Neutrino Physics

- The beginning: beta decay crisis: violation of energy conservation?
- Wolfgang Pauli proposes the neutrino; Enrico Fermi formulates the theory of nuclear beta decay.
- Is the antineutrino identical with the neutrino?
- Detection of the neutrino: the Reines-Cowan experiment.
- Muon decay crisis: one or two types of neutrinos?
- The two-neutrino experiment.
- The third lepton generation; detection of the tau neutrino.

Beta decay crisis: violation of energy conservation?

In the early years of studying nuclear beta decay it was ***wrongly*** assumed that the beta decay reaction had the form of

$$\boxed{(A,Z)\rightarrow(A,Z+1)+e^{-}}$$

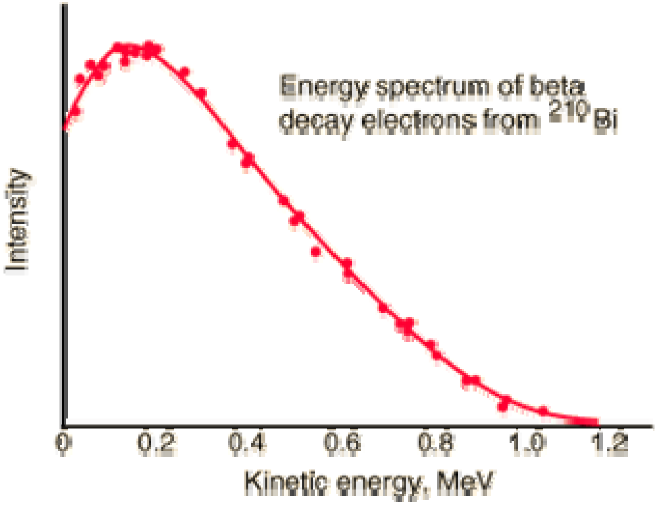
Then the electron should have a momentum given by

$$\boxed{p=\frac{1}{2M}\sqrt{\left[M^{2}-(m_{1}-m_{2})^{2}\right]\left[M^{2}-(m_{1}+m_{2})^{2}\right]}}$$

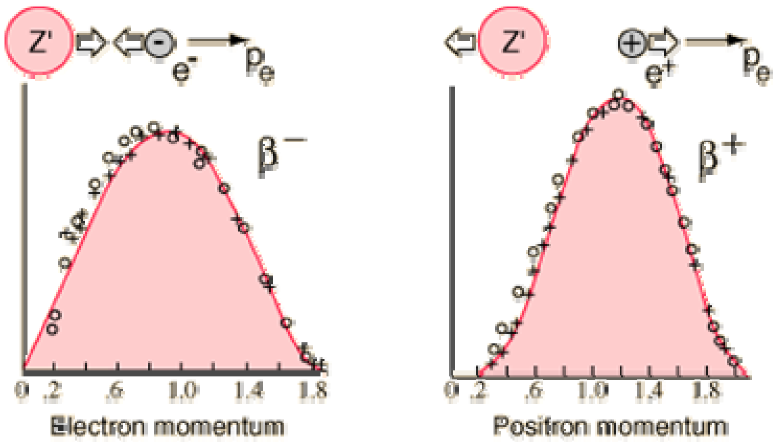
with $M=M(A,Z)$, $m_1=M(A,Z+1)$ and $m_2=m_e$

The particular value of some specific beta decay is not important. Important is that the momentum, and hence the energy of the electron should have a fixed value defined by the masses of the three particles involved in the decay. This is not observed as can be seen on the following examples.

Experimental Beta Decay Spectra:


Energy spectrum of beta decay electrons from ^{210}Bi

From G.J. Neary, Proc. Phys. Soc. (London), **A175**, 71 (1940).



Momentum spectra from the beta decay of ^{64}Cu

From J.R. Reitz, Phys. Rev. **77**, 50 (1950).

From these and many more examples it is seen that the electrons from beta decay have a continuum of energies ranging from zero to some maximum value.

This discrepancy between theory and experiment was the ***beta decay crisis***.

One way out was suggested by **Niels Bohr**: a possible violation of the conservation of energy in nuclear processes.

Another way out was proposed by **Wolfgang Pauli**: the existence of a neutral particle that was not “seen” in beta decay. Pauli called it “neutron”. When soon after that the neutron was discovered by Chadwick, Enrico Fermi gave Pauli’s neutral particle the name ***neutrino***: “little neutron” in Italian.


Niels Bohr


Wolfgang Pauli


James Chadwick

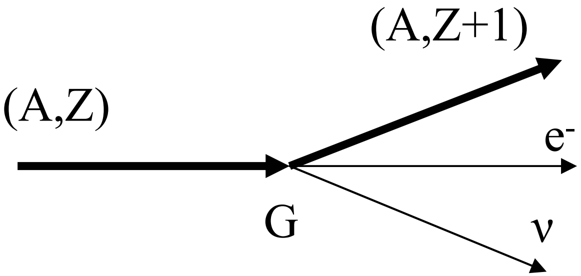

Enrico Fermi

Thus according to Pauli the beta decay reaction must be written as

$$\boxed{(A,Z) \rightarrow (A,Z+1) + e^{-} + \nu}$$

Enrico Fermi formulated the theory of nuclear beta decay assuming that the neutrino was a neutral particle with spin ½ and a very small mass, much smaller than the mass of the electron. He made this theory as similar to quantum electrodynamics as possible. There were two important differences:

