Nuclear and Particle Physics

Lecture 10: Revision

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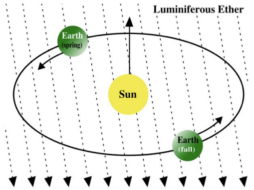
The Ether Problem

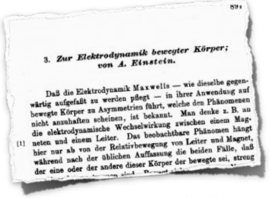
New experiments and discoveries at the end of the 19th century suggested the existence of a luminiferous ether, as a medium for the propagation of light. The word ether (aether or æther) stems via Latin from the Greek αιθήρ, which was one of Aristotle's 5 elements.

Electromagnetic waves had been postulated by Maxwell and experimentally detected by Hertz. Light, as an electromagnetic wave, was expected to travel in a medium like sound waves travel through air. As the solar system moved through the ether and the Earth moved around the Sun, an effect on the speed of light from this movement was generally expected.



Einstein's theory

- **First postulate:**
  The laws of physics are the same in all inertial reference frames
- **Second postulate:**
  The speed of light is the same in all inertial frames regardless of the velocity of the source or the observer.



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3. *Zur Elektrodynamik bewegter Körper;*
von A. Einstein.

Daß die Elektrodynamik Maxwells — wie dieselbe gegenwärtig aufgefaßt zu werden pflegt — in ihrer Anwendung auf bewegte Körper zu Asymmetrien führt, welche den Phänomenen nicht anzuhaften scheinen, ist bekannt. Man denke z. B. an die elektrodynamische Wechselwirkung zwischen einem Magneten und einem Leiter. Das beobachtbare Phänomen hängt [1] hier nur ab von der Relativbewegung von Leiter und Magnet, während nach der üblichen Auffassung die beiden Fälle, daß der eine oder der andere dieser Körper der bewegte sei, streng

A. Einstein in 1905

Transformation of coordinates

We have obtained the transformations between two sets of coordinates of events (x,y,z,t) and (x',y',z',t') measured in frames S and S' respectively, where:

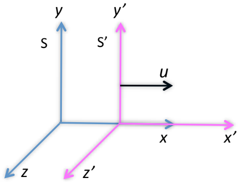
- S' moves at velocity u with respect to S along the common x-x' axis
- The origins of both reference frames coincide at $t=t'=0$
- (x,y,z,t) and (x',y',z',t') are space-time coordinates

$$x' = \frac{x-ut}{\sqrt{1-\beta^2}} \quad \text{where} \quad \beta = \frac{u}{c}$$

$$y' = y$$

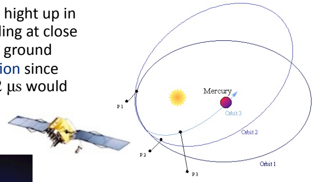
$$z' = z$$

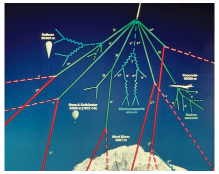
$$t' = \frac{t-\beta x/u}{\sqrt{1-\beta^2}}$$



Experimental evidence

- Cosmic ray muons created hight up in the atmosphere and traveling at close to the speed of light reach ground level because of time dilation since their mean lifetime $\tau \simeq 2.2\ \mu s$ would not be enough ...





- The perihelion precession of Mercury's orbit
- Deflection of light by the Sun
- The gravitational redshift of light
- Accelerators and particles ...
- Gravitational lensing
- GPS corrections (else a drift of about 10km per day would occur!)

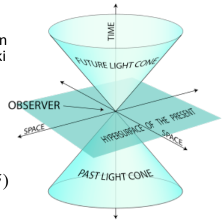
Minkowski spacetime

- Hermann Minkowski proposed in 1907 a four-dimensional interpretation of Special Relativity
- He introduced the unification of space and time into an inseparable 4D entity ('the World')
- The Lorentz geometry of Special Relativity can be elegantly represented in the 4D Minkowski spacetime

$$X = (ct,x,y,z) = (ct,\vec{r})$$

$$V = \frac{dX}{d\tau} = \gamma\frac{d}{dt}(ct,\vec{r}) = \gamma(c,\frac{d\vec{r}}{dt}) = \gamma(c,\vec{v})$$

$$P = m\gamma(c,\vec{v}) = (E/c,\vec{p})$$



Invariant mass

- Applying the scalar product to the 4-momentum defined in (2), we can construct the *invariant*

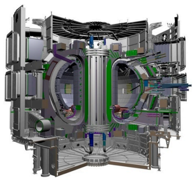
$$P^2 = \frac{E^2}{c^2} - \vec{p}^2 = m^2c^2 \qquad (3)$$

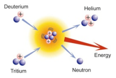
where $m = \frac{\sqrt{P^2}}{c}$ is called the invariant mass, which for a particle is identical to its rest mass.

- Equation (3) can be also written in the form

$$\boxed{E^2 = \vec{p}^2c^2 + m^2c^4} \qquad (4)$$

- Note that since the 4-momentum squared is Lorentz invariant, one can choose an inertial system where $\vec{p} = 0$ and then $E = mc^2$.





