EUROPEAN UNION
MINISTRY OF EDUCATION, YOUTH AND SPORTS
OP Education for Competitivness
INVESTICE DO ROZVOJE VZDĚLÁVÁNÍ

NUCLEAR PHYSICS

1. Introduction

- ***nucleus*** – E. Rutherford, 1914 the first reaction: $^{4}_{2}\alpha + ^{14}_{7}N \rightarrow ^{17}_{8}O + ^{1}_{1}H$

- ***nuclear forces*** = a new kind of very strong forces
    - distance about 10^{-15} m (size of atom 10^{-10} m)
    - attract mainly the surrounding nucleons
    - p-p!!!, p-n, n-n

- ***nuclear reactions*** = nucleus changes or releases/absorbs energy, conservation of:
    - charge
    - momentum
    - number of nucleons
    - energy and mass

      if energy of an object changes by E, its mass must change by Δm

Example: 1 kg of water heated from 20 ºC to 100 ºC absorbs 1x80x4200 J = 336 kJ = *E*, its mass rises by $\frac{E}{c^2}$ so by 3.7×10^{-14} kg only.

- equivalent energy for mass unit $m_u = 1.66 \times 10^{-27}$ kg

$$E = m_u c^2 = 931\,\text{MeV}$$

http://www.windows2universe.org/physical_science/physics/atom_particle/atomic_nucleus.html

http://en.wikipedia.org/wiki/Atom

http://www.lbl.gov/abc/wallchart/teachersguide/pdf/Chap02.pdf

http://www.youtube.com/watch?v=PdFsb2sWrW4

2. Mass defect (Δm) and binding energy of the nucleus (E_B)

- the nucleus is always a bit lighter than the sum of masses of the nucleons it contains. The difference is called *mass defect* and it is connected with the *binding energy* of the nucleus.

mass of a proton

mass of a neutron

no. of protons

no. of neutrons

$$E_B = (\underbrace{Zm_p + Nm_n - m_{nucleus}}_{\Delta m})c^2$$

TENTO PROJEKT JE SPOLUFINANCOVÁN EVROPSKÝM SOCIÁLNÍM FONDEM A STÁTNÍM ROZPOČTEM ČESKÉ REPUBLIKY

- ***binding energy per nucleon***

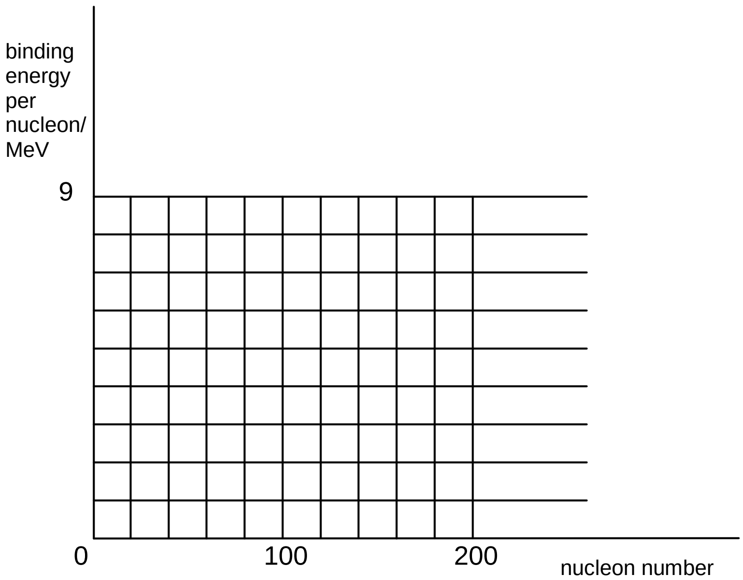
$$e_B = \frac{E_B}{A} \qquad A = Z + N \text{ ... number of nucleons}$$

this is a very important quantity to state, if some nuclear reaction can be used as a source of energy

energy can be given out only when we move “up the slope” of the following graph – only when the binding energy per nucleon of the products of the reaction is bigger than the binding energy per the original nucleon(s) – fusion of light nuclei (H) or fission of the heavy nucleus

Use the following grid and sketch the graph showing how the binding energy per nucleon varies with nucleon number (general trend). Mark there: $^{2}_{1}H$, $^{6}_{3}Li$, $^{10}_{5}B$, $^{238}_{92}U$

Graph (1):



3. Nuclear reactions

a) NUCLEAR DECAY

the nucleus changes “slightly” (or not at all - energy is released)

b) NUCLEAR FISSION

the nucleus is split into the products of roughly the same mass, energy is released

c) NUCLEAR FUSION

two light nuclei form one heavier and energy is released

a) NUCLEAR DECAY, radioactivity

Radioactivity was discovered in 1896 by Henri Becquerel – U compounds emit some kind of radiation which affects photographic plates. It can also ionize gases.