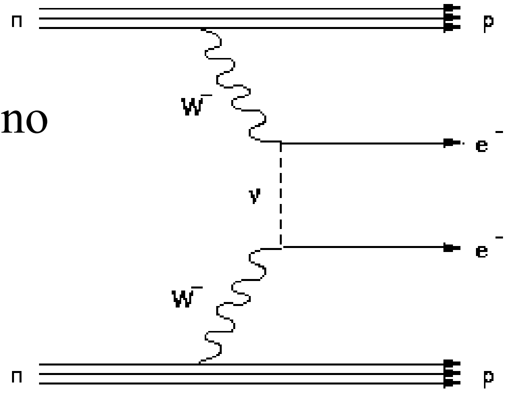
- There was nothing like the photon as a carrier of the weak force;
- The coupling strength that determined the weak interaction was given by a new constant G; this constant is nowadays called the ***Fermi constant***



Comparison of the theoretical with experimental spectra soon showed that the neutrino mass was unmeasurably small. Eventually it was thought that the neutrino mass was exactly zero.

Another problem had to do with the possible existence of an antineutrino. In other words, the question arose: does an antineutrino exist that is distinct from the neutrino? ***The answer can come only from experiment.***

If the neutrino is identical with the antineutrino, then a neutrinoless double-beta decay should be possible. Such a neutrino is called **Majorana** neutrino (the other kind is the **Dirac** neutrino).



A Majorana neutrino must also have a nonzero mass. The neutrinoless double-beta decay is ***lepton number violating***.

The most advanced search for neutrinoless DBD is the ***NEMO*** experiment, see http://nemo.in2p3.fr/

To date there is no evidence for neutrinoless DBD

The negative result of neutrinoless DBD means that the neutrino is distinct from the antineutrino. All experimental evidence is that the neutrino can be assigned a lepton number identical with that of the electron, and the antineutrino a lepton number identical with that of the positron. With this assignment the lepton number is empirically known to be conserved in all reactions.

Searches for lepton number violation are an important and active area of research.

Accepting that the neutrino is a Dirac particle, we must finally write the β decay equation as

$$\boxed{(A,Z)\rightarrow(A,Z+1)+e^{-}+\overline{\nu}}$$

or for β^{+} decay

$$\boxed{(A,Z)\rightarrow(A,Z-1)+e^{+}+\nu}$$

Detection of the neutrino: the Reines-Cowan experiment.

However successful the Fermi theory of beta decay was, the conclusive experimental test that the neutrino was not just a hypothetical particle had to be an experiment in which the neutrino could be demonstrated to cause a reaction.

Such an experiment of ***direct neutrino observation*** was first carried out by ***Frederick Reines*** and ***Clyde L. Cowan***.

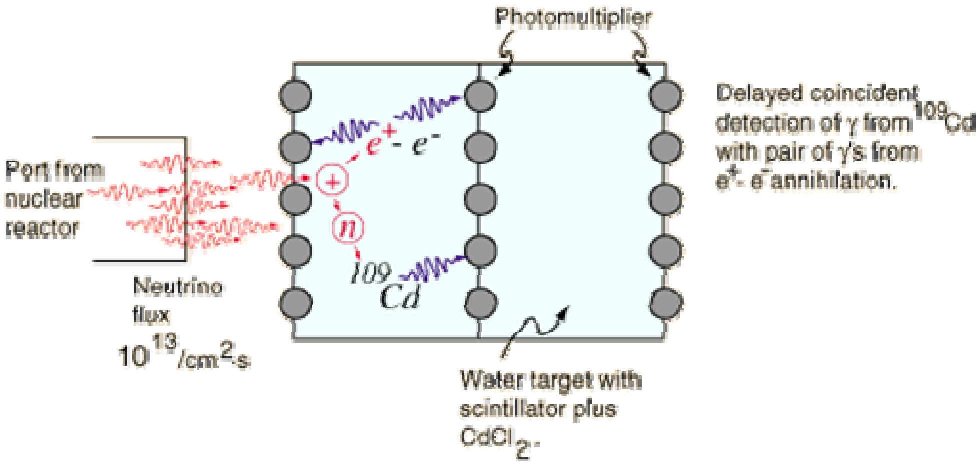
The source of neutrinos had to be of a sufficient intensity which became available only in the late 1940s – early 1950s as a result of the construction of high-flux nuclear reactors.

Schematic diagram of the neutrino detection experiment of Reines and Cowan

Antineutrinos from a nuclear reactor cause the inverse beta decay reaction

$$\boxed{\overline{\nu} + p \rightarrow n + e^{+}}$$

The positron slows down and annihilates with an atomic electron into a pair of photons. The photons travel back-to-back; each photon has an energy equal to the rest energy of the electron, about 0.5 MeV. Passing through liquid scintillator, the photons give light pulses which are seen be arrays of PM tubes.

