Notes

**Basic**

Has a very low probability of interacting with matter, which leads to difficulty of observation

**History**

1930: Pauli proposed the existence of a particle so that conservation of energy, momentum and spin could be fulfilled in beta decay experiments (in contrast, Bohr: statistical version of conservation laws); called it neutron

$$n^{0}\rightarrow p^{+}+e^{-}+ν ̅\_{e}$$

1932: Chadwick discovered the neutron (much larger mass, neutral)

Name neutrino given by Enrico Fermi in 1933

Clyde Cowan, Frederick Reines experiment 1956

Used the predicted weak interaction:

$$ν ̅\_{e}+p^{+}\rightarrow n^{0}+e^{+}$$

nuclear reactor: antineutrinos through beta-decay

Flux: $5×10^{13}\frac{1}{s cm^{2}} $

Cadmium: good neutron absorber, about 5 microsecond delay for metastable state; checked coincidence

$$n^{0}+ ^{108}Cd\rightarrow ^{109m}Cd\rightarrow ^{109}Cd+γ$$

200 l water (hydrogen – proton core), 40 kg absorbed cadmium-chloride, 110 photomultipliers

scintillator material: visible light detected with photomultiplier tubes (gamma pair, single gamma)

12 m below ground, to shield from cosmic rays

3 reactions per hour: cross section $6,3×10^{-44}cm^{2}$

AGS alternating gradient synchrotron, Brookhaven

Donut experiment at FermiLab (*Direct Observation of the Nu Tau) 2000;*

DONUT: charmed meson decays into tau (-> tau-neutrino), and tau-antineutrino; interaction in emulsion, tau leptons decay after about 2 mm

magnet; concrete, iron, and lead shield from other sources

**Old experiments**

Homestake Gold Mine – South Dakota; lead by astrophysicists Raymond Davis (experiment design), John N. Bahcall (theory – Sun, model of nuclear fusion)

University of Pennsylvania took it over in 1984, operated between 1970 and 1994

Cl2 C = C Cl2 perchloroethylene (dry-cleaning fluid)

helium bubbled every 4 weeks; stable argon added to measure extraction efficiency

**Kamioka Nuclear Decay Experiment** (originally for proton decay); Mozumi Mine, 1000 m underground

detects Cerenkov radiation (cone) in matter – 3000 t of water in a cylindrical tank

Cerenkov: radiation emitted by charged particle, faster than the speed of light in a medium; the intersection of the cone and the PMTs allow analysis (timing, charge -> vertex, direction, flavor)

electron scattering: electrons can receive huge energies from the neutrinos

$$ν\_{e}+e^{-}\rightarrow e^{-}'+ν\_{e}'$$

muons travel almost straight through - sharp ring, electrons scatter multiple times – fuzzy ring

gave first directional information that the Sun is indeed a neutrino source

implosion: shockwave of mechanical stress, chain reaction

Outer detector: +8 m diameter, +3 m height around central 34, 36 m dimensions – optically separated; smaller PMT array faces the OD to identify outside sources

Atmospheric neutrinos: energy not sufficient for tau neutrino detection (no tau particles are created)

**Sudbury**

Creighton Mine, 2000 m below the surface; 1000 t in a sphere, largest man-made underground cavity

the heavy water is surrounded by light water: buoyancy, shielding

Solar neutrinos: energy not sufficient for tau or mu particle creation

the 2 MeV gammas are below the detector energy threshold

Later enhanced with other neutron-detecting devices

**Oscillation**

Super-K published evidence of atmospheric neutrino oscillation in 1998, but it was not that conclusive

the effect is the result of the eigenstate non-equality; they are created in flavor eigenstates, interact based on flavor eigenstates, but “exist” in mass eigenstates

only slight differences in mass -> very long, macroscopic coherence length of oscillation

$α$ flavor, i mass eigenbases; U unitary transformation

$s\_{ij}=\sin(\left(θ\_{ij}\right))$ ; $c\_{ij}=\cos(\left(θ\_{ij}\right))$ ; $α\_{1,2}$ relevant if $ν$ is Majorana-particle; $δ$ phase factor; $θ\_{ij}$ three mixing angles

ultrarelativistic case is always observed

heavier eigenstates oscillate slower, lighter mass eigenstates oscillate faster

parameters: three mixing angles, three mass differences

black electron, blue muon, red tau; slow solar, fast atmospheric oscillations

MSW effect: describes neutrino oscillation when propagating through matter

charged current coherent forward scattering

in the Sun’s core a resonance occurs; high and low energy neutrinos behave differently

Seesaw: very large Majorana mass for right-handed neutrinos

(Majorana particle: it is its own antiparticle)

**Opera**

collaboration between CERN and LNGS (Gran Sasso)

there are two detector supermodules

the bricks have to be extracted for development when the beam is not on

results are analyzed for each track, noting events and bricks, and comparing results to MC simulations

SPS (super proton synchrotron) protons go on carbon targets, generating pions and kaons

BCT beam current transformer

one just has to mention the neutrinos faster than the speed of light!

Common view GPS devices, backed by atomic clocks

average time of flight: 60 ns shorter

complex timing system was their downfall

**IceCube Neutrino Observatory**

Amundsen-Scott station: in place since 1956, at the geographic South Pole; 2800 m above sea level on a high plateau; operated by NSF (National Science Foundation)

Avr. temperature: between -26 and -30 0C in January, -56 and -63 0C in July; 200 inhabitants in “summer” (Oct-Feb), ~50 in “winter”; the ice that deep is very clear and dark

Constructed between 2005 and 2010

Super-Kamiokande detector tank: ~40 m diameter sphere; IceCube: ~ 1000 m in height, diameter – man-made vs natural

**DOM:** spherical optical sensor (with transparent silicone scintillator gel) with a PMT

neutrino flavor + proton/neutron -> electron, muon, positron, antimuon, (tau, antitau?)

Cherenkov cone angle: measures particle velocity; cone boundary sharpness: electron or muon differentiation (electrons generate showers)

IceTop: Cherenkov detector tanks, two per each string, for cosmic ray shower detection (coincidence)

Deep Core Low-Energy Extension: denser spacing, calibrated for neutrino energies below 100 GeV

5160 detectors, Super-K has 11000 -> better angular resolution there

Predicted: 1 neutrino event every 20 minutes (with the given energy ranges)

Interesting point: data is sent via satellite, or recorded on tapes and shipped away yearly

**Targets:**

Electrons and their showers are usually contained within the detector, hard to pinpoint source

Taus hard to distinguish from electrons (cascade), usually decay before getting to another DOM (would need to detect double-bang, cascade both at tau creation and decay, would be possible around PeV energies, none discovered so far)

Good muon detection (Earth as a filter ☺)

They are trying to locate astronomical point sources; extraterrestrial or even extra-galactic; would need **high neutrino fluxes in given directions**

Pontecorvo-Maki-Nakagawa-Sakata matrix parameter theta\_23, effectively the mixing angle between tau and mu neutrino

WIMP: weakly interacting massive particles, which is a dark matter model; they could accumulate in the Sun’s core, and if they annihilated, could produce excess neutrinos -> limits for flux; also could detect other high-energy super-symmetric particles (theoretic)

Black hole (at the galaxy centers) particle jets supposedly have a higher energy particle population
GC: Galactic Center