goldhaber's research in the fields of nuclear physics and

ample: while on an experiment on proton decay, which would

Birthday Wishes to Maurice

From Sam Aronson, BNL

We'll celebrate a wonderful milestone n Monday, April 18 — the 100th birthday of former BNL Director Maurice Goldhaber, a Distinguished Scientist Emeritus whose outstanding contributions to science and to Brookhaven Lab have been honored throughout his career. He is also a valued friend of many, known for his sparkling wit and appreciated for his courtesy to all. Happy birthday, Maurice, from all of us.

From Nicholas Samios, BNL

Maurice Goldhaber is one of the great physicists of the twentieth century. His physics interests are global, from the neutron to the periodic table of nuclei, to the neutrino and all its complexity and then back to the stability of the proton. He is a human physics google. His essence can be encapsulated by his elegant proposition for measuring the helicity of the neutrino, accomplished with A.W. Sunyar and L. Grodzins. It required his encyclopedic knowledge of esoteric nuclei and complete command of the complex physics involved. Without Maurice it may not have been done even up to today. A most productive and imaginative physicist.

From Peter Bond, BNL

Maurice: I fondly recall our various interactions over the years which began with my visit to BNL in 1972 and your graciously taking me to dinner with Trudy, the Sunyars and the Sprouses at the Bellport Inn. While in the early years we didn't have many occasions to talk, I began to learn about what an extraordinary scientist you were. One of the greatest compliments I heard about your science was from Nobel Prize

1.) Early History (1931- 1973) the first 40+ years

- Based on "Neutrino Physics" 2nd edition, Klaus Winter, Cambridge, 2000. ***1957 Recollections by W. Pauli***

1920 – Rutherford postulates the Neutron's existence

a *sort* of p^+e^- bound state (not seen)

Beta decay puzzle: N→N'+e^- (E_e spectrum continuous)

What happened to the "missing energy"?

Also, Bose/Fermi Statistics Problem

Pauli (Dec 4, 1930) postcard to: ***Dear Radioactive Ladies and Gentlemen:***

He could not be in attendance because he had to attend A Christmas Ball!

- But, he wanted to propose a solution to the Beta decay puzzle that would preserve energy conservation (anti-Bohr Solution.)

  N ➔ N'+e^-+"neutron" (takes away "missing energy")

  His ***<u>"neutron"</u>*** had spin ½, mass ≈ m_e, & large magnetic moment, penetrating power ≥ gamma rays (escape detection)

  Officially reported by Pauli in 1931 Pasadena Talk

  <u>1934 Pauli paper finally appears! Very Cautious</u>

  (Remember only 2 particles were known e^- & p^+ pre 1932)

<u>In the meantime</u>: ***1932 Chadwick discovers the real Neutron***

Fermi renames the "Pauli" particle ***<u>neutrino</u>*** (little neutron)

<u>1933 Fermi Theory of Beta Decay</u>

(very weak interaction with matter – almost invisible!)