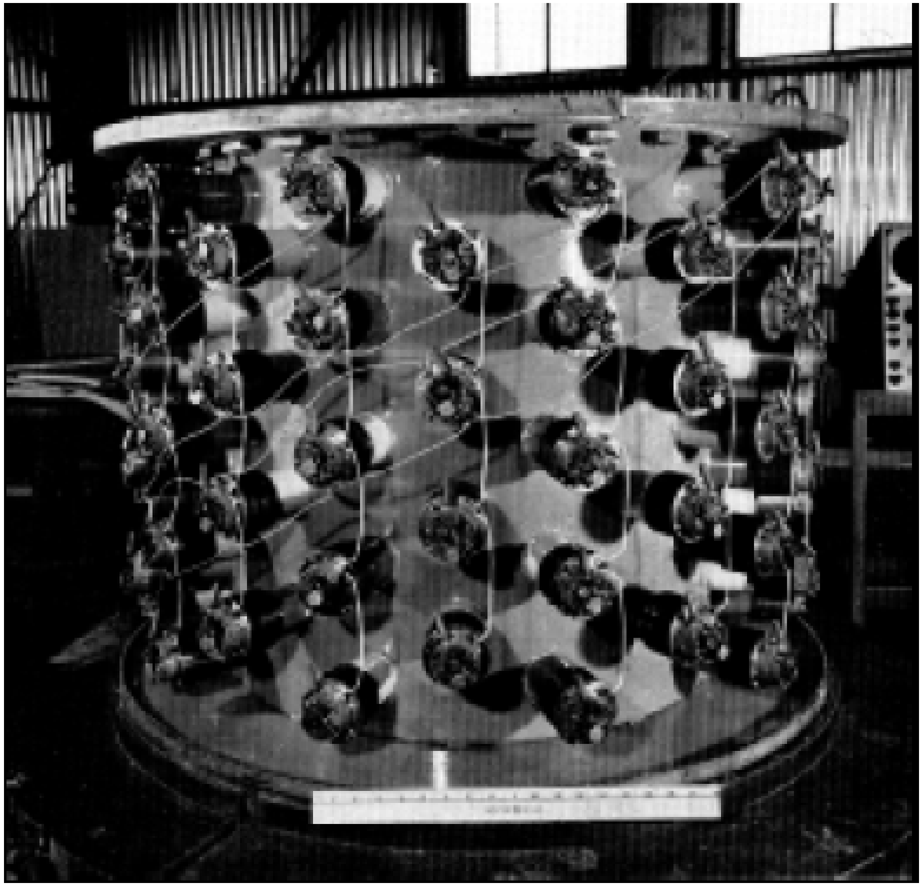


The detector vessel is filled with water in which cadmium chloride is dissolved. The neutrons from the inverse beta decay are captured by cadmium nuclei:

$$\boxed{n + {}^{108}Cd \rightarrow {}^{109}Cd^{*} \rightarrow {}^{109}Cd + \gamma}$$

The photon from this reaction is detected 5 μs after the photon pair: ***delayed coincidence***.

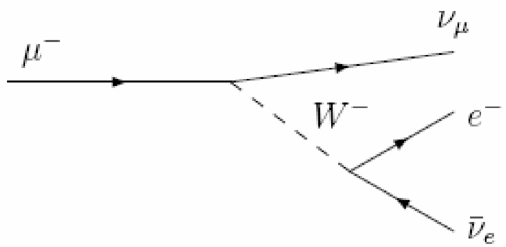
Photo of the Reines-Cowan experiment



Muon decay crisis: one or two types of neutrinos?

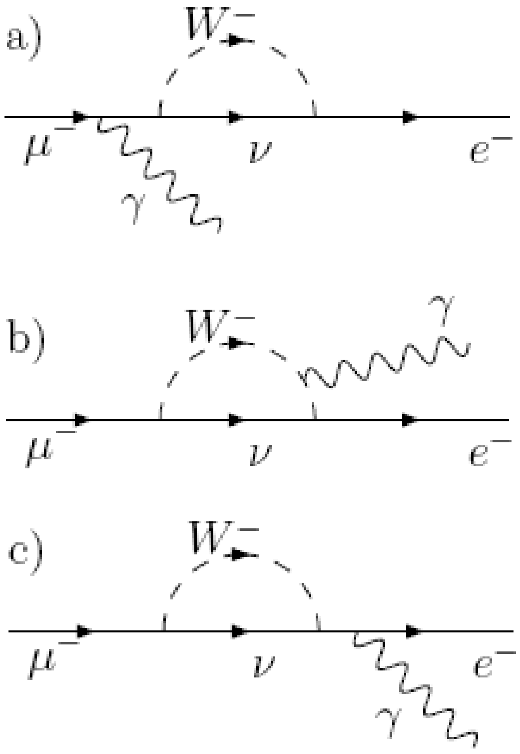
In the late 50s, after the discovery of parity violation in the weak interactions, the hypothesis of an intermediate vector boson was gaining ground. Such a heavy boson – heavier than the proton – was thought to be a candidate for the carrier of the weak interaction.

First calculations were carried out and they soon led to difficulties.



muon decay: $\mu^- \to e^- \nu_\mu \bar{\nu}_e$

One of the problems was a serious discrepancy between the calculated and observed rates of muon decays into electron and photon and into an electron and neutrino and antineutrino.



Feynman diagrams of hypothetical decay $\mu^- \to e^- \gamma$

assuming there is only one kind of neutrino.

This can be calculated without detailed knowledge of the ***W*** **IVB** and compared with the decay

$$\mu^- \to e^- \nu \bar{\nu}$$

In the ratio of the decay rates of these processes all ***W*** parameters cancel and one gets a very simple answer:

$$\boxed{\frac{\Gamma\left(\mu^- \to e^- \gamma\right)}{\Gamma\left(\mu^- \to e^- \nu \bar{\nu}\right)} \sim \frac{1}{24\pi} \frac{e^2}{\hbar c} \sim 10^{-4}}$$

The experimental upper limit is less than 10^{-11}.