Marie Curie – other substances – radium, polonium – behave in a similar way

Finish the table:

radiation	nature	range/penetrating power	ionization	deflection in el. or mag. field
α				
β				
γ				
n				

- ***decay law***

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

t ... time interval ($t = t_1 - t_0$)

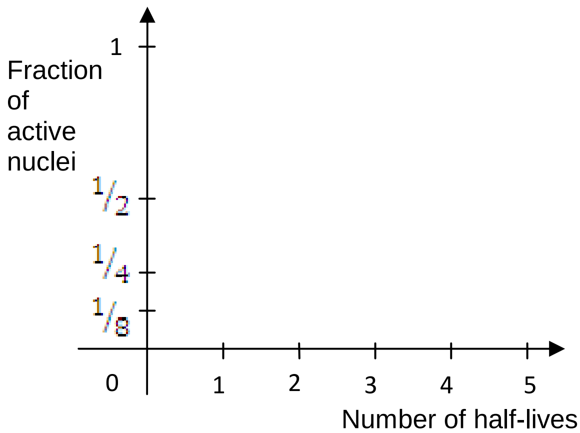
λ ... radioactive decay constant (depends on material)

N_0 ... initial number of undecayed nuclei (t_0)

N ... final number of undecayed nuclei (t_1)

Sketch the radioactive decay curve:

Graph (2)



- ***half-life*** *($t_{1/2}$)* = time taken for the number of active nuclei to fall to half its value

relation between the radioactive decay constant of some material and its half-life

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

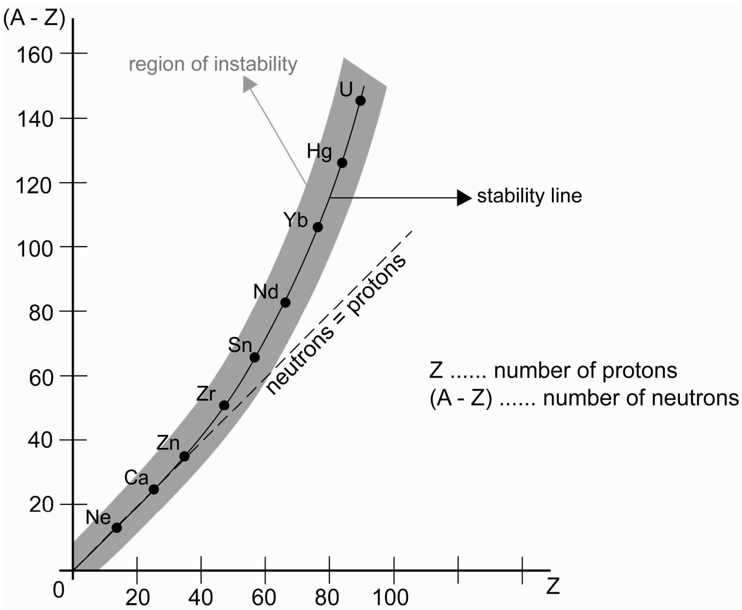
$$\frac{1}{2} = \frac{1}{e^{\lambda t_{1/2}}}$$

$$\ln 2 = \lambda t_{1/2} \quad (= 0.693)$$

- ***activity of a source (A)*** = number of disintegrations per second
$[A] = \mathrm{Bq}$ ... becquerel 1 Bq = one disintegration per second

- ***nuclear stability***
heavier nuclei need more neutrons than protons to be stable, as the nuclear forces are the short-range ones and more distant protons are repelled by electrostatic force – see the graph:

Graph (3):



- ***detectors***
humans do not have sensors – underestimation of effects!!!

