Mysteries of the Neutrinos

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Outline

- How was the neutrino discovered?
- How do you detect a neutrino?
  – neutrino interactions
- What do we know about neutrinos?
- How much does a neutrino weigh?
  – neutrino oscillation
- Where are all the right-handed neutrinos?
  – helicity
- What is an antineutrino?
- Neutrino experiments – present and future

The History of the Neutrino (1)

- 1911-1927: β-decay:

$$n \rightarrow p + e^-$$

  - Models expected **discrete** energy spectrum of electron
  - **Continuous** spectrum found!

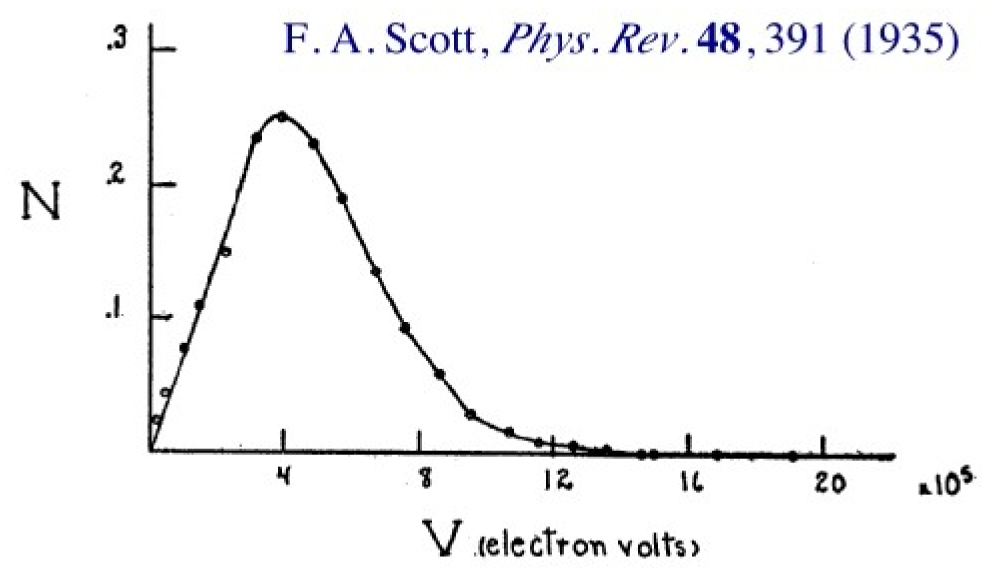


FIG. 5. Energy distribution curve of the beta-rays.

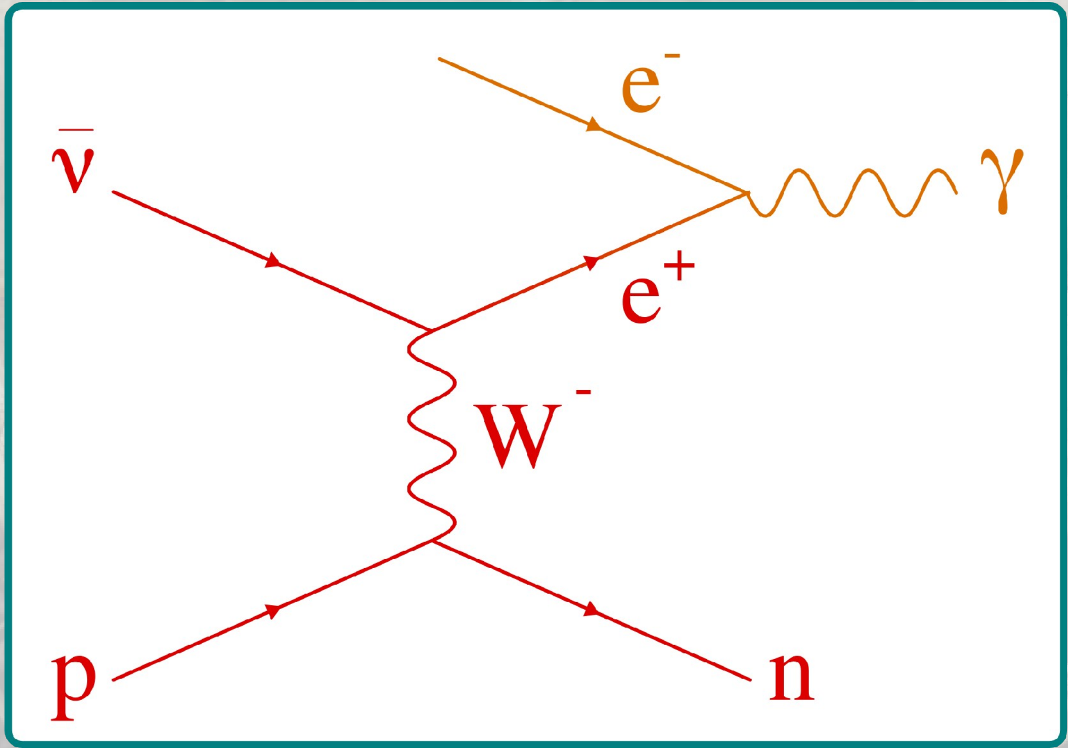
The History of the Neutrino (2)

