# Neutrino Mystery and History Script - 1

Rick Dower
5/5/2020

**Title - Slide 1**
On April 15, 2020, Dennis Overbye, wrote in the *New York Times* about results from the T2K experiment:

> Scientists on Wednesday announced that they were perhaps one step closer to understanding why the universe contains something rather than nothing.
> Part of the blame, or the glory, they say, may belong to the flimsiest, quirkiest and most elusive elements of nature: neutrinos. These ghostly subatomic particles stream from the Big Bang, the sun, exploding stars and other cosmic catastrophes, flooding the universe and slipping through walls and our bodies by the billions every second, like moonlight through a screen door.

Studying the characteristics of neutrinos is one of the great challenges facing scientists at Fermilab and other laboratories around the world. The effort to understand neutrinos goes back to the early days of radioactivity and the characteristics of $\alpha$, $\beta$, and $\gamma$ radiation.

**$\alpha$ and $\gamma$ Question - Slide 2**
Here are some examples of $\alpha$ and $\gamma$ decay with their characteristic discrete energy values for the emitted particles. We know that the characteristic energies of photons in the spectral lines of atoms result from the energy conservation and discrete energy levels of electrons in atoms.
COULD A SIMILAR MECHANISM IN NUCLEI APPLY HERE?
WHAT DO YOU THINK?

**$\alpha$ and $\gamma$ Answer - Slide 3**
Applying conservation laws to the $\alpha$ and $\gamma$ decays gives the discrete energy values of the particles.

**$\beta$ Question - Slide 4**
Beta radioactivity is different. James Chadwick studied $\beta$ radiation in Berlin in 1914 with Hans Geiger. Chadwick continued his studies while he was interned in Berlin during WW I. He found that $\beta$ radiation showed a continuous spectrum of electron energies instead of the discrete spectrum of $\alpha$ and $\gamma$ radiation.

**$\beta$ Spectrometer - Slide 5**
Commercially available radioactive sources, a Geiger counter, and a pair of permanent magnets on an iron armature are all the apparatus needed to examine $\beta$ particle energy spectra.
Here is an experimental set-up to measure $\beta$ particle energies at Roxbury Latin School.

**β Spectrometer Measurement and Mathematics - Slide 6**
The radius of curvature of charged particles moving perpendicular to a magnetic field is directly proportional to the particle momentum. The angle between detector and source determines the momentum and energy of the beta particles detected.

**Energy Spectra for Two β-decays - Slide 7**
Strontium-90 decays to yttrium-90, which then decays to zirconium-90.
Each decay produces a spread of β particle energies and has a characteristic peak value and a characteristic maximum value. The maximum value is determined by energy and momentum conservation. At lower energies, energy and momentum do not seem to be conserved.
Niels Bohr suggested that, perhaps, energy and momentum were not conserved in β-decay.
IS THERE AN ALTERNATIVE?

**Wolfgang Pauli's Speculation – Slide 8**
Pauli's electrically neutral and low mass particle would be very difficult to detect.
Today theorists readily postulate unseen particles to account for anomalous results.
That was not the case in 1930. In his letter Pauli said, "But so far I dare not publish anything about this."

**Electron Neutrino Discovery – Slide 9**
HOW CAN NEUTRINOS BE DETECTED - before the development of the Ghostbusters trap?

In 1956, about 25 years after Pauli's neutrino speculation, Fred Reines and Clyde Cowan took on the challenge of demonstrating the existence of neutrinos. They dubbed their experiment "Project Poltergeist." They first considered trying to detect neutrinos produced in an atomic bomb blast before the blast destroyed their apparatus. However, detecting neutrinos from a nuclear reactor proved more feasible.

**Reines-Cowan Neutrino Detection Experiment – Slide 10**
Reines and Cowan found evidence for antineutrinos with a large detector placed below the Savanah River nuclear reactor. The detector consisted of two tanks of water in which cadmium chloride was dissolved. The water tanks were sandwiched between even larger tanks of liquid scintillator surrounded by phototubes to detect γ-ray signals. In the water tanks electron antineutrinos from the reactor initiated inverse β-decay in which protons convert to neutrons and positrons. The positrons promptly annihilate with electrons in the surrounding water to produce two oppositely directed, 0.511 MeV, γ rays. After bouncing around for a few microseconds, the ejected neutron is absorbed by a Cd-108 nucleus to produce a metastable Cd-109 nucleus. The Cd-109 promptly decays to a stable state by emitting more γ rays. The two photodetector current spikes separated by a few microseconds was the characteristic signal of neutrino detection. After their success, Reines and Cowan sent Pauli a telegram at CERN to announce their discovery. Pauli replied, "Everything comes to him who knows how to wait."