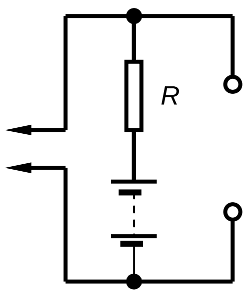
detectors are based on different principles, some detect the intensity, some show trajectories

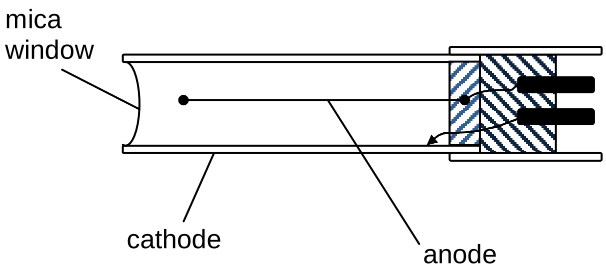
i) **ionization of a gas** – detection of intensity

Geiger-Müller (G-M) tube

pulses of current – beeps or counts

for β and γ only (explain)





ionization chamber

similar arrangement – pulses of current

mainly for α (explain)

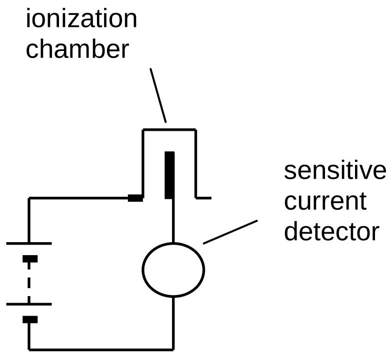
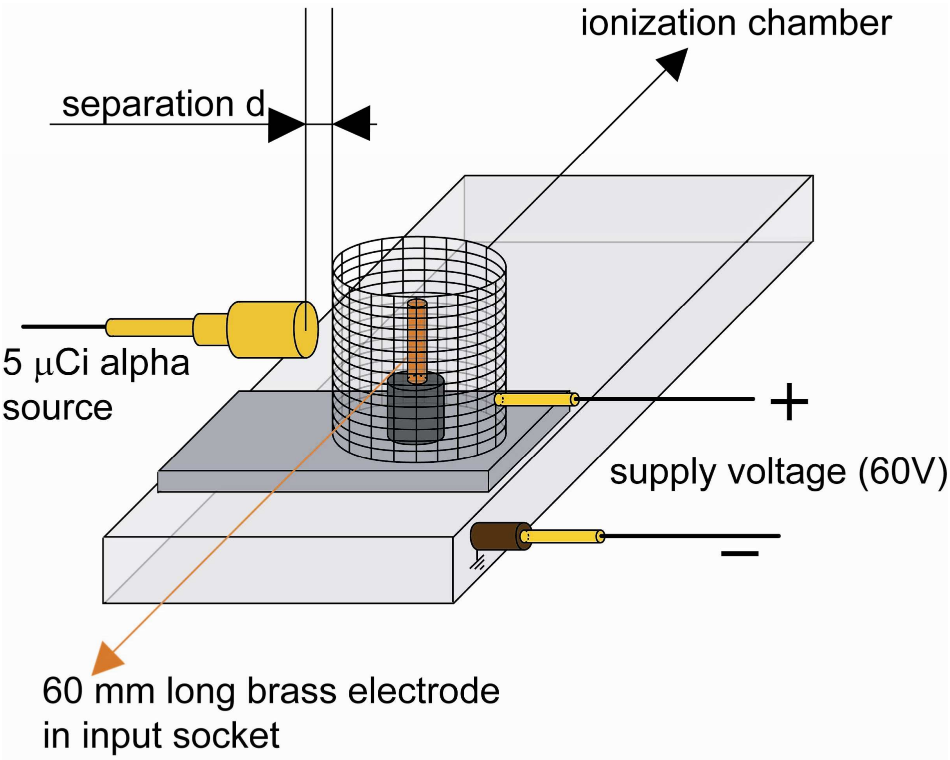