- December 4th 1930, Wolfgang Pauli
  - Suggested **new particle** was to blame

$$n \rightarrow p + e^- + \bar{\nu}_e$$

  - Electrically neutral
  - Spin ½
  - $m_\nu < 0.01\, m_p$
- 1934, Enrico Fermi
  - Fermi's interaction
- 1956, Cowan and Reines
  - Direct detection via inverse β-decay

Detecting Neutrinos – Inverse Beta Decay (1)



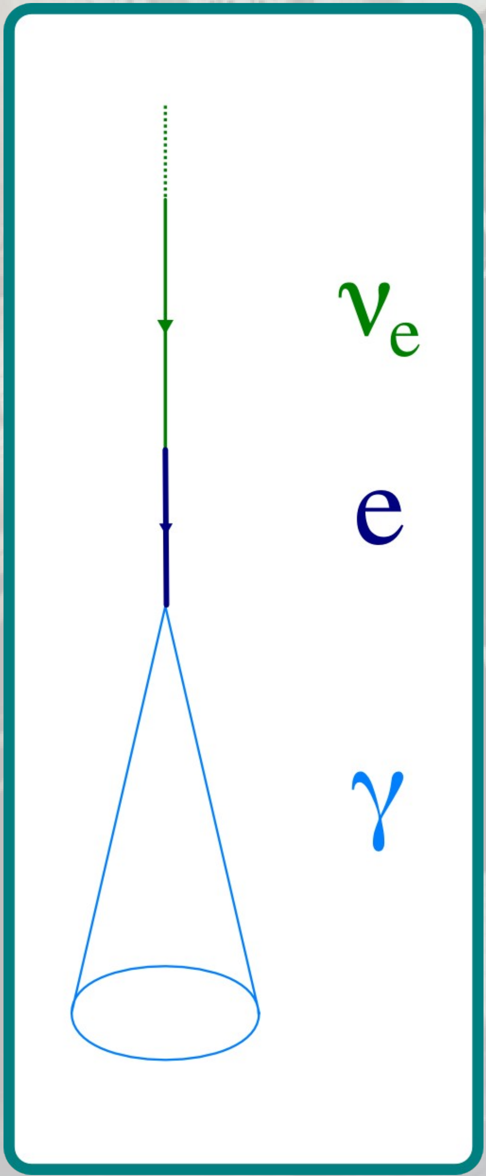
- Antineutrino interacts with proton via weak force to produce positron
- Positron then annihilates with electron, emitting characteristic 0.5 MeV radiation

Detecting Neutrinos – Inverse Beta Decay (2)

- Scintillation Detectors
  - Cowan and Reines (1956)
- Chlorine Detectors
  - $^{37}\mathrm{Cl} \rightarrow {}^{37}\mathrm{Ar}$
  - Homestake Mine
- Gallium Detectors
  - $^{71}\mathrm{Ga} \rightarrow {}^{71}\mathrm{Ge}$
  - GALLAX

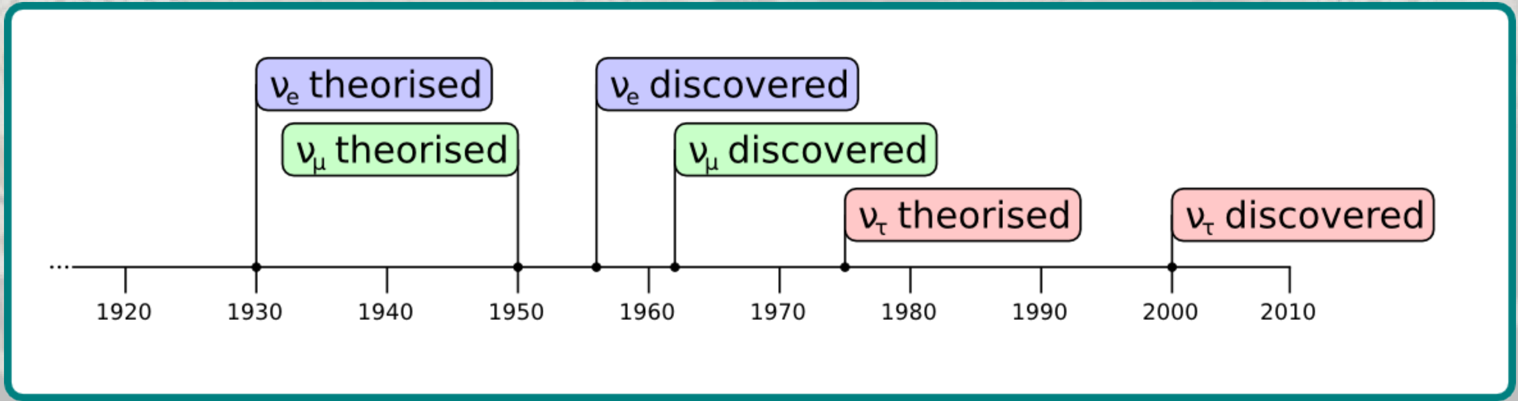
Detecting Neutrinos – Cherenkov Radiation

- Neutrino interacts with a nucleus
  - Decays into corresponding charged lepton
- Rapid deceleration of the lepton
  - Caused by $v_{\text{lepton}} > c_{\text{medium}}$
  - Emits photons (in 'light cone') to reduce energy
- Light cones dependent on mass
  - Flavour and flux of neutrino can be determined



Neutrino Fact File

- 3 neutrino **flavours** – one for each charged lepton (electron, muon, tau)



- **Neutral** – only interact via weak force
- **Very abundant** – produced from nuclear reactors, supernovae and cosmic ray showers.
  - On average, 50 trillion neutrinos pass through your body every second!

