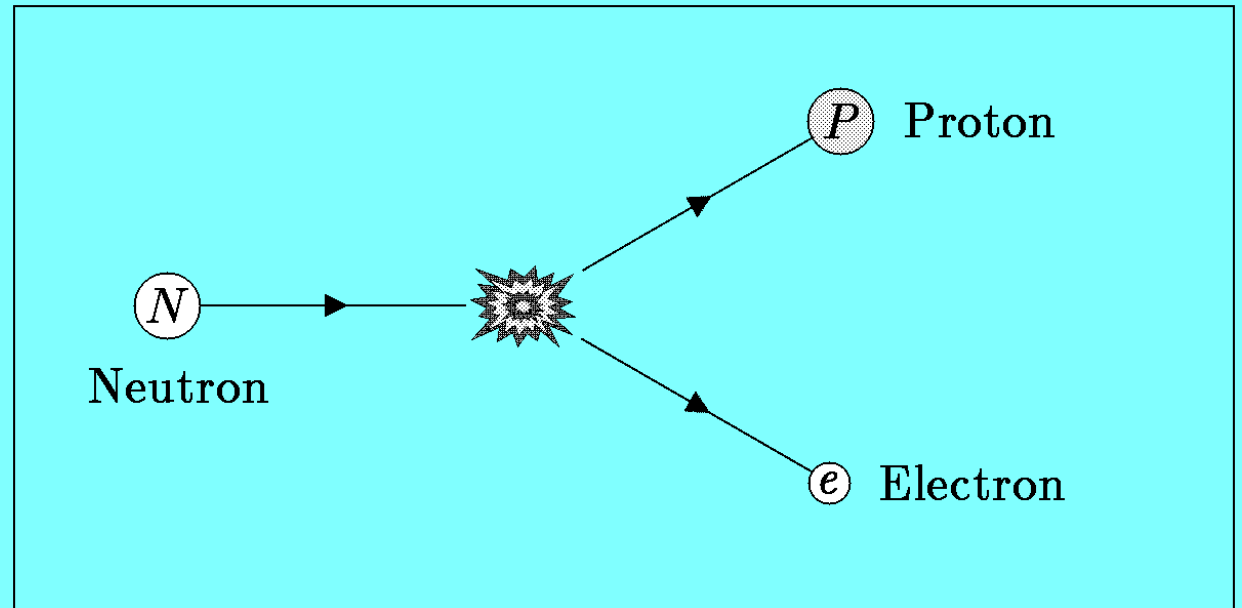
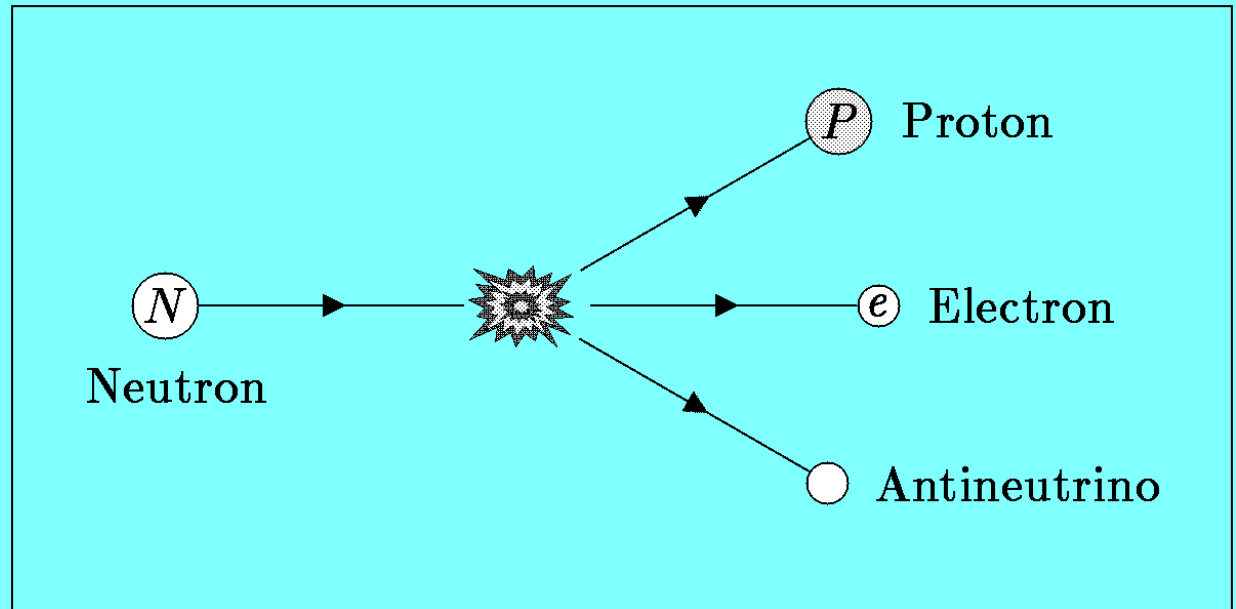