Figure (1):



ii) **ionization + change in state of matter –** observation of trajectories

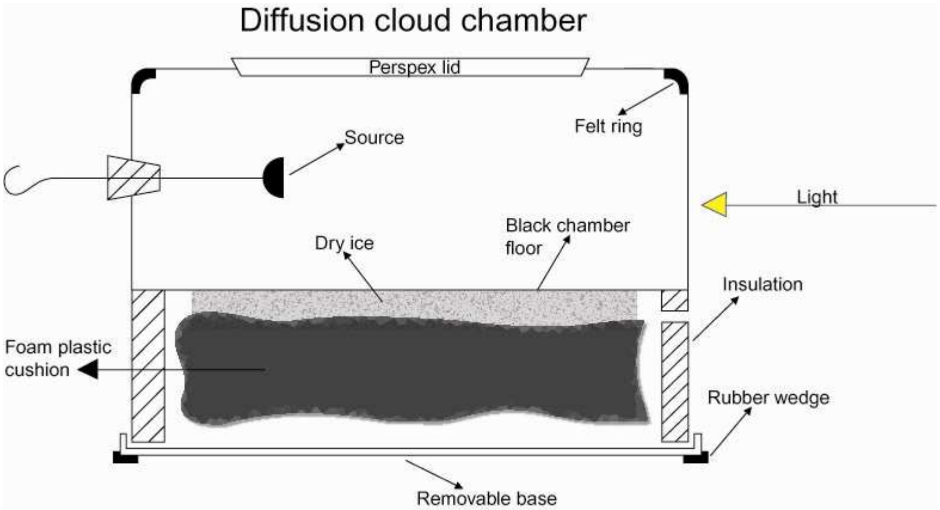
cloud chamber

source inside

saturated alcohol vapour inside – radiation passes – ionization + condensation –"droplets"

show the trajectories (short+thick, longer+thinner – for which radiation?)

Figure (2):



bubble chamber

liquid hydrogen – trail of bubbles when radiation passes

iii) **photographic emulsion** – like being exposed to light

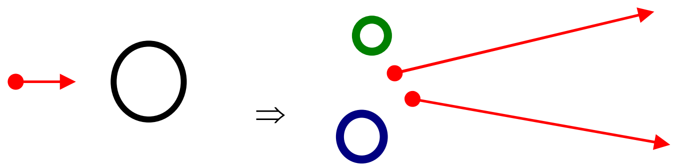
iv) **fluorescence of phosphor in a scintillation counter**

Q: Discuss the uses of the detectors mentioned above.

http://www.youtube.com/watch?v=2D3xXEkmU8g&feature=related

b) NUCLEAR FISSION

- the nucleus is split into the products of roughly the same mass, energy is released
- 1932 – Chadwick discovered neutron
- 1939 Fermi (It.); Hahn + Strassman (Ger.) – uranium can split when bombarded by neutrons = new type of reaction!
  - the nucleus is split into two large FISSION FRAGMENTS of roughly equal mass
  - the mass decrease(defect) is appreciable – energy released!
  - other fission neutrons emitted can cause a CHAIN REACTION – important to control the reaction



$$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{90}_{36}Kr + ^{144}_{56}Ba + 2^{1}_{0}n \qquad + 200\,MeV$$

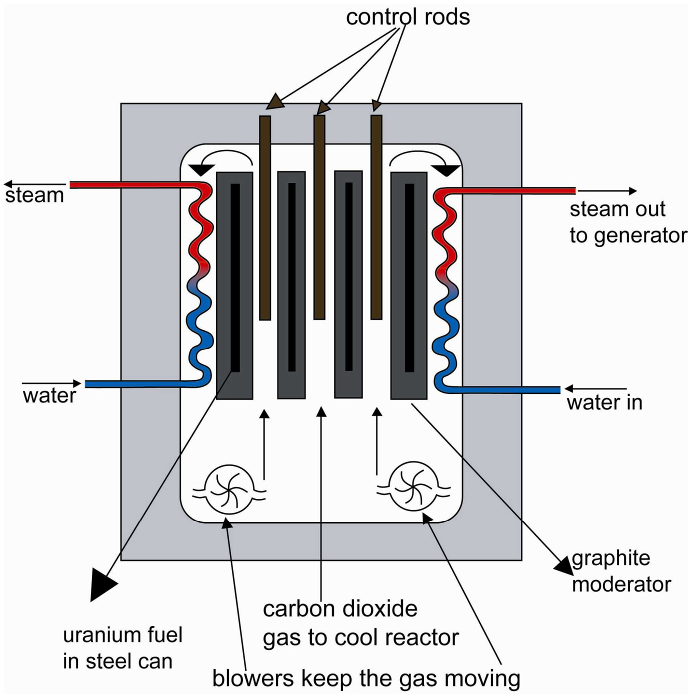
- the fission fragments can be different and 3n can be released
- Δm and therefore energy released can be about 45times bigger than during chemical reactions
- problem – fragments are not stable – decay – radioactivity, long half-life

NUCLEAR REACTOR

In additional material (1) read the article and explain the importance of different parts of the nuclear reactor.