Mysteries of the Neutrinos

- Flavour and Mass
  - Do neutrinos change flavour over time?
- Helicity
  - Why are only left-handed neutrinos observed?
- Antineutrinos
  - Is the neutrino its own antiparticle?

Neutrino Oscillations (1)

- Predicted by Bruno Pontecorvo, 1957
- Suggested that **neutrino mass and flavour eigenstates are not the same.**
- Related by the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix:

$$\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \\ |\nu_\tau\rangle \end{pmatrix} = U \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \end{pmatrix}$$

for mass eigenstates $|\nu_1\rangle$, $|\nu_2\rangle$, $|\nu_3\rangle$.

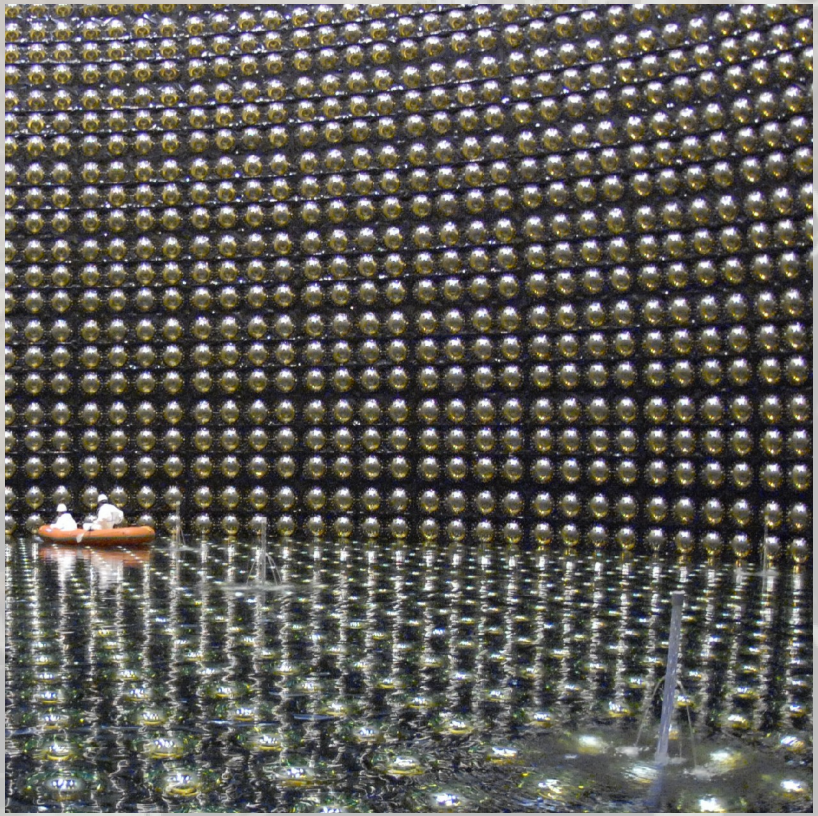
Neutrino Oscillations (2)

- The elements of U (**transition probabilities**) depend on:
  - **Mixing angles** θ_{12} , θ_{13} , θ_{23}
  - **Mass differences** between mass eigenstates Δm_{12} , Δm_{13} , Δm_{23}
  - (Possibly) CP-violation phase δ

- As transition probabilities are dependent on mass differences, **evidence of neutrino oscillation implies a non-zero neutrino mass.**

