**MIT Course 8.033, Fall 2005, Particle physics**
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**Last revised October 22 2006**

# Topics

- Important particles
- Nuclear physics terminology
- Rest mass & binding energy
- Photons
- Particle physics processes
- Examples: photon emission & absorbtion
- Example: Compton scattering

## Rest energies of important particles

| Particle | Symbol | Rest energy |
|---|---:|---:|
| electron | $e^-$ | 0.511 MeV |
| muon | $\mu^-$ | 105.6 MeV |
| tau | $\tau^-$ | 1777 MeV |
| proton | $p^+$ | 938.26 MeV |
| neutron | $n$ | 939.55 MeV |
| charged pion | $\pi^+$, $\pi^-$ | 139.6 MeV |
| neutral pion | $\pi^0$ | 135.0 MeV |
| neutrinos | $\nu_e$, $\nu_\mu$, $\mu_\tau$ | $< 0.14$ eV |
| photon | $\gamma$ | 0 MeV |
| graviton | $g$ | 0 MeV |
| $C^{12}/12$ | amu | 931.5 MeV |

- For more, see particle physics handouts.
- Open question: why?
  Why is proton/electron mass ratio 1836, say?

## Nuclear physics terminology

- The *atomic number* $Z$ of a nucleus is its number of protons.
- The *atomic weight* $A$ of a nucleus is its number of nucleons (protons + neutrons).
- $Z$ determines the name of the element (its order in the periodic table).
- Nuclei with same $Z$ and different $A$ are said to be different *isotopes* of the same element.
- Notation example: $Fe^{56}$ means $Z = 26$ (iron) and $A = 56$.
- The *mass excess* for a nucleus is $m_0 - A$ amu, *i.e.*, its rest mass minus the number of nucleons times amu.
- By this definition, the mass excess of $C^{12}$ is zero.
- Historically (before people knew exactly what they were), Helium nuclei, electrons and energetic photons were called $\alpha$-particles, $\beta$-particles and $\gamma$-particles, respectively, and linguistic vestiges of this live on:
  - The process $n \to p^+ + e^- + \bar{\nu}$ is called $\beta$-decay.
  - High energy photons are denoted $\gamma$-rays, and photons are denoted $\gamma$ (which is of course confusing in 8.033)!

## Rest mass and binding energy

- The rest energy of an object is its energy in the frame where it has zero momentum.
- This rest energy is the sum of *all* energy contributions, both positive (like rest masses and kinetic energies of its constituent particles) and negative (like potential energy from force holding constituents together).
- The *binding energy* of a nucleus is rest energy of its neutrons and protons free minus rest energy of the nucleus.
- Electric repulsion between protons *increases* mass of nucleus.
- Attraction between nucleons (strong force) *decreases* mass of nucleus.
- Only nuclei whose $(Z, A)$ give positive binding energy can exist
- Semi-empirical relationship (von Weizsäcker 1935):

  $$\frac{E_{\text{binding}}}{c^2} \approx \left[15.8A - 18.3A^{2/3} - 0.714\frac{Z^2}{A^{1/3}} - 23.2\frac{(A-2Z)^2}{A} + (-1)^Z\frac{12}{A^{1/2}}\right] \text{MeV}$$

  The last term is omitted if $A$ is an odd number.
- Much work remains to be done in this field!

## Photoelectric effect

- Einstein's model was that
  - the photon carries energy $h\nu$
  - a certain work $W_e$ is required to liberate an electron from the metal
- This explained both of Lenard's 1902 observations:
  - light with frequency $h\nu < W_e$ liberates no electrons at all
  - light with frequency $h\nu > W_e$ liberates electrons with kinetic energy $h\nu - W_e$.
  - increasing the *intensity* of the light (the photon flux) didn't affect the existence of liberated electrons or their kinetic energy
- Bottom line: we can treat the photon as just another particle.

## Working with photons:

- Photon 4-vector:
$$\mathbf{P} = \hbar \begin{pmatrix} \mathbf{k} \\ k \end{pmatrix},$$
  where $k = \omega/c$.

- So $p = E/c$ for photons.

- Comparing $\mathbf{P}$ with the wave 4-vector $\mathbf{K}$ shows that
$$\mathbf{P} = \hbar\mathbf{K}.$$
  This relation in fact holds for *all* particles, even massive ones — as you'll see when you get to wave-particle duality in quantum mechanics. If you take a field theory course, you'll see this pop right out of the so-called Klein-Gordon equation.

- Doppler effect is just special case of $\mathbf{P}$-transformation for zero rest mass — show on PS6.

