Charged Lepton Flavour Violation: An Introduction to Muon Experiments

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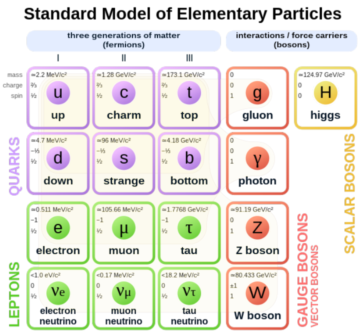
Standard Model conserved quantities

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

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

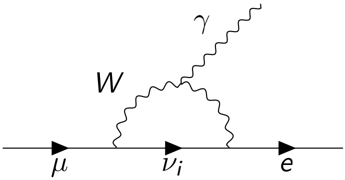
If neutrinos were massless, individual lepton flavour numbers L_e, L_μ, and L_τ would be conserved[1]. With massive neutrinos, only L is conserved. (Provided neutrinos are Dirac fermions and not Majorana fermions)



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

Charged Lepton Flavour Violation (CLFV)

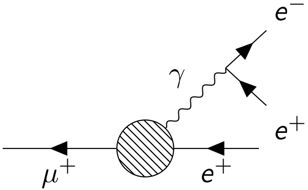
- We already see lepton flavour being violated in neutrino oscillation
- Best estimates of $\mu \to e\gamma$ rates by the same mechanism are $< 10^{-54}$, which are not realistically measurable[2]. Similar for other processes
- Thus observing these processes implies new physics is at play!
- Example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

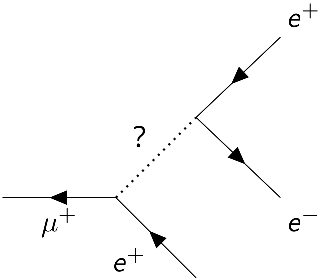


[2] de Gouvea, A., & Vogel, P. (2013). Lepton Flavor and Number Conservation, and Physics Beyond the Standard Model.

$\mu \to e\,e\,e$

- 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 energy loss
- Could be $\mu \to e\gamma$ with more steps, or could be something else entirely
- The SINDRUM experiment puts a rate limit of 10^{-12} with future experiments aiming for 10^{-16}.[3]

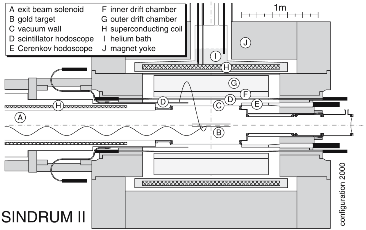




[3]Bellgardt, U. et al. (1988). Search for the decay $\mu+ \to$ e+e+e-.

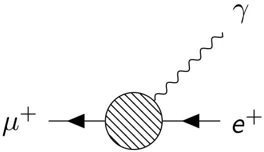
$\mu^- N \to e^- N$

- Conversion of a muon captured by a nucleus into an electron
- Bombarding a nucleus with muons to see an outgoing electron
- Should result in a monoenergetic electron, $\approx 104.96\,\mathrm{MeV}$ 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)

- 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 $< 4.2 \times 10^{-13}$ in 2016[5]

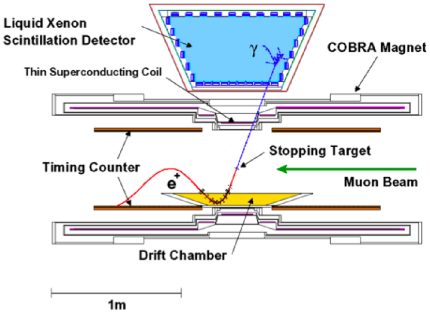


[5]Meucci, M. (2022). MEG II experiment status and prospect.

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

References I

Robert H. Bernstein and Peter S. Cooper.
Charged Lepton Flavor Violation: An Experimenter's Guide.
Physics Reports, 532(2):27–64, November 2013.
arXiv:1307.5787 [hep-ex, physics:hep-ph, physics:physics].

Andre de Gouvea and Petr Vogel.
Lepton Flavor and Number Conservation, and Physics Beyond the Standard Model.
Progress in Particle and Nuclear Physics, 71:75–92, July 2013.
arXiv:1303.4097 [hep-ph, physics:nucl-th].

Alessandro M. Baldini and on behalf of theMEGII Collaboration.
Status of the MEG II experiment at PSI.
Journal of Physics: Conference Series, 1137(1):012028, January 2019.
Publisher: IOP Publishing.

References II

Manuel Meucci.
MEG II experiment status and prospect, January 2022.
arXiv:2201.08200 [hep-ex, physics:physics].

Marco Ardu and Gianantonio Pezzullo.
Introduction to Charged Lepton Flavour Violation.
Universe, 8(6):299, May 2022.
arXiv:2204.08220 [hep-ex, physics:hep-ph].

W. Bertl, R. Engfer, E.A. Hermes, G. Kurz, T. Kozlowski, J. Kuth, G. Otter, F. Rosenbaum, N.M. Ryskulov, A. van der Schaaf, P. Wintz, I. Zychor, and The SINDRUM II Collaboration.
A search for μ-e conversion in muonic gold.
The European Physical Journal C - Particles and Fields, 47(2):337–346, August 2006.

U. Bellgardt, G. Otter, R. Eichler, L. Felawka, C. Niebuhr, H. K. Walter, W. Bertl, N. Lordong, J. Martino, S. Egli, R. Engfer, Ch. Grab, M. Grossmann-Handschin, E. A. Hermes, N. Kraus, F. Muheim, H. Pruys, A. Van Der Schaaf, and D. Vermeulen.
Search for the decay μ+ $\rightarrow$ e+e+e-.
Nuclear Physics B, 299(1):1–6, March 1988.

M.E. Peskin.
Concepts of Elementary Particle Physics.
Oxford Master Series in Condensed Matter Physics Series. Oxford University Press, 2019.

William J. Marciano, Toshinori Mori, and J. Michael Roney.
Charged Lepton Flavor Violation Experiments.
Annual Review of Nuclear and Particle Science, 58(1):315–341, November 2008.