Confirming Neutrino Oscillation

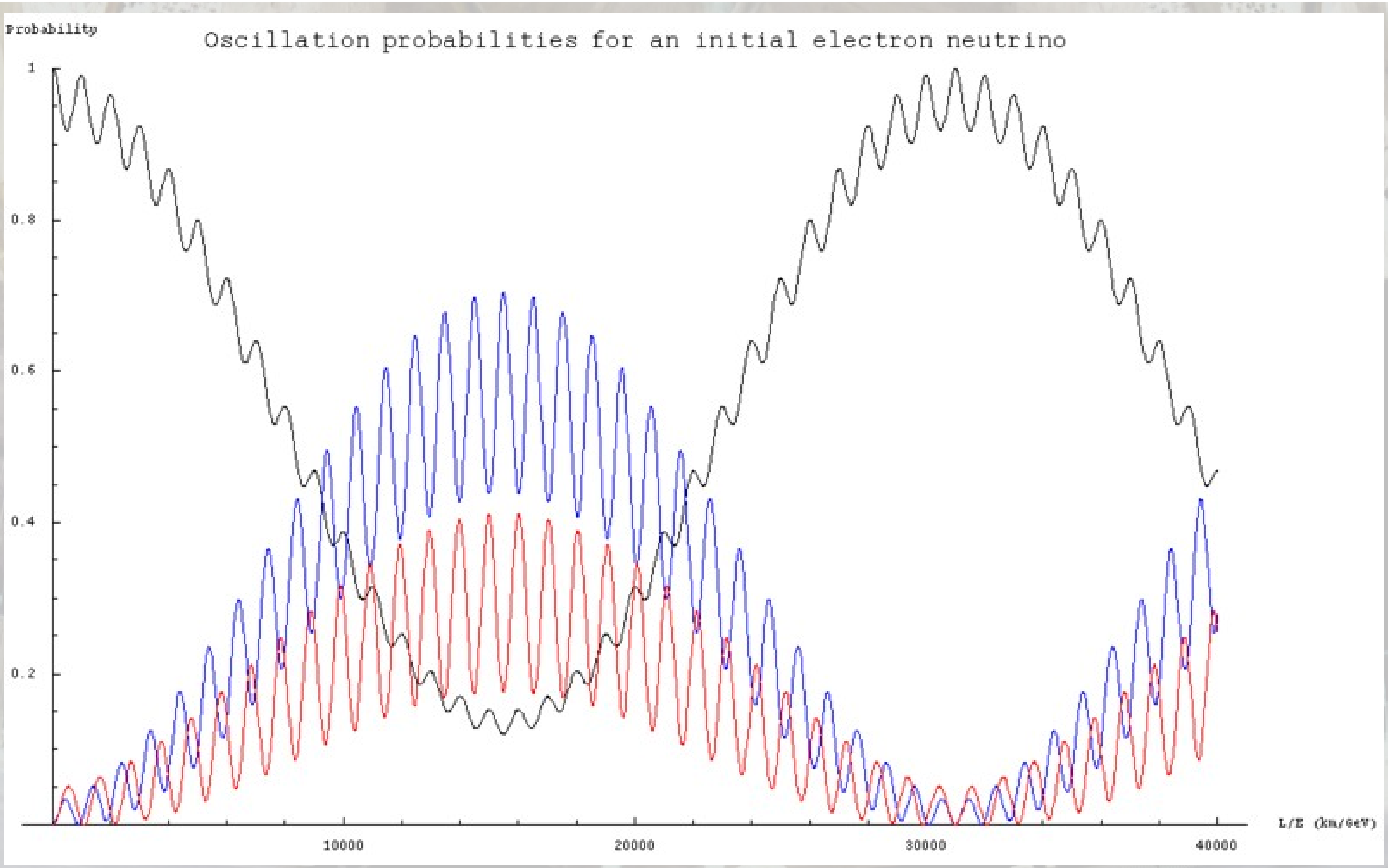
- 1998, SuperKamiokande
  - Conclusive proof of neutrino oscillation
- KamLAND, SuperKamiokande, K2K, MINOS
  - Measured mixing angles and mass differences



- Limits placed on mass expectation values:

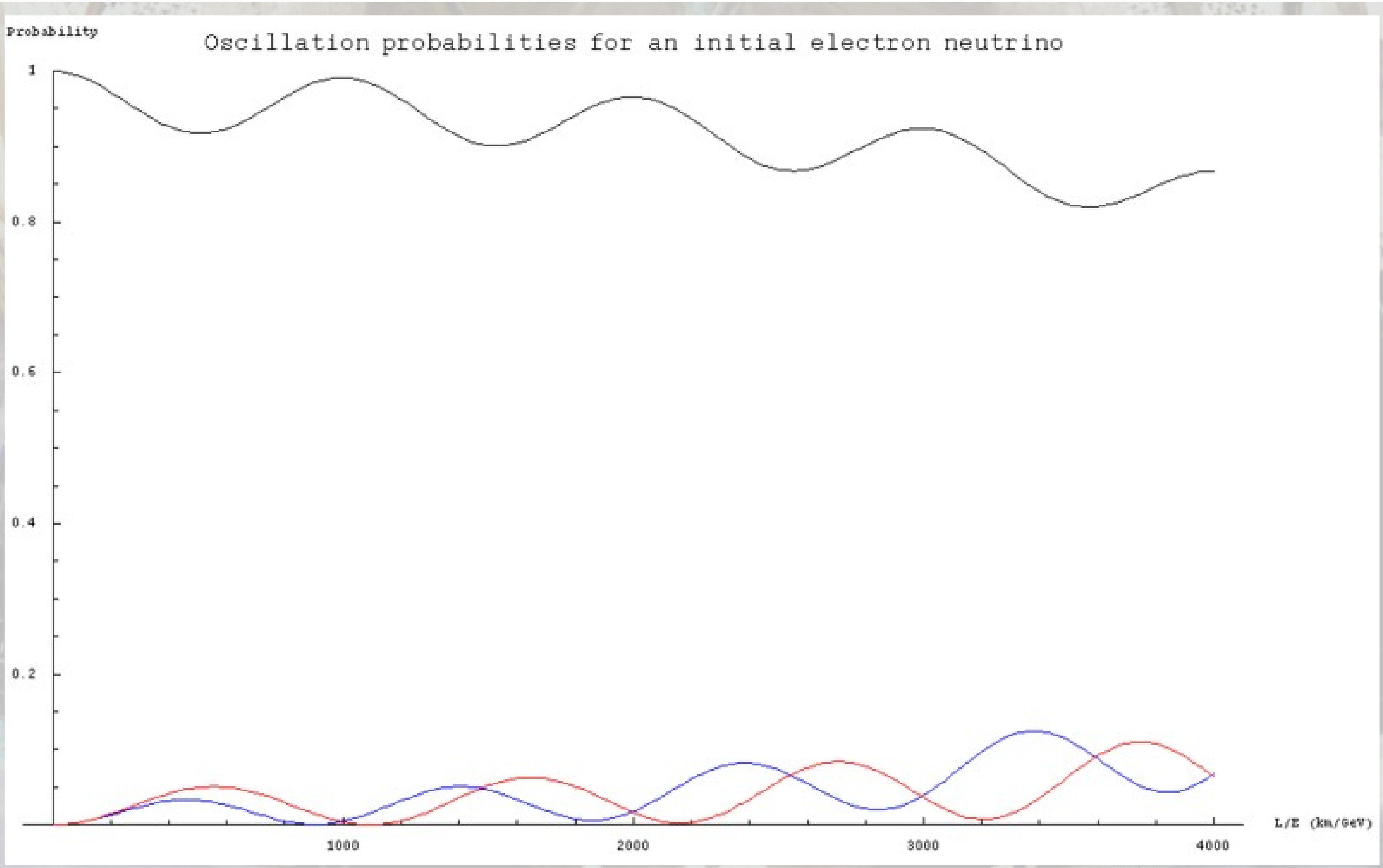
$$0 < \nu_e < 2.2 \text{ eV},\ 0 < \nu_\mu < 170 \text{ keV},\ 0 < \nu_\tau < 15.5 \text{ MeV}$$

