

Formulas and Constants

Particle Data

Mass in MeV/c², lifetime in seconds, charge in units of the proton charge.

Leptons (spin 1/2)

| Generation | Flavor | Charge | Mass* | Lifetime | Principal Decays |
|------------|-------------------------------|--------|----------|--------------------------|---|
| first | <i>e</i> (electron) | -1 | 0.510999 | ∞ | - |
| | ν_e (<i>e</i> neutrino) | 0 | 0 | ∞ | - |
| second | μ (muon) | -1 | 105.659 | 2.19703×10^{-6} | $e\nu_\mu\bar{\nu}_e$ |
| | ν_μ (μ neutrino) | 0 | 0 | ∞ | - |
| third | τ (tau) | -1 | 1776.99 | 2.91×10^{-13} | $e\nu_\tau\bar{\nu}_e, \mu\nu_\tau\bar{\nu}_\mu, \pi^-\nu_\tau$ |
| | ν_τ (τ neutrino) | 0 | 0 | ∞ | - |

*Neutrino masses are extremely small, and for most purposes can be taken to be zero; for details see Chapter 11.

Quarks (spin 1/2)

| Generation | Flavor | Charge | Mass* |
|------------|--------------------|--------|--------|
| first | <i>d</i> (down) | -1/3 | 7 |
| | <i>u</i> (up) | 2/3 | 3 |
| second | <i>s</i> (strange) | -1/3 | 120 |
| | <i>c</i> (charm) | 2/3 | 1200 |
| third | <i>b</i> (bottom) | -1/3 | 4300 |
| | <i>t</i> (top) | 2/3 | 174000 |

*Light quark masses are imprecise and speculative; for effective masses in mesons and baryons, see Chapter 5.

Mediators (spin 1)

| Force | Mediator | Charge | Mass* | Lifetime | Principal Decays |
|-----------------|---------------------|---------|--------|------------------------|--|
| Strong | <i>g</i> (8 gluons) | 0 | 0 | ∞ | - |
| Electromagnetic | γ (photon) | 0 | 0 | ∞ | - |
| Weak | W^\pm (charged) | ± 1 | 80,420 | 3.11×10^{-25} | $e^+\nu_e, \mu^+\nu_\mu, \tau^+\nu_\tau, cX \rightarrow$ hadrons |
| | Z^0 (neutral) | 0 | 91,190 | 2.64×10^{-25} | $e^+e^-, \mu^+\mu^-, \tau^+\tau^-, q\bar{q} \rightarrow$ hadrons |

McKenna (UBC, Milwaukee), Jason (Eastern Michigan), (ford).
l, at Stanford and in for making this

DAVID GRIFFITHS
2008

Baryons (spin 1/2)

| Baryon | Quark Content | Charge | Mass | Lifetime | Principal Decays | |
|---------------|---------------|--------|---------|------------------------|--|-------------------|
| N | p | uud | 1 | 938.272 | ∞ | — |
| | n | udd | 0 | 939.565 | 885.7 | $p e \bar{\nu}_e$ |
| Δ | uds | 0 | 1115.68 | 2.63×10^{-10} | $p \pi^-, n \pi^0$ | |
| Σ^+ | uus | 1 | 1189.37 | 8.02×10^{-11} | $p \pi^0, n \pi^+$ | |
| Σ^0 | uds | 0 | 1192.64 | 7.4×10^{-20} | $\Lambda \gamma$ | |
| Σ^- | dds | -1 | 1197.45 | 1.48×10^{-10} | $n \pi^-$ | |
| Ξ^0 | uss | 0 | 1314.8 | 2.90×10^{-10} | $\Lambda \pi^0$ | |
| Ξ^- | dss | -1 | 1321.3 | 1.64×10^{-10} | $\Lambda \pi^-$ | |
| Λ_c^+ | udc | 1 | 2286.5 | 2.00×10^{-13} | $p K \pi, \Lambda \pi \pi, \Sigma \pi \pi$ | |

