Little, Neutral, Mysterious: An Introduction to Neutrino Physics

The Physics of Neutrinos: Progress and Puzzles
The 87th Compton Lecture Series
Enrico Fermi Institute, University of Chicago

Andrew T. Mastbaum
"MATTER"

- Proton: (+)
- Neutron: (0)
- Electron: (-)
"MATTER"

Proton

Neutron

Electron

"ANTIMATTER"

Antiproton

Antineutron

Positron


(+) Proton

(0) Neutron

(-) Electron

(0) Antineutron

(-) Antiproton

(+) Positron
"MATTER"

Neutron

Proton

Electron

"ANTIMATTER"

Antineutron

Antiproton

Positron

Quarks

Antiquarks
\[ E = mc^2 \]
Pair Production

Energy $\rightarrow$ Matter + Antimatter

$E = mc^2$
Pair Production

energy → matter + antimatter

Pair Annihilation

matter + antimatter → energy

\[ E = mc^2 \]
\[
\gamma \rightarrow \nu \bar{\nu} \rightarrow \text{(matter)} \quad ?
\]

Image: Hubble Deep Field, NASA
The Physics of Neutrinos: Progress and Puzzles
The 87th Compton Lecture Series

Goals

I hope you leave this series with an understanding of...

• What neutrinos are and how they fit into our model of physical interactions
• Major experimental efforts ongoing in neutrino physics
• Open questions in neutrinos and particle physics
• Neutrinos as objects of study in their own right, and neutrinos as messengers of other interesting physics
The Physics of Neutrinos: Progress and Puzzles
The 87th Compton Lecture Series

Agenda
(subject to change)

<table>
<thead>
<tr>
<th>Date</th>
<th>Topic</th>
</tr>
</thead>
<tbody>
<tr>
<td>March 31</td>
<td>Little, Neutral, Mysterious: An Introduction to Neutrino Physics</td>
</tr>
<tr>
<td>April 7</td>
<td>Neutrinos from the Sun</td>
</tr>
<tr>
<td>April 14</td>
<td>Neutrinos from Space</td>
</tr>
<tr>
<td>April 21</td>
<td>Neutrinos from Reactors</td>
</tr>
<tr>
<td>April 28</td>
<td>Neutrino Cosmology</td>
</tr>
<tr>
<td>May 5</td>
<td>How Many Neutrinos Are There, Anyway?: Sterile Neutrino Searches</td>
</tr>
<tr>
<td>May 12</td>
<td>Why Are We Here?: Long-Baseline Neutrino Physics and CP</td>
</tr>
<tr>
<td>May 19</td>
<td>How Little Is Little?: Neutrino Mass</td>
</tr>
<tr>
<td>May 26</td>
<td>No lecture</td>
</tr>
<tr>
<td>June 2</td>
<td>Where We Are, Where We’re Going</td>
</tr>
</tbody>
</table>
I. Discovery
# Nuclear Decays

## When Things Fall Apart

<table>
<thead>
<tr>
<th>Decay Type</th>
<th>Description</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Alpha Decay</strong></td>
<td>Nucleus emits an &quot;alpha&quot; (two protons, two neutrons)</td>
<td>((A, Z) \rightarrow (A - 4, Z - 2) + \alpha)</td>
</tr>
<tr>
<td><strong>Beta Decay</strong></td>
<td>Nucleus emits an electron (&quot;beta&quot;)</td>
<td>((A, Z) \rightarrow (A, Z + 1) + \beta)</td>
</tr>
<tr>
<td><strong>Gamma Decay</strong></td>
<td>Nucleus emits a photon (&quot;gamma&quot;)</td>
<td>((A, Z) \rightarrow (A, Z) + \gamma)</td>
</tr>
</tbody>
</table>

---

Pierre & Marie Curie

Acc. 90-105 - Science Service, Records, 1920s-1970s, Smithsonian Institution Archives
Trouble with Beta Decays c. 1927

\[(A, Z) \rightarrow (A, Z + 1) + \beta\]

\[\frac{1}{E} = \left[ \frac{m_i^2 - m_f^2 - m_e^2}{2m_i^2} \right] c^2\]

Expected beta decay spectrum
Trouble with Beta Decays  
c. 1927

\[(A, Z) \rightarrow (A, Z + 1) + \beta\]

Measurement of beta decay spectrum


**Fig. 5.** Energy distribution curve of the beta-rays.
Trouble with Beta Decays c. 1927

Beta Decay

Nucleus emits an electron ("beta")

\[(A, Z) \rightarrow (A, Z + 1) + \beta\]

\[\begin{array}{c}
\text{\textcolor{red}{\text{\textbullet}}} \\
\text{\textcolor{blue}{\text{\textbullet}}} \\
\text{\textcolor{red}{\text{\textbullet}}} \\
\end{array}\]

\[\begin{array}{c}
\text{\textcolor{blue}{\text{\textbullet}}} \\
\text{\textcolor{blue}{\text{\textbullet}}} \\
\text{\textcolor{red}{\text{\textbullet}}} \\
\end{array}\]

\[\begin{array}{c}
\text{\textcolor{green}{\text{\textbullet}}} \\
\end{array}\]

Option 1: Energy just disappears.

Energy isn't conserved in the universe, physics goes back to the drawing board.

Fig. 5. Energy distribution curve of the beta-rays.
Dear Radioactive Ladies and Gentlemen...
Dear Radioactive Ladies and Gentlemen,

I have hit upon a desperate remedy ... there could exist electrically-neutral particles [emitted in beta decay] ... The continuous beta spectrum would then make sense ... in addition to the electron, a neutron is emitted such that the sum of the energies of neutron and electron is constant.

I do not dare to publish anything

Unfortunately, I cannot personally appear ... since I am indispensable here in Zürich because of a ball
"I have done a terrible thing today by proposing a particle that cannot be detected; it is something no theorist should ever do."