Q: In our NPS we use water as both moderator and coolant. Is it an advantage?

Figure (3):



c) NUCLEAR FUSION

- principal source of the Sun's energy and hydrogen bomb
- ${}^{2}_{1}H + {}^{2}_{1}H \rightarrow {}^{3}_{2}He + {}^{1}_{0}n \quad + 3.3\,MeV$
- ${}^{2}_{1}H + {}^{3}_{1}H \rightarrow {}^{4}_{2}He + {}^{1}_{0}n \quad + 17.6\,MeV$
- less energy gain per reaction, but NOT per unit mass!!!
- problem
  - strong repulsion of the shells – heated to 10^9 K – vessel???
  - how to control the hot plasma?

THERMONUCLEAR FUSION

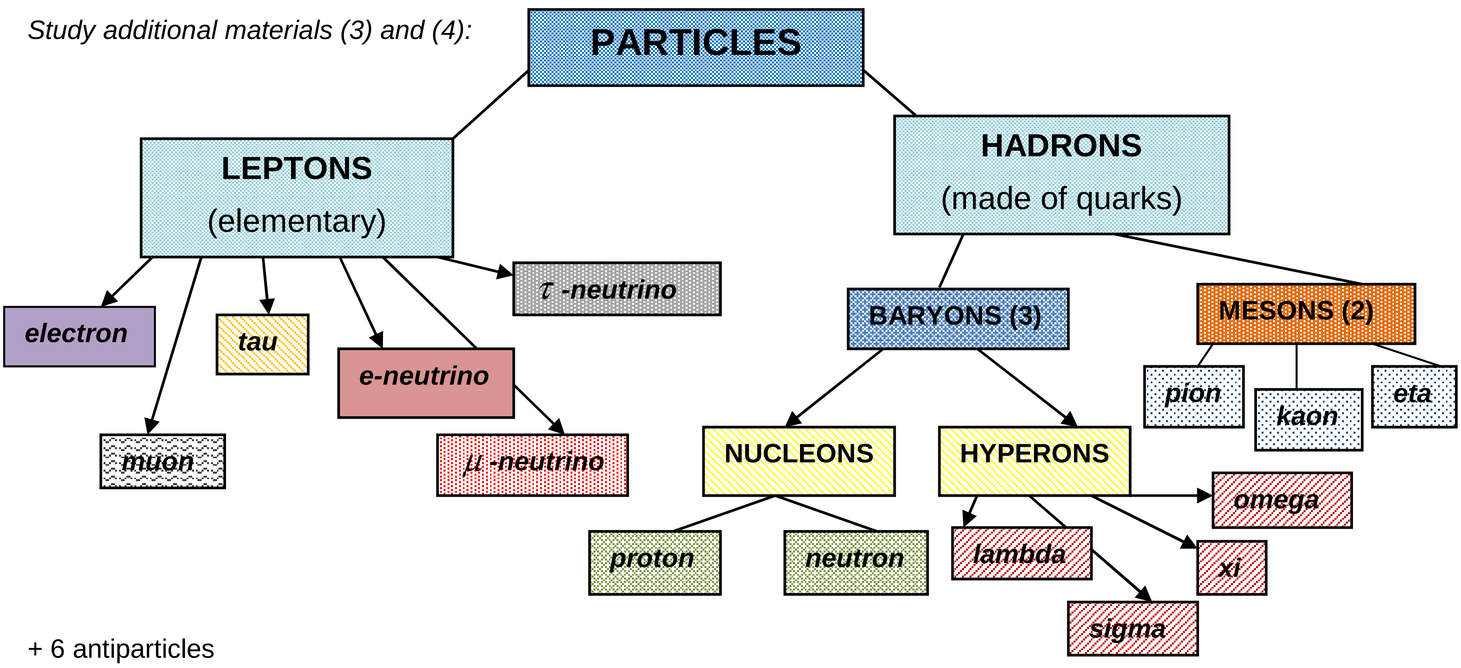
- uncontrolled – bomb (fission can be used to reach the temperature)
- controlled – H in oceans – unlimited source, problems to control, container, ... the reactor would use a great proportion of the energy produced

Q: See additional material (2) and compare the nuclear fission and fusion as sources of energy (adv., disadv.)

