What is a Neutrino?

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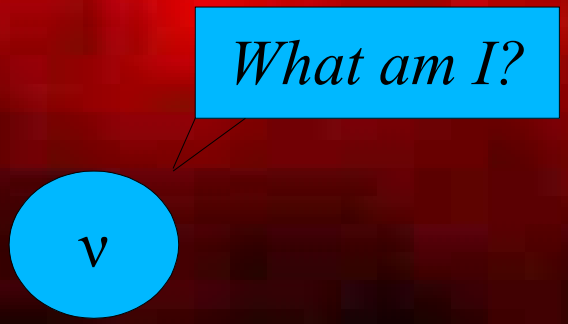


Quantum Weirdness

$$\lambda = h/p$$

- Quanta are not particles
  - But can be approximated as such in limit of large momenta
- Quanta are not waves
  - But can be approximated as such in limit of low momenta

Examples

- Monsieur de Broglie
  - riding his bicycle at about 25 mph would have a wavelength $\lambda \approx 10^{-37}$m (and about 10^{30} eV/c momentum)
- Photons
  - visible light at $\lambda \approx 500$nm has about 2.5 eV/c per photon
- Neutrinos...

Wolfgang Pauli

Pauli & Bohr at the top of physics

- Made up neutrino to conserve lepton number
- $n \rightarrow p^{+} + e^{-} + \underline{\nu}_{e}$
- Had already worked for Dirac vis a vis the positron

The Standard Model

- Tabulation of the results of “particle” physics
- Like the periodic table in Chemistry
- A good guide, but starting to get a little too stretched at the seams...

The Weak Interaction

- Allows quarks & leptons to change flavor
- For example, neutron decay can be written

$$d(ud) \rightarrow u(ud) + e^- + \underline{\nu}_e$$

- (quarks not involved in the decay but still bound in the baryon are in parentheses)
- Similar c to s and t to b reactions also occur

Massive Particles

- Must travel at subluminal velocities
- How fast they travel through the vacuum at a given energy depends on the mass

$$|\psi(t)> = e^{-iEt}|\psi(0)>$$

with $E = \sqrt{p^2 + m^2}$

Bruno Pontecorvo

- Born in 1913 (Pisa, Italy)
- Worked under Fermi
- Fled Italian fascism to North America in the mid-1930's
- Proposed inverse β-decay detection of neutrinos in 1946 via
- $^{37}Cl + \nu_e \rightarrow {}^{37}Ar + e^-$
- Fled to the USSR after arrest of Klaus Fuchs in 1950
- Predicted neutrino oscillations in 1957
- Dies in 1993 (Dubna, Russia)