— Wolfgang Pauli, 1930
Trouble with Beta Decays

Beta Decay

Nucleus emits an electron ("beta")

\[(A, Z) \rightarrow (A, Z + 1) + \beta + \bar{\nu}_e\]

Option 1: Energy just disappears.
Energy isn’t conserved in the universe, physics goes back to the drawing board.

Option 2: Some invisible participant is carrying some energy away.
We invent a new decay product which shares the energy and somehow evades detection.


*Fig. 5. Energy distribution curve of the beta-rays.*
1934: Fermi's Theory

Enrico Fermi works out a theory of beta decay, with a neutral particle carrying away energy.

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

\[ \bullet \rightarrow \bullet + \bullet + \bullet \]
Enrico Fermi works out a theory of beta decay, with a neutral particle carrying away energy.

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

\[ \lambda_i \rightarrow f = \frac{2\pi}{\hbar} |M|^2 \rho \]

Fermi's Theory of Beta Decay*

Fred L. Wilson

6006 Chestwood # 286, Houston, Texas 77036

(Received 15 March 1968; revision received 19 August 1969)

A complete English translation is given of the classic Enrico Fermi paper on beta decay published in Zeitschrift für Physik in 1934.

**INTRODUCTION**

In 1934, Enrico Fermi, then a professor of theoretical physics at the University of Rome, Italy, proposed his clear and simple description of \( \beta \) decay. He assumed the existence of the neutrino which Pauli had suggested to preserve the principle of conservation of energy, and he treated the ejection of electrons and neutrinos from a nucleus by a method similar to the radiation theory of photon emission from atoms. Fermi derived quantitative expressions for the lifetime of the nucleus.
Enrico Fermi works out a theory of beta decay, with a neutral particle carrying away energy.

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

\[ M \sim G_F (\bar{u}_p \gamma^\mu u_n)(\bar{u}_e \gamma^\mu u_\nu) \]

\[ \lambda_{i\rightarrow f} = \frac{2\pi}{\hbar} |M|^2 \rho \]

**Fermi's Theory of Beta Decay**

Fred L. Wilson
6088 Chestwood Dr 286, Houston, Texas 77036
(Received 15 March 1968; revision received 19 August 1968)

**Introduction**

In 1934, Enrico Fermi, then a professor of theoretical physics at the University of Rome, Italy, proposed his clear and simple description of \( \beta \) decay. He assumed the existence of the neutrino which Pauli had suggested to preserve the principle of conservation of energy, and he treated the ejection of electrons and neutrinos from a nucleus by a method similar to the radiation theory of photon emission from atoms. Fermi derived quantitatively expressions for the lifetime of the beta particles.

To appreciate the impact produced by Fermi’s theory of \( \beta \) decay on modern physics, one may note that it is rather amazing what varieties of observed phenomena (and what thicknesses of the Physical Review) are based on his one paper on the subject. For example, the experiment proposed by Yang and Lee in 1956 to test conservation of parity, involved the properties of \( \beta \) decay of \( ^{197}Au \).

With his paper on \( \beta \) decay, Fermi brought to a close his purely theoretical studies and became a father of nuclear physics.
1934: Fermi's Theory

Hans Bethe & Rudolf Peierls calculate the neutrino cross section

Beta Decay

\[ n \rightarrow p + e^- + \bar{\nu}_e \]
1934: Fermi's Theory

Hans Bethe & Rudolf Peierls calculate the neutrino cross section

**Beta Decay**
\[ n \rightarrow p + e^- + \bar{\nu}_e \]

**Inverse Beta Decay**
\[ \bar{\nu}_e + p \rightarrow n + e^+ \]
The following comparison of the structure given by Badami and by me for the line $\lambda 5639.7$ ($6^2 \frac{1}{2} F_2 - 6^2 \frac{1}{2} S_2$) shows to what extent the hollow cathode patterns are more clearly resolved:

<table>
<thead>
<tr>
<th></th>
<th>Bedami</th>
<th>Tolansky</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>205</td>
<td>217</td>
</tr>
<tr>
<td></td>
<td>450</td>
<td>399</td>
</tr>
<tr>
<td></td>
<td>594</td>
<td>477</td>
</tr>
<tr>
<td></td>
<td>780</td>
<td>605</td>
</tr>
<tr>
<td></td>
<td></td>
<td>725\times 10^{-4}</td>
</tr>
</tbody>
</table>

It is seen that Badami's values are those which would arise from the blending of components due to excessive line width.

Full details with analysis will be communicated elsewhere shortly.

S. Tolansky.

Astrophysics Department, Imperial College of Science, London, S.W.7.
March 3.

1 J. S. Badami, Z. Phys., 79, 206; 1932.

The "Neutrino"

The view has recently been put forward\(^1\) that a neutral particle of about electronic mass, and spin \(\frac{1}{2}\) (where \(h = \frac{2\pi}{l}\)) exists, and that this 'neutrino' is emitted together with an electron in \(\beta\)-decay. This assumption allows the conservation laws of energy and angular momentum to hold in nuclear physics\(^1\). Both the emitted electron and neutrino could be described either (a) as having existed before in the nucleus or (b) as being created at the time of emission. In a recent paper\(^2\) Fermi has proposed a model of \(\beta\)-disintegration using (b) which seems to be confirmed by experiment.

According to (a), one should picture the neutron as being built up of a proton, an electron and a neutrino, while if one accepts (b), the roles of neutron and proton would be symmetrical\(^1\) and one would expect that neutron electrons could also be emitted. This last possibility, however, has not received any experimental support.

In the first case, one of the two nuclei (Rh) is known to emit \(\beta\)-rays. In each of the last two cases one of the two isotopes is stated to be exceedingly rare and its identification might be due to experimental error. The other three cases actually lie close together and have medium weight. A particular case of isotopes are proton and neutron. Since all experimentally deduced values of the neutron mass lie between 1-0068 and 1-0078, they are certainly both stable even if the mass of the neutrino should be zero.

