Preliminaries

Introduction to Nuclear Science

Simon Fraser University
Spring 2011

NUCS 342 — January 6, 2011

Outline

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1. Useful links
2. Nuclear Science Minor

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Useful links

- For chemistry web site see this link.
- For class website see this link.
- For general information on NuSc 342 see this link.
- For detailed NuSc 342 schedule see this link.
- For useful NuSc 342 numerical constants this link.

Nuclear Science Minor

Minor in Nuclear Science requires completion of 14 upper division credits from the following courses:

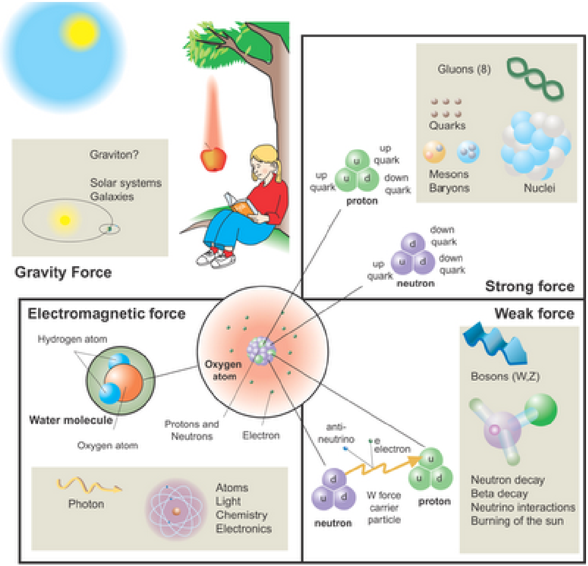
- NuSc 341-3 Introduction to Radiochemistry
- NuSc 342-3 Introduction to Nuclear Science
- NuSc 344-3 Nucleosynthesis and Distribution of the Elements
- NuSc 346-2 Radiochemistry Laboratory ← unique in Canada
- PHYS 385-3 Quantum Physics
- NuSc 444-3 Special Topics in Nuclear Science
- CHEM 482-3 Directed Study in Advanced Topics of Chemistry
- PHYS 485-3 Particle Physics

NuSc courses are currently being taught by Profs C. Andreoiu, J.C. Brodovich, and K. Starosta, PHYS courses by Prof. M. Vetterli.

Scales in the Universe

For a great applet showing scales in the Universe see this link.

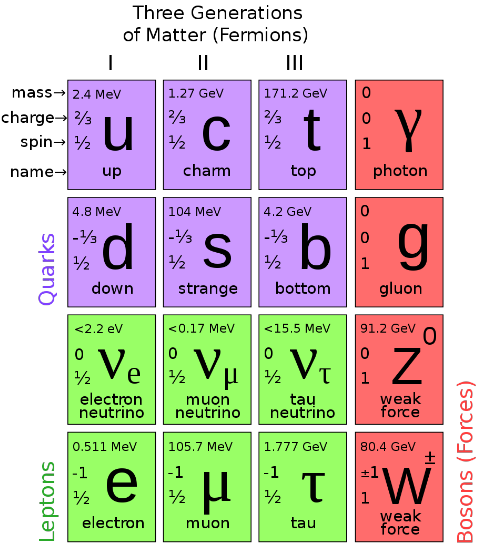
Fundamental Forces



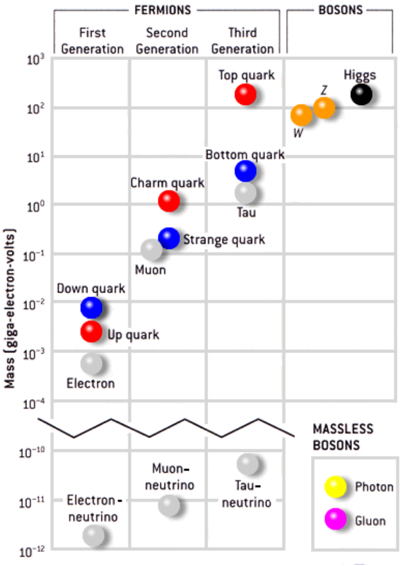
Fundamental Forces

Force	Range [m]	Relative strength nucleus: within	Relative strength nucleus: beyond	Impact
Strong	10^{-15}	100	0	Nuclei
Electromagnetic	∞	1	1	Chem/Bio
Weak	10^{-18}	10^{-5}	0	Nuclei
Gravity	∞	10^{-43}	10^{-43}	Universe