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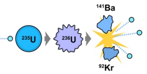
$E=mc^2$



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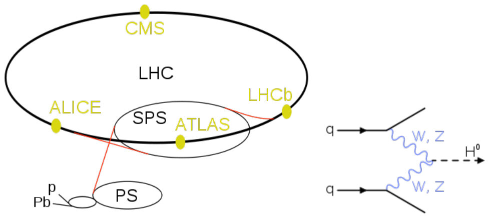
Energy release comparisons

Event	Type	TNT Equivalent	Energy released
Tsar Bomba	3-stage Teller-Ulam design Thermonuclear test bomb	50 MT	210,000 TJ
Castle Romeo	Thermonuclear test bomb	15 MT	63,000 TJ
Chernobyl (one unit) during one year	RBMK-1000 reactor 1GWe (3.2 GWt)		30,000 TJ
Three Mile Island Unit 1 operated one year	PWR reactor 800 MWe		24,000 TJ
Fukushima Unit 1 operated one year	BWR3 reactor (GE) 439 MWe		14,000 TJ
Peacekeeper	ICBM weapon	10 x 300 kT	12,500 TJ
Fat Man (Nagasaki)	^{239}Pu implosion-type bomb	21 kT	88 TJ
Little Boy (Hiroshima)	^{235}U gun-type bomb	15 kT	64 TJ

The LHC

- Predicted by the Standard Model, the Higgs mechanism is the process that gives mass to elementary particles: simply put, particles gain mass by interacting with the Higgs field that permeates all space
- ATLAS and CMS at CERN have reported a possible find with mass within 115-127 GeV/c²



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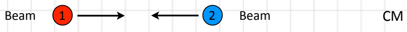
p-p collisions

The LHC collides 7TeV protons. What is the invariant mass of the 2-proton system ?



We have 2TeV protons colliding head to head:

$$P_1 = (E/c, \vec{p}) \qquad P_2 = (E/c, -\vec{p})$$

Then

$$s = M_{2p}^2 = (P_1 + P_2)^2/c^2 =$$

$$= (E+E)^2/c^4 - (\underbrace{\vec{p} - \vec{p}}_{=0})/c^2 = \left(2E/c^2\right)^2$$

i.e. $M_{2p} = \underline{14 TeV/c^2}$

Comparison with fixed target experiment

What beam energy in a fixed target experiment would be needed to produce the same CM energy as in the p-p collision discussed before?

We have a proton with energy E and momentum p colliding with a proton practically at rest:

$$P_1 = (E/c, \vec{p}) \qquad P_2 = (m_p c, 0)$$

Then

with (3)

$$s = M_{2p}^2 = (P_1 + P_2)^2/c^2 = (E + m_p c^2)^2/c^4 - \vec{p}^2/c^2 =$$

$$= 2m_p^2 + 2Em_p/c^2$$

negligible

and

$$E = \frac{(M_{2p}^2 - 2m_p^2)}{2m_p c^2} = \frac{(14^2 - \cancel{2\times 0.001^2})}{2\times 0.001} = \underline{98000\, TeV} \ !!$$

Nuclear reactions

A simple example of a nuclear reaction is firing α-particles at beryllium:

A B C D

$${}^{4}_{2}\alpha + {}^{9}_{4}Be \rightarrow {}^{12}_{6}C + {}^{1}_{0}n$$

Projectile **Target** **Products**

4 + 9 = 12 + 1
2 + 4 = 6 + 0

This can be equivalently written as:

$${}^{9}_{4}Be(\alpha, n){}^{12}_{6}C$$

In reactions not involving β-decay the total number of neutrons and protons are both conserved:

$$Z_A + Z_B = Z_C + Z_D \qquad N_A + N_B = N_C + N_D$$

Energy released in reactions: Q-value

In a generic reaction:

A + B → C + D

m_A	m_B	m_C	m_D	(masses)
K_A	K_B	K_C	K_D	(kinetic energies)

Energy conservation condition is written as:

$$m_A c^2 + K_A + m_B c^2 + K_B = m_C c^2 + K_C + m_D c_2 + K_D$$

From this can calculate the *energy released* from the reaction, the so-called *Q*-value:

$$Q = K_{final} - K_{initial} = (K_C + K_D) - (K_A + K_D) \Rightarrow$$

$$\boxed{Q = (m_A + m_B)c^2 - (m_C + m_D)c^2}$$

Threshold energy

The velocity of the cm frame is: $u = \frac{m_A}{m_A + m_B} v_A$

The threshold energy is defined in the CM system for A+B→C+D by the condition that C and D are produced with zero kinetic energy:

$$m_A c^2 + \frac{1}{2} m_A (v_A - u)^2 + m_B c^2 + \frac{1}{2} m_B u^2 = m_C c^2 + m_D c^2$$

$$\Rightarrow \quad \frac{1}{2} m_A (v_A - u)^2 + \frac{1}{2} m_B u^2 = -Q$$

The threshold kinetic energy K_{th} in the lab system is given by:

$$K_{th} = \frac{m_A v_A^2}{2}$$

By eliminating u we obtain: $\boxed{K_{th} = -\left(1 + \frac{m_A}{m_B}\right) Q}$

Examples

1) $p + {}^{7}_{3}Li \rightarrow {}^{4}_{2}He + {}^{4}_{2}He$

$$Q = (m_p + m_{Li} - 2m_\alpha)c^2$$

$$m_p = 1.007825\,u, \quad m_{Li} = 7.01600\,u,$$

$$m_\alpha = 4.0026\,u, \quad 1uc^2 = 931.502\,MeV$$

$$\Rightarrow \quad Q = (1.0078 + 7.01600 - 2\times 4.0026)u \times 931.5\,MeV/u = 17.32\,MeV$$

2) ${}^{4}_{2}He + {}^{14}_{7}N \rightarrow {}^{17}_{8}O + {}^{1}_{1}H$ or ${}^{14}_{7}N(\alpha, p){}^{17}_{8}O$

$$Q = (m_\alpha + m_N - m_O - m_p)c^2$$

$$m_N = 14.003074u, \quad m_O = 16.999131u$$

$$\Rightarrow \quad Q = (4.0026 + 14.0031 - 16.9991 - 1.0078)u \times 931.5\,MeV/u$$