## Particle physics processes

- We know of four fundamental interactions: gravitational, electromagnetic, weak and strong. In particle physics, the first is negligible.
- See the handouts for summmaries of particles and interactions.
- Summary of particle physics processes we consider:
  - Absorption (two particles in, one out)
  - Emission/decay (one particle in, two out)
  - Collision/scattering/annihilation/creation (two particles in, two out)
- **Footnote:** if you take a course in quantum field theory, you'll find that two in, two out ("four-vertex") interactions can generally be reduced to two separate three-vertex interactions, where the momentum and energy transfer between the two colliding particles is mediated by an intermediate particle. For instance, an elastic collision between two electrons can be reduced to a photon exchange: one electron emits a photon that's later absorbed by the other.
- Which processes are allowed in nature? All that aren't forbidden by a conservation law, *e.g.*,
  - Energy-momentum conservation (**P** conserved)
  - Charge conservation
  - Baryon number conservation
  - Lepton number conservation
  - Parity conservation (except in weak interactions)
- Everything is provisional:
  - Momentum conservation appeared to be violated in $\beta$-decay, but was rescued with neutrino discovery (proposed by Wolfgang Pauli 1931, detected by Fred Reines & Clyde Cowan 1956).
  - Parity conservation was believed to be universally valid until the shock of 1956 (Yang, Lee, Wu).
  - Many physicists believe (but haven't shown) that lepton and/or baryon number is violated ever so slightly, *e.g.*, that protons decay if you wait $\gg 10^{32}$ years.
- There's more to it: computing lifetimes and scattering probabilities requires quantum field theory - in this course, we'll limit ourselves to drawing conclusions from energy-momentum conservation.

## Common interaction processes

- Chemical reactions: atoms get rearranged in new ways, perhaps emitting or absorbing photons and electrons. Non-relativistic.
- Nuclear reactions: nucleons get rearranged in new ways, perhaps emitting or absorbing photons, electrons, positrons and neutrinos (electron/positrons and neutrinos must be involved whenever there are conversions betweens protons and neutrons, to conserve charge and lepton number).
- Elementary particle interactions: energy, momentum, charge, lepton number *etc.* gets rearranged in new ways, corresponding to scattering, destruction and creation of particles.

Examples:

- Molecule + molecule $\rightarrow$ new molecules + $\gamma$ (chemical reaction)
- $\gamma$ + atom $\rightarrow$ exited atom (excitation)
- $\gamma$ + atom $\rightarrow$ $e^-$ + atom (ionization; photoelectric effect)
- Nucleus + nucleus $\rightarrow$ new nuclei + $\gamma/e^-/\nu$ (nuclear reaction)
- $n \rightarrow p^+ + e^- + \bar{\nu}$ (beta decay)
- $\gamma + \gamma \rightarrow e^- + e^+$ (pair creation)
- $\gamma$ + particle $\rightarrow$ particle + $e^-$ + $e^+$
- $\gamma + e^- \rightarrow \gamma + e^-$ (Compton scattering)

## Photon emission & absorbtion:

- Photon absorbtion ($X + \gamma \to X^*$): If a particle at rest with mass $m_0$ absorbs a photon of frequency $\omega$, it acquires a speed

$$\beta' = \frac{\hbar\omega}{m_0 c^2 + \hbar\omega}.$$

- Photon emission with recoil ($X^* \to X + \gamma$): if a particle emits energy $\hbar\omega$ as a photon, thereby reducing its rest mass from $m_0$ to $m_0' \equiv m_0 - Q_0/c^2$, then

$$\hbar\omega = \left(1 - \frac{Q_0}{2m_0c^2}\right) Q_0.$$

  Thus the photon energy $\hbar\omega < Q_0$ because of recoil, whereby some of the released energy $Q_0$ turns into kinetic energy of the recoiling particle.

- This works in reverse too: to increase its rest energy by $Q_0$, the particle needs to absorb a photon with energy $\hbar\omega > Q_0$ to compensate for the recoil.

- This recoil effect (the term $Q_0/2m_0c^2$ in the parenthesis above) is normally negligibly small $\sim 10^{-8}$ for typical *atomic* transition energies ($\sim 10eV$) — for comparison, Doppler line broadening is of order $\beta \sim 10^{-6}$ for room temperature atoms moving with thermal velocities of hundreds of meters per second.

- However, it is important for *nuclear* transition energies, which are of order a thousand times larger (Moon's experiment 1951).

- Mössbauer effect (1961 Nobel Prize for Ph.D. thesis work) all but eliminates recoil, making $m_0$ the rest mass of the whole crystal rather than one particle. Allows measuring 2cm/s Doppler shifts!

- Pound & Rebka experiment from Harvard Tower 1960 used this to detect tiny $\sim 10^{-14}$ gravitational redshift.

## Compton scattering

- Compton scattering ($\gamma + e^- \rightarrow \gamma + e^-$) with electron initially at rest:
$$h\nu' = \frac{h\nu}{1 + \frac{h\nu}{m_e c^2}(1 - \cos\theta)}$$

- Such an elastic photon-electron collision is called *Compton scattering* when the photon transfers energy to the electron and *inverse Compton scattering* when the electron transfers energy to the photon.

- The former occurs when shining x-rays at matter.

- The latter occurs frequently in astrophysics.

- Them two are of course equivalent in special relativity, since you can always Lorentz transform into a frame where, before the collision, either the electron has much more energy than the photon or vice versa.

| Property | Independent of velocity? | |
|---|---|---|
| | Classically? | Relativistically? |
| Charge $q$ | Y | Y |
| Spin | Y | Y |
| Lepton number | Y | Y |
| Duration $\Delta t$ | Y | N |
| Length $L$ | Y | N |
| Mass $m$ | Y | N |
| Proper duration $\Delta\tau$ | Y | Y |
| Proper length $L_0$ | Y | Y |
| Rest mass $m_0$ | Y | Y |
| Momentum $p$ | N | N |
| Energy $E$ | N | N |