**Muon Discovery, Rabi's Question– Slide 11**
With Chadwick's neutron discovery and Anderson's positron discovery in 1932 (along with Pauli's neutrino speculation of 1930), physicists seemed to have a nearly complete understanding of the particles that make up the world. That changed in 1936 when Carl Anderson and his student Seth Neddermeyer discovered the muon. The muon was like an electron but about 200 times more massive. I. I. Rabi (Physics Nobel Prize – 1944) remarked "Who ordered that?" Why do we need a muon to explain the universe?

**Muon Decay – Slide 12**
Muons were observed to decay to electrons with unobserved neutral particles needed to conserve energy and momentum.     WERE THESE NEUTRAL PARTICLES ALSO NEUTRINOS?

**Pion Discovery – Slide 13**
In 1947, Cecil Powell and his research group examined cosmic rays with high density, fine grained so called "nuclear," photographic emulsions. They discovered pions among the cosmic ray tracks. Charged pions decay into muons, again with neutral particles needed for energy and momentum conservation.     MORE NEUTRINOS?

**Muon Neutrino Question – Slide 14**
How did a U. S. Navy cruiser help show that neutrinos come in two sorts (flavors)?
ANY GUESSES?

**Muon Neutrino Discovery Experiment – Slide 15**
Note the 13.5 m thick steel shielding from a dismantled cruiser between the Alternating Gradient Synchrotron (AGS) ring at Brookhaven and the spark chamber detector. The shielding helps keep all particles, except neutrinos (and occasional cosmic rays), from interacting with the detector. Background is minimized by only activating the spark chamber for 30 ns every 1.2 s when the proton beam was directed at the target and muon neutrinos were produced from pion decay.

Observe the long muon spark track in the detector. Only a high momentum muon could pass through that many 1-inch thick aluminum plates without producing a shower of particles or other interaction. Muon neutrinos that accompanied pion decay produced only muons in the detector. Thus, muon neutrinos are distinct from electron neutrinos.

**$\tau$ Lepton Discovery Suggests a Third Neutrino – Slide 16**
In 1975, Martin Perl and his team used the Stanford Positron-Electron Asymmetric Ring (SPEAR) at the Stanford Linear Accelerator Center (SLAC) to collide beams of 4 GeV positrons and electrons. They found evidence for a third generation charged lepton much more massive than the muon, the $\tau$ (mass = 1777 MeV, mean life $2.9 \times 10^{-13}$ s). A tau decays almost immediately to a muon or electron and corresponding neutrino. In analogy with muons and electrons, the $\tau$ lepton was assumed to have an accompanying neutrino, $\nu_\tau$.

**DONuT Experiment at Fermilab – Slide 17**

In 2000 a Fermilab team was able to demonstrate the existence of the tau neutrino. In the left-side image from left to right, we see high energy protons hit a tungsten target to produce taus and other particles. The taus immediately decay to produce $\nu_\tau$. Charged particles are deflected by the magnet and absorbed by shielding so that only neutrinos pass to detector.

In the right-side image from lower right to upper left, we see shielding to screen out charged particles, followed by emulsion planes to detect kinked tracks indicating tau decays. Emulsion layers are followed by tracking chambers, calorimeter chamber to measure charged particle energy, and muon chambers to identify muons produced in tau decays or $\nu_\mu$ interactions.

**DONuT Collaboration Discovers $\nu_\tau$ in Nuclear Emulsions – Slide 18**
The Direct Observation of Nu Tau (DONuT) collaboration at Fermilab found evidence of 4 kinked tracks indicating tau decays in nuclear emulsions out of 6,600,000 events. The Feynman diagram shows a $W^-$ particle mediating the weak decay of the tau. WHAT IS THE $W^-$ PARTICLE?

**Electroweak Interaction Theory – Slide 19**
The electroweak interaction theory developed by Steven Weinberg, Sheldon Glashow, and Abdus Salam unifies electromagnetic and weak interactions and accounts for a massless photon that mediates electromagnetic interactions along with massive weak bosons ($W^+$, $W^-$, and Z) that mediate weak interactions.