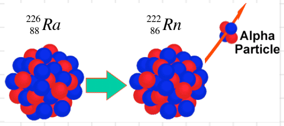
$$= -1.178\,MeV < 0$$

$$K_{th} = -(1 + m_\alpha/m_N)Q = (1 + 4/14)Q = 1.514\,MeV$$

Example: α-decay

Let us consider the α-decay of ^{226}Ra:

$${}^{226}_{88}Ra \rightarrow {}^{222}_{86}Rn + {}^{4}_{2}He$$



and calculate Q with:

$$Q = (m_{Ra226} - m_{Rn222} - m_\alpha)c^2$$

$$m_{Ra226} = 226.025\,u$$

$$m_{Rn222} = 222.017\,u$$

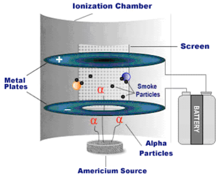
$$m_{He4} = 4.002\,u$$

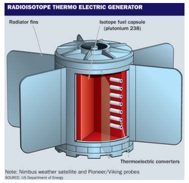
$$\Rightarrow \quad Q = (226.025 - 222.017 - 4.002)u \times 931.5\,MeV/u = \underline{5.589\,MeV}$$

We notice that $Q>0$. This energy is converted into the kinetic energies of the daughter nucleus and the α-particle.

Alpha particles

- Smoke detector
  - Operate as an ionisation chamber, smoke absorbs alpha particles cutting the current and causing an alarm
- Single event upsets
  - Random switching of electronic circuits due to alpha (or other radiation) generating charge in the circuit
- Radioisotope thermoelectric generators
  - Heat from radioactive decay is converted to electricity via thermoelectric (Seebeck) effect.
    Used in satellites, space probes, etc.
- Earthquakes
  - Radioactivity results in molten core of Earth → plate tectonics and earthquakes
- Radiotherapy
  - Targeted deposits of energy





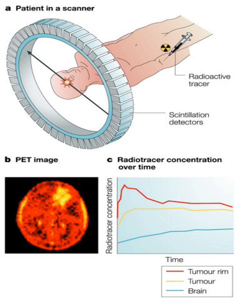
Note: Nimbus weather satellite and Pioneer/Viking probes
SOURCE: US Department of Energy

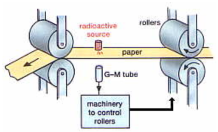
Beta radiation

- PET - Positron Emission Tomography

$$\beta^{+} + e^{-} \rightarrow \gamma + \gamma$$

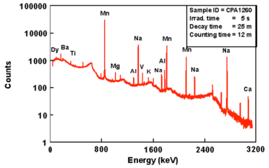
- Thickness monitoring in manufacturing
  - Thickness of paper of thin metal





Gamma radiation

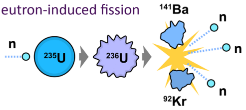
- Radiotherapy
  - Cancer treatment
- Neutron activation analysis
  - Excite nuclei by firing neutrons at them and look at resulting γ-ray spectrum, similar to atomic spectra
  - Sensitive from micro- to picograms of elements
- Gamma ray bursts
  - are flashes of γ-rays associated with extremely energetic explosions in distant galaxies
  - the most luminous electromagnetic events known



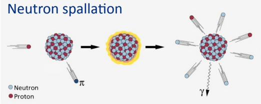
Neutron radiation

- Neutrons are components of atomic nucleus, zero electric charge, $m_n \approx m_p$
- Sources of neutron radiation:
  - interaction of cosmic radiation with the atmosphere
  - neutron emission during fission (e.g. in nuclear reactors)
  - particle accelerators (spallation sources, e.g. ISIS, SNS)
- Interaction with matter:
  - neutron capture (n is captured by a nucleus and α or γ is emitted)
  - elastic scattering (recoiling nuclei collide and produce charge or scintillation light that can be detected)

Neutron-induced fission



Neutron spallation



Hydrogen-rich materials make the best neutron shielding: e.g. water, polyethylene, paraffin wax, concrete

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Interaction of radiation with matter

Alpha particles:

- Energy loss of heavy charged particles ($m > m_e$) is due to electromagnetic interactions between charged particle and atomic electrons
- Slow moving heavy charged particles ionise more
- Alpha particles exhibit a Bragg peak and a well defined range

Beta particles:

- Ionisation
  Extraction of an electron from an atom or molecule
- Bremmstrahlung
  energy is lost via emission of electromagnetic radiation in the field of a nucleus

Gamma rays:

- Photoelectric effect: An incoming photon of sufficient energy is absorbed by an atomic electron, which then has sufficient energy to escape from the atom
- Compton scattering: An incoming photon scatters off an atomic electron. The resulting photon has less energy and the electron is ejected from the atom
- Pair production: An electron-positron pair is formed in the electric field of a nucleus

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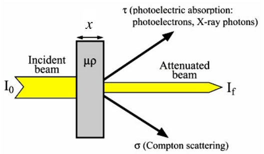
Absorption of γ-rays



Photon absorption in Pb

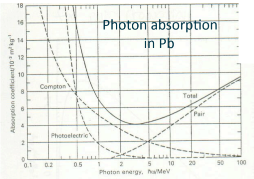
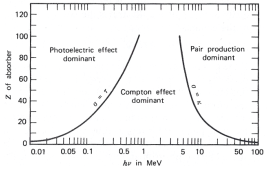


Figure 4.16. The total mass absorption coefficient for high energy photons in lead, indicating the contributions associated with the photoelectric absorption, Compton scattering and electron–positron pair production. (From H. A. Enge (1966). *Introduction to nuclear physics*, page 193. London: Addison-Wesley Publishing Co.)

Absorption coefficient given as $\mu\rho$

$$\frac{dI}{I} = -\mu\rho x \quad \Rightarrow \quad I_f = I_0 e^{-\mu\rho x}$$

$$\mu = \sum \mu_{photoelectric} + \mu_{Compton} + \mu_{pair}$$



Biological effects of radiation

- Radiation damages cells by ionising the atoms
- The unit of activity i.e. number of disintegrations per second is the becquerel (Bq).
  This unit is independent of the type of radiation and its energy.
- *Absorbed dose* is defined as the energy absorbed in the medium from the radiation and is measured in gray (Gy).
- 1Gy = 1J of energy absorbed in 1kg
- As we have seen, different radiations ionise media via different processes and this results in different biological effects for each radiation.
  A relative biological effectiveness (RBE) can be determined for each type of radiation.