The Standard Model of Elementary Particles



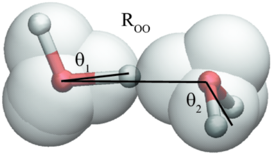
Masses of Elementary Particles



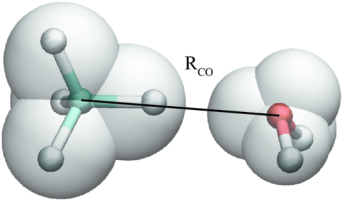
Effective Interactions between molecules

- In complex systems interactions between fundamental constituents do not always provide the most effective description of the system.
- A known example in Chemistry is provided by the Van der Waals forces between dimer molecules.
- For a description of dimer interactions it is much more efficient to use effective Van der Waals forces between molecules then the fundamental electromagnetic forces between constituent atoms.
- The effective Van der Waals force is a residual force resulting from a superposition of the fundamental electromagnetic (predominantly Coulomb) forces.
- The effective force is weak, since the dimers are neutral. The interactions are complex as they arise due to dipole and higher-order moments either resulting from the molecular structure or induced by the intermolecular interactions.

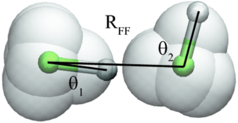
Van der Waals forces



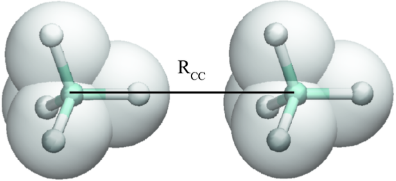
$(H_2O)_2$ $E = -35.5$ (-5.44 kcal/mol)
$R_{OO} = 2.29$ (2.92 Å),
$\theta_1 = 4.6°$ ($6°$), $\theta_2 = 112.4°$ ($123°$)



$CH_4 \bullet OH_2$ $E = -3.9$ (-0.9 kcal/mol)
$R_{OC} = 3.18$ (3.51 Å)



$(HF)_2$ $E = -53.7$ (-4.56 kcal/mol)
$R_{FF} = 2.13$ (2.73 Å),
$\theta_1 = 5.8°$ ($7°$), $\theta_2 = 103.5°$ ($112°$)



$(CH_4)_2$ $E = -0.5$ (-0.3 kcal/mol)
$R_{CC} = 3.91$ (4.13 Å)

Effective Interactions in nuclei

- In principle nuclei can be viewed as system of quarks bound by the strong force mediated by gluons.
- In practise, this is a very inefficient way to describe low-energy (up to $\sim$100 MeV) nuclear excitations.
- In the low-energy range nuclei are much better described as systems composed of protons and neutrons.
- Since protons and neutrons are made up from three quarks the effective nuclear interactions is a (complex) superposition of strong interactions between these constituent quarks.
- One of the goals of nuclear science is to describe in an efficient way effective interactions between nucleons and provide predictive theory for nuclear structure and reactions.

Degrees of Freedom

- Degrees of freedom in NuSc 342 will be understood as the constituents of a system chosen for the description of system properties.
- For the van der Waals example above one can either choose molecules, atoms, nuclei and electrons or even quarks and leptons as degrees of freedom.
- Choice of degrees of freedom is crucial, it should capture the most important properties of the system without bringing unnecessary computational complications.
- In NuSc 342 the degrees of freedom are: nucleons (protons and neutrons), alpha particles, atomic nuclei as well as electrons, positrons, and neutrinos.