Baryons (spin 3/2)

| Baryon | Quark Content | Charge | Mass | Lifetime | Principal Decays |
|------------|----------------------|-------------|------|-----------------------|---------------------------|
| Δ | uuu, uud, udd, ddd | 2, 1, 0, -1 | 1232 | 5.6×10^{-24} | $N \pi$ |
| Σ^* | uus, uds, dds | 1, 0, -1 | 1385 | 1.8×10^{-23} | $\Lambda \pi, \Sigma \pi$ |
| Ξ^* | uss, dss | 0, -1 | 1533 | 6.9×10^{-23} | $\Xi \pi$ |
| Ω^- | sss | -1 | 1672 | 8.2×10^{-11} | $\Lambda K^-, \Xi \pi$ |

Pseudoscalar Mesons (spin 0)

| Meson | Quark Content | Charge | Mass | Lifetime | Principal Decays |
|------------------|--|--------|---------|---|--|
| π^\pm | $u\bar{d}, d\bar{u}$ | 1, -1 | 139.570 | 2.60×10^{-8} | $\mu \nu \mu$ |
| π^0 | $(u\bar{u} - d\bar{d})/\sqrt{2}$ | 0 | 134.977 | 8.4×10^{-17} | $\gamma \gamma$ |
| K^\pm | $u\bar{s}, s\bar{u}$ | 1, -1 | 493.68 | 1.24×10^{-8} | $\mu \nu \mu, \pi \pi, \pi \pi \pi$ |
| K^0, \bar{K}^0 | $d\bar{s}, s\bar{d}$ | 0 | 497.65 | $\begin{cases} K_S^0: 8.95 \times 10^{-11} \\ K_L^0: 5.11 \times 10^{-8} \end{cases}$ | $\pi \pi$ $\pi e \nu_e, \pi \mu \nu \mu, \pi \pi \pi$ |
| η | $(u\bar{u} + d\bar{d} - 2s\bar{s})/\sqrt{6}$ | 0 | 547.51 | 5.1×10^{-19} | $\gamma \gamma, \pi \pi \pi$ |
| η' | $(u\bar{u} + d\bar{d} + s\bar{s})/\sqrt{3}$ | 0 | 957.78 | 3.2×10^{-21} | $\eta \pi \pi, \rho \gamma$ |
| D^\pm | $c\bar{u}, d\bar{c}$ | 1, -1 | 1869.3 | 1.04×10^{-12} | $K \pi \pi, K \mu \nu \mu, K e \nu_e$ |
| D^0, \bar{D}^0 | $c\bar{u}, u\bar{c}$ | 0 | 1864.5 | 4.1×10^{-13} | $K \pi \pi, K e \nu_e, K \mu \nu \mu$ |
| D_s^\pm | $c\bar{s}, s\bar{c}$ | 1, -1 | 1968.2 | 5.0×10^{-13} | $\eta \rho, \phi \pi \pi, \phi \rho$ |
| B^\pm | $u\bar{b}, b\bar{u}$ | 1, -1 | 5279.0 | 1.6×10^{-12} | $D^* \ell \nu_\ell, D \ell \nu_\ell, D^* \pi \pi$ |
| B^0, \bar{B}^0 | $d\bar{b}, b\bar{d}$ | 0 | 5279.4 | 1.5×10^{-12} | $D^* \ell \nu_\ell, D \ell \nu_\ell, D^* \pi \pi$ |

Vector Mesons (spin 1)

| Meson | Quark Content | Charge | Mass | Lifetime | Principal Decays |
|------------|--|----------|-------|---------------------|---------------------------------------|
| ρ | $u\bar{d}, (u\bar{u} - d\bar{d})/\sqrt{2}, d\bar{u}$ | 1, 0, -1 | 775.5 | 4×10^{-24} | $\pi \pi$ |
| K^* | $u\bar{s}, d\bar{s}, s\bar{d}, s\bar{u}$ | 1, 0, -1 | 894 | 1×10^{-23} | $K \pi$ |
| ω | $(u\bar{u} + d\bar{d})/\sqrt{2}$ | 0 | 782.6 | 8×10^{-23} | $\pi \pi \pi, \pi \gamma$ |
| ψ | $c\bar{c}$ | 0 | 3097 | 7×10^{-21} | $e^+ e^-, \mu^+ \mu^-, 5\pi, 7\pi$ |
| D^* | $c\bar{d}, c\bar{u}, u\bar{c}, d\bar{c}$ | 1, 0, -1 | 2008 | 3×10^{-21} | $D \pi, D \gamma$ |
| Υ | $b\bar{b}$ | 0 | 9460 | 1×10^{-20} | $e^+ e^-, \mu^+ \mu^-, \tau^+ \tau^-$ |