The possibility of creating neutrinos necessarily implies the existence of annihilation processes. The most interesting amongst these would be the following: a neutrino hits a nucleus and a positive or negative electron is created while the neutrino disappears and the charge of the nucleus changes by 1.

The cross section \(\sigma\) for such processes for a neutrino of given energy may be estimated from the lifetime \(\tau\) of \(\beta\)-radiating nuclei giving neutrinos of the same energy. (This estimate is in accord with Fermi's model but is more general.) Dimensionally, the connexion will be

\[ \sigma = A\tau \]

where \(A\) has the dimension cm.\(^3\) sec. The longest length and time which can possibly be involved are \(h/\text{mc}\) and \(h/\text{mc}^2\). Therefore

\[ \sigma < \frac{h^2}{m^2 c^4} \]

For an energy of \(3 \times 10^9\) volts, \(\tau\) is 3 minutes and therefore \(\sigma < 10^{-44}\) cm.\(^3\) (corresponding to a penetrating power of \(10^6\) km. in solid matter). It is therefore absolutely impossible to observe processes of this kind with the neutrinos created in nuclear transformations.

With increasing energy, \(\sigma\) increases (in Fermi's model\(^2\) for large energies as \((E/\text{mc}^2)^4\)) but even if one assumes a very steep increase, it seems highly improbable that, even for cosmic ray energies, \(\sigma\) becomes large enough to allow the process to be observed.
Hans Bethe & Rudolf Peierls calculate the neutrino cross section

1934: Fermi's Theory

Beta Decay

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

Inverse Beta Decay

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

The following comparison of the structure given by Badami by me for the line \( \lambda 5639 \text{ } \alpha \) cathode patterns

<table>
<thead>
<tr>
<th>Badami</th>
<th>6 (6)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tolansky</td>
<td>8 (7)</td>
</tr>
</tbody>
</table>

It is seen that the isotope of the nucleus (Al) is known to emit \( \beta \)-rays. In each of the last two cases one of the isotope of the nucleus changes by 1.

The possibility of creating neutrinos necessarily implies the existence of annihilation processes. The most interesting amongst them would be the following: a neutrino hits a nucleus and a positive or negative electron is created while the neutrino disappears and the charge of the nucleus changes by 1.

Astrophysics Department, Imperial College of Science, London, S.W.7.
March 3.

S. Tolansky.

For an energy of \( 2.3 \times 10^4 \) volts, \( t \) is 3 minutes and therefore \( \sigma \leq 10^{-44} \text{ cm}^2 \) (corresponding to a penetrating power of \( 10^{14} \text{ km.} \) in solid matter). It is therefore absolutely impossible to observe processes of this kind with the neutrinos created in nuclear transformations.

---

Hans Bethe

Sir Rudolf Peierls
1934: Fermi's Theory

Hans Bethe & Rudolf Peierls calculate the neutrino cross section

---

Claim: A neutrino will go through 1000 light years of matter!

But...

event rate $\sim$ number of neutrinos $\times$ probability of interaction

$$R \ [1/s] = N_{\text{targets}} \times \Phi \ [\text{cm}^{-2}/s] \times \sigma \ [\text{cm}^2] \times \epsilon$$
Neutrino Department

Elementary Particle Detector
Neutrino Department

Elementary Particle Detector
Scintillator

Produces light when charged particles go through

uni-mainz.de

Linear alkylbenzene (LAB) as solvent
Neutrino Department

Photomultiplier Tube
An ultra-sensitive light detector

Photocathode
Focusing electrode
Photomultiplier Tube (PMT)

Primary electron
Secondary electrons
Dynode
Anode
Connector pins

Scintillator
Produces light when charged particles go through

Linear alkybenzene (LAB) as solvent
uni-mainz.de
Neutrino Department

Elementary Particle Detector

$\nu$
Neutrino Department

Cosmic Rays

Elementary Particle Detector

$v$
SNO+ Experiment
Sudbury, Ontario, Canada

Image: SNO+ Collaboration
Deep Underground Neutrino Experiment, Prototype Detector
CERN, Switzerland
CUORE Experiment
LNGS, Italy
"Herr Auge"
Los Alamos, NM, 1953
In 1951, when Fred Reines first contemplated an experiment to detect the neutrino, this particle was still a poltergeist, a fleeting yet haunting ghost in the world of physical reality. All its properties had been deduced but only theoretically. Its role was to carry away the missing energy and angular momentum in nuclear beta decay, the most familiar and widespread manifestation of what is now called the weak force. The neutrino surely had to exist. But someone had to demonstrate its reality. The relentless quest that led to the detection of the neutrino started with an energy crisis in the very young field of nuclear physics.
In 1951, when Fred Reines first contemplated an experiment to detect the neutrino, this particle was still a poltergeist, a fleeting yet haunting ghost in the world of physical reality. All its properties had been deduced but only theoretically. Its role was to carry away the missing energy and angular momentum in nuclear beta decay, the most familiar and widespread manifestation of what is now called the weak force. The neutrino surely had to exist. But someone had to demonstrate its reality. The relentless quest that led to the detection of the neutrino started with an energy crisis in the very young field of nuclear physics.
Hunting the Neutrino
Plan A: Project Poltergeist

In 1951, when Fred Reines first contemplated an experiment to detect the neutrino, this particle was still a poltergeist, a fleeting yet haunting ghost in the world of physical reality. All its properties had been deduced but only theoretically. Its role was to carry away the missing energy and angular momentum in nuclear beta decay, the most familiar and widespread manifestation of what is now called the weak force. The neutrino surely had to exist. But someone had to demonstrate its reality. The relentless quest that led to the detection of the neutrino started with an energy crisis in the very young field of nuclear physics.
Hunting the Neutrino
Plan A: Project Poltergeist

In 1951, when Fred Reines first contemplated an experiment to detect the neutrino, this particle was still a poltergeist, a fleeting yet haunting ghost in the world of physical reality. All its properties had been deduced but only theoretically. Its role was to carry away the missing energy and angular momentum in nuclear beta decay, the most familiar and widespread manifestation of what is now called the weak force. The neutrino surely had to exist. But someone had to demonstrate its reality. The relentless quest that led to the detection of the neutrino started with an energy crisis in the very young field of nuclear physics.

