Physics 226 Equation & Data Summary (Final)

Relativity

time dilation/Lorentz contraction: $\gamma \equiv 1/\sqrt{1-\vec{v}^2/c^2}$

4-coordinates: $x^\mu = (x^0, x^1, x^2, x^3)\,, \quad x^0 \equiv ct$

Lorentz transformation matrix: $\|\Lambda^\mu{}_\nu\| = \begin{pmatrix} \gamma & \gamma(v/c) & 0 & 0 \\ \gamma(v/c) & \gamma & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$ for boost along $\hat{x}$

Lorentz invariant dot product: $a \cdot b \equiv -a^0 b^0 + \vec{a} \cdot \vec{b} = -a^0 b^0 + a^1 b^1 + a^2 b^2 + a^3 b^3$

invariant interval: $s^2 = -(\Delta x^0)^2 + (\Delta x^1)^2 + (\Delta x^2)^2 + (\Delta x^3)^2$

4-velocity: $u \equiv \dfrac{dx(\tau)}{d\tau}\,, \qquad u^\mu = (\gamma c, \gamma\,\vec{v})\,, \qquad u^2 = -c^2$

4-momentum: $p \equiv m\,u\,, \qquad p^\mu = (E/c, \vec{p}) = (\gamma mc, \gamma m\vec{v})$

$p^2 = -(E/c)^2 + \vec{p}^2 = -m^2c^2$

4-force: $f \equiv \dfrac{dp}{d\tau}\,, \qquad p \cdot f = 0$

4-acceleration: $a \equiv \dfrac{du}{d\tau}\,, \qquad u \cdot a = 0$

constant acceleration: $u^0(\tau)/c = \cosh\dfrac{F\tau}{mc}\,, \quad u^1(\tau)/c = \sinh\dfrac{F\tau}{mc}$

wave-vector: $k^\mu \equiv (\omega/c, \vec{k})$

observed frequency: $\omega_{\rm obs} = -u_{\rm obs} \cdot k$

E&M field strength: $\|F^\mu{}_\nu\| \equiv \begin{pmatrix} 0 & E_x & E_y & E_z \\ E_x & 0 & cB_z & -cB_y \\ E_y & -cB_z & 0 & cB_x \\ E_z & cB_y & -cB_x & 0 \end{pmatrix}$

Lorentz force: $f^\mu_{\rm Lorentz} \equiv \dfrac{q}{c}\,F^\mu{}_\nu\,u^\nu$

Constants and Units

$\alpha = e^2/(4\pi\epsilon_0\hbar c) = 1/137.0\cdots$

$c = 2.997\cdots \times 10^8$ m/s

$\hbar = 6.582\cdots \times 10^{-22}$ MeV s

$= 1.055\cdots \times 10^{-34}$ J s

$k_{\rm B} = 8.617\cdots \times 10^{-5}$ eV/K

$\hbar c = 197.3\cdots$ MeV fm

$N_A = 6.022\cdots \times 10^{23}$ mol^{-1}

1 (metric) ton $= 10^3$ kg

1 amu $= 1$ g/(N_A mol) $= 931.5\cdots$ MeV/c^2 $= 1.661\cdots \times 10^{-27}$ kg

1 fm $= 10^{-15}$ m

1 barn $= 10^{-28}$ m^2

$(\hbar c)^2 = 0.389\cdots$ GeV^2 mbarn

Quantum Mechanics

Hamiltonian:	$H = H^\dagger\,,$	$i\hbar\frac{d}{dt}\|\psi(t)\rangle = H\|\psi(t)\rangle$
time evolution:	$U(t) = e^{-iHt}\,,$	$\|\psi(t)\rangle = U(t)\|\psi(0)\rangle$
symmetry (time independent):	$T^\dagger = T^{-1}\,,$	$[T, H] = 0$
conserved charge:	$Q^\dagger = Q\,,$	$[Q, H] = 0$
continuous symmetry:	$T(a) = e^{iQa}$	
angular momentum addition:	$J_1 + J_2 \Rightarrow J_{\text{tot}} \in \{J_1 + J_2, \cdots, \lvert J_1 - J_2\rvert\}$	
	$\frac{1}{2} + \frac{1}{2} \Rightarrow \begin{cases} J = 1\text{:} & \{\uparrow\uparrow, (\uparrow\downarrow + \downarrow\uparrow), \downarrow\downarrow\} \\ J = 0\text{:} & (\uparrow\downarrow - \downarrow\uparrow) \end{cases}$	

Nuclei

nucleus	**symbol**	**rest energy**	**lifetime**	**spin**[*]	**decay type**
neutron	n	939.6 MeV	15 min	1/2	β decay
hydrogen	${}^{1}_{1}\mathrm{H}$	938.27 MeV	stable	1/2	—
deuterium	${}^{2}_{1}\mathrm{H}$	1875.61 MeV	stable	1	—
tritium	${}^{3}_{1}\mathrm{H}$	2808.92 MeV	17.8 yr	1/2	β decay
helium-3	${}^{3}_{2}\mathrm{He}$	2808.39 MeV	stable	1/2	—
helium-4	${}^{4}_{2}\mathrm{He}$	3727.38 MeV	stable	0	—
helium-6	${}^{6}_{2}\mathrm{He}$	5605.5 MeV	1.16 s	0	β decay
lithium-6	${}^{6}_{3}\mathrm{Li}$	5601.5 MeV	stable	1	—
lithium-7	${}^{7}_{3}\mathrm{Li}$	6533.8 MeV	stable	3/2	—
beryllium-7	${}^{7}_{4}\mathrm{Be}$	6534.2 MeV	77 day	3/2	e^- capture
beryllium-10	${}^{10}_{4}\mathrm{Be}$	9325.5 MeV	2.2 Myr	0	β decay
boron-10	${}^{10}_{5}\mathrm{B}$	9324.4 MeV	stable	3	—
boron-11	${}^{11}_{5}\mathrm{B}$	10253 MeV	stable	3/2	—
boron-14	${}^{14}_{5}\mathrm{B}$	13062 MeV	18 ms	2	β decay
carbon-11	${}^{11}_{6}\mathrm{C}$	10254 MeV	29 m	3/2	e^+ emission
carbon-12	${}^{12}_{6}\mathrm{C}$	11175 MeV	stable	0	—
carbon-14	${}^{14}_{6}\mathrm{C}$	13041 MeV	5.7 Kyr	0	β decay
oxygen-16	${}^{16}_{8}\mathrm{O}$	14899 MeV	stable	0	—
calcium-41	${}^{41}_{20}\mathrm{Ca}$	38146 MeV	1.5 Myr	7/2	e^- capture
bismuth-209	${}^{209}_{83}\mathrm{Bi}$	194622 MeV	2×10^{19} yr	9/2	α decay