$\phi \rightarrow ss \rightarrow KK \rightarrow$

Spin 1/2

Pauli Matrices:

$$\sigma_x \equiv \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \quad \sigma_y \equiv \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}, \quad \sigma_z \equiv \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

$$\sigma_i \sigma_j = \delta_{ij} + i \epsilon_{ijk} \sigma_k, \quad (\mathbf{a} \cdot \boldsymbol{\sigma})(\mathbf{b} \cdot \boldsymbol{\sigma}) = \mathbf{a} \cdot \mathbf{b} + i \boldsymbol{\sigma} \cdot (\mathbf{a} \times \mathbf{b})$$

$$\sigma_i^\dagger = \sigma_i = \sigma_i^{-1}, \quad e^{i\boldsymbol{\theta} \cdot \boldsymbol{\sigma}} = \cos \theta + i(\hat{\boldsymbol{\theta}} \cdot \boldsymbol{\sigma}) \sin \theta$$

Dirac Matrices:

$$\gamma^0 \equiv \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}, \quad \gamma^i \equiv \begin{pmatrix} 0 & \sigma_i \\ -\sigma_i & 0 \end{pmatrix}, \quad \gamma^{0\dagger} = \gamma^0, \quad \gamma^{i\dagger} = -\gamma^i, \quad \gamma^0 \gamma^{\mu\dagger} \gamma^0 = \gamma^\mu$$

$$\{\gamma^\mu, \gamma^\nu\} = 2g^{\mu\nu}, \quad g^{\mu\nu} = g_{\mu\nu} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$$

$$\gamma^5 \equiv i\gamma^0\gamma^1\gamma^2\gamma^3 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \quad \{\gamma^\mu, \gamma^5\} = 0, \quad (\gamma^5)^2 = 1$$

(For product rules and trace theorems see Appendix C.)

Dirac Equation:

$$i\hbar\gamma^\mu \partial_\mu \psi - mc\psi = 0$$

$$(\not{p} - mc)u = 0, \quad (\not{p} + mc)v = 0, \quad \bar{u}(\not{p} - mc) = 0, \quad \bar{v}(\not{p} + mc) = 0$$

$$\bar{\psi} \equiv \psi^\dagger \gamma^0, \quad \bar{\Gamma} \equiv \gamma^0 \Gamma^\dagger \gamma^0, \quad \not{a} \equiv a_\mu \gamma^\mu$$

Feynman Rules

| | External Lines | Propagators |
|-----------|---|--|
| Spin 0: | Nothing | $\frac{i}{q^2 - (mc)^2}$ |
| Spin 1/2: | <div style="border-left: 1px solid black; border-right: 1px solid black; padding: 0 10px;"> Incoming particle: u Incoming antiparticle: \bar{v} Outgoing particle: \bar{u} Outgoing antiparticle: v </div> | $\frac{i(\not{q} + mc)}{q^2 - (mc)^2}$ |

| |
|-------------------------------------|
| Principal Decays |
| - |
| $p\bar{e}\bar{\nu}_e$ |
| $p\pi^-, n\pi^0$ |
| $p\pi^0, n\pi^+$ |
| $\Lambda\gamma$ |
| $n\pi^-$ |
| $\Lambda\pi^0$ |
| $\Lambda\pi^-$ |
| $K\pi, \Lambda\pi\pi, \Sigma\pi\pi$ |

| |
|-------------------------|
| Principal Decays |
| $N\pi$ |
| $\Lambda\pi, \Sigma\pi$ |
| $\Xi\pi$ |
| $\Lambda K^-, \Xi\pi$ |