Boatloads of neutrinos here

Nuclear explosive

Fireball

30 m

40 m

Buried signal line for triggering release

Back fill

Vacuum pump

Vacuum line

Suspended detector

Vacuum tank

Feathers and foam rubber

Los Alamos Science 25 (1997)
Hunting the Neutrino
Plan A: Project Poltergeist

In 1951, when Fred Reines first contemplated an experiment to detect the neutrino, this particle was still a poltergeist, a fleeting yet haunting ghost in the world of physical reality. All its properties had been deduced but only theoretically. Its role was to carry away the missing energy and angular momentum in nuclear beta decay, the most familiar and widespread manifestation of what is now called the weak force. The neutrino surely had to exist. But someone had to demonstrate its reality. The relentless quest that led to the detection of the neutrino started with an energy crisis in the very young field of nuclear physics.

Nope.

An "interesting" idea, but.... there's a better way.
Nuclear Reactors
A Bit of UChicago History!

Lise Meitner & Otto Hahn
Laboratory R&D, c. 1938

Maria Goeppert-Mayer

CP1 and the UChicago team
Proof of Concept, 1942

CP1 Cake, UChicago EFI, 2017

Enrico Fermi Nuclear Plant
Commercial Use, 1958 - present

235U
neutron
fission
more neutrons

235U
more fission
yup

238U

yup
you get it

wikipedia.org
Savannah River Site, SC
US Department of Energy
July 1956

Photo from 2011
CC BY 2.0, DOE SRS
Neutrino detector

neutrinos!

Fred Reines & Clyde Cowan

Dept. of Physics, UC Irvine

Neutrinos!
Neutrino detector

\[ \bar{\nu} + p \rightarrow e^+ + n \]
Neutrino Signature

1. Flash of light from positron
2. Neutron bounces around
3. Nucleus captures neutron
4. Capturing nucleus emits gamma rays — second flash!
Neutrino Signature

1. Flash of light from positron
2. Neutron bounces around
3. Nucleus captures neutron
4. Capturing neutron emits gamma rays — second flash!

After 26 years, the "undetectable" neutrino is found!

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

1995 Nobel Prize in Physics
Frederick Reines, "for the detection of the neutrino"
(Clyde Cowan passed away in 1974)
II. The Plot Thickens
The Plot Thickens

Putting the \( \bar{\nu}_e \) in Antineutrinos

**Beta Decay**

\[ n \rightarrow p + e^- + \nu \]
The Plot Thickens

Putting the $\bar{\nu}$ in $\bar{\nu}_e$: Antineutrinos

**Beta Decay**

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

**Inverse Beta Decay**

(Cowan & Reines, 1956)

\[ \nu + p \rightarrow n + e^+ \]
The Plot Thickens Putting the $\bar{\nu}$ in $\bar{\nu}_e$: Antineutrinos

**Beta Decay**

$n \rightarrow p + e^- + \nu$

**Inverse Beta Decay**

(Cowan & Reines, 1956)

$\nu + p \rightarrow n + e^+$

$\nu + n \rightarrow p + e^-$
The Plot Thickens

Putting the $\bar{\nu}$ in $\bar{\nu}_e$: Antineutrinos

Beta Decay

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

Inverse Beta Decay

(Cowan & Reines, 1956)

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

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

\[ \nu + ^{37}\text{Cl} \rightarrow e^- + ^{37}\text{Ar} \]

Ray Davis, Jr.

BNL
Beta Decay \[ n \rightarrow p + e^- + \nu \]

Inverse Beta Decay \[ \nu + p \rightarrow n + e^+ \]

(Cowan & Reines, 1956)

\[ \nu + \text{^{37}Cl} \rightarrow e^- + \text{^{37}Ar} \]

**Attempt to Detect the Antineutrinos from a Nuclear Reactor**


*E. Cornell, Jr.*

Department of Chemistry, Brookhaven National Laboratory, Upton, Long Island, New York

(Restricted September 21, 1956)

**I. INTRODUCTION**

There have been a number of experiments performed in the past to detect the neutrinos by scattering processes and nuclear interactions. The most sensitive of these experiments serve to place a limit on the scattering cross section for antineutrinos on electrons of less than \(10^{-6} \text{ cm}^2/\text{electron} \) and for nuclear interactions of less than \(10^{-7} \text{ cm}^2/\text{atom} \).

Recently, Reins and Cowan of the Los Alamos Laboratory performed an experiment with a large hydrogen liquid scintillator having a high sensitivity for detecting the interaction \(p\bar{e}^-\nu\) within the Liquid. Measurements were made with this scintillator located adjacent to the Hanford reactor within a shield designed to absorb alpha radiation from the reactor in which the scintillator was sensitive. Under these conditions they observed an increase in counting rate of the scintillator of \(0.61 \pm 0.30\) decay counts per minute when the reactor was operating over that observed with the reactor off. This increase in counting rate, if \(p\bar{e}^-\nu\) correspondes to a cross section of \(10^{-6} \text{ cm}^2/\text{atom} \), would be expected to observe the interaction of 0.146.330 decay counts per minute when the reactor was operating over that observed with the reactor off.

