

# Muon decay

The following muon data is from Particle Data Group.

## $\mu$ MEAN LIFE $\tau$

Measurements with an error  $> 0.001 \times 10^{-6}$  s have been omitted.

VALUE ( $10^{-6}$ s)	DOCUMENT ID	TECN	CHG	COMMENT
<b>2.1969811<math>\pm</math>0.0000022 OUR AVERAGE</b>				
2.1969803 $\pm$ 0.0000021 $\pm$ 0.0000007 <sup>1</sup>	TISHCHENKO 13	CNTR	+	Surface $\mu^+$ at PSI
2.197083 $\pm$ 0.000032 $\pm$ 0.000015	BARCZYK 08	CNTR	+	Muons from $\pi^+$ decay at rest
2.197013 $\pm$ 0.000021 $\pm$ 0.000011	CHITWOOD 07	CNTR	+	Surface $\mu^+$ at PSI
2.197078 $\pm$ 0.000073	BARDIN 84	CNTR	+	
2.197025 $\pm$ 0.000155	BARDIN 84	CNTR	–	
2.19695 $\pm$ 0.00006	GIOVANETTI 84	CNTR	+	
2.19711 $\pm$ 0.00008	BALANDIN 74	CNTR	+	
2.1973 $\pm$ 0.0003	DUCLOS 73	CNTR	+	
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2.1969803 $\pm$ 0.0000022	WEBBER 11	CNTR	+	Surface $\mu^+$ at PSI
<sup>1</sup> TISHCHENKO 13 uses $1.6 \times 10^{12}$ $\mu^+$ events and supersedes WEBBER 11.				

From “V minus A” theory we have the following formula for muon lifetime  $\tau$ .

$$\tau = \frac{96\pi^2 h}{G_F^2 (m_\mu c^2)^5}$$

Symbol  $G_F$  is Fermi coupling constant,  $m_\mu$  is muon mass.

From NIST we have

$$G_F = 1.1663787 \times 10^{-5} \text{ GeV}^{-2}$$

$$m_\mu = 1.883531627 \times 10^{-28} \text{ kilogram}$$

$$h = 6.62607015 \times 10^{-34} \text{ joule second (exact)}$$

$$c = 299792458 \text{ meter second}^{-1} \text{ (exact)}$$

$$1 \text{ eV} = 1.602176634 \times 10^{-19} \text{ joule (exact)}$$

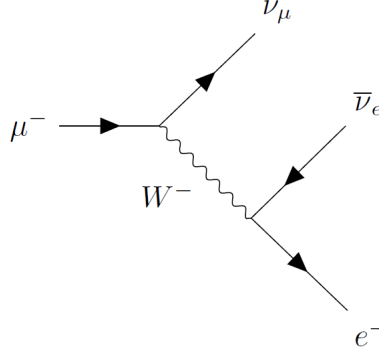
Hence

$$\tau = \frac{96\pi^2 h}{G_F^2 (m_\mu c^2)^5} = 2.18735 \times 10^{-6} \text{ second}$$

The result is a bit smaller than the PDG value.

$$\frac{\text{theoretical value}}{\text{measured value}} = \frac{2.18735 \times 10^{-6} \text{ second}}{2.19698 \times 10^{-6} \text{ second}} = 0.9956$$

As the following diagram shows, a muon decays into a muon neutrino, an electron anti-neutrino, and an electron.



Particle	Symbol	Momentum	Spinor (up)	Spinor (down)
Muon	$\mu^-$	$p_1$	$u_{11}$	$u_{12}$
Muon neutrino	$\nu_\mu$	$p_2$	$u_{21}$	$u_{22}$
Electron anti-neutrino	$\bar{\nu}_e$	$p_3$	$v_{31}$	$v_{32}$
Electron	$e^-$	$p_4$	$u_{41}$	$u_{42}$

We will use the following momentum vectors.

$$\begin{aligned}
 p_1 &= \begin{pmatrix} E_1 \\ p_{1x} \\ p_{1y} \\ p_{1z} \end{pmatrix} & p_2 &= \begin{pmatrix} E_2 \\ p_{2x} \\ p_{2y} \\ p_{2z} \end{pmatrix} & p_3 &= \begin{pmatrix} E_3 \\ p_{3x} \\ p_{3y} \\ p_{3z} \end{pmatrix} & p_4 &= \begin{pmatrix} E_4 \\ p_{4x} \\ p_{4y} \\ p_{4z} \end{pmatrix} \\
 \mu^- & & \nu_\mu & & \bar{\nu}_e & & e^-
 \end{aligned}$$

And we will use the following unnormalized spinors.

$$\begin{aligned}
 u_{11} &= \begin{pmatrix} E_1 + m_\mu \\ 0 \\ p_{1z} \\ p_{1x} + ip_{1y} \end{pmatrix} & u_{21} &= \begin{pmatrix} E_2 + m_2 \\ 0 \\ p_{2z} \\ p_{2x} + ip_{2y} \end{pmatrix} & v_{31} &= \begin{pmatrix} p_{3z} \\ p_{3x} + ip_{3y} \\ E_3 + m_3 \\ 0 \end{pmatrix} & u_{41} &= \begin{pmatrix} E_4 + m_4 \\ 0 \\ p_{4z} \\ p_{4x} + ip_{4y} \end{pmatrix} \\
 \mu^- \text{ spin up} & & \nu_\mu \text{ spin up} & & \bar{\nu}_e \text{ spin up} & & e^- \text{ spin up} \\
 \\
 u_{12} &= \begin{pmatrix} 0 \\ E_1 + m_\mu \\ p_{1x} - ip_{1y} \\ -p_{1z} \end{pmatrix} & u_{22} &= \begin{pmatrix} 0 \\ E_2 + m_2 \\ p_{2x} - ip_{2y} \\ -p_{2z} \end{pmatrix} & v_{32} &= \begin{pmatrix} p_{3x} - ip_{3y} \\ -p_{3z} \\ 0 \\ E_3 + m_3 \end{pmatrix} & u_{42} &= \begin{pmatrix} 0 \\ E_4 + m_4 \\ p_{4x} - ip_{4y} \\ -p_{4z} \end{pmatrix} \\
 \mu^- \text{ spin down} & & \nu_\mu \text{ spin down} & & \bar{\nu}_e \text{ spin down} & & e^- \text{ spin down}
 \end{aligned}$$

