Neutrinos

Saturday Morning Physics

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Standard Model and Neutrinos
Elementary Particles

What does elementary mean?

Leptons

- Electron (e) charge: -1

Quarks

- Up (u) charge: +2/3
- Down (d) charge: -1/3

Protons = 2 up and 1 down
Partial Standard Model of Elementary Particles

The difference between the generations is the MASS!
The Fundamental Forces of the Universe Influence the Behavior of Particles!

Thanks to the electromagnetic force, we can’t walk through walls!
The Fundamental Forces of the Universe

Influence the Behavior of Particles!

How about the weak force?

Let’s take a detour first....

Nature Can Produce Particles!!!
The sun is an ultimate nuclear fusion reactor!
Neutrinos emitted from the Sun, other stars, and including the **BIG BANG** are traveling through out **SPACE!!**
Millions and millions and millions of neutrinos are also passing through YOU at this very MOMENT!

~ 65 billion of neutrinos / cm$^2$ / sec from the Sun.
This lecture focuses on this section of the picture.

Will not talk about The God particle.

Will talk just indirectly about this particles.

The Complete Picture
What are neutrinos?

3 neutrinos types (flavors): no charge, only interact by weak force

- $\nu_e$ (electron neutrino)
- $\nu_\mu$ (muon neutrino)
- $\nu_\tau$ (tau neutrino)

2 mediators of weak force

- $W^+$ (charge: +1)
- $W^-$ (charge: 0)

What is the Weak force that influences the nature of neutrinos?

Why are neutrinos SO important?
The Discovery of the Neutrino
Radioactive Decay
unstable atomic nucleus loses energy by emitting particles
transforms an atom into a different type of atom or into a lower energy

Alpha Decay
\( \alpha \) 2 protons 2 neutrons

Beta Decay
\( e^- \) electron

Gamma Decay
\( \gamma \) photons
Studying Beta Decay

Rhodium → Palladium + Electron (Beta Particle)

98,652.876 MeV/c²

98,649.196 MeV/c²

0.511 MeV/c²

electron kinetic energy: 98652.876 – 98649.196 – 0.511 = 3.169 MeV.
Measured Energy Spectrum of the Beta Particle

Could it be possible?

Does the Beta Decay Violate the Law of Energy Conservation?
In 1930, Wolfgang Pauli proposed that another particle (a neutral particle, a particle that can not be detected) is emitted along with the electron.

However, Pauli was skeptical about the proposal.

In fact, on Dec. 4, 1930, Pauli wrote a letter to a conference organizer proposing the idea of a neutral particle.
In 1933, Enrico Fermi brought the particle into reality.

Fermi’s theory showed that the neutron (also bound in the nucleus) decays into a proton and simultaneously emits an electron and a neutrino.

The WEAK FORCE turns the neutron into a proton.
Back to the Beta Decay

Measured Energy Spectrum of the Beta Particle

Energy is shared between the particles.
• Fermi’s theory of energy remains conserved.

• A new particle, the neutrino, is proposed.

• Next step is to detect the neutrino.
Finding the Neutrino
Nature has many symmetries
Symmetry in Interactions

\[ e^- \quad e^+ \]

\[ \text{time} \]
Symmetry Plays a Fundamental Role in Particle Physics

**Time Reversal**

Any particle interaction that occurs forward in time can also occur backwards.

Beta-Decay

- neutron
- proton
- neutrino

Inverse Beta-Decay

- electron (+), which is named the positron
- neutrino
- proton
- neutron

We can DETECT the neutrino by the inverse beta-decay.
In 1936, Yukawa proposed the W boson. The carrier of the WEAK FORCE.

- neutron
- proton
- electron
- antineutrino

The weak force is one of the four fundamental forces of nature.

Weak force is 10,000 times weaker than the electromagnetic force.
Physicists use scattering experiments to understand and discover particles.

Scattering experiments measure the cross section of a particle interaction.

Cross-section is the number of counts in which the particle interacts with another particle.