Neutrino Oscillation Simulations – Electron Neutrino



Images: Wikipedia (Neutrino Oscillation)

Neutrino Oscillation Simulations – Electron Neutrino



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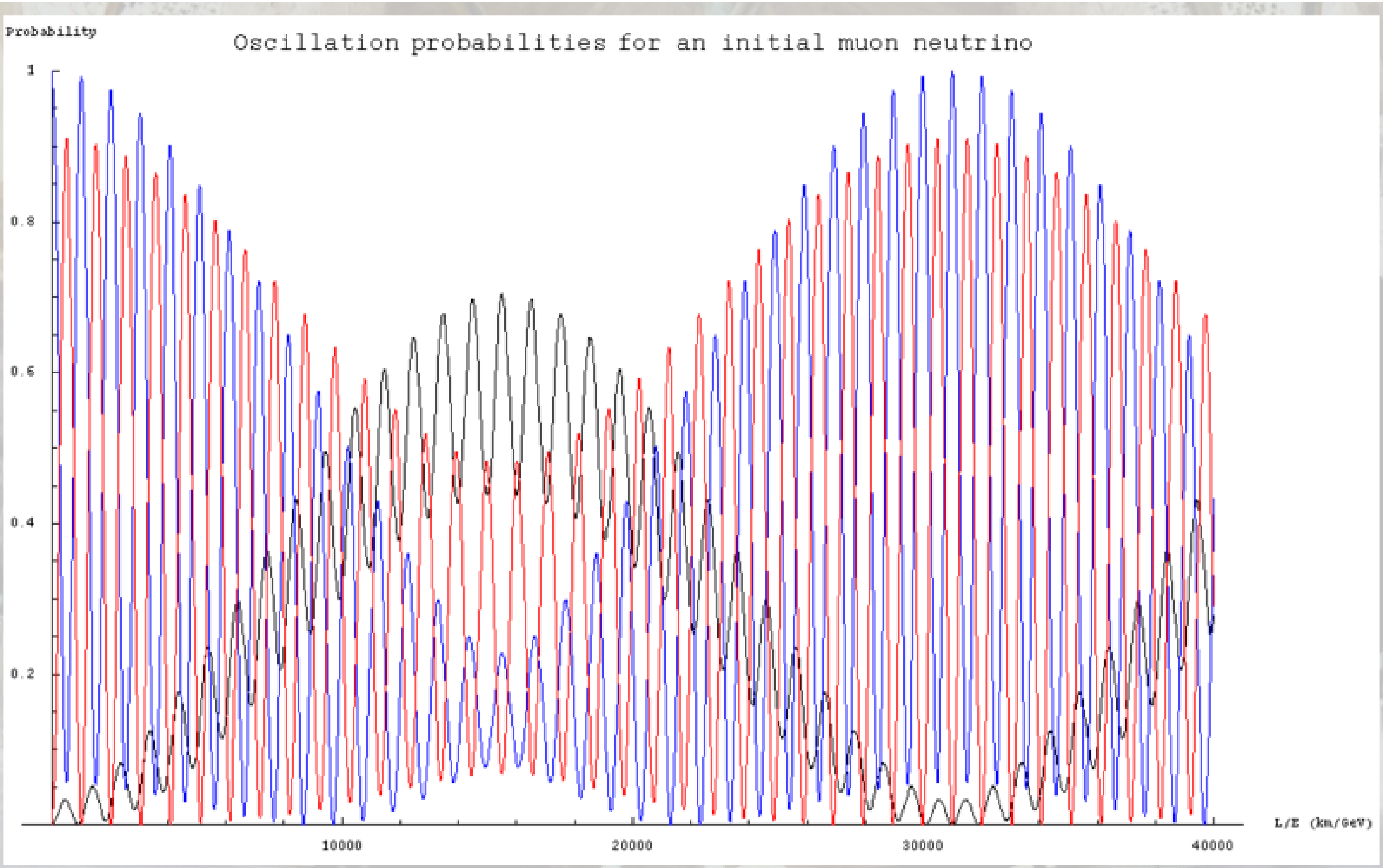
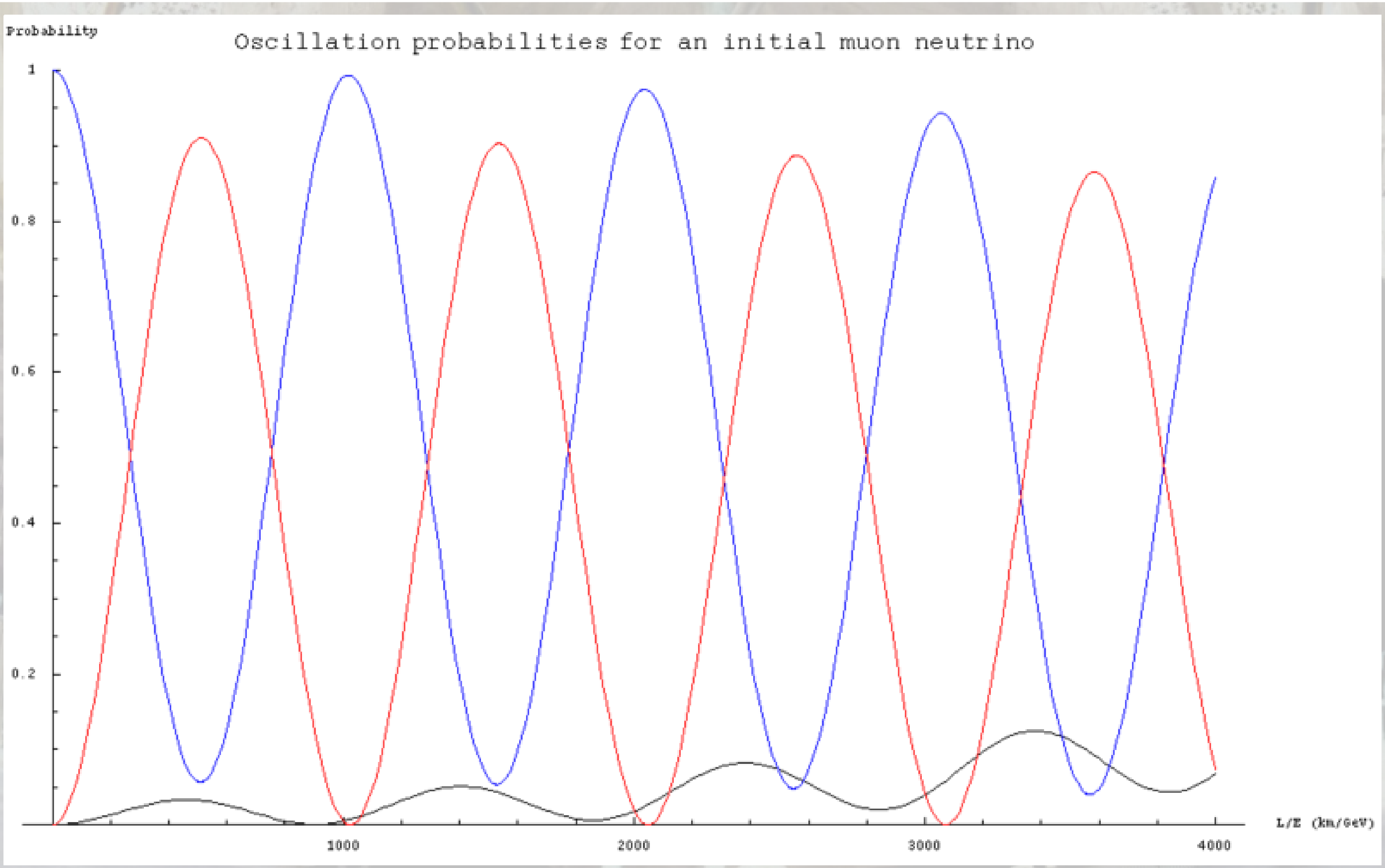
Neutrino Oscillation Simulations – Muon Neutrino