In 1949, Pontecorvo suggested a radiological method of detecting the neutrinos by employing the reaction \(CP\nu/\nu\).\(\text{Ar} \). The experiment involved enclosing a large volume of carbon, irradiated with a nuclear reactor, containing Ar by physical methods, and counting the electron capture decay of the resulting Ar. A positive experiment of this type would show that these particles are not to be distinguished in their nuclear reactions. A negative experiment carried to the desired sensitivity would indicate that the reactions and antineutrinos differ in their nuclear reactions, or that the present theory of beta decay is incorrect. The present theory of beta decay and the principle of detailed balancing lead to a reliable calculated cross section for the inverse process. The only evidence concerning the nuclear interactions of neutrinos and antineutrinos comes at present from a study of the half-life of the double beta-decay process. Several studies have indicated that neutrinos and antineutrinos do differ in their interaction with nucleons.
The Plot Thickens  Putting the $\bar{\nu}_e$: Antineutrinos

**Beta Decay**

$$n \rightarrow p + e^- + \nu$$

**Inverse Beta Decay**

(Cowan & Reines, 1956)

$$\nu + p \rightarrow n + e^+$$

$$\nu + n \rightarrow p + e^-$$

$$\nu + ^{37}\text{Cl} \rightarrow e^- + ^{37}\text{Ar}$$

Attempt to Detect the Antineutrinos from a Nuclear Reactor by the $^{129}\text{I}(\bar{\nu},e^-)^{129}\text{Xe}$ Reaction*

Ray Davis, Jr.

<table>
<thead>
<tr>
<th>BNL</th>
<th>BNL</th>
<th>BNL</th>
</tr>
</thead>
</table>

*Raymond Davis, Jr., Department of Chemistry, Brookhaven National Laboratory, Upton, Long Island, New York*

**I. INTRODUCTION**

There have been a number of experiments performed in the past to detect the neutrinos by scattering processes and nuclear interactions. The most sensitive of these experiments were to place a target on the scattering cross section for antineutrons on electrons of less than 10$^{10}$ cm$^2$/electron and for nuclear interactions of less than 10$^{20}$ cm$^{-2}$/sec.

Recently Reines and Cowan of the Los Alamos Laboratory performed an experiment with a large hydrogen-carbon liquid scintillator having a high sensitivity for detecting the reaction $p(\bar{\nu},e^-)$ within the liquid. Measurements were made with this scintillator located adjacent to the Hanford reactor within a shield designed to absorb all other radiations from the reactor to which the scintillator was sensitive. Under these conditions they observed an increase in counting rate of the scintillator of $0.64 \pm 0.30$ delayed event per minute when the reactor was operating over that observed with the reactor off. This increase in counting rate, if attributed to the reaction $p(\bar{\nu},e^-)$, corresponds to a cross section of $10^{-30}$ cm$^2$/atom.

In 1956 Pontecorvo$^{(a)}$ suggested a radiochemical method of detecting the neutrinos by employing the reaction $^{129}\text{I}(\bar{\nu},e^-)^{129}\text{Xe}$. The experiment involved imploding a large volume of carbon triiodide onto a nuclear reactor, measuring the $^{129}\text{Xe}$ by physical methods, and counting the electron capture decay of this isotope. If a neutrino ($\nu$) is emitted which may be formally distinguished from an antineutrino ($\bar{\nu}$) which accompanies negative beta emission, a nuclear reaction similar to equation (1) would be observed.

If neutrinos and antineutrinos are identical in their interactions with nucleus one should be able to observe the process upon counting the experiment to the required sensitivity. However, if neutrinos and antineutrinos differ in their interactions with nucleus one would not expect to detect the reaction $^{129}\text{I}(\bar{\nu},e^-)^{129}\text{Xe}$. A positive experiment of this type would show that these particles are not to be distinguished in their nuclear reactions. A negative experiment carried to the required sensitivity would indicate that neutrinos and antineutrinos differ in their nuclear reactions, or that the present theory of beta decay is incorrect. The present theory of beta decay and the principle of detailed balancing lead to a reliable calculated cross section for the inverse process. The only evidence concerning the nuclear interactions of neutrinos and antineutrinos comes at present mainly from a study of the half-life of the double beta-decay process. These studies have indicated that neutrinos and antineutrinos do indeed differ in their interactions with nucleus.

An experiment has been performed in which a 200-liter (55-gallon) drum of carbon triiodide was
The Plot Thickens  Putting the $\bar{\nu}_e$: Antineutrinos

**Beta Decay**  \[ n \rightarrow p + e^- + \nu \]  

**Inverse Beta Decay**  \[ \nu + p \rightarrow n + e^+ \]  
*(Cowan & Reines, 1956)*

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

\[ \nu + ^{37}\text{Cl} \rightarrow e^- + ^{37}\text{Ar} \]  

Ray Davis, Jr.

---

**Attempt to Detect Antineutrinos from a Nuclear Reactor**

- **Reactions:** $^{\text{Cl}27}(\nu,e^-)^{\text{Ar}37}$

Raymond Davis, Jr.

---

**INTRODUCTION**

There have been a number of experiments performed in the past to detect the neutrinos by counting processes and nuclear interactions. The most sensitive of these experiments serve to place a limit on the scattering cross section for neutrinos at energies of less than $10^{-28}$ cm$^2$/electron and for nuclear interaction of less than $10^{-30}$ cm$^2$/electron.

Recently Reines and Cowan of the Los Alamos Laboratory performed an experiment with a large argon gas bubble scintillator having a high sensitivity for detecting the interaction $p
\bar{\nu}_e$ within the liquid. Measurements were made with this scintillator located adjacent to the enveloping vessel within a shield designed to absorb other radiations from the reactor from which the scintillator was sensitive. Under these conditions they observed an increase in counting rate of the scintillator of 0.14 at 10,200 enantiometers per minute when the reactor was operating over that observed with the reactor off. This increase in counting rate, if $p
\bar{\nu}_e$ correspond to a cross section of $10^{-28}$ cm$^2$/electron.

In 1956 P. J. F. Pienaar suggested a radioluminescent method of detecting the neutrinos by employing the reaction $^{\text{Cl}27}(\nu,e^-)^{\text{Ar}37}$. The experiment involved isolating a large volume of carbon tetrachloride near a nuclear reactor, measuring the $^{\text{Ar}37}$ by physical methods, and counting the electron capture decay of this isotope.
No detection!