Symbol  $E_n$  is total energy of particle  $n$ .

$$\begin{aligned}
 E_1 &= \sqrt{(p_{1x})^2 + (p_{1y})^2 + (p_{1z})^2 + m_\mu^2} \\
 E_2 &= \sqrt{(p_{2x})^2 + (p_{2y})^2 + (p_{2z})^2 + m_2^2} \\
 E_3 &= \sqrt{(p_{3x})^2 + (p_{3y})^2 + (p_{3z})^2 + m_3^2} \\
 E_4 &= \sqrt{(p_{4x})^2 + (p_{4y})^2 + (p_{4z})^2 + m_4^2}
 \end{aligned}$$

This is the probability amplitude for spin state  $abcd$ . The formula is derived from Feynman diagrams for muon decay.

$$\mathcal{M}_{abcd} = \frac{G_F}{\sqrt{2}N} \begin{pmatrix} \bar{u}_{4d} & \gamma^\mu (1 - \gamma^5) & v_{3c} \end{pmatrix} \begin{pmatrix} \bar{u}_{2b} & \gamma_\mu (1 - \gamma^5) & u_{1a} \end{pmatrix}$$

$\begin{matrix} e^- & & \bar{\nu}_e & \nu_\mu & \mu^- \end{matrix}$

Symbol  $N$  is the following spinor normalization constant.

$$N = (E_1 + m_\mu)(E_2 + m_2)(E_3 + m_3)(E_4 + m_4)$$

Recall that the magnitude squared of an amplitude is a probability density.

$$|\mathcal{M}_{abcd}|^2 = \mathcal{M}_{abcd}^* \mathcal{M}_{abcd}$$

In a typical muon decay experiment the spins are not observed. Consequently, the experimental result is an average of spin states. The average is computed by summing over all spin states and dividing by the number of initial spin states. The muon has two spin states hence the divisor is two.

$$\langle |\mathcal{M}|^2 \rangle = \frac{1}{2} \sum_{a=1}^2 \sum_{b=1}^2 \sum_{c=1}^2 \sum_{d=1}^2 |\mathcal{M}_{abcd}|^2$$

The result is a simple formula.

$$\langle |\mathcal{M}|^2 \rangle = 64 G_F^2 (p_1 \cdot p_3) (p_2 \cdot p_4) \quad (1)$$

In component notation we have

$$\langle |\mathcal{M}|^2 \rangle = 64 G_F^2 (p_1^\mu g_{\mu\nu} p_3^\nu) (p_2^\rho g_{\rho\sigma} p_4^\sigma)$$

where

$$g_{\mu\nu} = g_{\rho\sigma} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$$

Muon decay rate  $\Gamma$  is essentially an expectation value (weighted average) for all possible values of particle momentum. In the muon rest frame we have  $p_1 = (m_\mu, 0, 0, 0)$  and by Fermi's golden rule

$$\Gamma = \frac{1}{512\pi^5 m_\mu} \int_{-\infty}^{\infty} \cdots \int_{-\infty}^{\infty} \langle |\mathcal{M}|^2 \rangle \delta(p_1 - p_2 - p_3 - p_4) \frac{d^3 p_2}{E_2} \frac{d^3 p_3}{E_3} \frac{d^3 p_4}{E_4}$$

Altogether there are nine integrals, three for each of  $p_2$ ,  $p_3$ , and  $p_4$ . The delta function restricts the integration space to values that conserve energy and momentum.

It can be shown that

$$\Gamma = \frac{G_F^2 m_\mu^5}{192\pi^3}$$

Muon lifetime  $\tau$  is the inverse of decay rate.

$$\tau = \frac{1}{\Gamma} = \frac{192\pi^3}{G_F^2 m_\mu^5}$$

Change natural units to  $\hbar$  and  $c$ .

$$\tau = \frac{96\pi^2 \hbar}{G_F^2 (m_\mu c^2)^5}$$

Probability density  $\langle |\mathcal{M}|^2 \rangle$  can also be computed using the following Casimir trick.

$$\langle |\mathcal{M}|^2 \rangle = \frac{G_F^2}{4} \text{Tr} \left( \not{p}_4 \gamma^\mu (1 - \gamma^5) \not{p}_3 \gamma^\nu (1 - \gamma^5) \right) \text{Tr} \left( \not{p}_2 \gamma_\mu (1 - \gamma^5) \not{p}_1 \gamma_\nu (1 - \gamma^5) \right)$$

The slashed symbols are  $4 \times 4$  matrices computed as

$$\not{p} = p \cdot \gamma = p^0 \gamma^0 - p^1 \gamma^1 - p^2 \gamma^2 - p^3 \gamma^3$$

For example,

$$\not{p}_1 = \begin{pmatrix} E_1 & 0 & -p_{1z} & -p_{1x} + ip_{1y} \\ 0 & E_1 & -p_{1x} - ip_{1y} & p_{1z} \\ p_{1z} & p_{1x} - ip_{1y} & -E_1 & 0 \\ p_{1x} + ip_{1y} & -p_{1z} & 0 & -E_1 \end{pmatrix}$$