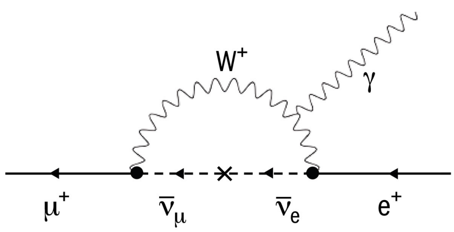
Charged lepton-flavour violation

Lepton-flavour conservation is a mainstay of every introductory particle-physics course, yet it is merely a so-called accidental symmetry of the Standard Model. Unlike gauge symmetries, it arises because only massless left-handed neutrinos are included in the model. The corresponding mass and interaction terms of the Lagrangian can therefore be simultaneously diagonalised, which means that interactions always conserve lepton flavour. This is not the case in the quark sector, and as a result quark flavour is not conserved in weak interactions. Since lepton flavour is not considered to be a fundamental symmetry, most extensions of the SM predict its violation at a level that could be observed by state-of-the-art experiments.

Charged lepton-flavour violation in the SM – a very small neutrino oscillation

The presence of only massless left-handed neutrinos in the Standard Model gives rise to the accidental symmetry of lepton-flavour conservation – yet neutrino oscillation experiments have observed neutrinos changing flavour in-transit from sources as far away as the Sun and as near as a nuclear reactor. Such neutral lepton-flavour violation implies that neutrinos have tiny masses and that their flavour eigenstates are distinct from their mass eigenstates. Phases develop between the mass eigenstates as a neutrino travels, and the wavefunction becomes a mixture of the flavour eigenstates, rather than the unique original flavour, as would remain the case for truly massless neutrinos.

The effect on charged lepton-flavour violation is subtle and small. In most neutrino oscillation experiments, a neutrino is created in a charged-current interaction and observed in a later interaction via the creation of a charged lepton of the corresponding flavour in the detector.



$\mu^+ \to e^+ \gamma$ may proceed in a similar way, but where the same W boson is involved in both the creation and destruction of the neutrino, and the neutrino oscillates in between.

In this process, the neutrino oscillation $\overline{\nu_\mu} \to \overline{\nu_e}$ has to occur at an energy scale $E \sim m_W$, over an extremely short distance of $L \sim 1/m_W$. Considering only two neutrino species with masses m_1 and m_2, the probability for the oscillation is proportional to $\sin^2\left(\frac{m_1^2 - m_2^2}{4E/L}\right)$.

Hence, the $\mu \to e\gamma$ branching ratio is suppressed by the tiny factor $((m_1^2 - m_2^2)/m_W^2)^2 \lesssim 10^{-49}$. The exact calculation, including the most recent estimates of the neutrino mixing matrix elements, gives $\mathrm{BR}(\mu \to e\gamma) \sim 10^{-54}$. A data sample of muons as large as the number of protons in the Earth would not be enough to see such an improbable decay. Charged lepton-flavour violation is therefore a clear signature of new physics with no SM backgrounds.