Evidence that we have "antineutrinos" that do this:
\[
\bar{\nu} + p \rightarrow n + e^+
\]

And "neutrinos" that do this:
\[
\nu + n \rightarrow p + e^-
\]

A distinct particle and antiparticle

\[ \nu \neq \bar{\nu} \]
So far, we've discussed interactions involving **electrons**.
So far, we've discussed interactions involving **electrons**.
So far, we've discussed interactions involving **electrons**.
So far, we've discussed interactions involving **electrons**.

\[ \nu \longrightarrow e^- + \text{??} \]

In 1937, the **muon** is discovered. Like a heavy electron, but it decays:

\[ \mu^- \longrightarrow e^- + \text{??} \]
So far, we've discussed interactions involving **electrons**.

In 1937, the **muon** is discovered. Like a heavy electron, but it decays:

\[
\mu^- \rightarrow e^- + \ ?
\]

In 1947, the **pion** is discovered. Decays into a muon:

\[
\pi^- \rightarrow \mu^- + \ ?
\]
So far, we've discussed interactions involving **electrons**.

![Diagram of electron interaction](image)

**In 1937, the muon is discovered.**

Like a heavy electron, but it decays:

\[
\mu^- \rightarrow e^- + ?
\]

![Diagram of muon interaction](image)

**In 1947, the pion is discovered.**

Decays into a muon:

\[
\pi^- \rightarrow \mu^- + ?
\]

![Diagram of pion interaction](image)
So far, we've discussed interactions involving **electrons**.

\[ \nu_e \rightarrow e^- \]

In 1937, the **muon** is discovered. 
Like a heavy electron, but it decays:

\[ \mu^- \rightarrow e^- + ? \]

In 1947, the **pion** is discovered. 
Decays into a muon:

\[ \pi^- \rightarrow \mu^- + ? \]

**Carl Anderson**

Cloud Chamber
Where do we get a lot of these muon neutrinos?

Make some "cosmic rays!"

\[
\pi^+ \rightarrow \mu^+ + \nu
\]

Primary Cosmic Ray → Atmospheric Stuff → \(\pi^+\) → \(\mu^+\) + \(\nu\)
Where do we get a lot of these muon neutrinos?

Make some "cosmic rays!"

\[
\pi^+ \to \mu^+ + \nu
\]
Where do we get a lot of these muon neutrinos?

Make some "cosmic rays!"

\[
\pi^+ \rightarrow \mu^+ + \nu
\]
Where do we get a lot of these muon neutrinos?

Make some "cosmic rays!"

\[
\pi^+ \rightarrow \mu^+ + \nu
\]
Where do we get a lot of these muon neutrinos?

Make some "cosmic rays!"

\[ \pi^+ \rightarrow \mu^+ + \nu \]

Proton Beam \rightarrow Target \rightarrow Neutrino Detector

1962

Leon Lederman
Melvin Schwartz
Jack Steinberger
Where do we get a lot of these muon neutrinos?

Make some "cosmic rays!"

\[ \pi^+ \rightarrow \mu^+ + \nu \]
Where do we get a lot of these muon neutrinos?

Make some "cosmic rays!"

$$\pi^+ \rightarrow \mu^+ + \nu$$

1962
Where do we get a lot of these muon neutrinos?

Make some "cosmic rays!"

\[ \pi^+ \rightarrow \mu^+ + \nu \]

1962
Where do we get a lot of these muon neutrinos?

Make some "cosmic rays!"

\[ \pi^+ \rightarrow \mu^+ + \nu \]

Proton Beam

Target

Magnet

\[ \mu^+ \rightarrow \nu \]

Absorber

1962

Leon Lederman
Melvin Schwartz
Jack Steinberger
Where do we get a lot of these muon neutrinos?

Make some "cosmic rays!"

There exist distinct muon-type and electron-type neutrinos (and antineutrinos)

1988 Nobel Prize in Physics
Lederman, Schwartz, and Steinberger
"for the neutrino beam method and the demonstration of the doublet structure of the leptons through the discovery of the muon neutrino"
The Plot Thickens

In 1975, the **tau lepton** is discovered by Perl et al. It's like a REALLY heavy electron.

2000: **Two flavors of neutrinos**

Located at Fermilab!
The Plot Thickens

Three!
2000: Two flavors of neutrinos

In 1975, the tau neutrino was discovered by Perl et al. It's like a REALLY heavy electron.

Based on four events, the existence of a tau-type neutrino is confirmed.

\[ \nu_e \]

\[ \nu_\mu \]

\[ \nu_\tau \]

1995 Nobel Prize in Physics
Martin Perl (shared with Reines)
"for the discovery of the tau lepton"

Located at Fermilab!
The Standard Model
Pulling it all together

So far, we've got:

\[ \nu_e, \nu_\mu, \nu_\tau \]
\[ \bar{\nu}_e, \bar{\nu}_\mu, \bar{\nu}_\tau \]

That do this:

\[ \nu_e \rightarrow e^- \quad \mu^- \quad \nu_\mu \rightarrow \mu^+ \quad \tau^- \rightarrow \tau^+ \]

All massless and neutral

Plus all the normal matter:

\[ e^- \quad n \quad p \quad \text{quarks} \]

and antimatter counterparts

And other stuff we've found:

\[ \pi^+ = u\bar{d} \quad K^+ = u\bar{s} \]
\[ \pi^- = \bar{u}d \quad \Delta^{++} = uuu \]

etc.

And a whole bunch of rules!
"FUNDAMENTAL" PARTICLES

1617

Robert Fludd

P. Meyers, Princeton
c. 1992

c. 1869

1970s

Standard Model of Elementary Particles

CC BY-SA 3.0 MissMJ, Wikimedia Commons
The Standard Model

A Mathematical Model

The Standard Model collects all the known matter particles and encodes their interactions.

Mathematically, it's a relativistic quantum field theory that's all about groups and symmetry.