4. Elementary particles

- matter composed of protons, neutrons and electrons cannot be used to explain massXmass, energyXmass, energyXenergy interactions
- neutrino – always produced during β decay, needed to create elements in the Universe which are heavier than hydrogen
- pion – its exchange is responsible for the strong nuclear interaction
- hundreds of others discovered, they decay rapidly after being created in collisions – particle accelerators needed – cyclotrons and synchrotrons, both use charged particle – proton – moving in a circular/spiral path in the outer magnetic field and electric field in order to accelerate
- **cyclotron –** one frequency, continuous beam of protons, speed is limited
- **synchrotron –** frequency differs as protons become heavier with speed, pulses of proton bunches

Study additional materials (3) and (4):



+ 6 antiparticles

+ many others

See additional material (5)

+antiparticles made of antiquarks

BOSONS have zero or integral spin – they obey Bose-Einsteins statistics, photons as well

half-integral spin **FERMIONS** – they obey Fermi-Dirac statistics and Pauli's exclusion principle

LEPTONS

- are NOT affected by strong nuclear interactions
- electron – stable, light
- neutrinos – stable, "zero" mass, problem with detection – even an iron plate 1 light year wide would not slow them down!
- $n \rightarrow p^+ + e^- + \bar{\nu}_e$ (elecron antineutrino) $p^+ \rightarrow n + e^+ + \nu_e$ (electron neutrino)

$$e^+ + e^- \rightarrow 2\gamma$$

HADRONS

- are affected by strong nuclear interactions and made of quarks

MESONS hold nucleons in the nucleus together when exchanged = force carriers, they are bosons

BARYONS represent "matter", they are fermions

nucleons are the only stable ones, neutrons are stable in the nucleus only

many others – heavier – decay rapidly

quarks are the components of hadrons, they cannot exist separately and they have properties –"quantum numbers" called **flavour** and **colour**, others are still being discovered

COLOUR

red *green* *blue*

+ anticolours

FLAVOUR

u	*d*	*c*	*s*	*t*	*b*
up	*down*	*charm*	*strange /side*	*top /truth*	*bottom /beauty*

+ antiflavours

mesons are made of 1 quark + 1 antiquark of corresponding anticolour – they are COLOURLESS

baryons are made of 3 quarks of different colour – they are WHITE

colours exist only within the hadrons!!!

the presence of 2 identical quarks in one hadron violates Pauli's exclusion principle – examples

pion$^+$: $u\bar{d}$

kaon$^+$: $u\bar{s}$

colour + anticolour

proton: *uud*

neutron: *ddu*

omega: *sss*

different colours

charges of quarks:

$+\frac{2}{3}$ for u, c, t $\left(-\frac{2}{3} \text{ for } \bar{u}, \bar{c}, \bar{t}\right)$

$-\frac{1}{3}$ for d, s, b $\left(+\frac{1}{3} \text{ for } \bar{d}, \bar{s}, \bar{b}\right)$

Quarks are held together because of exchange of **GLUONS**, mass 0, v=c, composed of colour + different anticolour (blue-antired gluon etc.), emission or absorption of a gluon changes the colour of the quark

http://www.youtube.com/watch?v=Vi91qyjuknM&feature=related

The four fundamental interactions

The GRAVITON has not been experimentally detected as yet

Interaction	*Particles Affected*	*Range*	*Relative Strength*	*Particles Exchanged*	*Role in Universe*
Strong	Quarks Hadrons	$\sim 10^{-15}$ m	1	Gluons Mesons	Holds quarks together to form nucleons Holds nucleons together to form atomic nuclei
Electromagnetic	Charged particles	∞	$\sim 10^{-2}$ m	Photons	Determines structure of atoms, molecules, solids, and liquids; is important factor in astronomical universe
Weak	Quarks and leptons	$\sim 10^{-17}$ m	$\sim 10^{-5}$ m	Intermediate bosons W^+, W^-, Z	Mediates transformations of quarks and leptons; helps determine compositions of atomic nuclei
Gravitational	All	∞	$\sim 10^{-30}$ m	Gravitons	Assembles matter into planets, stars, and galaxies

http://www.youtube.com/watch?v=-P4N-0Wbtyk&NR=1

One of the goals of physics is a single theoretical picture that unites all the ways in which particles of matter interact with each other. Much progress has been made, but the task is not finished.