“Seeing” Neutrinos

Karol Lang
University of Texas at Austin
Department of Physics, Pizza seminar, November 30, 2010

"You can observe a lot just by watching."
Yogi Bera
We are recruiting new students to our group
- PhD opportunities
- Undergraduate senior/honors theses topics

If interested:
- KL’s office: RLM 10.208
- Talk to others in the lab (RLM 10.216)

For your reference, this talk will be posted on
- [www.hep.utexas.edu/~lang/talks/PizzaSeminar-2010](http://www.hep.utexas.edu/~lang/talks/PizzaSeminar-2010)
How to find a research group:  
**a brief (unofficial) guide**

◆ You are here to do research not take classes!
◆ You are expected to be industrious in finding a group
◆ Here are a few tips

  □ Do you have time?
    ✓ 15-20 hrs per week, may be possible with less
    ✓ Possibly more for graduate students
    ✓ Weekends including
    ✓ This should become your priority, thus commitment

  □ Think about what you are truly interested in
    ✓ theory?
    ✓ or experiment?

  □ Narrow down the field
    ✓ This may be tougher than it sounds
    ✓ Talk to graduate (or undergraduate) advisor
    ✓ Follow up with other faculty
    ✓ Talk **directly** with a head of a group as advised

  □ Try it – there is no replacement for “being there”
    ✓ This is serious for both sides
    ✓ Spend time with your possible future advisor, understand your future
    ✓ If “unhappy” → start over

◆ There is a form distributed about a month ago. I wonder how many responses you have....

Karol Lang  "Seeing" Neutrinos  Pizza Seminar, U of Texas, 454530, 2010
1. Introduction (to particle physics)
2. Sources of neutrinos
3. Neutrino interactions
4. Some experiments
5. MINOS
The Standard Model

Quarks are *confined* in states bound by gluons: hadrons

**Baryons qqq and Antibaryons ũũũ**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Name</th>
<th>Quark content</th>
<th>Electric charge</th>
<th>Mass GeV/c²</th>
<th>Spin</th>
</tr>
</thead>
<tbody>
<tr>
<td>p</td>
<td>proton</td>
<td>uud</td>
<td>1</td>
<td>0.938</td>
<td>1/2</td>
</tr>
<tr>
<td>ũūũ</td>
<td>antiproton</td>
<td>ũũũũ</td>
<td>-1</td>
<td>0.938</td>
<td>1/2</td>
</tr>
<tr>
<td>n</td>
<td>neutron</td>
<td>udd</td>
<td>0</td>
<td>0.940</td>
<td>1/2</td>
</tr>
</tbody>
</table>

**Mesons qũ**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Name</th>
<th>Quark content</th>
<th>Electric charge</th>
<th>Mass GeV/c²</th>
<th>Spin</th>
</tr>
</thead>
<tbody>
<tr>
<td>π⁺</td>
<td>pion</td>
<td>ud</td>
<td>+1</td>
<td>0.140</td>
<td>0</td>
</tr>
<tr>
<td>K⁻</td>
<td>kaon</td>
<td>su</td>
<td>-1</td>
<td>0.494</td>
<td>0</td>
</tr>
<tr>
<td>ρ⁺</td>
<td>rho</td>
<td>ud</td>
<td>+1</td>
<td>0.776</td>
<td>1</td>
</tr>
</tbody>
</table>

...+ anti-particles

Why this structure? What about gravity? ...

→ Many open questions
In the Standard Model mass of all massive particles is generated through “the Higgs mechanism”, which implies the existence of a new particle - the Higgs boson.

Does the Higgs boson exist?

What is the mass of the Higgs boson?

Now searched for at
- Tevatron at Fermilab
- Now also at LHC at CERN

Peter Higgs
## Four forces

### Particle Processes

These diagrams are an artist's conception. Blue-green shaded areas represent the cloud of gluons.

- **n → p e⁻ νₑ**
  - A free neutron (udd) decays to a proton (uud), an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron β (beta) decay.

- **e⁺ e⁻ → B⁰ B̄⁰**
  - An electron and positron (antinelectron) colliding at high energy can annihilate to produce $B^0$ and $B^0$ mesons via a virtual Z boson or a virtual photon.

---

## Properties of the Interactions

The strengths of the interactions (forces) are shown relative to the strength of the electromagnetic force for two u quarks separated by the specified distances.