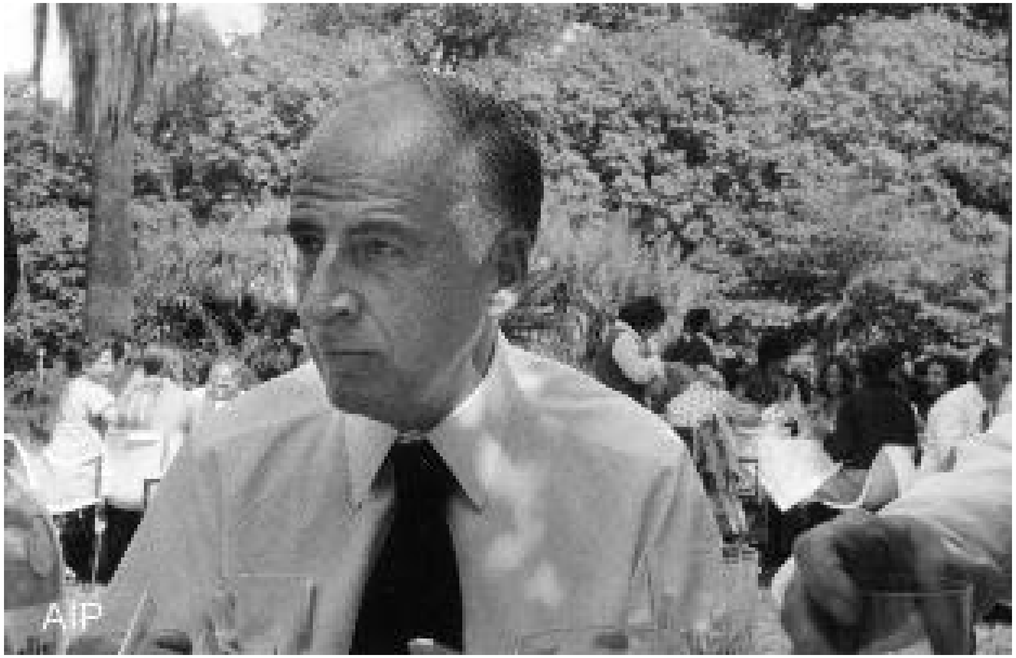
This discrepancy gave rise to the two-neutrino hypothesis: $\nu_\mu \neq \nu_e$

Experimental Test of the Two-Neutrino hypothesis

1.) Make a neutrino beam from pion decays into muons.
2.) pass the neutrino beam through a detector which must
    a) have ***enough dense mass*** for some neutrinos to interact and produce a muon and/or an electron;
    b) show the difference between electrons and muons.

Then, if you see about equal numbers of electrons and muons produced, you conclude that there is only one type of neutrino.
But if you see only muons produced, then you know that the muon neutrino is different from the electron neutrino.

Such an experiment was first proposed by Bruno Pontecorvo in 1959 (ЖЭТФ т. 37, вып. 6, с. 1751-1757 (1959)) and was carried out at the Brookhaven National Laboratory in 1962.



Bruno Pontecorvo (1913 – 1993) at a garden party in Dubna

The BNL experiment:

a beam of 15 GeV protons struck a beryllium target and produced mostly pions.

After 21 meters about 10% of the pions had decayed according to

$$\pi^- \to \mu^- \overline{\nu}; \quad \pi^+ \to \mu^+ \nu$$

Then the pions, muons and neutrinos passed into a 13.5 m steel absorber that absorbed all pions and muons, leaving only the neutrinos from the pion decay.

The detector consisted of ten 1-ton modules, each module consisting of nine 1 inch thick aluminium plates separated by ¾ inch gaps filled with a gas mixture. There was a high voltage between the aluminium plates, so the ionization from a charged particle passing through the gas gives rise to sparks between the plates (such a detector is called ***spark chamber***).

Muons passing through the spark chambers leave practically straight tracks. Electrons produce showers which can be cleanly distinguished from the muon tracks. The result of the experiment was that there were only muons produced, and hence ***muon neutrinos are not identical with electron neutrinos***.

The Third Neutrino: ν_τ

After the discovery of the third charged lepton, the tau lepton, it was natural to assume that there was also a third neutral lepton, the tau neutrino, which must be different from the electron and muon neutrinos.

Indirect evidence of its existence came from the LEP experiments at CERN where it was shown, by comparison with precision calculations, that the Z boson peak could be quantitatively described only with 3 light neutrinos.

But as always, indirect evidence is thought to be unsatisfactory: one wants direct evidence. In the present case this is similar to the direct evidence of the existence of the neutrino (the Reines-Cowan experiment) and to the two-neutrino experiment at BNL: one is looking for a reaction induced by a tau neutrino.

DONUT Experiment

Direct Observation of the NUTau

Fermilab experiment *E 872*

http://www-donut.fnal.gov/

Design of the DONUT Experiment

The General Idea:

The general concept behind the DONUT experiment (Direct Observation of the NU Tau) was to create a beam of tau neutrinos that would interact to form tau leptons, which could then be observed.

The set-up is as follows:

An 800 GeV beam of protons from the TeVatron collides into the beam dump, a large block of tungsten, to produce the charm particle ***D_s*** (a meson comprised of charm and strange quarks). About 7% of ***D_s*** mesons decay to an ***anti-tau neutrino*** and a ***tau lepton:***

$$D_s^+ \to \tau^+ \nu_\tau ; \quad D_s^- \to \tau^- \overline{\nu}_\tau$$

All tau decays go into a ***tau neutrino*** + other particles.

About 35% of tau decays are to a charged lepton and a ***tau neutrino:***

$$\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau \left(17.37\%\right); \quad \tau^- \to e^- \bar{\nu}_e \nu_\tau \left(17.83\%\right)$$

The neutrinos pass through 36m of shielding to a detector consisting of ***emulsion targets*** followed by a ***spectrometer***.

In the emulsion targets some tau neutrinos interact with a nucleon to produce a tau lepton, which is detectable by the various levels of the spectrometer.

Only a tau neutrino can produce a tau lepton;
tau leptons are recognised by their decay products.