Images: Wikipedia (Neutrino Oscillation)

Neutrino Oscillation Simulations – Muon Neutrino

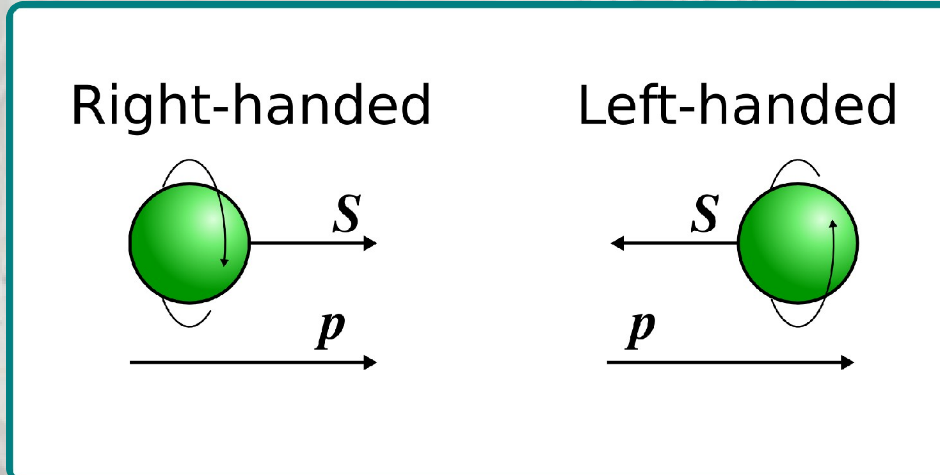


Images: Wikipedia (Neutrino Oscillation)