<table>
<thead>
<tr>
<th>Property</th>
<th>Gravitational Interaction</th>
<th>Weak Interaction (Electroweak)</th>
<th>Electromagnetic Interaction</th>
<th>Strong Interaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acts on:</td>
<td>Mass – Energy</td>
<td>Flavor</td>
<td>Electric Charge</td>
<td>Color Charge</td>
</tr>
<tr>
<td>Particles experiencing:</td>
<td>All</td>
<td>Quarks, Leptons</td>
<td>Electrically Charged</td>
<td>Quarks, Gluons</td>
</tr>
<tr>
<td>Particles mediating:</td>
<td>Graviton (not yet observed)</td>
<td>$W^+$ $W^-$ $Z^0$</td>
<td>$\gamma$</td>
<td>Gluons</td>
</tr>
<tr>
<td>Strength at $10^{-18}$ m</td>
<td>$10^{-41}$</td>
<td>0.8</td>
<td>1</td>
<td>25</td>
</tr>
<tr>
<td>Strength at $3\times10^{-17}$ m</td>
<td>$10^{-41}$</td>
<td>$10^{-4}$</td>
<td>1</td>
<td>60</td>
</tr>
</tbody>
</table>
Super Symmetry: fermions $\leftrightarrow$ bosons
Natural (sources of) neutrinos
A spectrum problem (<1930)

Entia non sunt multiplicanda praeter necessitatem.

(Entities must not be multiplied beyond necessity.)

(William of ) Occam’s razor (XIV century)
Invention of neutrino – “a desperate remedy”

Dear Radioactive Ladies and Gentlemen!

I have hit upon a desperate remedy to save...the law of conservation of energy.

...there could exist electrically neutral particles, which I will call neutrons, in the nuclei...

The continuous beta spectrum would then make sense with the assumption that in beta decay, in addition to the electron, a neutron is emitted such that the sum of the energies of neutron and electron is constant.

But so far I do not dare to publish anything about this idea, and trustfully turn first to you, dear radioactive ones, with the question of how likely it is to find experimental evidence for such a neutron...

I admit that my remedy may seem almost improbable because one probably would have seen those neutrons, if they exist, for a long time. But nothing ventured, nothing gained...

Thus, dear radioactive ones, scrutinize and judge.

Translation: Kurt Rießelmann

15 Dec 1930

Closing:

“Unfortunately, I cannot appear in Tubingen personally since I am indispensable here in Zurich because of a ball on the night of 6/7 December.”

Enrico Fermi took up Pauli’s idea and on its basis developed a theory of beta decay. Fermi also coined the term "neutrino", after Pauli had spoken of "neutron", but the latter designation was reserved for the heavy component of the atomic nucleus discovered in 1932.

Not until October 1933 at the 7th Solvay Conference in Brussels did Pauli dare to present his hypothesis in public. It then took a further 23 years before the experimental proof of the existence of the neutrino succeeded.
Radioactivity

$\alpha$ Decay

$^{263}_{106}$Sg

$^{259}_{104}$Rf

$^{4}_2$He

$^{14}_6$C

$^{14}_7$N

Beta Minus Decay

$^{18}_9$F

$^{18}_8$O

Beta Plus Decay

$^{152}_{66}$Dy

Gamma Decay

before

after

$\nu_e$ $
\bar{\nu}_e$

$\nu_e$

$\bar{\nu}_e$

$e^-$

$e^+$

$W^-$

$u$

d

d

$u$

$n \rightarrow p e^- \bar{\nu}_e$
Neutrino discovery (Reines and Cowan, 1956)

Detection: \textbf{"inverse beta decay"}

Reines and Cowan at Savannah River
Solar neutrinos – the Sun shines

Full details of how this happens called `Standard Solar Model’
Ray Davis’ chlorine experiment

- 1965-67: Davis builds 615 ton chlorine ($C_2Cl_4$) detector (cleaning fluid)
- Deep underground to suppress cosmic ray backgrounds.
  - Homestake Mine (4800 mwe depth)
- Low background proportional detector for $^{37}\text{Ar}$ decay.

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

detect

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

\[ t_{1/2} \approx 37 \text{ days} \]

- Detected $\sim 1/3$ of expected rate.
COBE (T = 2.725 K) and WMAP

Spectrum from the Far Infrared Absolute Spectrophotometer (FIRAS) which was part of the COBE (Cosmic Background Explorer) satellite. It shows almost perfect agreement with a 2.725 K blackbody spectrum.

Nobel 1978
Arno A. Penzias Robert W. Wilson

Nobel 2006
John C. Mather George F. Smoot
“for their discovery of the blackbody form and anisotropy of the cosmic microwave background radiation”
History of the Universe

Key:
- w, Z: bosons
- photon
- q: quark
- g: gluon
- e, m, t: electron, muon, tau
- neutrino
- meson
- star
- baryon
- ion
- galaxy
- atom
- black hole

Particle Data Group, LBNL, © 2000. Supported by DOE and NSF
Atmospheric neutrinos

\[ \pi^+ \rightarrow \mu^+ \nu_\mu \quad (e^+ \nu_e) \]

Courtesy: Auger Observatory
Detecting atmospheric neutrinos:
(Underground) SuperKamiokande Experiment

- 50 kton water (22.5 fid.vol.)
- 11,146 PMTs + 1,885 PMTs
- overburden 2,700 m.w.e.