"Voila: The tau neutrino is detected!" (quote from the DONUT web site)

The muon neutrinos produced in pion and kaon decays contribute about 23% to the total number of observed reactions. ***This is background.***

The mean energy of the neutrinos is 56 GeV for the taus and 54 GeV for the muon and electron neutrinos. There is 1 tau neutrino per 50 000 primary protons on the tungsten target per m^2 and 10 times more muon and electron neutrinos.

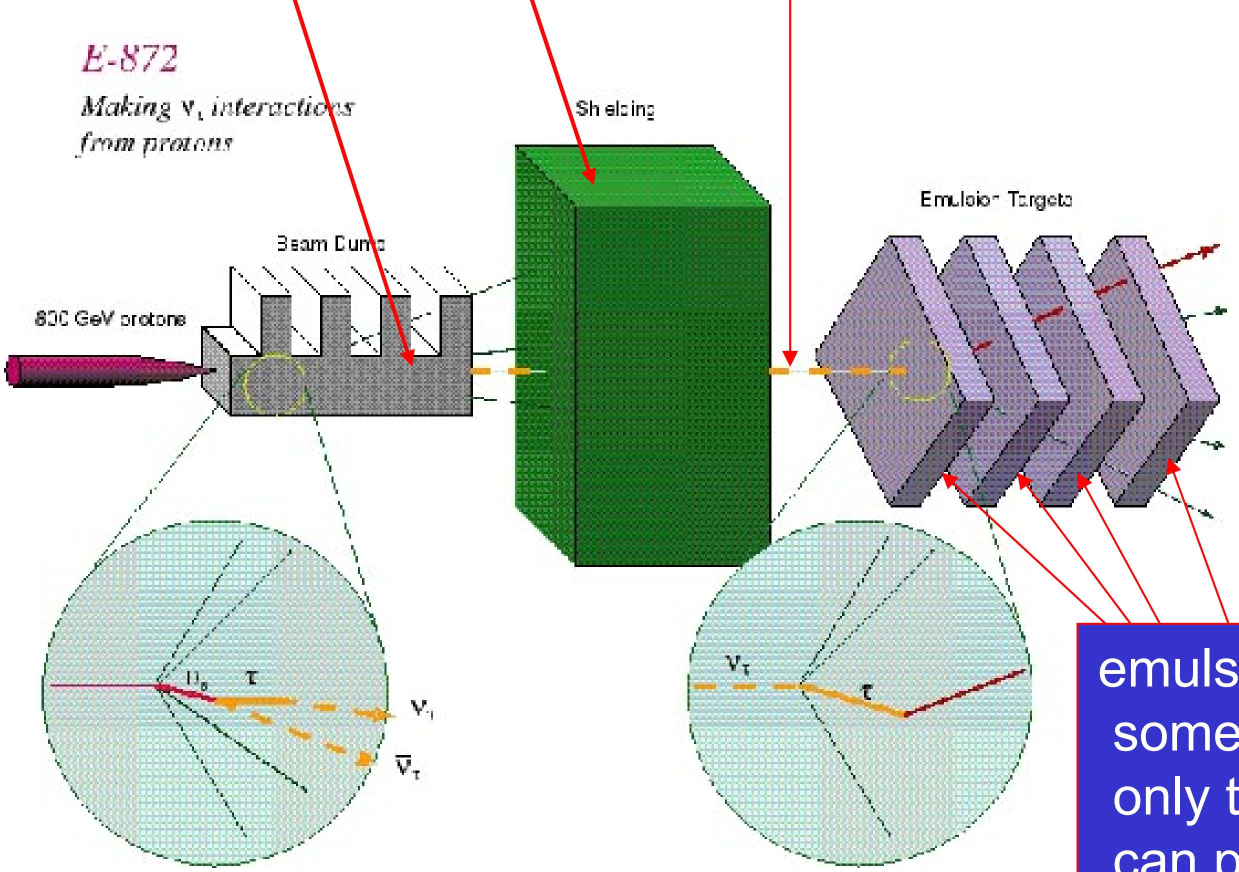
There are several uncertainties in the calculations of the expected number of neutrinos. For example, there is a 20% uncertainty in the D_s production and a 15% uncertainty due to the D_s ***branching ratio***, *i.e.* the probability of the particle to decay to a specific final state.

To remove all particles other than neutrinos, the beam is passed through a shield consisting of 36 meters of steel.

steel shielding

beam dump

only neutrinos can pass through the shielding; this neutrino beam contains tau neutrinos.



emulsion target where some neutrinos interact; only tau neutrinos can produce tau leptons.

Located 36 m from the beam dump sits the ***hybrid emulsion spectrometer***, measuring 16 m in length, comprised of 6 sections.

DONUT scientists had two difficulties to overcome in building a target/detector that had the resolution power to observe the tau neutrino:

First, the lifetime of the tau, partner to the tau neutrino, is extremely short:

