Rest Mass (or just, Mass)

electron, for example:

$\underline{m_e = 9.11\cdot 10^{-31}\ \text{kg}}$ ← not useful unit

Relativity: $E = m_e c^2$ (when electron is at rest)

$$= (9.11\cdot 10^{-31})(3.00\cdot 10^{8})^2 \text{ Joules}$$

$$= 81.9\cdot 10^{-31+16} \text{ Joules}$$

$\underline{m_e c^2 = 8.19\cdot 10^{-14} \text{ Joules}}$ ← still not useful

"Atomic" unit: eV - energy gained by fundamental charge e falling through an electrostatic potential diff. of 1 volt

$$\text{in MKS} = \underbrace{(1.602\cdot 10^{-19})}_{\text{fundamental charge in coulombs}} \times 1$$

$\underline{1\text{eV} = 1.60\cdot 10^{-19} \text{ Joules}}$

$$m_e c^2 = \frac{8.19}{1.60}\cdot\frac{10^{-14}}{10^{-19}} \text{ eV}$$

$$\simeq 5 \cdot 10^5$$

$$= 5.11\cdot 10^5$$

$m_e c^2 = 0.511\cdot 10^6$ eV 10^6 eV = 1 MeV

$$\boxed{m_e c^2 = 0.511 \text{ MeV} \simeq \tfrac{1}{2} \text{ MeV}}$$

Physics in the number:

$\simeq 10^5 \to 10^6$ bigger than energy/molecule released in a typical chemical reaction

→ A clean, safe way to convert all rest mass into useable energy could solve energy crises

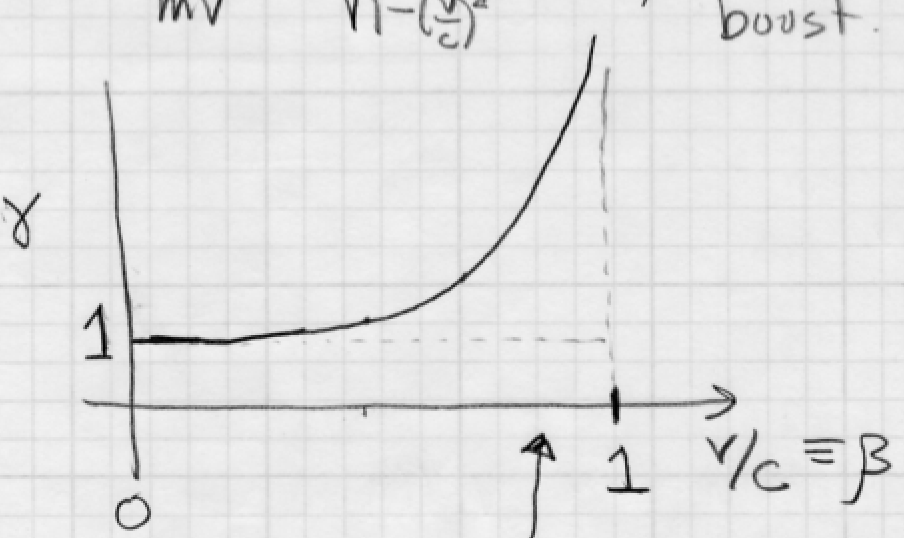
In particle physics, quoting the mc^2 that corresponds to the mass is so useful that we usually say: "The electron mass is 0.511 MeV." That is sloppy shorthand, but nonetheless, you need to get used to it!

Momentum

non-relatistically $\vec{p} = m\vec{v}$ or $p = mv$ (1 component)

relativistically, $p = \dfrac{mv}{\sqrt{1-(v/c)^2}}$

the ratio: $\dfrac{p}{mv} = \dfrac{1}{\sqrt{1-(\frac{v}{c})^2}} \equiv \gamma$, the lorentz boost.



γ gets ∞ big as $\beta = v/c \to 1$

For a particle *not* at rest, with momentum p, the total energy E is:

$$E = \sqrt{\underset{\substack{\uparrow \\ \text{"Einstein"}}}{(mc^2)^2} + \underset{\substack{\uparrow \\ \text{"kinetic term"}}}{(cp)^2}}$$

in *quadrature*

In particle physics, we then usually use the units of MeV for cp, and then we get sloppy and say: "the momentum, p, is X MeV," when we really mean $c \cdot p$.

I. The Periodic Tables

A. Fermions - all spin-$\frac{1}{2}$

1. Three Generations, roughly increasing in mass

strong holds nucleii together

2. Leptons - don't feel "strong" interactions ≡ have 0 "color" charge
   a. neutrinos - 3 types (known no more than 3)
      3 "flavors" e, μ, τ
      have 0 "electric" charge
      nearly massless, feel only weak interaction

weak causes β-decay

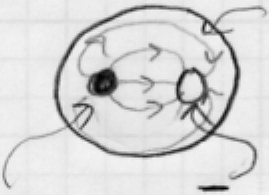
   b. charged leptons - 3 types too
      e^- - electron
      μ^- - muon, $m_\mu \simeq 200 m_e$
      τ^- - tau, $m_\tau \simeq 17 \cdot m_\mu$

   in addition to feeling the weak interaction, charged leptons feel the electromagnetic interaction: $Q = -1$