Units of cross-section:
area (cm\(^2\))
To observe the neutrino, scientists needed to detect the signatures of the positron and neutron.

**Positron**

\[ e^+ \]

- is a positive charged electron
- interacts via the electromagnetic force
- interaction results in emission of gamma rays

**Neutron**

\[ n^0 \]

- looking inside the neutron
- an atomic nucleus can capture a neutron
- strong force binds the neutron in the nucleus to create a heavier particle
- the heavier particle is unstable
- emits gamma rays to become stable
The HULK is unstable. Bruce Banner is stable.
One would think that finding the signature of the neutrino will be easy.

Physicists calculated the cross-section of the inverse beta-decay to be less than $10^{-44}$ m$^2$.

What does that mean? What is the rate?

Solar Neutrinos can travel up to a light year of lead before interacting (MeV scale).

Neutrinos at Fermilab can travel up to 200 earths before interacting (GeV scale).

$1\text{GeV} = 10^3 \text{ MeV} = 10^9 \text{eV}$
Neutrino interactions are extremely rare!

Need an intense source of neutrinos!

(more neutrino per area per time, higher flux)
In 1934, Fermi was developing nuclear fission, artificial radioactivity. He bombarded heavy elements with slow neutrons.
Fermi’s colleague Leo Szilard understood the military application of nuclear fission.

Both Fermi and Szilard recruited Albert Einstein to write a letter to President Franklin D. Roosevelt to encourage him to fund their work.

The Manhattan Project was put into action in 1942.

The most brilliant physicists of the era working together constructed the first atomic bomb!
After World War II, scientists aim to extend the knowledge of frontier particle physics.

From the explosion products of the nuclear bomb, scientists were given a manufactured nuclear reactor.

Neutrons are unstable particles. Neutrons decay via beta decay. Remember: Beta decay is the emission of an electron and neutrino.

Nuclear reactors were expected to produce neutrino beams on the order of $10^{12} - 10^{13}$ neutrino / sec / cm$^2$. 

Let's do some Science!!!
Two decades later, a team lead by Clyde L. Cowan and Frederick Reines designed an experiment to detect neutrinos.

Neutrinos interact with a proton via inverse beta decay

Uses neutrinos from nuclear fission.

Detects the outgoing particles from the neutrino interaction.
Project Poltergeist

Results (1956)

Neutrinos are observed at a rate of 0.56 counts per hour!

We were able to produce and measure neutrinos here, on Earth!!!
What about using neutrinos emitted from the Sun...

In the late 1930s, physicists developed the solar model.

The solar model mathematically describes the nuclear fusion reactions that are occurring in the Sun’s core.
30 years after neutrinos were postulated...
In 1961, Ray Davis confirmed the detection of solar neutrinos. The Homestake Experiment used solar neutrino interactions to convert Chlorine-37 into radioactive Argon-37.

Where did all of the neutrinos go?

After correcting for detector effects and using the Solar Model prediction, the Davis’ group expected to see one solar neutrino per day.

However, they only saw one solar neutrino every fourth day.
Our measurement is wrong

Our understanding of how our detector behaves is wrong

Our understanding of how neutrinos behave is wrong

Our understanding of the way neutrinos are created in the sun is wrong

Where did all of the neutrinos go?
The Mysteries of Neutrinos
NEUTRINO EXPERIMENTS

NEUTRINO THEORIES
The muon was discovered (1936) before the muon neutrino.

There must be a 2nd generation of the neutrino.

Eventually, physicists discovered that there exist two types of neutrinos.

So, how many generations of neutrinos do exist?
Pions

A particle made from a quark and anti-quark pair.

There are three types of pions.

\[ \pi^+ \]
\[ \pi^- \]
\[ \pi^0 \]
So, how many generations of neutrinos do exist?
Atmospheric Neutrinos

- Cosmic rays (mostly protons) interact in the upper atmosphere creating hadronic showers (mostly pions).