Relative biological effectiveness

- **Equivalent dose**: H = Q × D, where D is the absorbed dose and Q is the RBE. The equivalent dose can not be measured directly.
- The RBE factors for each type radiation are:

Type and energy of radiation	**RBE**
Photons, all energies	1
Electrons and muons, all energies	1
Neutrons	
<10 keV	5
10 to 100 keV	10
> 0.1 to 2 MeV	20
> 2 to 20 MeV	10
> 20 MeV	5
Protons, other than recoil protons, >2 MeV	5
Alpha particles, fission fragments, heavy nuclei	20

- The unit for equivalent dose is the sievert (Sv)
- Equivalent dose should not be confused with *effective dose*, which takes into account the sensitivity to radiation of various body tissues

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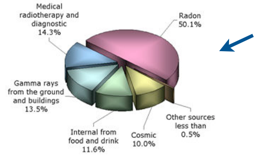
Radiation definitions and facts

- **Definitions:**
  - **Radiation** - energy traveling in the form of particles or waves, for example: microwaves, radio waves, light, medical X-rays, alpha, beta, gamma radiation
  - **Radioactivity** - a natural process through which unstable atoms of an element radiate excess energy in the form of particles or waves
  - **Radioactive material** - material that emits radiation
  - **Radioactive contamination** - radioactive material in unwanted places
- **Important facts:**
  - Radiation is commonplace
  - A person exposed to radiation does not become contaminated, except for neutron radiation which *can* induce radioactivity
  - Contamination is the result of direct contact with removable radioactive material
  - The distinction between harmful and safe depends on *quantity*. This is true about everything from paracetamol to arsenic
  - Dose is important

Examples of doses

	Equivalent Dose (Sv)
Dose required to sterilise medical products	25000
Typical total radiotherapy dose to cancer tumour	60
50% survival probability, whole body dose	4
Legal worker dose limit (whole body)	0.02
Average annual dose from all sources in Cornwall	0.008
Average annual dose from natural radiation	0.002
Typical chest X-ray dose	0.00002
Average dose from a flight from UK to Spain	0.00001



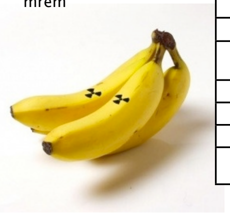
Sources of radiation dose to the UK population. Source: NPL website

The total annual equivalent dose is 0.0026 Sv, but individual doses vary enormously, depending on location and job

Banana Equivalent Dose

Bananas are a natural source of radioactive isotopes.

Eating one banana = 1 BED = 0.1 μSv = 0.01 mrem



Number of bananas	Equivalent exposure
100,000,000	Fatal dose (death within 2 weeks)
20,000,000	Typical targeted dose used in radiotherapy (one session)
70,000	Chest CT scan
20,000	Mammogram (single exposure)
200 - 1000	Chest X-ray
700	Living in a stone, brick or concrete building for one year
400	Flight from London to New York
100	Average daily background dose
50	Dental X-ray
1 - 100	Yearly dose from living near a nuclear power station

The law of radioactive decay

- If a sample of material contains N radioactive nuclei then the number decaying, *dN*, in a time *dt* will be proportional to *N*
- A quantity that decreases at a rate proportional to its value is said to be subject to exponential decay
- N_0 is the number of nuclei at time *t*=0 and *N(t)* is the number of nuclei that *have not* decayed by time *t*

$$\frac{dN}{dt} = -\lambda N$$

$$\lambda = -\frac{dN/dt}{N}$$

λ is the decay constant defined as the probability per unit time that a nucleus will decay

$$N(t) = N_0 e^{-\lambda t}$$

Mean lifetime τ

In general the *mean* of a variable x that is distributed according to f(x) is given by:

$$\bar{x} = \frac{\int x f(x)dx}{\int f(x)dx}$$

To determine the mean life i.e. the mean time until an unstable nucleus decays we apply:

$$\bar{t} = \tau = \frac{\int_0^\infty t\lambda e^{-\lambda t}dt}{\int_0^\infty \lambda e^{-\lambda t}dt} = \frac{1}{\lambda}$$

$$N(t) = N_0 e^{-\lambda t} = N_0 e^{-t/\tau}$$

$$A(t) = A_0 e^{-\lambda t} = A_0 e^{-t/\tau}$$

The mean lifetime τ of the nucleus is the inverse of the decay constant λ.

Fraction surviving after 1 mean lifetime = e^{-1} = 0.37

after 2 mean lifetimes = e^{-2} = 0.135 etc.

Half-life $t_{1/2}$

- The half-life is the time after which half the sample has decayed:

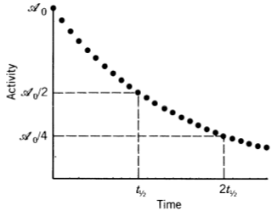
$$\text{When } N = \frac{N_0}{2} \quad t = t_{1/2}$$

$$\frac{N_0}{2} = N_0 e^{-\lambda t_{1/2}}$$

$$\Rightarrow e^{\lambda t_{1/2}} = 2$$

$$\Rightarrow \lambda t_{1/2} = \ln(2)$$

$$\Rightarrow t_{1/2} = \frac{\ln 2}{\lambda} = \tau \ln 2$$



Half-life < mean lifetime

Fraction surviving N half-lives=2^{-N}

Radioactive decay formulae

Concept	Equation	Definition
Exponential decay	$N(t) = N_0 e^{-\lambda t}$	Number of nuclei that have not decayed by time *t*
Activity	$A(t) = \lambda N_0 e^{-\lambda t}$	Number of nuclei decaying per unit time, where $\lambda N_0 = A_0$
Decay probability	$P_{decay}(t) = \lambda e^{-\lambda t}$	Probability of a single nucleus decaying in the interval *t* → *t+dt*
Mean lifetime	$\tau = 1/\lambda$	Mean time until an unstable nucleus decays
Half-life	$t_{1/2} = \ln 2/\lambda$	Time after which half the radioactive sample has decayed

Decay chains

Many heavy nuclei decay via complicated series involving several successive decays. Take the case of A → B → C, where C is stable and only A is present initially:

The number of nuclei A vary according to:

$$N_A(t) = N_o e^{-\lambda_A t}$$

The number of nuclei B as a function of time can be found from:

$$\frac{dN_B(t)}{dt} = -\lambda_B N_B(t) + \lambda_A N_A(t)$$

where the first term is the decay of nuclei B and the second term is due to B being created from the decay of A.