[*] In units of $\hbar$.
[†] In units of $|e| = 1.602\cdots \times 10^{-19}$ C.

Mesons

particle	symbol	rest energy	lifetime	spin	charge[†]
pion	π^0	135.0 MeV	8×10^{-17} s	0	0
pion	π^+, π^-	139.57 MeV	26 ns	0	$+1, -1$
kaon	K^+, K^-	493.7 MeV	12 ns	0	$+1, -1$
kaon	$K^0, \bar{K}^0$	497.7 MeV	90 ps/51 ns	0	0
eta	η	547.5 MeV	5×10^{-19} s	0	0
rho	ρ^+, ρ^0, ρ^-	775 MeV	4×10^{-24} s	1	$+1, 0, -1$
omega	ω	783 MeV	8×10^{-23} s	1	0
K-star	K^{*+}, K^{*-}	891.7 MeV	10^{-23} s	1	$+1, -1$
K-star	$K^{*0}, \bar{K}^{*0}$	896.0 MeV	10^{-23} s	1	0
eta-prime	η'	958 MeV	3×10^{-21} s	0	0
phi	ϕ	1020 MeV	2×10^{-22} s	1	0

Baryons

particle	symbol	rest energy	lifetime	spin	charge[†]
proton	p	938 MeV	stable	$\frac{1}{2}$	$+1$
neutron	n	940 MeV	886 s	$\frac{1}{2}$	0
Lambda	Λ	1116 MeV	0.26 ns	$\frac{1}{2}$	0
Sigma	Σ^+	1189 MeV	80 ps	$\frac{1}{2}$	$+1$
Sigma	Σ^0	1193 MeV	7×10^{-20} s	$\frac{1}{2}$	0
Sigma	Σ^-	1197 MeV	0.15 ns	$\frac{1}{2}$	-1
Delta	$\Delta^{++}, \Delta^+, \Delta^0, \Delta^-$	1232 MeV	6×10^{-24} s	$\frac{3}{2}$	$+2, +1, 0, -1$
Cascade	Ξ^0	1315 MeV	0.29 ns	$\frac{1}{2}$	0
Cascade	Ξ^-	1321 MeV	0.16 ns	$\frac{1}{2}$	-1
Sigma-star	$\Sigma^{*+}, \Sigma^{*0}, \Sigma^{*-}$	1385 MeV	2×10^{-23} s	$\frac{3}{2}$	$+1, 0, -1$
Cascade-star	Ξ^{*0}, Ξ^{*-}	1530 MeV	7×10^{-23} s	$\frac{3}{2}$	$0, -1$
Omega	Ω^-	1672 MeV	82 ps	$\frac{3}{2}$	-1

[*] In units of $\hbar$.
[†] In units of $|e| = 1.602 \cdots \times 10^{-19}$ C.

Leptons

particle	symbol	rest energy	lifetime	spin*	charge†	L
electron (anti)neutrino	$\nu_e(\bar{\nu}_e)$	< 2 eV	$\approx$ stable	1/2	0	$+1(-1)$
muon (anti)neutrino	$\nu_\mu(\bar{\nu}_\mu)$	< 2 eV	$\approx$ stable	1/2	0	$+1(-1)$
tau (anti)neutrino	$\nu_\tau(\bar{\nu}_\tau)$	< 2 eV	$\approx$ stable	1/2	0	$+1(-1)$
electron(positron)	$e^-(e^+)$	0.511 MeV	stable	1/2	$-1(+1)$	$+1(-1)$
muon(antimuon)	$\mu^-(\mu^+)$	105.7 MeV	2 μs	1/2	$-1(+1)$	$+1(-1)$
tau(antitau)	$\tau^-(\tau^+)$	1777 MeV	0.3 ps	1/2	$-1(+1)$	$+1(-1)$

Gauge Bosons

particle	symbol	rest energy	lifetime	spin*	charge†
photon	γ	0	stable	1	0
gluon	g	0	—	1	0
W-boson	$W^\pm$	80.4 GeV	3×10^{-25} s	1	± 1
Z-boson	Z	91.2 GeV	3×10^{-25} s	1	0

Quarks

flavor	symbol	mass	spin*	charge†
up	u	≈ 2 MeV/c^2	1/2	2/3
down	d	≈ 5 MeV/c^2	1/2	$-1/3$
strange	s	≈ 95 MeV/c^2	1/2	$-1/3$
charm	c	1.2 GeV/c^2	1/2	2/3
bottom	b	4.2 GeV/c^2	1/2	$-1/3$
top	t	173 GeV/c^2	1/2	2/3

*In units of $\hbar$.
†In units of $|e| = 1.602\cdots \times 10^{-19}$ C.