**Gargamelle Observes Weak Neutral Currents – Slide 20**
Of course, theories are more readily accepted when their experimental consequences are verified. Experimenters at CERN observed the scattering of electrons by muon neutrinos in the large Gargamelle bubble chamber, verifying the electroweak theory prediction.
The W and Z bosons were found with the UA1 and UA2 detectors at CERN in1983 among the debris produced by colliding proton and antiproton beams from the Super Proton Synchrotron. Carlo Rubbia led the UA1 collaboration.

**How Many Neutrino Types? – Slide 21**
Having been surprised by one, then two, then three neutrino types, one wonders how many neutrino flavors nature provides. The Large Electron Positron (LEP) collider in a 27 km nearly circular tunnel (about 100 m underground) at CERN had enough beam energy to produce vast numbers of Z bosons. Comparing the Z production probability, *i.e*. cross section, and decay ratios with predictions from the Standard Model of particle physics allowed the determination that there are three flavors of low mass neutrinos. The dot below the "3ν" label on the graph is an experimental point at the peak of the 3–neutrino curve.

The Standard Model of particle physics has three neutrino flavors of zero mass.
DO THEY TRAVEL AT THE SPEED OF LIGHT, AS EXPECTED FOR ZERO MASS PARTICLES?
HOW WOULD YOU MEASURE NEUTRINO SPEED?

**How Fast Do Neutrinos Travel? – Slide 22**

The speed of light was first determined from astronomical measurements. Likewise, the speed of neutrinos was first estimated from an astronomical measurement. A 12.5 s burst of neutrinos arrived at three neutrino detectors about 07:35:40 UT on February 23, 1987. A brightening Type II supernova in the large Magellanic Cloud (168,000 light years distant) was caught on film about 3 hours later. Core collapse models of Type II supernovae indicate that neutrinos are produced as electrons and protons combine to form neutrons. The neutrinos diffuse out of the collapsing stellar core over several seconds while light may take hours to escape from the dense core to the outer surface layers of the massive star.

Clearly, neutrinos travel close to the speed of light. Estimates of neutrino speed for a particular detected neutrino energy yield an upper limit of 6 $eV/c^2$ for the neutrino mass.

The neutrino energy radiated by the 1987A supernova during 12.5 s was of the order of $10^{46}$ J, equivalent to the electromagnetic energy radiated by 4 billion suns over a span of 1000 years.

**What Is the Solar Neutrino Problem? – Slide 23**

While observations of neutrinos from SN1987A confirmed our understanding of Type II supernovae, there was a problem closer to home. In the 1960s John Bahcall undertook detailed calculations that became the Standard Solar Model of the nuclear reactions powering the Sun. Ray Davis was interested in detecting solar neutrinos. Relying on Bahcall's calculations, Davis devised a large experiment to detect solar neutrinos and compare the result with Bahcall's predictions. In the photo, the cavern surrounding the tank of $C_2Cl_4$ on which Davis stands was filled with water to prevent neutrons from the walls from reaching the detector tank. Davis ran the experiment for about 30 years continually refining his measurement technique and demonstrating that he could, indeed, count radioactive argon atoms produced by neutrino interaction. The problem: he detected only 1/3 of the predicted neutrinos.

**Solar Neutrino Problem – Slide 24**

Theorists initially thought that the experiment was probably in error, since counting a few atoms out of over $10^{31}$ in the detector seemed daunting. Experimentalists initially thought the complicated calculations of the Standard Solar Model were probably in error. Further refinements by Bahcall and Davis reduced uncertainties and showed the correctness of their work. Finally, in the 1980s and 1990s, two gallium-based experiments confirmed the deficit of solar electron neutrinos compared with the Standard Solar Model predictions.

**Kamiokande II Provides A New Perspective – Slide 25**

A new type of neutrino detector developed my Masatoshi Koshiba (2002 Nobel Prize) cast doubt of the Standard Model of particle physics rather than Bahcall's Standard Solar Model. A large tank of water ($3 \times 10^6$ L) surrounded by phototubes and placed in a zinc mine under a mountain in Japan looked for Cerenkov radiation from electrons and muons produced by neutrino interactions. High energy electrons and muons produced by electron and muon neutrinos indicate the original neutrino travel directions. Electron and muon interactions are distinguishable.