Lorentz transformation

- Describes a relationship between a position and time in a stationary (x,t) and moving (x',t') reference frames.
- Plays a role in the description of nuclear reactions which happen at speeds which are on the order of a few percent of the speed of light ($c = 3 \times 10^8$ [m/s]) with (x,t) and (x',t') representing the target (laboratory) and projectile (beam) reference frames, respectively.

$$t \neq t'$$

$$x = \gamma(x' + vt') \qquad ct = \gamma(ct' + \beta x')$$

$$\beta = \frac{v}{c} \qquad \gamma = \frac{1}{\sqrt{1-\beta^2}}$$

$$x' = \gamma(x - vt) \qquad ct' = \gamma(ct - \beta x)$$

The low-speed limit of the Lorentz transformation

$$t \neq t'$$

$$x = \gamma(x' + vt') \qquad ct = \gamma(ct' + \beta x')$$

$$\beta = \frac{v}{c} \qquad \gamma = \frac{1}{\sqrt{1-\beta^2}}$$

$$x' = \gamma(x - vt) \qquad ct' = \gamma(ct - \beta x)$$

but for $v << c$ $\quad \beta \to 0$, $\gamma \to 1$, and

$$x = x' + vt' \qquad ct = ct'$$

which is exactly the Galilean transformation used in classical mechanics.

Conservation of momentum at low speed

At $v << c$ momentum is defined as:

$$\vec{p} = m\vec{v}$$

The second Newton's law can be expressed as

$$\vec{F} = \frac{d\vec{p}}{dt}$$

In the absence of external force $\vec{F} = 0$

$$\frac{d\vec{p}}{dt} = 0 \quad \Longrightarrow \quad \vec{p} = \text{const.}$$

and momentum is conserved.

Conservation of momentum at high speed

To maintain the same form of Newton's law and the conservation of momentum up to $v \sim c$ momentum has to be defined as

$$\vec{p} = \gamma m \vec{v}.$$

At low speed $v << c$, $\beta \sim 0$, $\gamma \sim 1$ momentum becomes

$$\vec{p} = m \vec{v}.$$

Conservation of energy at low speed

At $v << c$ kinetic energy is defined as:

$$T = \frac{1}{2}mv^2 = \frac{p^2}{2m}$$

In the absence of external force momentum is conserved $\vec{p}$=const. which implies p^2=const. and T=const., which means that the kinetic energy is conserved.

Mass-energy theorem

In 1905 Albert Einstein following his derivation of the Special Theory of Relativity identifies relation between mass and energy of an object at rest:

$$E = mc^2.$$

The corresponding relation for moving object is

$$E = \gamma mc^2.$$

Subsequent experiments confirm conversion between mass and energy in atomic and nuclear processes.

Energy, momentum and mass at high speed

At high speed the relation between energy, mass and momentum can be derived from

$$\begin{aligned} m^2c^4 &= \frac{E^2}{\gamma^2} = E^2(1-\beta^2) = E^2 - \frac{v^2}{c^2}\gamma^2 m^2 c^4 = \\ &= E^2 - \gamma^2 m^2 v^2 c^2 = E^2 - p^2c^2 \end{aligned}$$

or

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

Above equation is known as the relativistic energy-momentum relationship. It defines total energy of an object with mass m moving with momentum p in the absence of external force.

Kinetic energy

Kinetic energy is a difference between energy of an moving object and the energy of the same object at rest.

$$T = E - mc^2 = \gamma mc^2 - mc^2 = (\gamma - 1)mc^2$$

further evaluation of this equation requires the following approximation which works well at low speed $v << c$, $\beta << 1$:

$$\gamma \approx 1 + \frac{1}{2}\beta^2$$

which implies for the kinetic energy at low speed:

$$T = (\gamma - 1)mc^2 \approx (1 + \tfrac{1}{2}\beta^2 - 1)mc^2 = \tfrac{1}{2}m\beta c^2 = \tfrac{1}{2}mv^2.$$