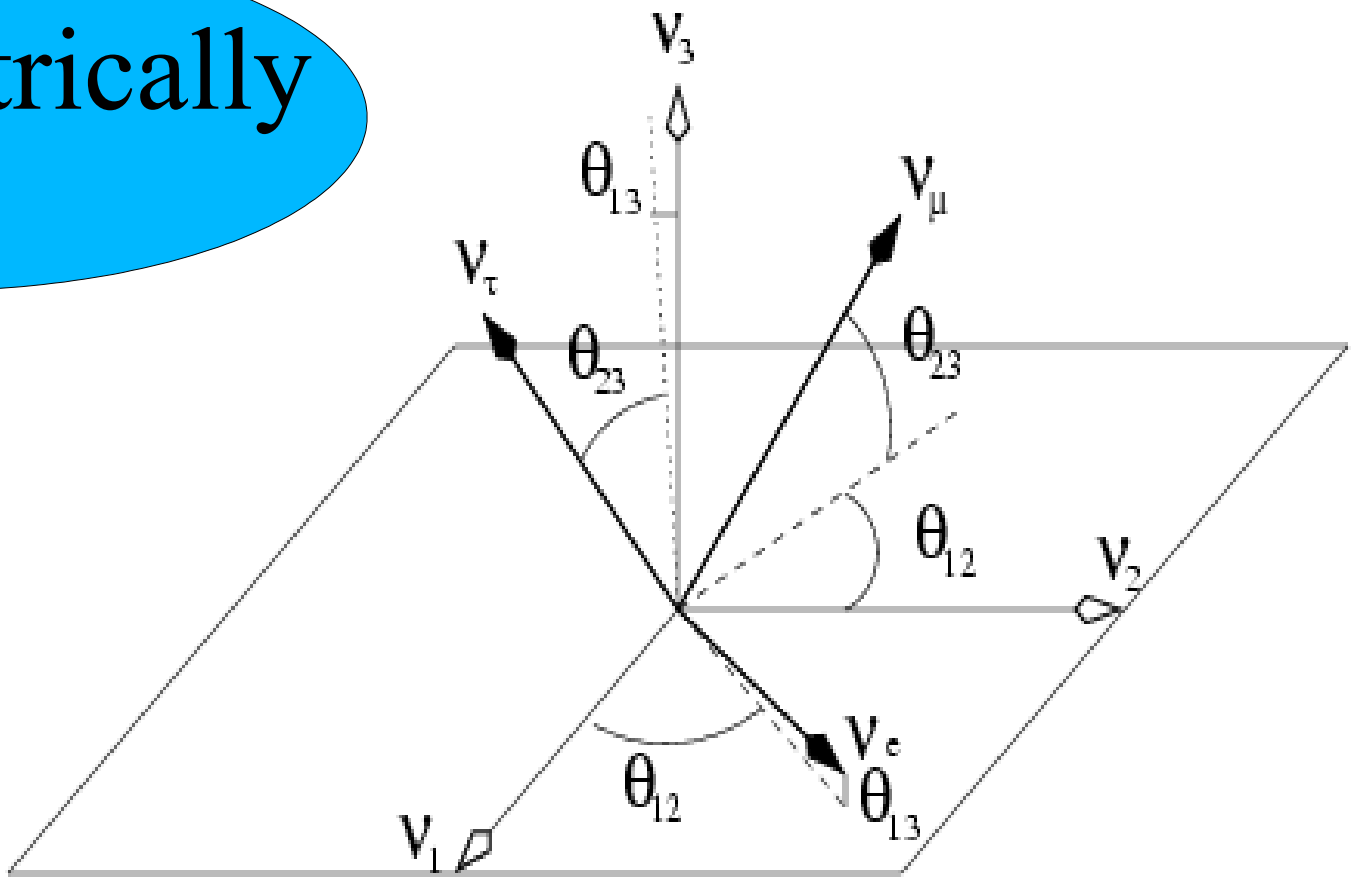
Pontecorvo's Idea

- The mass eigenstates of neutrinos don't correspond to the flavor eigenstates.
- This is expressed by the PMNS matrix:

$$\begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix} \approx \begin{bmatrix} 3/4 & -1/8 & 1/8 \\ 1/4 & 3/8 & -3/8 \\ 0 & 1/2 & 1/2 \end{bmatrix} \begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix}$$

(All terms are squareroots)

Geometrically



$\theta_{12} \approx \pi/6$

$\theta_{23} \approx \pi/4$

$\theta_{13} \approx 0\ (< .2)$

Quarks do it,too

- This is expressed by the CKM matrix:

$$\begin{bmatrix} d \\ s \\ b \end{bmatrix} \approx \begin{bmatrix} .97 & .22 & .0037 \\ .22 & .97 & .04 \\ 0 & .04 & .99 \end{bmatrix} \begin{bmatrix} d_m \\ s_m \\ b_m \end{bmatrix}$$