Right-Handed Neutrinos – Helicity

- Projection of spin on direction of motion:

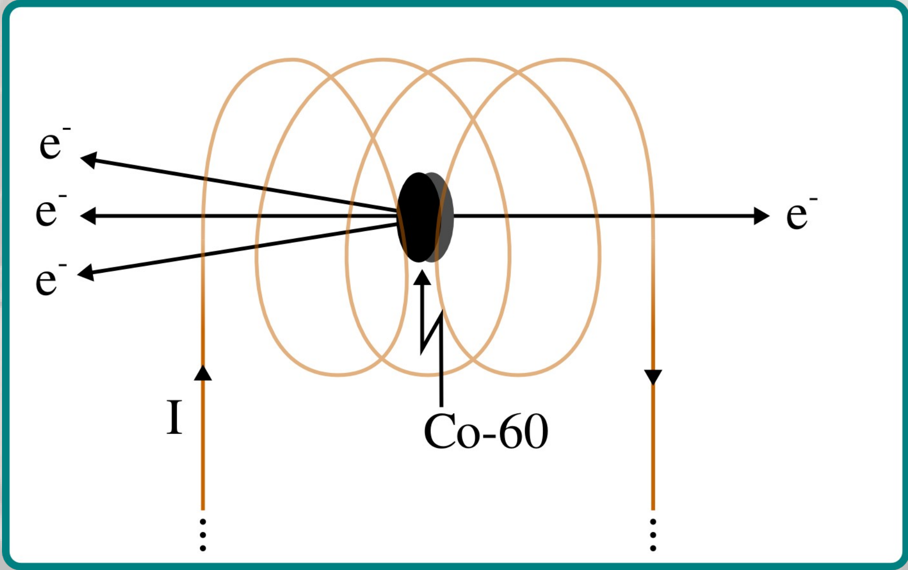
$$h = \underline{S} \cdot \hat{p}$$



- The laws of physics remain the same if charges are negated and an experiment is mirrored (parity is flipped) – **CP Symmetry**
  - **Disproven** using neutrino asymmetry…

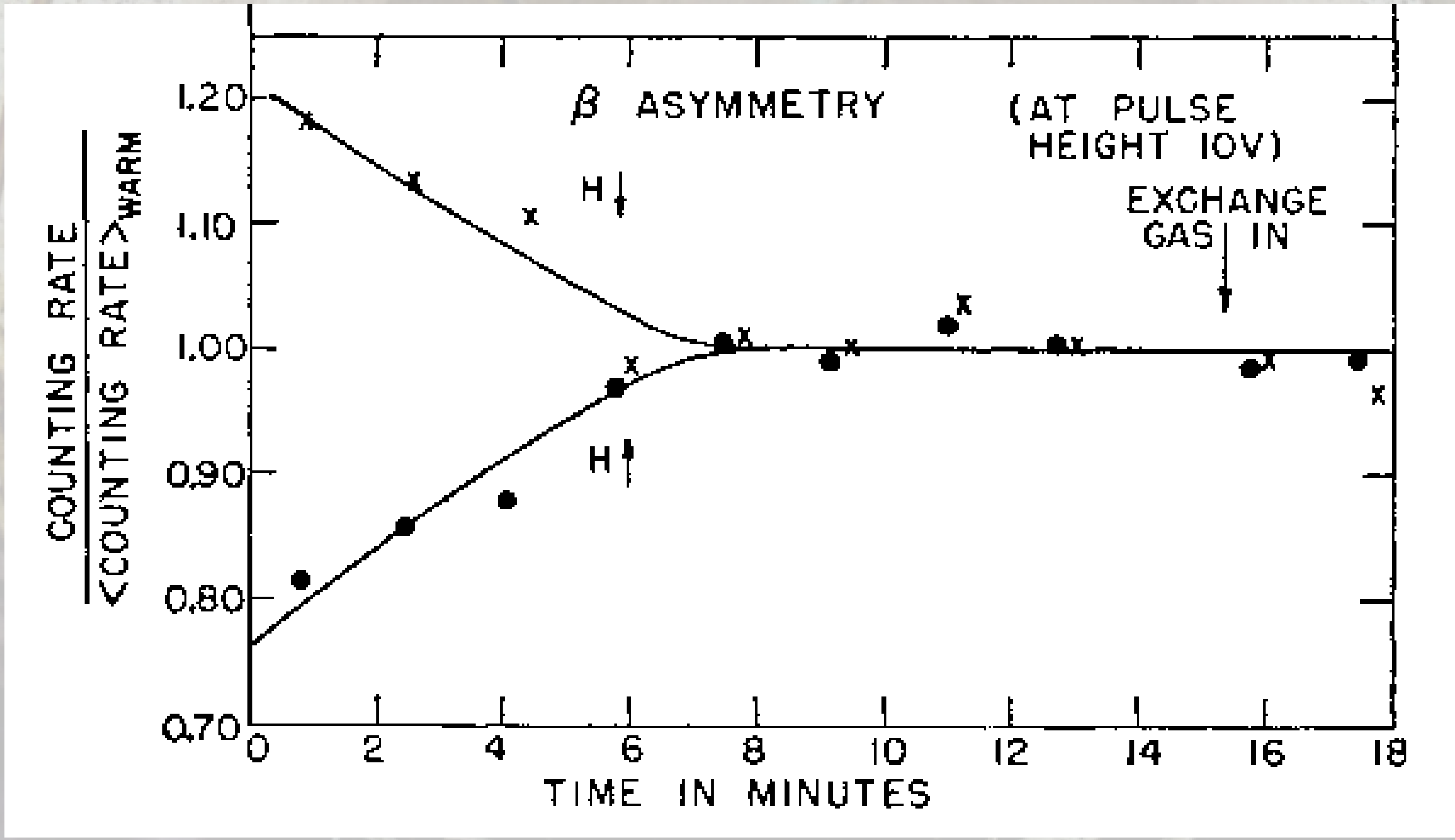
Right-Handed Neutrinos – The Wu Experiment (1)