| |
|--|
| Principal Decays |
| $\mu\nu_\mu$ |
| $\gamma\gamma$ |
| $\mu\nu_\mu, \pi\pi, \pi\pi\pi$ |
| $\pi\pi$ |
| $\pi e\nu_e, \pi\mu\nu_\mu, \pi\pi\pi$ |
| $\gamma\gamma, \pi\pi\pi$ |
| $\eta\pi\pi, \rho\gamma$ |
| $K\pi\pi, K\mu\nu_\mu, K e\nu_e$ |
| $K\pi\pi, K e\nu_e, K\mu\nu_\mu$ |
| $\eta\rho, \phi\pi\pi, \phi\rho$ |
| $D^* e\nu_e, D e\nu_e, D^* \pi\pi\pi$ |
| $D^* e\nu_e, D e\nu_e, D^* \pi\pi$ |

| |
|------------------------------------|
| Principal Decays |
| $\pi\pi$ |
| $K\pi$ |
| $\pi\pi\pi, \pi\gamma$ |
| $\tau^-, \mu^+\mu^-, 5\pi, 7\pi$ |
| $D\pi, D\gamma$ |
| $\tau^-, \mu^+\mu^-, \tau^+\tau^-$ |

$$\text{Spin 1: } \begin{cases} \text{Incoming: } \epsilon_\mu \\ \text{Outgoing: } \epsilon_\mu^* \end{cases} \begin{cases} \text{Massless: } \frac{-ig_{\mu\nu}}{q^2} \\ \text{Massive: } \frac{-i[g_{\mu\nu} - q_\mu q_\nu / (mc)^2]}{q^2 - (mc)^2} \end{cases}$$

(For vertex factors see Appendix D.)

Fundamental Constants

| | | | | |
|------------------------------|------------|---|---|--|
| Planck's constant: | \hbar | = | $1.05457 \times 10^{-34} \text{ J s}$ | |
| | | = | $6.58212 \times 10^{-22} \text{ MeV s}$ | |
| Speed of light: | c | = | $2.99792 \times 10^8 \text{ m/s}$ | |
| Mass of electron: | m_e | = | $9.10938 \times 10^{-31} \text{ kg} = 0.510999 \text{ MeV}/c^2$ | |
| Mass of proton: | m_p | = | $1.67262 \times 10^{-27} \text{ kg} = 938.272 \text{ MeV}/c^2$ | |
| Electron charge (magnitude): | e | = | $1.60218 \times 10^{-19} \text{ C}$ | |
| | | = | $4.80320 \times 10^{-10} \text{ esu}$ | |
| Fine structure constant: | α | = | $e^2/\hbar c = 1/137.036$ | |
| Bohr radius: | a | = | $\hbar^2/m_e e^2 = 5.29177 \times 10^{-11} \text{ m}$ | |
| Bohr energies: | E_n | = | $-m_e e^4 / 2\hbar^2 n^2 = -13.6057/n^2 \text{ eV}$ | |
| Classical electron radius: | r_e | = | $e^2/m_e c^2 = 2.81794 \times 10^{-15} \text{ m}$ | |
| QED coupling constant: | g_e | = | $e\sqrt{4\pi/\hbar c} = 0.302822$ | $g_e \text{ (SI)} = \frac{e}{\sqrt{1/(\hbar c \epsilon_0)}}$ |
| Weak coupling constants: | g_w | = | $g_e / \sin \theta_w = 0.6295;$ | |
| | g_z | = | $g_w / \cos \theta_w = 0.7180$ | |
| Weak mixing angle: | θ_w | = | 28.76° ($\sin^2 \theta_w = 0.2314$) | |
| Strong coupling constant: | g_s | = | 1.214 | |

Conversion Factors

| | | |
|----------------------|---|---------------------------------------|
| 1 Å | = | $0.1 \text{ nm} = 10^{-10} \text{ m}$ |
| 1 fm | = | 10^{-15} m |
| 1 barn | = | 10^{-28} m^2 |
| 1 eV | = | $1.60218 \times 10^{-19} \text{ J}$ |
| 1 MeV/c ² | = | $1.78266 \times 10^{-30} \text{ kg}$ |
| 1 Coulomb | = | $2.99792 \times 10^9 \text{ esu}$ |

Marshall Holloway, Richard Baker (Purdue)