Integrating, we can get $N_B(t)$ and its activity $A_B(t)$:

$$N_B(t) = \frac{\lambda_A}{\lambda_B - \lambda_A} N_0 \left(e^{-\lambda_A t} - e^{-\lambda_B t}\right)$$

$$A_B(t) = \lambda_B N_B(t) = \frac{\lambda_A \lambda_B}{\lambda_B - \lambda_A} N_0 \left(e^{-\lambda_A t} - e^{-\lambda_B t}\right)$$

There are four alpha decay chains (series) in nature:

Thorium (4n)
Neptunium (4n+1)
Radium (4n+2)
Actinium (4n+3)

Thorium series and the age of the Earth

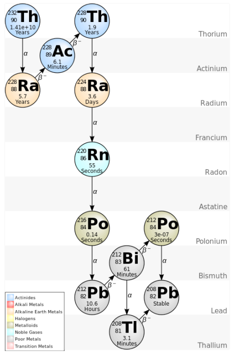


Image credits: Wikipedia

^{232}Th has a very long half life ($t_{1/2}$ = 14Gy) and goes through a long decay chain to stable ^{208}Pb.

It effectively behaves as if $^{232}\mathrm{Th} \rightarrow {}^{232}\mathrm{Pb}$

By measuring the relative abundance of ^{208}Pb:

$$\frac{N(^{208}Pb)}{N(^{232}Th)} = \frac{N_0(1 - e^{-\lambda_{Th}t})}{N_0 e^{-\lambda_{Th}t}}$$

one can estimate of the age of the Earth at 4.54 billion years.

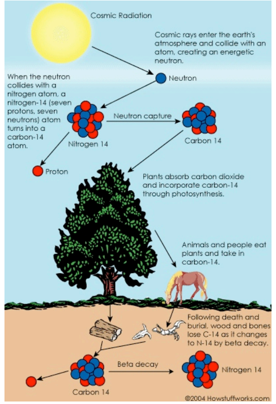
Radiocarbon dating

- Carbon is a fundamental part of living tissue.
- There are 3 isotopes of carbon - ^{12}C, ^{13}C and ^{14}C - in the atmosphere, from where they are absorbed by living organisms.
  - The ratio of ^{14}C/^{12}C is known to be γ_0 = 1.8×10^{-12}
  - ^{14}C is permanently created by cosmic rays, i.e. this isotopic ratio is constant in nature
- The concentration of ^{14}C in living organisms is the same as that in the environment
- When the organism dies it no longer absorbs ^{14}C. The ^{14}C in the organism decays but the amount of ^{12}C remains constant

$$^{14}C/^{12}C = \gamma = \gamma_0 e^{-\lambda t}$$

- By measuring the ratio of ^{14}C/^{12}C one can find out how much time has passed

$$t = \ln(\gamma_0/\gamma)/\lambda$$



Isotopes, isotones and isobars

- Isotopes:
  - Nuclei with the same number of protons Z (same chemical element) but different numbers of neutrons
- Isotones:
  - Nuclei with the same number of neutrons but different proton number
- Isobars:
  - Nuclei with the same mass number but different numbers of protons and neutrons

$$^{35}_{17}Cl_{18} \qquad ^{37}_{17}Cl_{20}$$

$$^{114}_{48}Cd_{66} \qquad ^{115}_{49}In_{66}$$

$$^{14}_{6}C_{8} \qquad ^{14}_{7}N_{7} \qquad ^{14}_{8}O_{6}$$

$$A = Z + N$$

How stable is a nucleus ?
Binding energy

- The binding energy, B, of a nucleus is the difference in mass energy between the free particles and the bound state
- This is related to the stability of nuclei, the greater the binding energy the more stable the nucleus

- It is often useful to look at binding energy/nucleon: B/A
i.e. the energy required to remove a nucleon from the nucleus, similar to atomic ionisation energy

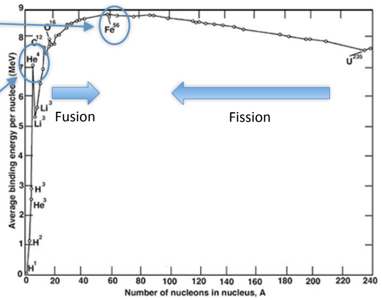
$$B = \left\{ \underbrace{Zm_p + Nm_n}_{\text{Free nucleons}} - \underbrace{\left[m\left({}^{A}X\right) - Zm_e \right]}_{\text{Bound state}} \right\} c^2$$

$$B = \left[Zm\left({}^{1}_{1}H\right) + Nm_n - m\left({}^{A}X\right) \right] c^2$$