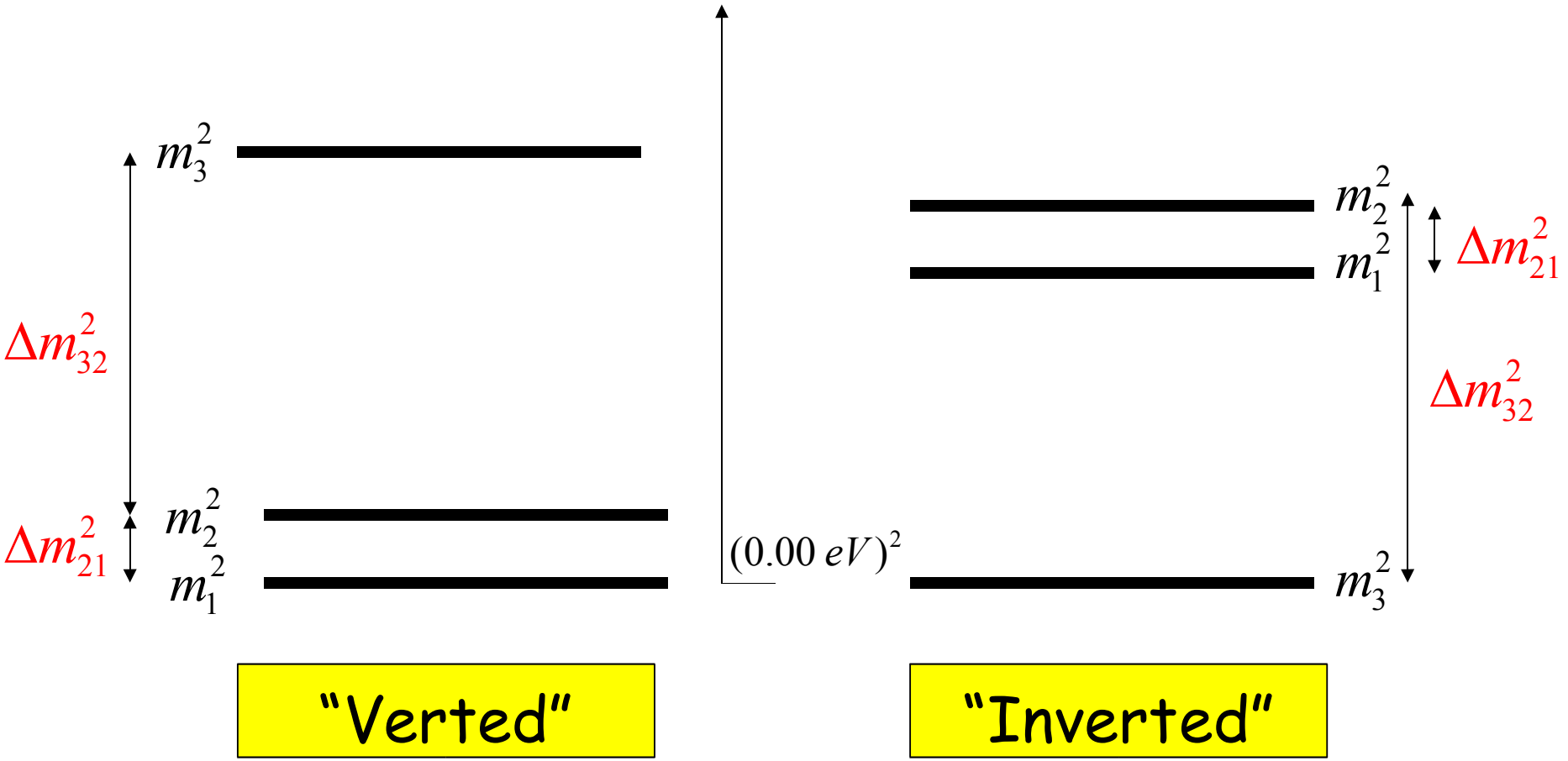
(Here the weak eigenstates are on the left)

- Note that there is almost no mixing in this case

Mass Differences

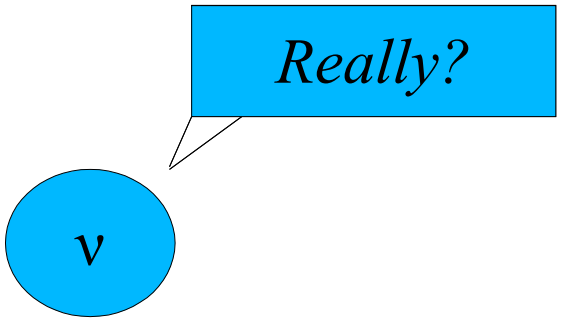
- So far, only the differences between the mass eigenstates can be measured
- $|\Delta m_{12}| \approx 9$ meV
- $|\Delta m_{32}| \approx 50$ meV
- Overall upper bound ~200meV

Neutrino Mass Hierarchies



So what is a neutrino?

A massive neutral lepton that interacts weakly. To calculate its propagation, use the mass basis. To calculate its probability of interacting weakly, use the flavor basis.