# 1914, James Chadwick



Energy is lost!  
What to do?

# 1930, Wolfgang Pauli, A Desperate Solution



A new particle so elusive that nobody can detect it!

Enrico Fermi named it the *neutrino* — the “little neutral one.”

# 1930-1935: The Search for the Neutrino



## 1930-1935: The Search for the Neutrino

No neutrinos found.



# 1935-1940: The Search for the Neutrino



# 1935-1940: The Search for the Neutrino

No neutrinos found!



# 1940-1945: The Search for the Neutrino



# 1940-1945: The Search for the Neutrino

Still no neutrinos found!!





# 1945-1950: The Search for the Neutrino



# 1945-1950: The Search for the Neutrino

Where are those neutrinos??



# 1950-1955: The Search for the Neutrino



## 1950-1955: The Search for the Neutrino

Where are those XXXXXX neutrinos???

June 14, 1956



June 14, 1956

- ★ Neutrino observed at the Savannah River nuclear reactor, in South Carolina, by Clyde L. Cowan, Jr., and Frederick Reines.

June 14, 1956

- ★ Neutrino observed at the Savannah River nuclear reactor, in South Carolina, by Clyde L. Cowan, Jr., and Frederick Reines.
- ★ Pauli receives a telegram.

**June 14, 1956**

- ★ Neutrino observed at the Savannah River nuclear reactor, in South Carolina, by Clyde L. Cowan, Jr., and Frederick Reines.
- ★ Pauli receives a telegram. He was right.



June 14, 1956

- ★ Neutrino observed at the Savannah River nuclear reactor, in South Carolina, by Clyde L. Cowan, Jr., and Frederick Reines.
- ★ Pauli receives a telegram. He was right.
- ★ Enrico Fermi is no longer alive to see his little neutral one.

**June 14, 1956**

- ★ Neutrino observed at the Savannah River nuclear reactor, in South Carolina, by Clyde L. Cowan, Jr., and Frederick Reines.
- ★ Pauli receives a telegram. He was right.
- ★ Enrico Fermi is no longer alive to see his little neutral one.
- ★ The conservation of energy wins a battle.

June 14, 1956

- ★ Neutrino observed at the Savannah River nuclear reactor, in South Carolina, by Clyde L. Cowan, Jr., and Frederick Reines.
- ★ Pauli receives a telegram. He was right.
- ★ Enrico Fermi is no longer alive to see his little neutral one.
- ★ The conservation of energy wins a battle.
- ★ In 1995, Frederick Reines is awarded the Nobel Prize in Physics for his discovery.