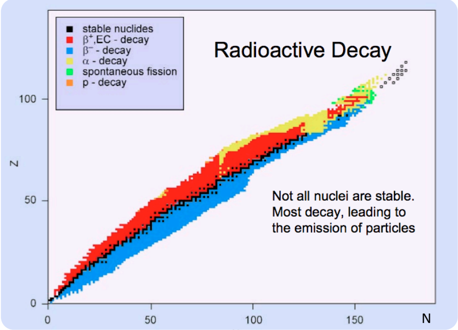
Binding energy per nucleon

Fe is the most stable nucleus

Light nuclei are not stable but $^4_2$He – alpha particles are



What nuclei exist



Not all nuclei are stable. Most decay, leading to the emission of particles

---

Beta-stability valley

Using the Bethe-Weizsäcker semi-empirical formula for the binding energy:

$$B_{tot}(Z,A) = a_v A - a_s A^{2/3} - a_c \frac{Z^2}{A^{1/3}} - a_a \frac{(A-2Z)^2}{A}$$

$$M(Z,A) = Z \cdot M_p + (A-Z)M_n - B_{tot}(Z,A)$$

$$a_a \frac{(A-2Z)^2}{A} = a_a \frac{A^2 - 4AZ + 4Z^2}{A} = a_a\left(A - 4Z + \frac{4Z^2}{A}\right)$$

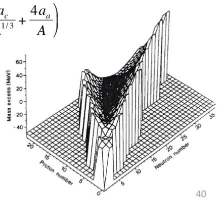
$$M = A\left[M_n - a_v + \frac{a_s}{A^{1/3}} + a_a\right] + Z\left[M_p - M_n - 4Za_a\right] + Z^2\left(\frac{a_c}{A^{1/3}} + \frac{4a_a}{A}\right)$$

The coefficients a_n are calculated by fitting to experimentally measured masses of nuclei.

This the equation of a parabola $M(Z) = a + bZ + cZ^2$
Minimising M:

$$\left(\frac{\partial M}{\partial Z}\right)_A = 0 = b + 2cZ_A$$

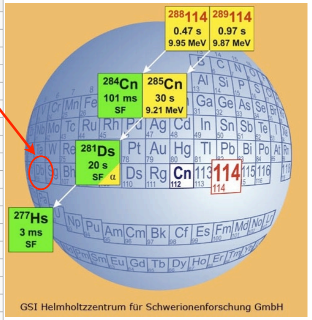
$$\frac{Z_A}{A} \approx \frac{1}{2} \frac{81}{80 + 0.6A^{2/3}}$$



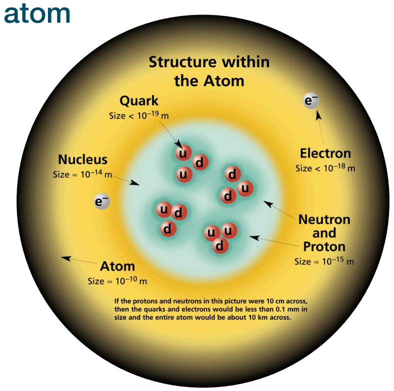
The search for new elements

Number	Name	Longest-lived isotope	Half-life
100	Fermium	^{257}Fm	101 days
101	Mendelevium	^{258}Md	52 days
102	Nobelium	^{259}No	58 minutes
103	Lawrencium	^{262}Lr	3.6 hours
104	Rutherfordium	^{267}Rf	1.3 hours
105	Dubnium	^{268}Db	29 hours
106	Seaborgium	^{271}Sg	1.9 minutes
107	Bohrium	^{270}Bh	61 seconds
108	Hassium	^{277}Hs	~12 minutes
109	Meitnerium	^{278}Mt	7.6 seconds
110	Darmstadtium	^{281}Ds	11 seconds
111	Roentgenium	^{281}Rg	26 seconds
112	Copernicium	^{285}Cn	29 seconds
113	Ununtrium	^{286}Uut	19.6 seconds
114	Ununquadium	^{289}Uuq	2.6 seconds
115	Ununpentium	^{289}Uup	220 ms
116	Ununhexium	^{293}Uuh	61 ms
117	Ununseptium	^{294}Uus	78 ms

2009 Poster

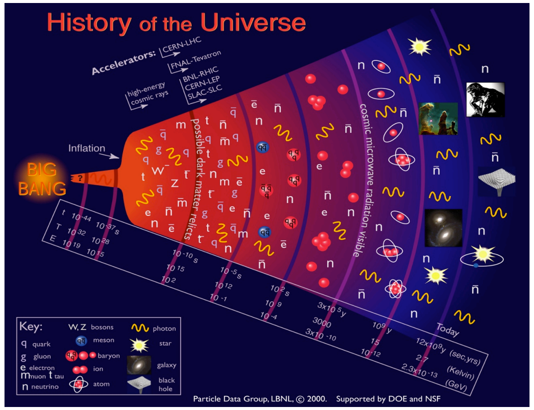


The atom



If the protons and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

Image credits: PDG



Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

Fundamental interactions

$$V_s(r) = -\frac{g_s^2}{4\pi}\frac{e^{-r/R}}{r}$$

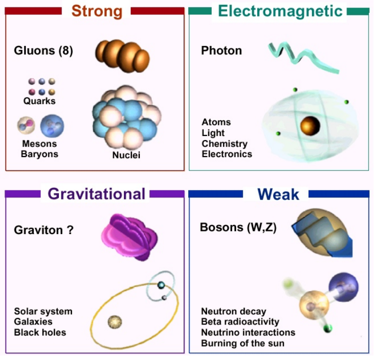
$$R = \frac{\hbar}{m_\pi c}$$

$$F_e(r) = -\frac{q_1 q_2}{4\pi\varepsilon_0 r^2}$$

$$V_e(r) = \frac{q_1 q_2}{4\pi\varepsilon_0 r}$$

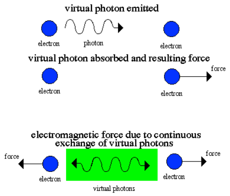
$$F_g(r) = G\frac{m_1 m_2}{r^2}$$

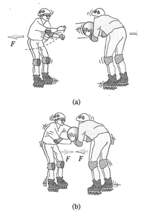
$$V_g(r) = -G\frac{m_1 m_2}{r}$$



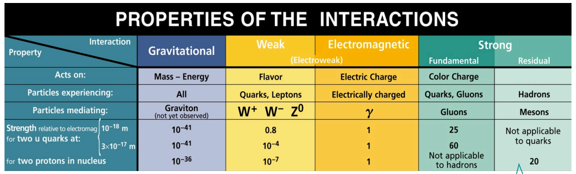
Force carriers

- How is the force between particles manifested ?
- In classical physics this is described by the force law or potential
- Another way of describing it is via *"force carriers"*
- A force carrier is emitted by one particle and the other particle absorbs it