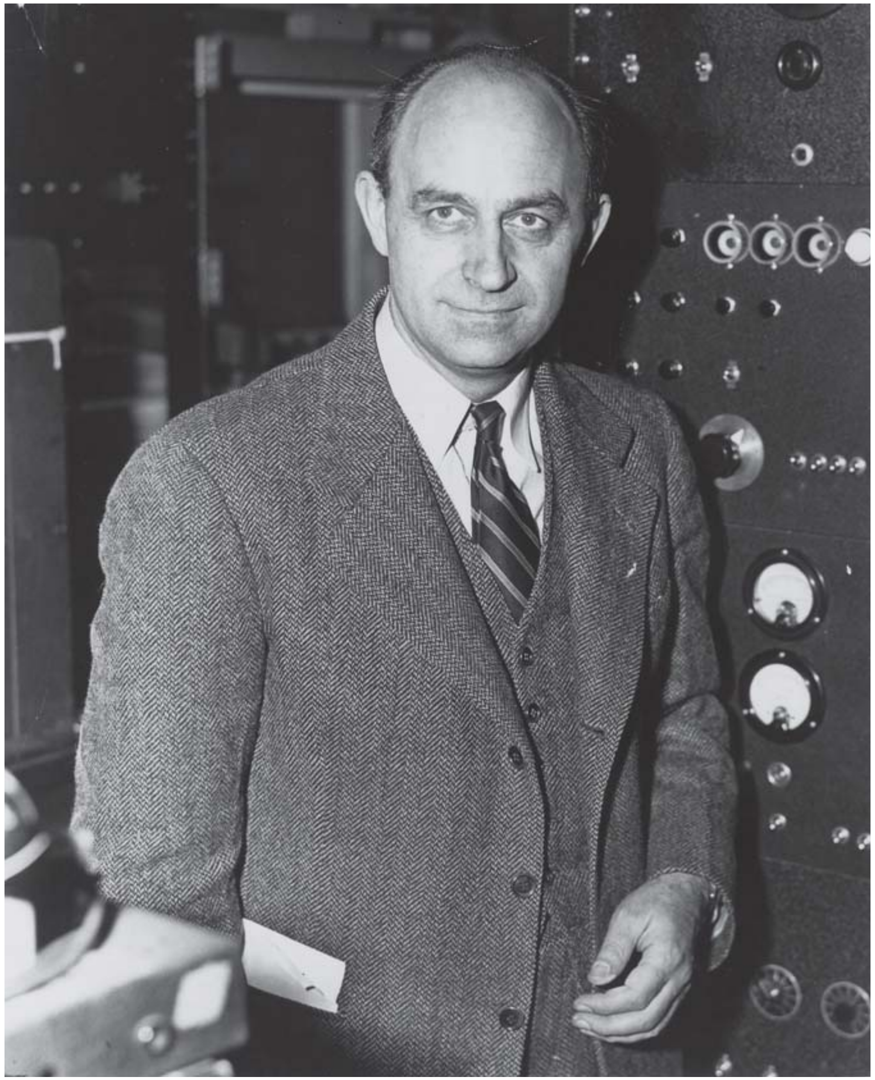
Ghost Like Particle: *$m_\nu \approx 0$ beta spectrum*

Wolfgang Pauli (1900-1958)

Wolfgang Pauli




Enrico Fermi (1901-1954)



Pauli, Heisenberg & Fermi

Fermi Theory of Beta decay

Originally only vector interaction of npev (dim 6 operator)

Mimicing QED photon exchange $1/q^2 \rightarrow G_F$

Parametrized by $G_F = 1.16638 \times 10^{-5} GeV^{-2}$

Weak interactions grew with energy! Unitarity Issues

Not general enough to describe all β decays

Seemed to need V, A, S, P, & T Interactions

(i) Fermi transitions: $\Delta J=0$, $0 \rightarrow 0$ eg ($O^{14} \rightarrow N^{14} + e^+ + \nu$) V&S

(ii) Gamow-Teller transitions: $\Delta J = 1$ eg ($He^6 \rightarrow Li^6 + e + \bar{\nu}$) A&T

(iii) Mixed transitions: $\Delta J=0$, $\frac{1}{2} \rightarrow \frac{1}{2}$ eg ($n \rightarrow p + e + \bar{\nu}$) V,A,S,T

Later expanded to include muon decay and strange decays

<u>*Fermi Theory of Beta decay*</u>

Switch to lecture on Board

Discovery of the Neutrino: Cowan, Reines et al. ***1953-56***

(Hanford & Savannah River Plants)

Use a nuclear reactor 10^{13} antineutrinos/cm^2sec

(Produced by nuclear beta decays)

Looked for: anti-v + p ➔ e^+ + n ***(Found it!) e^+ & n detected***

(inverse neutron decay n➔p+e^-+ant-v)