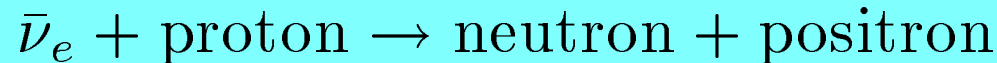
June 14, 1956

- ★ Neutrino observed at the Savannah River nuclear reactor, in South Carolina, by Clyde L. Cowan, Jr., and Frederick Reines.
- ★ Pauli receives a telegram. He was right.
- ★ Enrico Fermi is no longer alive to see his little neutral one.
- ★ The conservation of energy wins a battle.
- ★ In 1995, Frederick Reines is awarded the Nobel Prize in Physics for his discovery.
- ★ Clyde Cowan is no longer alive to receive the prize.

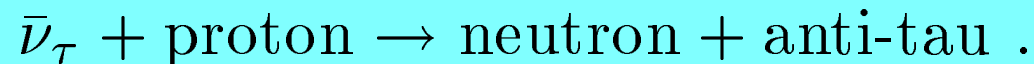
# Three Kinds of Neutrinos

★ In 1956, Cowan and Reines detected the first neutrino — what we now call an electron neutrino.

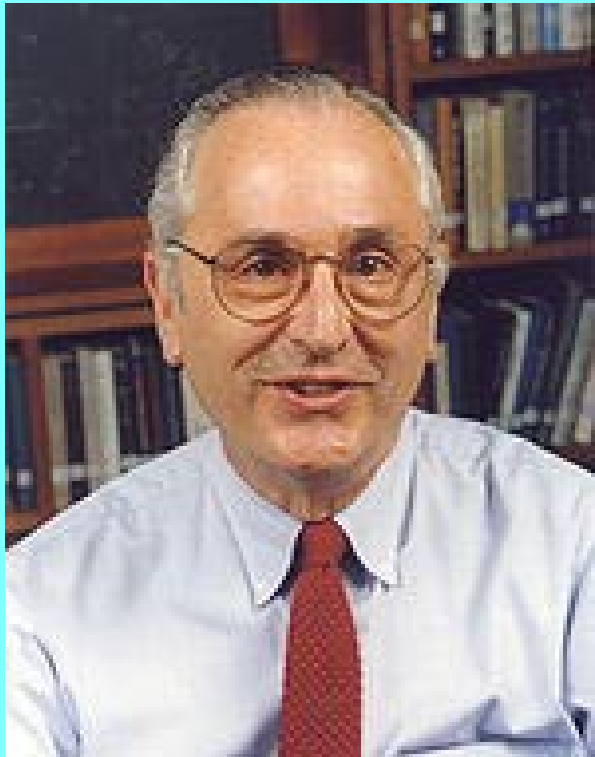
★ In 1962, Leon Lederman, Melvin Schwartz, and Jack Steinberger discovered a second type of neutrino — now called the muon neutrino. It is different because it reacts differently:



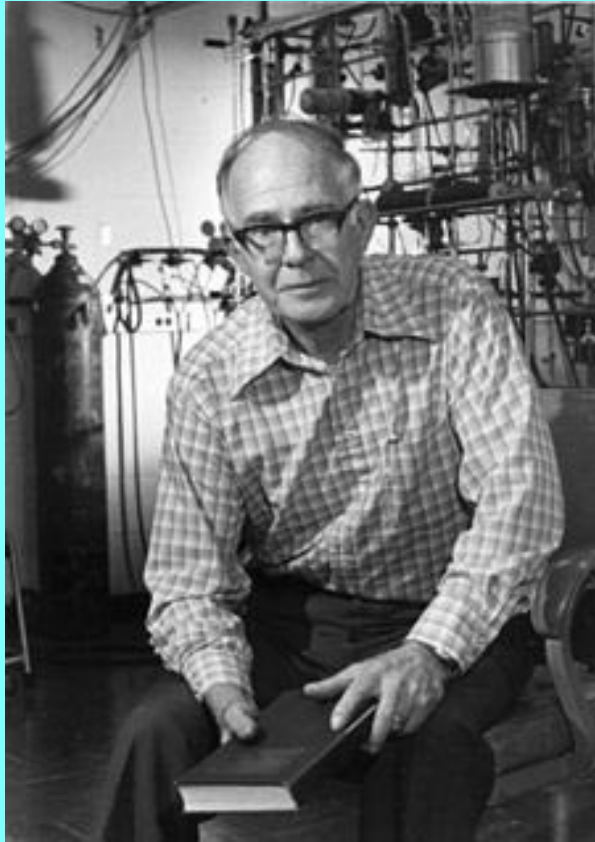
★ In 2000, the DONUT collaboration at Fermilab (**D**irect **O**bservation of the **Nu Tau**) detected the third type, the tau neutrino (which was by then expected):