Hydrogen Wave Function

Probability density plots.

\[ \psi_{nlm}(r, \theta, \varphi) = \sqrt{\left(\frac{2}{n a_0}\right)^3 \frac{(n-l-1)!}{2n![(n+l)]!}} e^{-\rho/2} \rho^{l+1} L_{n-l-1}^l(\rho) \cdot Y_{lm}(\theta, \varphi) \]
The Standard Model
Fundamental Symmetries

Noether's Theorem (1918) relates symmetries to conserved quantities

Time invariance ↔ Energy conservation
i.e. physics is the same at all times

Translation invariance ↔ Momentum conservation
i.e. physics is the same at all positions

Rotation invariance ↔ Angular momentum conservation
i.e. physics is the same at all angles

CP invariance ↔ Matter + antimatter conservation
i.e. (Anti-)particles are the same but opposite charge, parity

These symmetries underpin the Standard Model, our most fundamental understanding of nature
# The Standard Model

## Particle Menagerie

### Quarks

<table>
<thead>
<tr>
<th>I</th>
<th>II</th>
<th>III</th>
</tr>
</thead>
<tbody>
<tr>
<td>u</td>
<td>c</td>
<td>t</td>
</tr>
<tr>
<td>up</td>
<td>charm</td>
<td>top</td>
</tr>
<tr>
<td>0.003 GeV/c$^2$</td>
<td>1.3 GeV/c$^2$</td>
<td>175 GeV/c$^2$</td>
</tr>
<tr>
<td>d</td>
<td>s</td>
<td>b</td>
</tr>
<tr>
<td>down</td>
<td>strange</td>
<td>bottom</td>
</tr>
<tr>
<td>0.006 GeV/c$^2$</td>
<td>0.1 GeV/c$^2$</td>
<td>4.3 GeV/c$^2$</td>
</tr>
</tbody>
</table>

### Leptons

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_e$</td>
<td>$\nu_\mu$</td>
<td>$\nu_\tau$</td>
</tr>
<tr>
<td>electron neutrino</td>
<td>muon neutrino</td>
<td>tau neutrino</td>
</tr>
<tr>
<td>&lt;10$^{-8}$ GeV/c$^2$</td>
<td>&lt;10$^{-4}$ GeV/c$^2$</td>
<td>&lt;0.02 GeV/c$^2$</td>
</tr>
<tr>
<td>e$^-$</td>
<td>$\mu^-$</td>
<td>$\tau^-$</td>
</tr>
<tr>
<td>electron</td>
<td>muon</td>
<td>tau</td>
</tr>
<tr>
<td>511 keV/c$^2$</td>
<td>0.106 GeV/c$^2$</td>
<td>1.78 GeV/c$^2$</td>
</tr>
</tbody>
</table>

### Bosons

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma$</td>
<td>photon</td>
</tr>
<tr>
<td>0</td>
<td></td>
</tr>
<tr>
<td>$g$</td>
<td>gluon</td>
</tr>
<tr>
<td>0</td>
<td></td>
</tr>
<tr>
<td>$W^{\pm}$</td>
<td>W boson</td>
</tr>
<tr>
<td>80.4 GeV/c$^2$</td>
<td></td>
</tr>
<tr>
<td>$Z^0$</td>
<td>Z boson</td>
</tr>
<tr>
<td>91.2 GeV/c$^2$</td>
<td></td>
</tr>
<tr>
<td>$H$</td>
<td>Higgs boson</td>
</tr>
<tr>
<td>125 GeV/c$^2$</td>
<td></td>
</tr>
</tbody>
</table>
The Standard Model

Particle Menagerie

<table>
<thead>
<tr>
<th>QUARKS</th>
<th>LEPTONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>II</td>
</tr>
<tr>
<td>$u$ up</td>
<td>$c$ charm</td>
</tr>
<tr>
<td>0.003 GeV/c²</td>
<td>1.3 GeV/c²</td>
</tr>
<tr>
<td>$d$ down</td>
<td>$s$ strange</td>
</tr>
<tr>
<td>0.006 GeV/c²</td>
<td>0.1 GeV/c²</td>
</tr>
</tbody>
</table>

Quarks organize into

**Hadrons**

**Mesons**
- $q\bar{q}$
  - e.g.
    - $\pi^+ = u\bar{d}$
    - $\pi^- = \bar{u}d$
    - $K^+ = u\bar{s}$

**Baryons**
- $qqq$
  - e.g.
    - $p = udu$
    - $n = udd$
    - $\Delta^{++} = uuu$

Higgs boson

$$125 \text{ GeV/c}^2$$
The Standard Model
Particle Menagerie

**QUARKS**

<table>
<thead>
<tr>
<th>I</th>
<th>II</th>
<th>III</th>
</tr>
</thead>
<tbody>
<tr>
<td>u</td>
<td>c</td>
<td>t</td>
</tr>
<tr>
<td>up</td>
<td>charm</td>
<td>top</td>
</tr>
<tr>
<td>0.003 GeV/c²</td>
<td>1.3 GeV/c²</td>
<td>175 GeV/c²</td>
</tr>
<tr>
<td>d</td>
<td>s</td>
<td>b</td>
</tr>
<tr>
<td>down</td>
<td>strange</td>
<td>bottom</td>
</tr>
<tr>
<td>0.006 GeV/c²</td>
<td>0.1 GeV/c²</td>
<td>4.3 GeV/c²</td>
</tr>
</tbody>
</table>

**LEPTONS**

<table>
<thead>
<tr>
<th>I</th>
<th>II</th>
<th>III</th>
</tr>
</thead>
<tbody>
<tr>
<td>νₑ</td>
<td>νₑ</td>
<td>νₑ</td>
</tr>
<tr>
<td>electron neutrino</td>
<td>muon neutrino</td>
<td>tau neutrino</td>
</tr>
<tr>
<td>&lt;10⁻⁸ GeV/c²</td>
<td>&lt;10⁻⁴ GeV/c²</td>
<td>&lt;0.02 GeV/c²</td>
</tr>
<tr>
<td>e⁻</td>
<td>μ⁻</td>
<td>τ⁻</td>
</tr>
<tr>
<td>electron</td>
<td>muon</td>
<td>tau</td>
</tr>
<tr>
<td>511 keV/c²</td>
<td>0.106 GeV/c²</td>
<td>1.78 GeV/c²</td>
</tr>
</tbody>
</table>