Agreed with $\sigma \approx 6.3 \times 10^{-44} cm^2$ expectation

50+ years later similar experiments being done

with power reactors ➔ higher statistics

Fred Reines (1918-1998)

Lee and Yang Parity Violation (1956)

The θ-τ (theta-tau) Puzzle

K➔2π & K➔3π observed

Same parent but different parities

Lee and Yang suggest P is violated by weak interactions

Discovered in β & μ decays (Wu et al; Lederman et al)

Found to be maximally violated! V&A or S(P)&T

Experiments favored S(P) & T (*MANY wrong experiments!*)

Marshak & Sudarshan   Feynman & Gell-Mann (CVC)

V-A Theory

Salam introduced the concept of γ_5 invariance into the neutrino equations. Neutrinos were either right or left-handed

Experimental Contradictions: Right ➔S(P)&T   Left➔V-A

V-A FINALLY FAVORED

- 1958 GOLDHABER, GRODZINS AND SUNYAR

  $^{152m}Eu + e^{-} \rightarrow {}^{152}Sm^{*} + \nu_e \rightarrow {}^{152}Sm + \nu_e + \gamma$

  SPIN of Nucleus $0 \rightarrow 1 \rightarrow 0$

Measure direction of neutrino and photon polarization, together give neutrino helicity right or left by angular momentum conservation.

Only weak nuclear reaction with this feature!

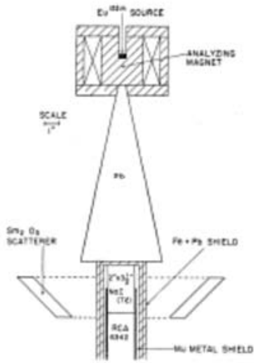
Neutrino turned out to be left-handed → **V-A**

Implied a number of experiments were wrong!

V-A → Intermediate Vector Boson $W^{\pm}$ → Electroweak Unification

Taken from J. Wilkerson (neutrino helicity)
Neutrinos are Left-Handed!

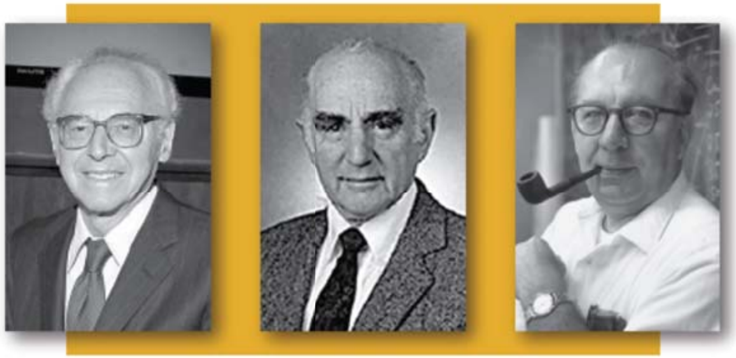
1958 Goldhaber-Grodzins-Sunyar



Helicity of Neutrinos*

M. Goldhaber, L. Grodzins, and A. W. Sunyar
Brookhaven National Laboratory, Upton, New York
(Received December 11, 1957)

A COMBINED analysis of circular polarization and resonant scattering of γ rays following orbital electron capture measures the helicity of the neutrino. We have carried out such a measurement with Eu^{152m}, which decays by orbital electron capture. If we assume the most plausible spin-parity assignment for this isomer compatible with its decay scheme,[1] 0−, we find that the neutrino is "left-handed," i.e., $\sigma_\nu \cdot \hat{p}_\nu = -1$ (negative helicity).



- Weak Interaction

  maximally violates parity

  V-A nature

  neutrinos emitted in beta-decay have intrinsic handedness

Two Neutrino Flavors?