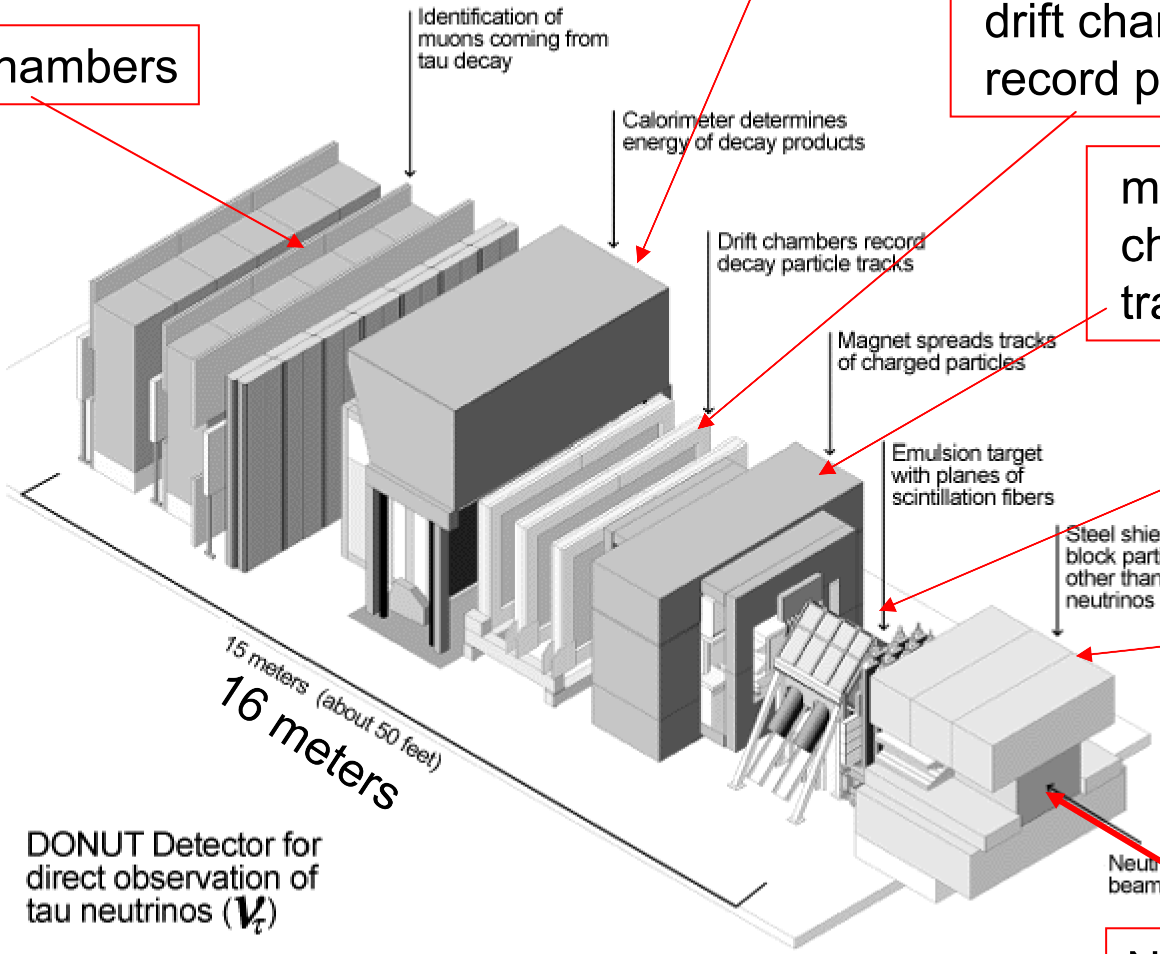
$$\tau_\tau \cong 0.3\,\mathrm{ps}$$

its mean decay length under the conditions of DONUT is ≈ 2.3 mm.

Second, the tau neutrino is extremely non-interacting.

So they had to build a detector with very fine resolution and sufficient target density to allow for events to take place. They chose a ***hybrid emulsion spectrometer*** (**HES**), because the ***dense emulsion*** gives plenty of targets for the incoming neutrinos and simultaneously record all events, while the **spectrometer** provides the necessary data to identify the event products.

DONUT Detector



DONUT Detector for direct observation of tau neutrinos (ν_τ)