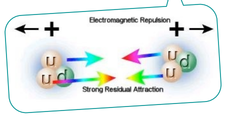
Four fundamental interactions



PROPERTIES OF THE INTERACTIONS

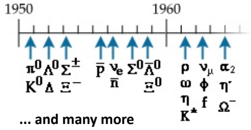
Property / Interaction	Gravitational	Weak	Electromagnetic	Strong	
		(Electroweak)		Fundamental	Residual
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge	
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons	Mesons
Strength relative to electromag for two u quarks at: 10^{-18} m	10^{-41}	0.8	1	25	Not applicable to quarks
3×10^{-17} m	10^{-41}	10^{-4}	1	60	
for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

- Each force acts between particles of a particular type
- Force is mediated by a *force carrier* particle



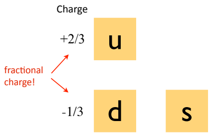
The Quark Model

By the middle of the 1960s, more than 200 ‘elementary’ particles had been discovered. Some particles seemed to have almost the same mass.



... and many more

The problem was solved by postulating the existence of quarks*, which (at that time) came in three “flavours”, up (u), down (d) and strange (s).



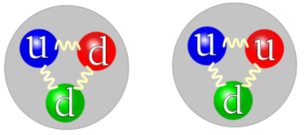
Various combinations of the quarks could produce the observed particle zoo.

M. Gell-Mann was awarded the 1969 Nobel Prize for this.

* the name quarks is taken from James Joyce’s ‘Finnegan’s Wake’

The proton and neutron

- Baryons are made of 3 quarks or three anti-quarks
- A proton consists of two *u*-quarks and one *d*-quark, while a neutron consists of two *d*-quarks and one *u*-quark:



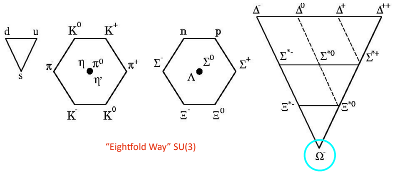
NEUTRON
Quark structure

PROTON
Quark structure

$$Q_{neutron}=\frac{2}{3}-\frac{1}{3}-\frac{1}{3}=0 \qquad Q_{proton}=\frac{2}{3}+\frac{2}{3}-\frac{1}{3}=+1$$

Symmetry groups

- Many of the detected particles could now be classified based on symmetry groups



“Eightfold Way” SU(3)

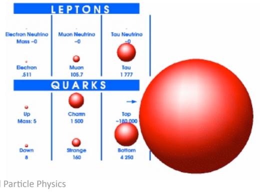
Baryons (strongly interacting fermions) consist of three quarks.

Mesons (strongly interacting bosons) consist of a quark and an anti-quark.

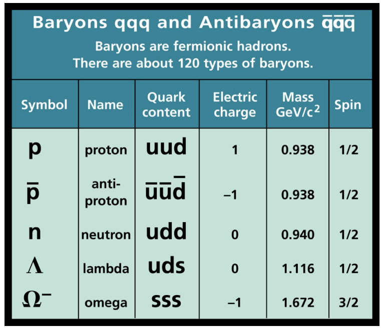
The prediction of the Ω^- hyperon and its properties before its subsequent discovery in 1964 was a major success for the model.

The Quark Model

- Generalisations to higher symmetry groups required the introduction of other three quarks in the theory.
- **charm (c)** - predicted in 1964 by S.Glashow and J. Bjoerken, was first observed in Nov 1974, at SLAC (B. Richter et al.) and BNL (S. Ting et al.)
- **bottom (b)** - was discovered in 1977 at Fermilab (L. Ledermann et al.) in the form of the Y-meson consisting of a *b* and an anti-*b*. The discovery of this 5th quark made it very likely that its partner the *t*-quark exists
- **top (t)** - was detected in 1995 by the Tevatron experiments CDF and D0 at Fermilab. The top is very heavy - about the weight of a tungsten (W) atom.



Baryons



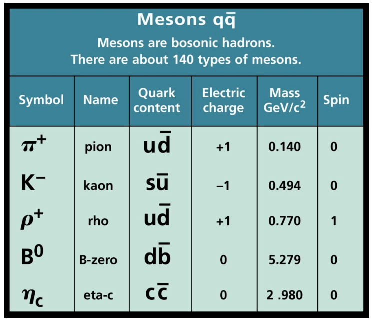
Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$

Baryons are fermionic hadrons.
There are about 120 types of baryons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	–1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	–1	1.672	3/2

Image credits: PDG

Mesons



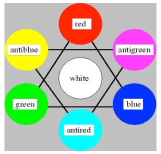
Mesons $q\bar{q}$

Mesons are bosonic hadrons.
There are about 140 types of mesons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	–1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2 .980	0

Image credits: PDG

Color and QCD



- In the quark model, the Δ^{++} particle (detected in 1951 by Fermi) has with charge +2 consists of three *u* quarks.

- It has spin 3/2, which means that the three spins 1/2 of the *u* quarks are aligned:

$$u\uparrow u\uparrow u\uparrow$$

- This violates the Pauli exclusion principle, and resolve this problem, in 1964 O. Greenberg proposed the idea of a **color charge.**

- So, in addition to electric charge, quarks carry “colour” charge in three colours: red, blue and green. Add also anti-colours for the anti-quarks.