- **γ** photon
- **g** gluon
- **W⁺/⁻** W boson
- **Z⁰** Z boson
- **H** Higgs boson
The Standard Model

Particle Menagerie

**QUARKS**

<table>
<thead>
<tr>
<th>I</th>
<th>II</th>
<th>III</th>
</tr>
</thead>
<tbody>
<tr>
<td>$u$ up</td>
<td>$c$ charm</td>
<td>$t$ top</td>
</tr>
<tr>
<td>+2/3</td>
<td>+2/3</td>
<td>+2/3</td>
</tr>
<tr>
<td>0.003 GeV/$c^2$</td>
<td>1.3 GeV/$c^2$</td>
<td>175 GeV/$c^2$</td>
</tr>
</tbody>
</table>

| $d$ down | $s$ strange | $b$ bottom |
| -1/3 | -1/3 | -1/3 |
| 0.006 GeV/$c^2$ | 0.1 GeV/$c^2$ | 4.3 GeV/$c^2$ |

**LEPTONS**

<table>
<thead>
<tr>
<th>$\nu_e$ electron neutrino</th>
<th>$\nu_\mu$ muon neutrino</th>
<th>$\nu_\tau$ tau neutrino</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$e^-$ electron</td>
<td>$\mu^-$ muon</td>
<td>$\tau^-$ tau</td>
</tr>
<tr>
<td>-1</td>
<td>-1</td>
<td>-1</td>
</tr>
<tr>
<td>511 keV/$c^2$</td>
<td>0.106 GeV/$c^2$</td>
<td>1.78 GeV/$c^2$</td>
</tr>
</tbody>
</table>

**Forces & Interactions**

Matter particles (quarks & leptons) interact by exchanging messenger particles called **bosons**.

**Example:** Electromagnetic interactions involve exchange of a **photon**.
The Standard Model

Particle Menagerie

**QUARKS**

<table>
<thead>
<tr>
<th>I</th>
<th>II</th>
<th>III</th>
</tr>
</thead>
<tbody>
<tr>
<td>u</td>
<td>c</td>
<td>t</td>
</tr>
<tr>
<td>up</td>
<td>charm</td>
<td>top</td>
</tr>
<tr>
<td>0.003 GeV/c²</td>
<td>1.3 GeV/c²</td>
<td>175 GeV/c²</td>
</tr>
<tr>
<td>d</td>
<td>s</td>
<td>b</td>
</tr>
<tr>
<td>down</td>
<td>strange</td>
<td>bottom</td>
</tr>
<tr>
<td>0.006 GeV/c²</td>
<td>0.1 GeV/c²</td>
<td>4.3 GeV/c²</td>
</tr>
</tbody>
</table>

**LEPTONS**

<table>
<thead>
<tr>
<th></th>
<th>e⁻</th>
<th>μ⁻</th>
<th>τ⁻</th>
</tr>
</thead>
<tbody>
<tr>
<td>ν_eeee</td>
<td>ν_μμμμ</td>
<td>ν_ττττ</td>
<td></td>
</tr>
<tr>
<td>electron neutrino</td>
<td>muon neutrino</td>
<td>tau neutrino</td>
<td></td>
</tr>
<tr>
<td>&lt;10⁻⁸ GeV/c²</td>
<td>&lt;10⁻⁴ GeV/c²</td>
<td>&lt;0.02 GeV/c²</td>
<td></td>
</tr>
<tr>
<td>e⁻</td>
<td>μ⁻</td>
<td>τ⁻</td>
<td></td>
</tr>
<tr>
<td>electron</td>
<td>muon</td>
<td>tau</td>
<td></td>
</tr>
<tr>
<td>511 keV/c²</td>
<td>0.106 GeV/c²</td>
<td>1.78 GeV/c²</td>
<td></td>
</tr>
</tbody>
</table>

**EM, strong, weak, Higgs**

**Electromagnetic force**

**Strong nuclear force**

**Weak nuclear force**

**Particle masses**

Higgs boson
125 GeV/c²

Electromagnetic force

Strong nuclear force

Weak nuclear force
The Standard Model

Beta Decay, 1930s

\[ n \rightarrow p + e^- + \bar{\nu}_e \]
The Standard Model

Beta Decay, Standard Model

\[ n \rightarrow p + e^- + \bar{\nu}_e \]
1913: Beta Decay Troubles

1953-1956: The Reines-Cowan Experiments
Detecting the Poltergeist

1930s: Proposal & Theory

1962: Muon Neutrinos

1970s: Standard Model

1990s - 2000s: The End of the Beginning
Next Week
The Solar Neutrino Problem

1960s: The first neutrino anomaly

\[ p + p \rightarrow ^2\text{H} + e^+ + \nu_e \]

99.6%

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

0.4%

\[ ^2\text{H} + p \rightarrow ^3\text{He} + \gamma \]

15%

\[ ^3\text{He} + ^3\text{He} \rightarrow ^4\text{He} + 2p \]

85%

\[ ^3\text{He} \rightarrow ^7\text{Be} + e^- + \nu_e \]

99.87%

\[ ^7\text{Be} + p \rightarrow ^8\text{B} + \gamma \]

0.13%

\[ ^8\text{B} \rightarrow ^8\text{Be}^* + e^+ + \nu_e \]

\[ ^8\text{Be}^* \rightarrow 2^4\text{He} \]


John Bahcall

Bahcall Photo: CC BY-SA 3.0 Dan Bahcall, Wikimedia Commons
The Solar Neutrino Problem

1960s: The first neutrino anomaly

The Homestake Solar Neutrino Experiment
The Solar Neutrino Problem

1960s: The first neutrino anomaly

The Homestake Solar Neutrino Experiment

Theoretical Prediction

Observed Data

Thank You!