- Roughly 2:1 muon neutrinos to electron neutrinos expected:

\[
\pi^+ \rightarrow \mu^+ + \nu_\mu \quad \rightarrow e^+ + \nu_e + \bar{\nu}_\mu
\]

- Events found in Kamiokande:

Why?
Physicists worried about the number of generations.

The best measurement comes from studying the decay of Z boson

→ measured 3 generations

Where \( f \) = quarks, leptons, neutrinos.
Recap: Leptons

- Electron: $e$ and $\nu_e$
- Muon: $\mu$ and $\nu_\mu$
- Tau: $\tau$ and $\nu_\tau$

Discovered in the mid 1970s

Discovered in 2000 at Fermilab DONUT experiment

3rd generation!!!!

OK! do we have everything???
Particle physics proposed that the measured neutrinos are NOT REAL particles!

In fact, the real neutrinos $\nu_1$, $\nu_2$, $\nu_3$ mix to create the flavor neutrinos, $\nu_e$, $\nu_\mu$, $\nu_\tau$!

The real neutrinos, $\nu_1$, $\nu_2$, $\nu_3$ have a well defined mass.
Wait....

So, the neutrinos that scientists have detected are a mixture of real neutrinos?
Neutrinos created with a specific flavor can evolve into a different flavor at a later time.

Diagram shows the probability of changing to another type of neutrino as a function of time.
Neutrino Oscillations

\[ P_{osc} = \sin^2 2\theta \sin^2 \left( \frac{1.27 \Delta m^2 L}{E} \right) \]

- \( \theta \) is the mixing angle
- \( \Delta m^2 = m_1^2 - m_2^2 (\text{eV}^2) \)
- \( L \) is the distance that neutrino travels (km)
- \( E \) is neutrino energy (GeV)

Oscillation probability

\[ f(L/E) \]
Understanding the Behavior of Neutrinos
In 1998, Super-Kamiokande (Japan) announced the finding of neutrinos with non-zero mass.

Study neutrino oscillations using atmospheric neutrinos.

Atmospheric neutrinos produced by the decay of particles resulting from interaction of particles with the Earth’s atmosphere.
In 2001, the results from Sudbury Neutrino Observatory (Canada) solved the mystery of the missing solar neutrinos puzzle.

SNO announced that the total number of all neutrino flavour agrees with the Solar model.
What is the Source of the Missing Solar Neutrinos?

Can neutrino oscillations explain the missing solar neutrinos?

By the time the neutrinos enter the Earth’s atmosphere, the electron neutrinos could be changing flavour.

40-year Puzzle Solved
Neutrino experiments.

So far, there are 4 types/sources of experiments:

- Solar
- Atmospheric
- Reactor
- Accelerator

Let's talk about it
Accelerator Neutrinos Strategy

Generate neutrinos from accelerators

$\nu$ beam $\rightarrow$ Near detector $\rightarrow$ Far detector

Oscillations

To have two functionally identical detectors

Oscillation probability = differences between measured and expected without oscillation
Fermilab Accelerator Complex

Neutrino beams:
- BNB
- NuMI
Future: LBNE
Several Neutrino experiments at Fermilab...
What do the detectors see?

ArgoNeuT

MINERvA

MiniBooNE

NOvA
We use the same principle of the atmospheric neutrinos
Beam of protons

Target

Pions

Muons

Carbon

Pion

Muon

Particles

Neutrino
Neutrinos at the Main Injector

Currently, $5 \times 10^{13}$ protons on target (POT) every 1.3 sec

~ same amount of neutrinos
The detector records information about the particles from neutrino interactions.
Neutrinos - Leo Aliaga

11/4/2017

Batavia, IL

810 km (503 miles)

Ash River, MN

NOvA Far Detector on surface

νμ
ντντ
νe
Why is it important for physicists to build more large detectors to understand neutrinos?
Neutrinos have mass.

BUT.. Why are the neutrinos SO light?

There is a very popular theory floating around.

BUT REALLY...

We do NOT know!
Neutrinos have mass.

The Standard Model is not complete.

Evidence that there are MANY behaviors in nature that we do not understand.
Remember, the neutrinos that scientists have detected are a mixture of real particles...

