Charged Lepton Flavour Violation: An Introduction to Muon Experiments

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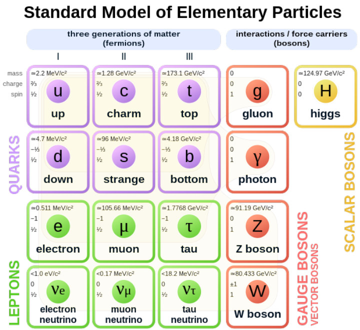
Standard Model conserved quantities

There are a few quantities that are strictly conserved in SM processes:

- Electric & colour charge
- Baryon number B
- Lepton number L

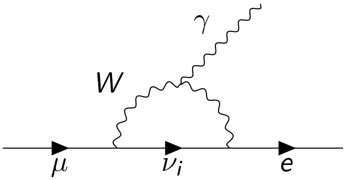
If neutrinos were massless, individual lepton flavour numbers L_e, L_μ, and L_τ would be conserved[1]. With massive neutrinos, only L is conserved. (Provided neutrinos are Dirac fermions and not Majorana fermions)



[1] M.E. Peskin, 2018, p.286

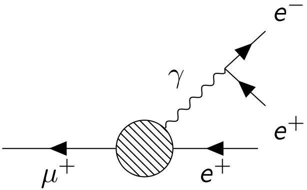
Charged Lepton Flavour Violation (CLFV)

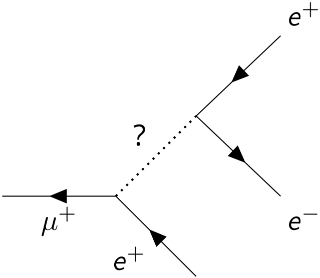
- We already see lepton flavour being violated in neutrino oscillation
- Best estimates of $\mu \to e\gamma$ rates by the same mechanism are $<10^{-54}$, which are not realistically measurable[2]. Similar for other processes
- Thus observing these processes implies new physics is at play!
- Example processes would be $\mu \to e\,e\,e$, $\mu \to e\gamma$, and $\tau \to \mu, e + X$
- Muons are much easier to study than tau leptons



[2] de Gouvea, A., & Vogel, P. (2013). Lepton Flavor and Number Conservation, and Physics Beyond the Standard Model.

- We could see this as $\mu^+ \to e^+ e^+ e^- \nu_\mu \overline{\nu}_e$ and not be new physics
- Thus we look for this with no missing energy
- Could be $\mu \to e\gamma$ with more steps, or could be something else entirely
- The SINDRUM experiment put a rate limit of 10^{-12} with future experiments (Mu3e) aiming for 10^{-16}.[3]

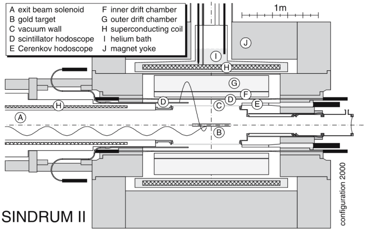




[3] Ardu, M., & Pezzullo, G. (2022). Introduction to Charged Lepton Flavour Violation

$\mu^- N \to e^- N$

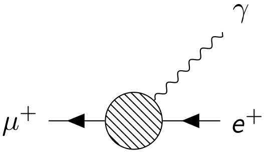
- Conversion of a muon captured by a nucleus into an electron
- Bombarding nuclei with muons to see an outgoing electron
- Should result in a monoenergetic electron, ≈ 105 MeV for most nuclei
- Important to ignore $\mu^- \to e^- \overline{\nu}_e \nu_\mu$
- Rates for gold and titanium are $\lesssim 10^{-13}$ from SINDRUM-II[4]
- Has potential to get to 10^{-18} at Fermilab and J-PARC with Al target



[4] Bertl, W., Engfer, R., Hermes, E. et al. A search for μ-e conversion in muonic gold. (2006)

$\mu^+ \to e^+\gamma$

- Longest studied process and with the most potential to reduce limits
- Background events are $\mu^+ \to e^+\overline{\nu}_e\nu_\mu$
- Must look for total energy of $e + \gamma$ to be m_μ
- MEG experiment reduced limits to 4.2×10^{-13} in 2016[5]

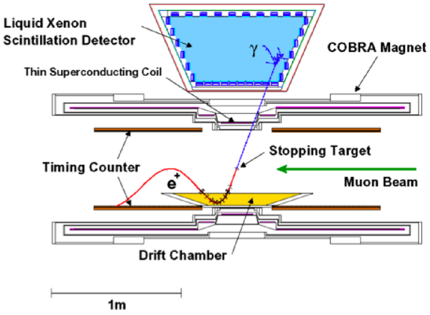


[5] Meucci, M. (2022). MEG II experiment status and prospect.

What the heck is MEG?

- Muon Electron Gamma detector at PSI in Zurich
- 3×10^7 μ^+ per second beam incident onto polyethylene stopping target
- Looks for coincident e^+ and γ events, each with energy 52.8 MeV
- MEG-II (Electric Boogaloo) aims to bring the limit down to 6×10^{-14}

- Large scintillation detector for photons and a drift chamber for positron spectrometry



Conclusion

- CLFV is allowed in the SM, but with rates far too low to be detected
- Seeing CLFV implies new physics is at play and could also help explain neutrino mass and oscillation
- Muon processes are most commonly studied, with upper limits on rates nearing 10^{-14} in some cases
- The new MEG-II detector and Al target muon conversion experiments show promise to greatly reduce those limits

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