- Muon decay (1947): $\mu \rightarrow e+\nu+\text{anti-}\nu$
- Required enlargement of Fermi theory

Were the neutrinos in Nuclear beta decay, muon decay and pion decay the same?

$$N \rightarrow N'+e^{+}+\nu_e$$

$$\pi^{+} \rightarrow \mu^{+}+\nu_\mu$$

$$\nu_\mu=\nu_e\ ?$$

<u>Schwinger (1957)</u>, Feinberg, Pontecorvo argued: They must be distinct for $W^{\pm}$ Bosons

Universality, $\mu \rightarrow e+\gamma$ FCNC Leptonic G.I.M.

Two Neutrino Experiment

Experimental Neutrino Beam Programs proposed by Pontecorvo (1959) & Schwartz (1960)

First High Energy Neutrino Beam at Brookhaven

p+target ➔$\pi^{\pm}$+X, π➔$\mu+\nu$, ν +target➔μ or e?

(We still make neutrino beams this way. Very Efficient)

Only Muons rather than both muons and electrons resulted

There were two distinct species ν_e and ν_μ

That was the famous 2 neutrino experiment ***(1962)*** of

Lederman, Schwartz and Steinberger et al.

Nobel Prize (1988) start of lepton Nobel prizes

More recently ν_τ (τ partner similarly confirmed as distinct

ν_μ as the fourth lepton

ν_μ is to leptons what charm is to quarks
Both needed for G.I.M. suppression of FCNC
Both were discovered at Brookhaven!

For some reason, their existence was resisted
Now their role seems so obvious

2.) ***Weak Neutral Currents***: $SU(2)_L x U(1)_Y$ confirmation

Efforts to unify Electromagnetism with Weak Interactions

Schwinger (1957) "***A Theory of Fundamental Interactions***"

γ & $W^{\pm}$ Bosons ➔ SO(3) (broken) Gauge Symmetry

coupling e ➔ $m_W \approx 37.5$GeV

- His Student ***S. Glashow*** (1961)➔ $SU(2)_L x U(1)_Y$ Algebra

"No Higgs Mechanism"

m_W & m_Z arbitrary (put in by hand)

$\gamma = B\cos\theta + W^0\sin\theta$ massless photon

$Z = W^0\cos\theta - B\sin\theta$ massive neutral gauge boson

$e = g\sin\theta$ *birth of the weak mixing angle*

Glashow: ***"It doesn't matter what your thesis is. What counts is your choice of an advisor"***

Weak Neutral Currents should exist!

Glashow's paper implied that EW Unification algebra required weak neutral currents.

(Given Little Attention)

Why weren't weak neutral currents searched for?

Perhaps because FCNC effects were so suppressed

eg. $K_L \rightarrow \mu^+ \mu^-$ highly G.I.M. suppressed

Even Georgi & Glashow returned (1972) to SO(3) with heavy leptons to avoid weak neutral currents

- **Salam & Weinberg** SU(2)xU(1) + Higgs Mechanism

generates $W^{\pm}$&Z masses

spontaneous sym. Breaking

via complex scalar doublet

$$\mathbf{m_W = m_Z \cos\theta \ \& \ e = g \sin\theta}$$

They speculated that the theory might be renormalizable!

Weak Neutral Currents right around the corner!

Just look for them!

Largely ignored until ‘tHooft proved renormalizability (1971)

Weak Neutral Currents Discovered (1973) Neutrino scattering! anti-ν_μ+e➔anti-ν_μ+e 1 event at CERN

Also, ν_μ+N➔ ν_μ+X deep-inelastic

1975 tau lepton discovered

- Implied 3 neutrino species all left-handed

Z width confirmation $Z \rightarrow \nu + \text{anti}-\nu$ (only 3 generations?)

Many Questions about Neutrinos Remained Open

Do neutrinos have mass? ***Why so small?***

Do the 3 generations mix? (*Lepton Flavor Violation?*)

Do neutrinos oscillate?

Are there heavy right-handed neutrinos? ***Why is parity violated?***

Is Lepton Number Violated? (*Majorana Masses $\Delta L=2$*)

Are there light sterile neutrinos?

Do neutrinos violate CP? CPT?

Do neutrinos have other interactions? …

(More Next Lecture)