3. Quarks - do feel "strong" interactions... and that radically alters the situation they have fraktional electric charge
   a. "down"-type: 3 types: d, s, b
      electric $Q = -1/3$ for all
   b. "up"-type 3 types: u, c, t
      electric $Q = +2/3$ for all
   c. all 6 have the same amount of strong charge, analogous to electric charge, but many, many times larger, but felt only by quarks. The strong charge is so huge that quarks ~~never~~ are free, but always must be confined in particles called hadrons
4. Antifermions
   a. for each of the 12 fermions
   b. spin $\frac{1}{2}$, same mass
   c. opposite: electric, weak, strong charge
   d. notation: $\nu \rightarrow \bar{\nu}$; $e^-, \mu^-, \tau^- \rightarrow e^+, \mu^+, \tau^+$
      $u\, d\, c\, s\, t\, b \rightarrow \bar{u}\, \bar{d}\, \bar{c}\, \bar{s}\, \bar{t}\, \bar{b}$

5. Hadrons

a. Mesons: a quark + an anti-quark.



"color" field lines

no <u>net</u> color charge

q_1 $\bar{q}_2$ ← pick any two; $6 + \frac{6 \cdot 5}{2}$

+color charge -color charge

same (like $u\bar{u}$, $d\bar{d}$, etc) different

so 21 independent states.

Ground states: no radial, orbital excitations;
↓↑ ← spin alignment

6 $u\bar{u}$, $d\bar{d}$, $s\bar{s}$, $c\bar{c}$, $b\bar{b}$, $t\bar{t}$ → π^0, η, η', η_c, η_b, ~~η_t~~

15 $u\bar{d}$, $u\bar{s}$, $u\bar{c}$, $u\bar{b}$, ~~$u\bar{t}$~~
π^+ K^+ $\bar{D}^0$ B^+

$d\bar{s}$, $d\bar{c}$, $d\bar{b}$, ~~$d\bar{t}$~~
K^0, D^- B^0

$s\bar{c}$, $s\bar{b}$ ~~$s\bar{t}$~~
D_s^- B_s^0

$c\bar{b}$ ~~$c\bar{t}$~~
B_c^+

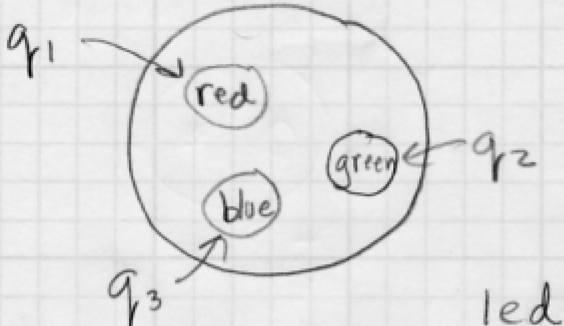
~~$b\bar{t}$~~

X means: not experimentally observed yet

10 well known | 5 not yet discovered (but expected)

A tower of excited states built upon these 10 ground states, with combinations of spin, orbital angular momentum, + radial excitations.

b. Baryons : 3 quarks



The existence of this type of stable state - the most famous is the proton - $\boxed{uud}$ also the neutron - $\boxed{ddu}$ led to the realization that color charge has a new degree of freedom - called "color". The strong charge on a quark comes in 3 types - called colors - usually and arbitrarily called Red, Green, + Blue.

By analogy with light, where the combination of R, G, B light gives white light, the net color of a baryon is zero... and so this configuration of quarks has no net color, and is low in energy, and "stable".

The ground states also all have spin $\frac{1}{2}$:
$\boxed{u\uparrow u\downarrow d\uparrow}$ = proton etc.

This complicates the counting of the # of states.

B. Bosons

1. Gravity - field excitation is "graviton" G
no experimental evidence
spin 2, massless
$F \propto 1/r^2$ "long range"

2. Electromagnetism -
field excitation is "photon" γ
spin 1, & massless

3. Strong force, or "Chromodynamics"
field excitation is "gluon" g

in many ways the gluon is the most interesting boson. It holds the quarks together in protons + neutrons. It is spin-1, and each gluon has a color + and anti-color.

eg: (Red)(Anti-Green) ← wouldn't that be nine?

1 is different, and "doesn't count"

8 remain.

4. Weak force → 3 different field excitations

$$Z^0, \underbrace{W^-, W^+}_{\text{particle + antiparticle.}}$$

massive: $F \propto \frac{e^{-mr}}{r^2}$

"short range"

5. The particle that "gives" all particles mass.. the "Higgs Boson"!

⇒ not seen yet!. spin-0

C. SUSY stands for "supersymmetry", a principle that suggests that:

for every spin-$\frac{1}{2}$ state: eg e^-

there exists a spin-0 state: called $\tilde{e}^-$

(actually 2, because of 2 spin $\frac{1}{2}$ - $\tilde{e}^-_R, \tilde{e}^-_L$).

and vice versa: $g \longrightarrow \tilde{g}$

spin-1 spin-$\frac{1}{2}$

SUSY not seen yet! → "partners" so massive, not yet produced.