calorimeter

muon chambers

drift chambers to record particle tracks

magnet to spread charged particle tracks

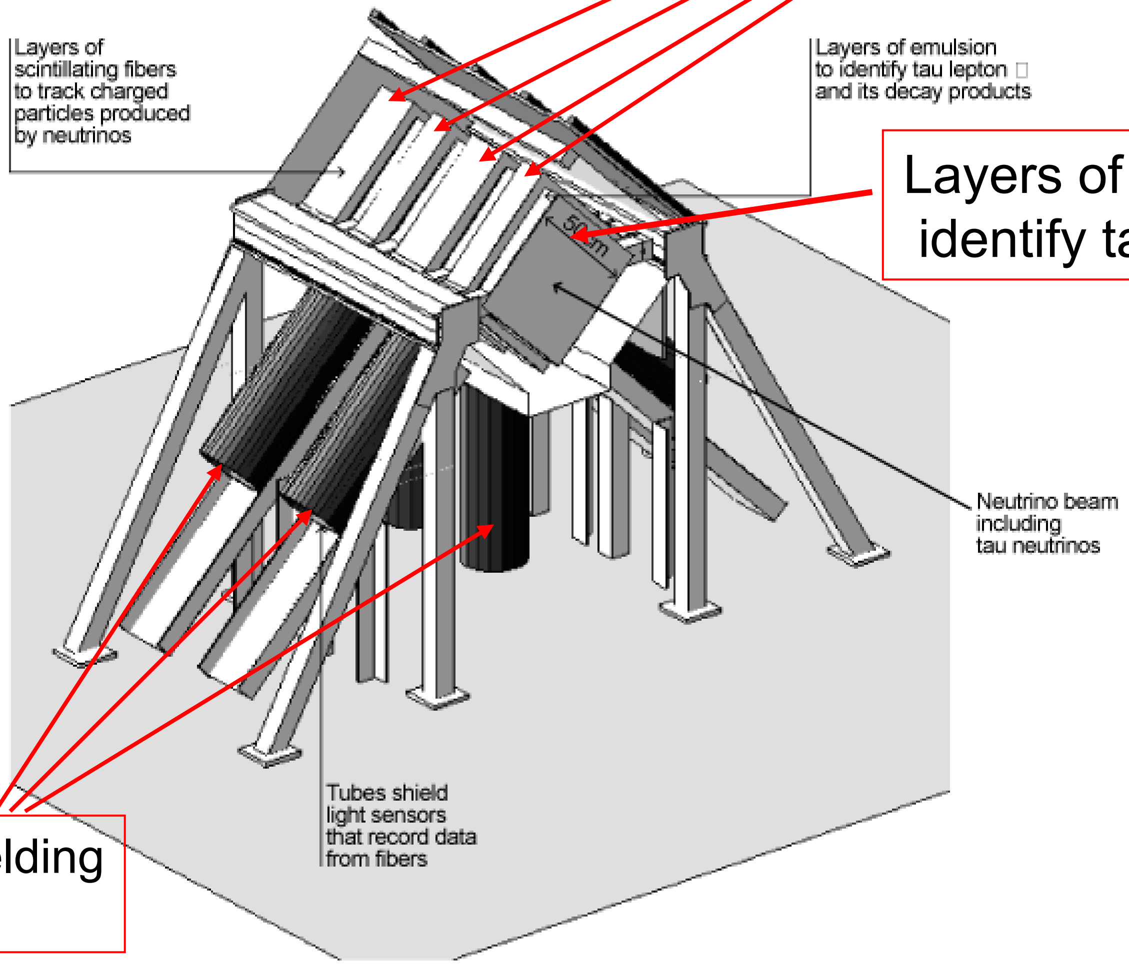
emulsion target

Shield to block particles other than neutrinos

16 meters

Neutrino beam

DONUT Target Station



Layers of scintillating fibres to track charged particles

Layers of emulsion to identify tau leptons

Light shielding tubes

Drift Chamber Tracking:

The rest of the spectrometer's job is to determine the charge and momentum of the passing particles so that they can be identified as products of interactions and their tracks can be interpolated back to the event vertex.

Specifically, drift chambers aid the scintillating fiber trackers in track discrimination. Drift chambers are fixed volumes of gas divided into discrete cells by sheets of closely spaced parallel wires. These wires are held at a high voltage with respect to 'sense' wires which line the middle of the cells at 1mm spacing. When a charged particle enters the drift chamber and ionizes an atom, the freed electron is accelerated through an electric potential to the ***sense wires***, liberating other electrons as it passes through. The sense wires output electrical signals.

The time delays between signals as the particle passes through a series of chambers determine the speed of the particle.

Drift chambers are designed to have as little impact on the passing particle as possible, thereby not changing its energy.

The drift chambers are placed in a magnetic field to determine the particle momenta:

Knowing that particles traveling perpendicular to a magnetic field **B** exhibit circular motion, and using the magnetic force law $\boldsymbol{F}=q\,\mathbf{v}\times\mathbf{B}$, you come to the expression $p = qrB$, where p is the momentum and r is the radius of curvature of the particle track. The radius of curvature is measured using the drift chambers, and hence the particle's momentum is calculated.

Electromagnetic Calorimeter:

The electromagnetic calorimeter is used to measure the electromagnetic energy produced by electron neutrino events in the emulsion and the energy of electrons produced in tau decays.

The calorimeter consists of ***lead glass*** (glass that is approximately 25% lead by weight) and ***scintillating glass*** attached to ***photomultiplier tubes***.

The presence of lead increases the instrument's index of refraction, slowing the speed of light through the glass. When a particle moves faster than the speed of light in a given medium the particle emits ***Cerenkov*** light (photons) in a cone shape, which is picked up by the ***photomultiplier*** tubes.

(calorimeter – continued:)

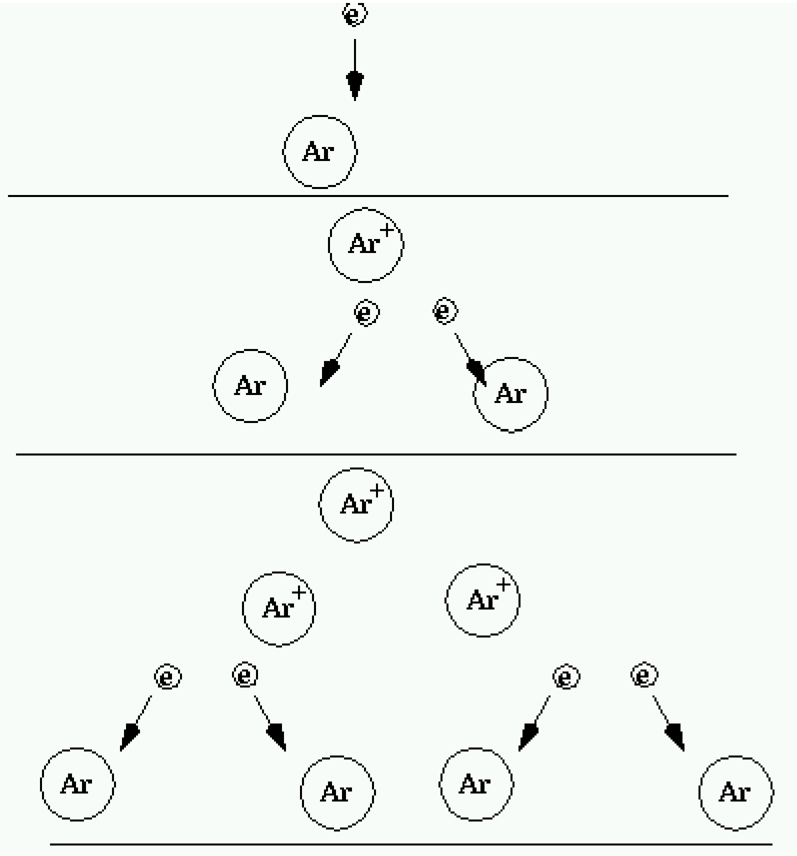
Additionally, electrons from upstream encounter lead nuclei and emit photons, leading to ***electromagnetic showering***.