# The Solar Neutrino Problem



- ★ The nuclear reactions in the Sun produce neutrinos, and solar theorists claim to be able to calculate the rate.
- ★ In particular, John Bahcall, in the 1960s, made very careful calculations of the solar neutrino production rate, with the hope of comparing with experiment.



- ★ Raymond Davis, Jr., in the late 1960s, constructed an experiment to measure solar neutrinos. He took over the Homestake Gold Mine in Lead, South Dakota, and constructed a 380 meter<sup>3</sup> tank of dry-cleaning fluid at a depth of almost a mile.
- ★ Solar neutrinos would interact with the chlorine in the tank, producing radioactive atoms of argon, which could be counted.

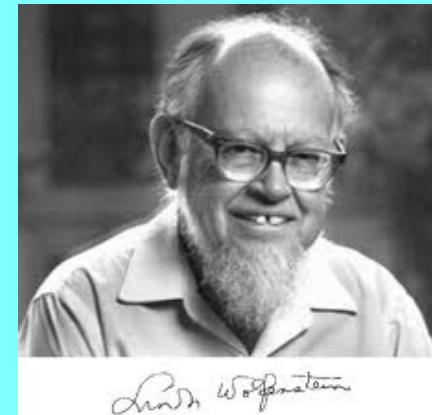
★ Result: **Too few neutrinos!**

★ Davis detected only about a third of the neutrinos that Bahcall had predicted.

★ For 30 years this discrepancy persisted, and was unresolved.



# Solar Neutrino Problem Solved: Neutrino Oscillations



In the 70s and 80s, Mikheyev, Smirnov, and Wolfenstein proposed that maybe the problem could be solved if neutrinos had a small mass. In the strange world of quantum theory, this would mean that one type of neutrino could “oscillate” into another.

- ★ The Sun produces electron neutrinos and the Homestake experiment could detect only electron neutrinos. So if the neutrinos oscillated into the other types, they would be missed.
- ★ In 2001, the Sudbury Neutrino Observatory was able to detect all three types of solar neutrinos. They found that the total number agreed with John Bahcall's predictions, but only about 1/3 were electron neutrinos.

- ★ The Sun produces electron neutrinos and the Homestake experiment could detect only electron neutrinos. So if the neutrinos oscillated into the other types, they would be missed.
- ★ In 2001, the Sudbury Neutrino Observatory was able to detect all three types of solar neutrinos. They found that the total number agreed with John Bahcall's predictions, but only about 1/3 were electron neutrinos.

**CASE CLOSED!**

- ★ The Sun produces electron neutrinos and the Homestake experiment could detect only electron neutrinos. So if the neutrinos oscillated into the other types, they would be missed.
- ★ In 2001, the Sudbury Neutrino Observatory was able to detect all three types of solar neutrinos. They found that the total number agreed with John Bahcall's predictions, but only about 1/3 were electron neutrinos.

**CASE CLOSED!**

**Neutrinos are weird.**

- ★ The Sun produces electron neutrinos and the Homestake experiment could detect only electron neutrinos. So if the neutrinos oscillated into the other types, they would be missed.
- ★ In 2001, the Sudbury Neutrino Observatory was able to detect all three types of solar neutrinos. They found that the total number agreed with John Bahcall's predictions, but only about 1/3 were electron neutrinos.

**CASE CLOSED!**

**Neutrinos are weird.**