- ^{60}Co: β-emitting radioisotope
- Nuclear spins aligned with magnetic field and sample cooled



- Electrons can only be emitted in two directions, depending on electron helicity
  - Direction of emission used to determine neutrino helicity

Right-Handed Neutrinos – The Wu Experiment (2)



Wu et. al, 1956

- **Parity** not conserved
  - Preference for emission **left-handed neutrinos**

Right-Handed Neutrinos – Where Are They?

- Further experiments have shown **no right-handed neutrinos have been found**

Why?

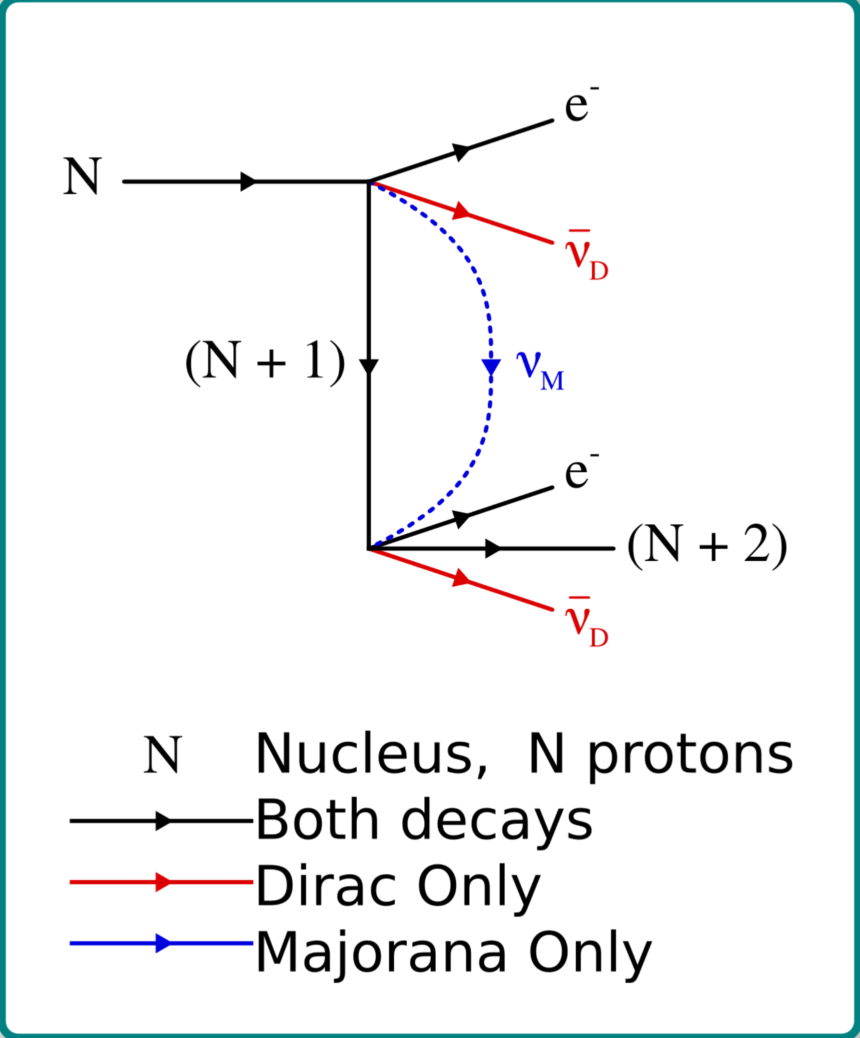
- Simply do not exist – but all other particles have left- and right-handed versions…
- Very different RHNs – heavy, do not react via weak force?
- Very small helicity mixing?

Antineutrinos

- It has not been determined whether the antineutrino is a distinctly different particle to the neutrino (a **Dirac particle**) or if it is the same particle (a **Majorana particle**)
- Dirac neutrinos would have a non-zero magnetic and electric dipole moments
  - Experimentally observable
- Majorana neutrinos would violate lepton number conservation

Double Beta Decay

- Distinguishes between Dirac and Majorana antineutrinos
- **Neutrinoless** double beta decay would imply Majorana antineutrinos
- Not yet observed



Neutrino Experiments

- Improve accuracy of mixing angles, mass differences and transition probabilities
  - MINOS, KamLAND
  - IceCube, NOvA (proposed)
- Improve measurements on neutrino helicity to test theories of RHNs
- Experimentally determine Dirac or Majorana antineutrinos via double beta decay

Thank You!

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