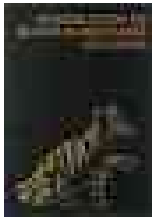


An Analogy

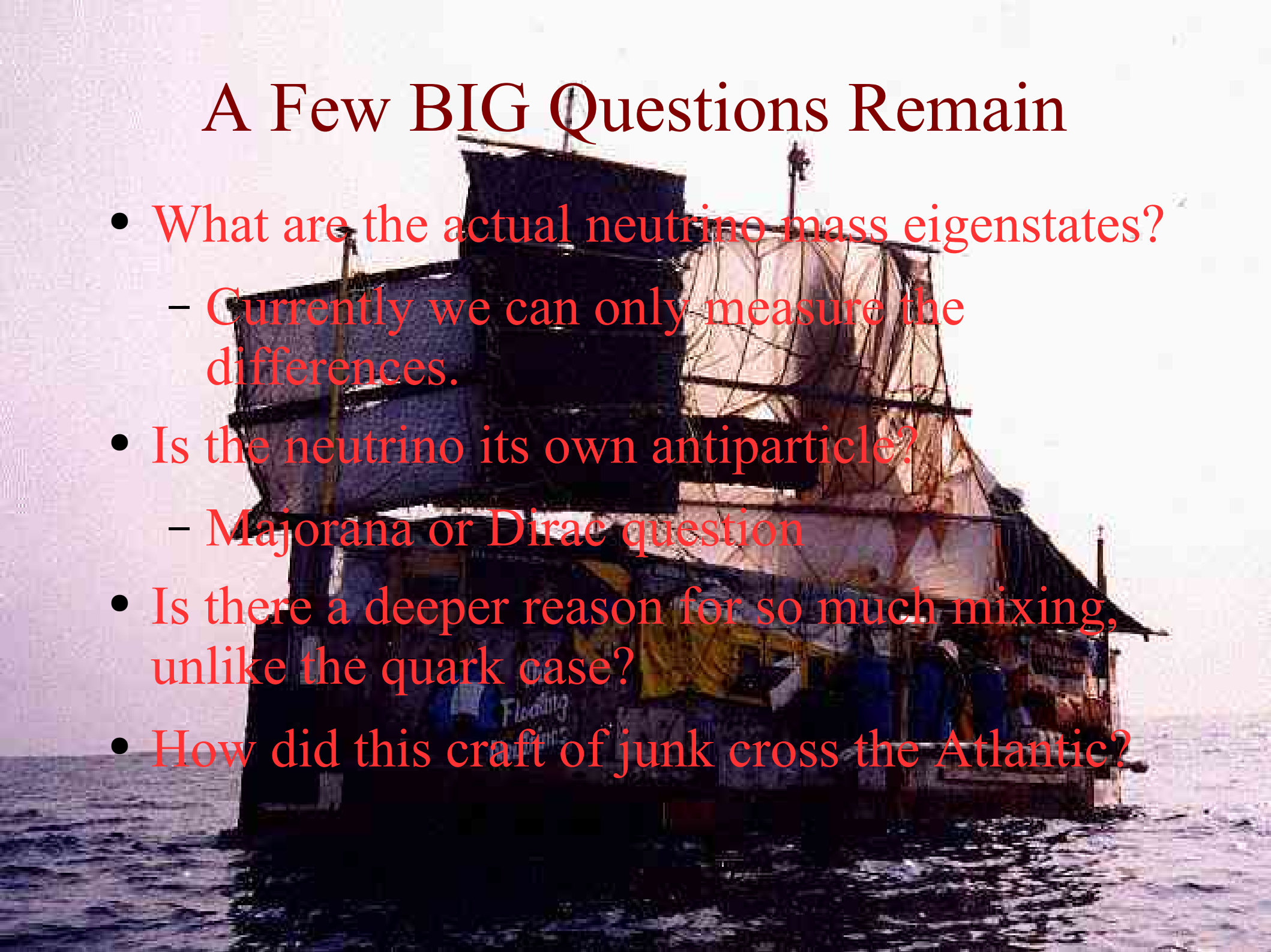
- An electron is a spin-½ particle
- We can measure this spin either up or down
- Nevertheless, an electron can be in a state where it has a certain probability to be up and a certain probability to be down
- Generally, we don't think of spin up and spin down electrons as two different particles, but as electrons with different spin orientations

Don't be surprised when neutrino oscillations become a textbook example of a macroscopic quantum effect.

Recommended reading: Neutrino Oscillations for Dummies



A Few BIG Questions Remain



- What are the actual neutrino mass eigenstates?
  - Currently we can only measure the differences.
- Is the neutrino its own antiparticle?
  - Majorana or Dirac question
- Is there a deeper reason for so much mixing, unlike the quark case?
- How did this craft of junk cross the Atlantic?