Electromagnetic showering is the ***production of electron-positron pairs*** by a photon that induces more pairs and photons and so on.

The Cerenkov light emitted by these electron positron pairs enters photomultiplier tubes. The photon, by way of the photoelectric effect, kicks an electron out of the valence shell of an alkali metal atom which is accelerated through a potential difference to the other end of the tube, producing an *avalanche of electrons* along the way.

The number of electrons detected at the end of the tube is proportional to the number of photons produced by the electromagnetic showering, which in turn is proportional to the energy of the incident electron.

Schematic of avalanche formation:



The last station of the detector is the

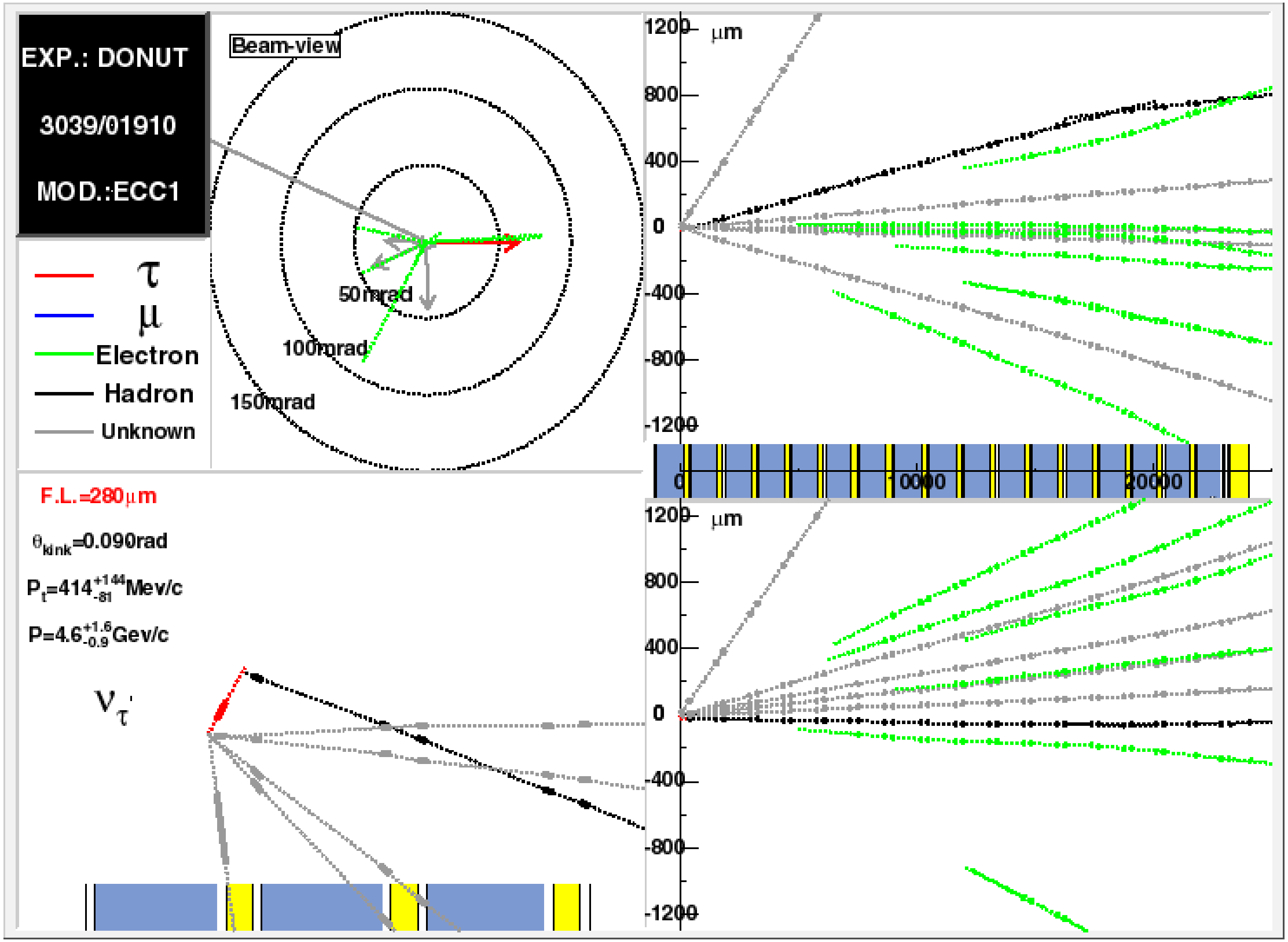
Muon Identification System:

The goal of the muon identification system is to identify charged current interactions of muons in the target and use that information to point to the event vertex. Additionally it is used to find muons from tau decays, which occurs in 17% of all tau decays.

This system has three layers of steel walls interleaved with proportional tubes totaling 4 m in length. The tubes are filled with an $ArCO_2$ gas mixture that becomes ionized when a charged particle passes through.

The freed electrons are accelerated to a wire running down the center of the tube that is held at a high potential with respect to the walls. This signal is amplified and processed, identifying and tracking muons.

Tau neutrino production in the DONUT detector exposed to a neutrino beam



Neutrino DIS

Shown here is the CDHS experiment – just to give you an impression of the scale of neutrino experiments