Do not know the ordering of the masses?

We do not know if the real neutrino $\nu_3$ consists of more $\nu_\mu$ or $\nu_\tau$.

All we know is the difference between the masses.
Why matter dominates over antimatter in the universe?

Detecting a difference in the behaviour of the neutrinos and antineutrinos

(Olena Shmahalo / Quanta Magazine)
we do not fully understand the universe.

There exists new detector technology to answer many of the unknown questions.
with new technology comes new challenges

Some challenges:
neutrino flux determination, reconstruction, incomplete theoretical models, cross-sections, etc..
What do neutrino physicists want?

- Neutrino
- Nucleon
- Charged lepton
What do neutrino physicists have?

- Neutrino
- Nucleus

- Charged lepton

- Neutron
- Many nucleons
- Nucleon and pions
- Nucleon and many pions
- Nucleon and many other type of particles
- Nothing

Very difficult to calculate

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An Example of a Neutrino Interaction

\[ \nu_\mu \rightarrow \mu^- \]

\( W \)

\( \Delta^{++} \)
Nobel Prize in 2015 for Discovering Neutrino Oscillations

Takaaki Kajita
Super-Kamiokande

Arthur B. McDonald
SNO
Thanks for your attention....

any question?
Backup
The rate of neutrino interactions is so small.

Therefore, large detectors composed of heavy atoms are needed.
Everything is Composed of Particles!

- Hydrogen
- Oxygen
- Nucleus
- Quarks

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The Fundamental Forces of the Universe Influence the Behavior of Particles!

- Electromagnetic
- Strong
- Weak
- Gravitational Not part of the Standard Model...
The Fundamental Forces of the Universe Influence the Behavior of Particles!

The electromagnetic force

Acts upon electrically charged particles

Keeps the electrons bound and orbiting around the atomic nucleus

Mediator: gamma (\(\gamma\))
The strong nuclear force

Holds the nucleus together

Range of the force is 0.000000000000001 meters
What is the energy of 1 MeV?

The energy of a flying mosquito is 1,000,000,000,000 electron volts.

where 1 MeV = 1,000,000 electron volts.
   = 1.6 x 10^{-13} Joules.

It is high energy for an elementary: for an electron at rest, it will make it to move at 0.94c.
Neutrino - nucleus cross-section needs to be accurately determined

Particularly MINERvA is a Fermilab cross-section dedicated experiment.

But in general all other Fermilab neutrino experiment also have cross-section studies.

BooNE experiments, MINERvA, DUNE, NOvA, MINOS T2K
After Fermi published his beta-decay theory, Ettore Majorana derived a theory to suggest that the neutrino may be its own anti-particle. Means that the neutrino and anti-neutrino are the same.
Remember THIS Guy!
He predicted that the neutrino and anti-neutrino are exactly the same.

This is important because ...

Big Bang created equal amount of matter and anti-matter.

- But due to unknown reasons matter overtook antimatter and what's left is mostly matter!
- This is called baryon asymmetry.
- This is one among the greatest unsolved problems in physics.
Remember THIS Guy!
He predicted that the neutrino and anti-neutrino are exactly the same.

Making precision measurements of the properties of neutrinos bring us a step closer to uncovering the biggest mysteries of the universe!

We are in a new ERA of Neutrino Detectors
This measurements is happening right now...


Normal Hierarchy, 90% CL
- NOvA $6.05 \times 10^{20}$ POT
- T2K 2014
- MINOS 2014

$\Delta m^2_{32} (10^{-3} \text{ eV}^2)$

$\sin^2 \theta_{23}$
The neutrino has to collide with a nucleon under various scenarios.....

Also, there is a pion cloud surrounding the nucleus.

The inside of a nucleon really looks like this!!!

3 valence quarks, and gluons holding them together.
Why is it so complicated?

The outgoing hadrons have to exit this complicated environment.

On the way out of the nucleus, the hadron can undergo various interactions with spectator nucleons.

The detector will see many, one, or no hadrons.