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This event occurred at 1998-04-04 08:35:22. It was reconstructed as a muon with momentum of 603 MeV. The time scale width is 162 ns. This event was followed by another event (not shown) 4 us later which was caused by an electron produced by the decay of the stopped muon. This gives us an additional confirmation that this is a muon.

This event occurred at 1998-04-04 21:26:08. It was reconstructed as an electron with momentum of 492 MeV. The time scale width is 130 ns.

**Cherenkov radiation**

\[ \cos \theta_C = \frac{1}{\beta n(\omega)} \quad \text{if} \quad \beta_C \geq \frac{1}{n} \]

\[ (n = \frac{c}{v} \quad \text{and} \quad \beta = \frac{v}{c}) \]

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Discovery of Neutrinos Oscillations (1998)

\[ \frac{N(\nu_\mu + \bar{\nu}_\mu)}{N(\nu_e + \bar{\nu}_e)} \neq 2 \]
Solar neutrinos in SuperK

Sun’s image using neutrinos

\[ \phi \]

\[ \theta \]
SNO (Sudbury Neutrino Observatory)

\[
\begin{align*}
\text{CC} & \quad \nu_e + d \rightarrow p + p + e^- \\ 
\text{ES} & \quad \nu + e^- \rightarrow \nu + e^- \\ 
\text{NC} & \quad \nu + d \rightarrow p + n + \nu
\end{align*}
\]

(Cerenkov)

(n-capture by $^{35}\text{Cl}$ - g scatter - Cerenkov)
Neutrinos are produced by weak interactions in **weak eigenstates** of three (conserved) flavors $\nu_e, \nu_\mu, \nu_\tau$.

In general, weak eigenstates are not the same as **mass eigenstates** $\nu_1, \nu_2, \nu_3$. (Similarly as for quarks.)

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix} =
\begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\
U_{\tau 1} & U_{\tau 2} & U_{\tau 3}
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]

Propagation of states is a function of mass

\[
\left| \nu_{\mu}, t \right> = |1\rangle \cos \theta \ e^{-im_1^2 t / 4 p} + |2\rangle \sin \theta \ e^{-im_2^2 t / 4 p}
\]

The mixing matrix is unitary matrices can be parametrized by 4 angles:

- 3 mixing angles $\theta_{12}, \theta_{13}, \theta_{23}$
- and a phase $\delta$
Consider neutrino oscillations for 2 flavors

\[ |\nu(t = 0)\rangle = |\nu_a\rangle = \cos \theta |\nu_1\rangle + \sin \theta |\nu_2\rangle \]

\[
\begin{pmatrix}
\nu_a \\
\nu_b
\end{pmatrix}_{\text{weak}} = 
\begin{pmatrix}
\cos \theta & \sin \theta \\
-\sin \theta & \cos \theta
\end{pmatrix} 
\begin{pmatrix}
\nu_1 \\
\nu_2
\end{pmatrix}_{\text{mass}}
\]

Neutrino in space (survival probability):

\[
P(\nu_a \rightarrow \nu_a) = \left(1 - \sin^2 2\theta \cdot \sin^2 \left(\frac{1.27 \cdot L \cdot \Delta m_{21}^2}{E}\right)\right)
\]

L in [km]
E in [GeV]
\(\Delta m_{21}^2 = m_2^2 - m_1^2\) in [eV^2]
While looking for a proton decay, two experiments, IMB and Kamiokande II

SN 1987-A seen by naked-eye (23 Feb 1987, Large Magellanic Cloud, d \approx 50 \text{kpc})

Calculated neutrino spectra from Supernovae


- **Detector** | **Type** | **Threshold** | **Mass (kton)** | **Detection reaction** | **Neutrino Number**
- KII | Cerenkov | 7.5 MeV | 2.14 | $\nu_e p \to n e$ | 11
- IMB | Cerenkov | 30 MeV | 6.8 | $\nu_e p \to n e^+$ | 8

Figure 12: Scatter plot of $N_{\text{hit}}$ against time relative to 7:35:35 UT, February 23, 1987.
Man-made neutrinos
Modern approach

**MINOS**

**Main Injector Neutrino Oscillation Studies**

- **Two-detector measurement**
  - long baseline (735km)
  - underground (CR shielding + physics)