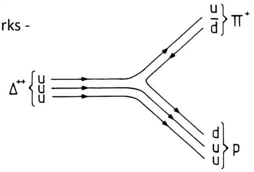
All particles contain a combination of quark colours which are “white”.

Quarks interact with each other via the exchange of gluons.

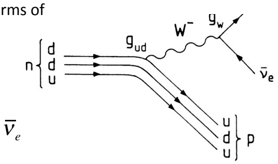
The Quark Model and decay processes

Strong decays of particles can be now understood in terms of individual quarks - e.g. the decay of the Delta++

$$\Delta^{++}\rightarrow p+\pi^+$$



The weak decay of the neutron can be represented in terms of quarks as:

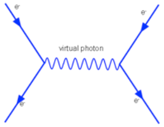


$$n\rightarrow p+e^-+\bar{\nu}_e$$

Feynman Diagrams

In the 1940s, Richard Feynman invented a pictorial technique to aid the calculations of processes involving photons and electrons.

The theory of interactions between photons and electrons is called Quantum Electrodynamics (QED), and remains the most precise physical theory we know of.



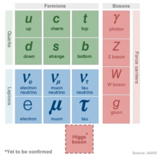
Feynman diagram conventions:

- Particles are represented by "world lines" in time and space
- Time flows along the horizontal axis from left to right.
- Space is represented in the vertical direction (all 3 spatial dimensions!).
- Electrons are represented by lines with arrows pointing from **left to right.**
- Positrons are represented by lines with arrows pointing from **right to left.**

i.e. a positron going forward in time is equivalent to a (positive energy) electron going backwards in time!

The Standard Model

- The combination of QCD and electroweak theories are collectively known as the standard model (of particle physics).
- The standard model represents our current complete knowledge of matter.
- To include gravity in the theory is a challenge (and is presently not possible consistently).
- There must be physics "beyond the standard model" to complete a "theory of everything".



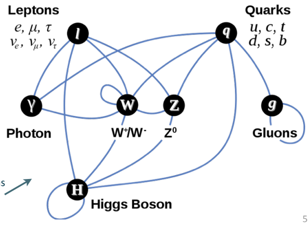


Diagram summarising the tree-level interactions between elementary particles described in the Standard Model

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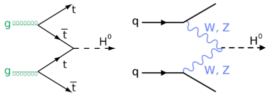
The Higgs Boson

- Predicted by the Standard Model (Higgs mechanism incorporated into the Standard Model by A. Salam and S. Weinberg). Named after Peter Higgs of Edinburgh University
- The Higgs mechanism is the process that gives mass to elementary particles: simply put, particles gain mass by interacting with the Higgs field that permeates all space
- Ongoing experiments at CERN and Fermilab are trying to detect the Higgs boson



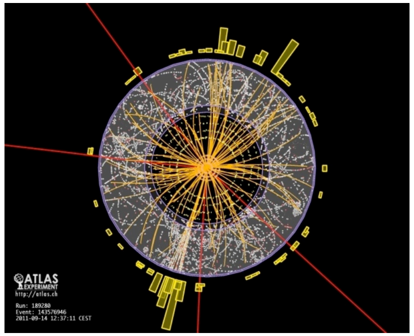
Feynman diagrams showing two ways the Higgs boson might be produced at the LHC.

- ATLAS and CMS at CERN have reported a possible find with mass within 115-127 GeV/c^2
- As of March 2012 the D0 and CDF Collaborations announced finds that could be interpreted as a Higgs boson with a mass of 115-135 GeV/c^2. The significance of the result is 2.2σ, not enough to rule out a statistical fluctuation.

the search continues ...

ATLAS and the Higgs

The red lines show four muon tracks in ATLAS. They could have been the byproducts of a short-lived Higgs boson - or they could have been more banal events.



The positron e⁺

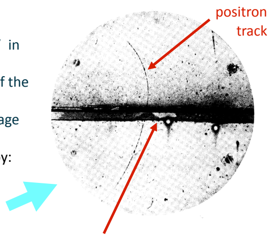
The positron was discovered in 1932 in experiments using a cloud chamber.

How does a cloud chamber work ?

- Charged particles leave trails of "clouds" in the super-saturated air.
- A magnetic field bends the trajectories of the charged particles
- A photograph is timed to capture the image

In this image a positron can be identified by:

- The direction of curvature (positive charge)
- The range of the track (i.e. it is not a proton)



positron track

Lead plate to slow particles

Carl D. Anderson was awarded the 1936 Nobel Prize for Physics for the discovery of the positron.

Image: C.D. Anderson, Physical Review 43 (1933) 491

Dirac's sea of negative energies

The positron had been predicted in 1928 by Paul Dirac as the antiparticle of the electron.

And we've come back full circle to Special Relativity because what prompted Dirac to theorise the existence of the positron e⁺ was his search for a physical meaning for the negative solution

$$E = -\sqrt{p^2c^2 + m_0^2c^4}$$

of the relativistic equation connecting energy, mass and momentum of a particle

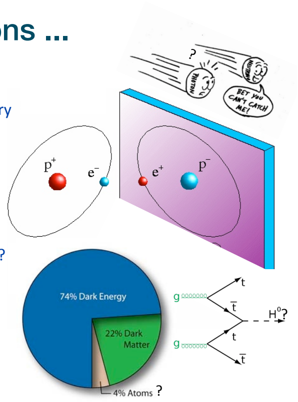
$$E^2 = p^2c^2 + m_0^2c^4$$

He suggested that the negative energy state is a "hole" in a sea of negative energy states, and ushered in the concept of antimatter.

Questions, questions ...

- Why is there an apparent asymmetry between the observed matter and antimatter in the universe ?
- What if the Higgs boson is not confirmed experimentally ?
- What if it's proven that indeed neutrinos can travel faster than light ?
- Is the 'dark' energy - 'dark' matter hypothesis valid ?

... and many more ...



The End

For questions, feedback or help before the exams please do not hesitate to contact me via email or by dropping by my office.

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