**Atmospheric Neutrinos – Slide 26**

WHAT TYPE OF PARTICLE PRODUCED THE RINGS OF PMT HITS IN (a) AND (b)?

In (a) and (b) images on the slide, the top and bottom circles represent the top and bottom of the detector. The rectangle represents the cylindrical side of the detector unrolled. Each dot represents light hitting one of the surrounding phototubes. In both images, the neutrinos enter the detector diagonally from below. The fuzzy circle in (a) results from Cerenkov light from an electron, whose low mass leads to more scattering from H and O atoms in the water. The more sharply defined ring in (b) is produced by Cerenkov light from a muon ($m_\mu$ = 207 $m_e$), which is less easily deflected from its original path.

Though originally constructed to search for proton decay signals, the Kamiokande experiment was sensitive to neutrinos produced in the atmosphere by the interaction of high energy cosmic rays with atomic nuclei. Those interactions produced pions which quickly decayed to muons and muon neutrinos. The muons subsequently decayed to electrons, electron neutrinos, and muon neutrinos. So, the experiment expected to see twice as many muon neutrinos as electron neutrinos.

**Kamiokande Results – Slide 27**

Kamiokande did see enhanced neutrino flux from the Sun. Confirming that the Sun was a source of neutrinos. However, most of the neutrinos observed were atmospheric neutrinos produced by cosmic ray interactions. Kamiokande saw that the ratio of the number of muon neutrinos to electron neutrinos ($n_\mu/n_e$) was 2/1 for neutrinos that entered from above, but $n_\mu/n_e$ < 2/1 for neutrinos that traveled through the Earth and entered from the side or from below. The greater the neutrino travel distance through the Earth, the closer the ratio was to 1/1. So, we have disappearing electron neutrinos from the Sun and disappearing muon neutrinos from the atmosphere.

WHAT HAPPENED TO THE DISAPPEARING NEUTRINOS?

**SNO Lab – Slide 28**

The Sudbury Neutrino Observatory (SNO) detector used heavy water ($D_2O$) rather than normal water to answer that question. Three different phases of the experiment lasting about 2 years each from 1999 to 2006 were conducted: 1. only $D_2O$, 2. 2 x $10^3$ kg NaCl added to enhance neutron capture efficiency, 3. NC interactions measured with neutron-sensitive proportional counters. The results of the three phases were in agreement that the CC signal due to $\nu_e$ was about 1/3 the NC signal due to all neutrino flavors, *i.e.* only about 1/3 of the solar neutrinos were $\nu_e$. The total number of solar neutrinos agreed with predictions from the Standard Solar Model. The agreement is impressive since the flux of neutrinos from the solar reaction that produces $B^8$ (to which SNO was sensitive) depends on the 24$^{th}$ power of the central temperature of the Sun. Also, the ES data agreed with the Super-K data. Although, Super-K had much better statistics, since it was a much larger detector.

**Neutrinos Have Mass – Slide 29**

The various neutrino experiments are in agreement that neutrinos can change flavor as they travel. Since they can change, they must travel in time at less that the speed of light, and, therefore, they must have some small, but finite, mass.

**Some Remaining Questions – Slide 30**

Characterizing more precisely the parameters that determine neutrino flavor changing is a challenge for current neutrino experiments, for example the Deep Underground Neutrino Experiment (DUNE) in development at Fermilab and the Sanford Underground Research Facility (SURF) in Lead, SD.

The absolute scale of neutrino masses is being investigated by the Karlsruhe TRItium Neutrino (KATRIN) experiment in Germany that examines the endpoint energy of tritium beta decay. Investigators hope to extend the current neutrino mass upper limit (2.3 $eV/c^2$ ) down to 0.2 $eV/c^2$.

Several experiments are looking for evidence of neutrinoless double beta decay. If found, such an interaction would indicate the neutrinos are their own antiparticles.

Sterile neutrinos are hypothetical particles that interact only through gravity. Several experiments are looking for them.

Ultrahigh energy neutrinos (TeV to PeV) from astrophysical sources are observed by ICE CUBE at the South Pole and the Pierre Auger Observatory in Argentina. The sources and production mechanisms of these neutrinos are under investigation.