- **High intensity beam from 120 GeV Main Injector**
  - (up to) $4 \times 10^{13}$ protons/pulse (0.4 MW beam)
  - (potential for $\sim 4 \times 10^{20}$ protons/year)
  - single turn extraction (8.67 $\mu$s)

- **Flexible & well-controlled beam**
  - two parabolic magnetic horns
  - movable target (→ energy spectrum)
Neutrinos at Main Injector (NuMI)

(Main Injector = MI)

- MI is fed 1.56 μs batches from 8 GeV Booster
  (MI ramp time ~1.5sec)

- NuMI designed for
  - 8.67 μsec single turn extraction
  - $4 \times 10^{13}$ ppp @ 120 GeV
  - 1.9 second cycle time
  - beam power ~400kW

- Typical performance to date:
  - $3.2 \times 10^{13}$ ppp @ 120 GeV
  - 2.2 second cycle time

- Achieved records:
  - $3.7 \times 10^{13}$ ppp @ 120 GeV
  - 2.0 second cycle time
  - 320 kW
Neutrino Beamline

120 GeV protons hit graphite target
Two magnetic horns focus positive $\pi$ & $K$

Parabolic Horn focal length:

$$f \approx \frac{2\pi}{\mu_0 I a} p$$
Mesons decay in flight in evacuated decay pipe

Do not hallucinate.
Parabolic magnetic horns

\[ |\vec{J}| = |\Delta p_T| = \int B(r)\,dl \approx \frac{\mu_0 I}{2\pi r} \cdot ar^2 \]

\[ f \approx \frac{r}{p_T}p = \frac{2\pi}{\mu_0 I \alpha p} \]
MINOS Target Hall

Hall probe

Horn 2 suspended from shielding module being lowered into shielding pit
Bubble chamber – not practical for high sensitivities (large statistics)

- liquid at 5 – 20 atmospheres
- bubbles form along the path of ionisation at relaxation – take photo
- magnetic field for deviation of charged particles
Gargamelle – Neutral current discovery (1973)

The first example of the neutral current process:

$$\nu_{\mu} \bar{\nu}_{\mu} + e^- \to \nu_{\mu} \bar{\nu}_{\mu} + e^-.$$  

The electron is projected forward with an energy of 400 MeV at an angle of 1.5° to the beam, entering from below.
Sampling calorimeter vs crystals

\[ e \rightarrow \text{PbWO}_4 \text{ crystals (simulation)} \]

Lead + clound chamber (picture)
MINOS “technology”

- 2.54 cm Fe
- WLS fiber
- Scintillator
- Steel
- 5.9 cm
- U V planes +/- 45°
- Clear Fiber cables
- Multi-anode PMT
- Near Det
- Far Det
- M16 8 fibers/pixel
- M64 1 fiber/pixel
- Extruded PS scint. 4.1 x 1 cm
- 8 fibers/pixel
- 1 fiber/pixel
- MINOS “technology”

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Far Detector –
735.3 km away (Soudan Mine, Mn)

Running since July 2003
- 2 Supermodules
- 5.4 kT
- 484 scint. planes
- CR veto shield (2,070 mwe)
- $B \sim 1.5T$ (R=2m)
- 93,120 strips (4.1 x 1.0 cm)
- 8-fold MUXed 2-ended readout
- 1551 M16s
- 722 km of WLS fiber
- 794 km of clear fiber
- $HAD = 56\% / E^{1/2}$
- $EM = 23\% / E^{1/2}$

Scintillator Plane
(8 modules, 192 strips)
Hadronic cascade (shower)

\[ E_\nu = E_{\text{shower}} + P_\mu \]

Monte Carlo

\[ E_\nu \leq E_{\text{shower}} \]
ν interactions in MINOS

ν_{μ} CC

"Nuclear Fragments"

ν_{μ} NC

"Nuclear Fragments"

ν_{e} CC

"Nuclear Fragments"

Electron “Shower”
MINOS event topologies

- $\nu_\mu \text{ CC Event}$
- $\bar{\nu}_\mu \text{ CC Event}$
- $\nu_\mu \text{ NC Event}$

Diagrams showing event topologies with different particle interactions and distributions in the $z$ position.
Oscillations of neutrinos vs anti-neutrinos

\[ |\Delta m^2| = 2.32^{+0.12}_{-0.08} \times 10^{-3} \text{ eV}^2 \]
\[ \sin^2(2\theta) > 0.90 \text{ (90\% C.L.)} \]

\[ |\Delta m^2| = 3.36^{+0.45}_{-0.40} \times 10^{-3} \text{ eV}^2 \]
\[ \sin^2(2\bar{\theta}) = 0.86 \pm 0.11 \]
◆ We are recruiting new students to our group
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