PROGRAM OF "PHYSICS"

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ANALYTICAL PHYSICS 2B

03 credits (45 periods)

Chapter 1 Geometric Optics

Chapter 2 Wave Optics

Chapter 3 Relativity

Chapter 4 Quantum Physics

Chapter 5 Nuclear Physics

Chapter 6 The Standard Model of Particle Physics

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PHYSICS 2B

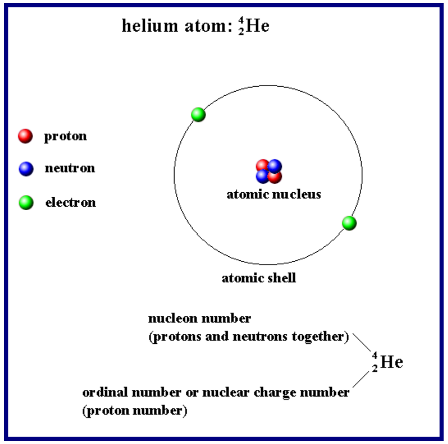
Chapter 5
Nuclear Physics

The strong interaction and the structure of the nucleus

Nuclear Reactions: Nuclear fission and fusion

Radioactivity: Radioactive decay and the neutrino

1 Properties of Nuclei



- Every atom contains at its center an extremely dense, positively charged nucleus, which is much smaller than the overall size of the atom but contains most of its total mass.
- Model : a nucleus is a sphere with a radius R that depends on the total number of nucleons (neutrons and protons): Nucleon number A (mass number)
- The proton mass and the neutron mass are both approximately $1\text{u} = 1.66053886 \times 10^{-27}\ \text{kg} = 931.5\ \text{MeV}/c^2$
- The number of protons in a nucleus is the atomic number Z. The number of neutrons is the neutron number N: $\boxed{{}^{A}_{Z}X}$

$$\boxed{A = Z + N}$$

- **The radii of most nuclei :** $\boxed{R = R_0 A^{1/3}}$

$$(R_0 = 1.2 \times 10^{-15}\,\text{m} = 1.2\ \text{fm})$$

- A single nuclear species having specific values of both Z and N is called a **nuclide**.

- Some nuclides that have the same Z but different N**: isotopes** of that element

EXAMPLE :

  - Chlorine (Cl, Z = 17). About 76% of chlorine nuclei have N = 18; the other 24% have N = 20.

- Two common isotopes of uranium with A = 235 and 238

Nucleus	Mass Number (Total Number Nucleons), A	Atomic Number (Number of Protons),	Neutron Number, $N = A - Z$
$^{1}_{1}\mathrm{H}$	1	1	0
$^{2}_{1}\mathrm{D}$	2	1	1
$^{4}_{2}\mathrm{He}$	4	2	2
$^{6}_{3}\mathrm{Li}$	6	3	3
$^{7}_{3}\mathrm{Li}$	7	3	4
$^{9}_{4}\mathrm{Be}$	9	4	5
$^{10}_{5}\mathrm{B}$	10	5	5
$^{11}_{5}\mathrm{B}$	11	5	6
$^{12}_{6}\mathrm{C}$	12	6	6
$^{13}_{6}\mathrm{C}$	13	6	7
$^{14}_{7}\mathrm{N}$	14	7	7
$^{16}_{8}\mathrm{O}$	16	8	8
$^{23}_{11}\mathrm{Na}$	23	11	12
$^{65}_{29}\mathrm{Cu}$	65	29	36
$^{200}_{80}\mathrm{Hg}$	200	80	120
$^{235}_{92}\mathrm{U}$	235	92	143
$^{238}_{92}\mathrm{U}$	238	92	146

2 Nuclear Binding and Nuclear Structure

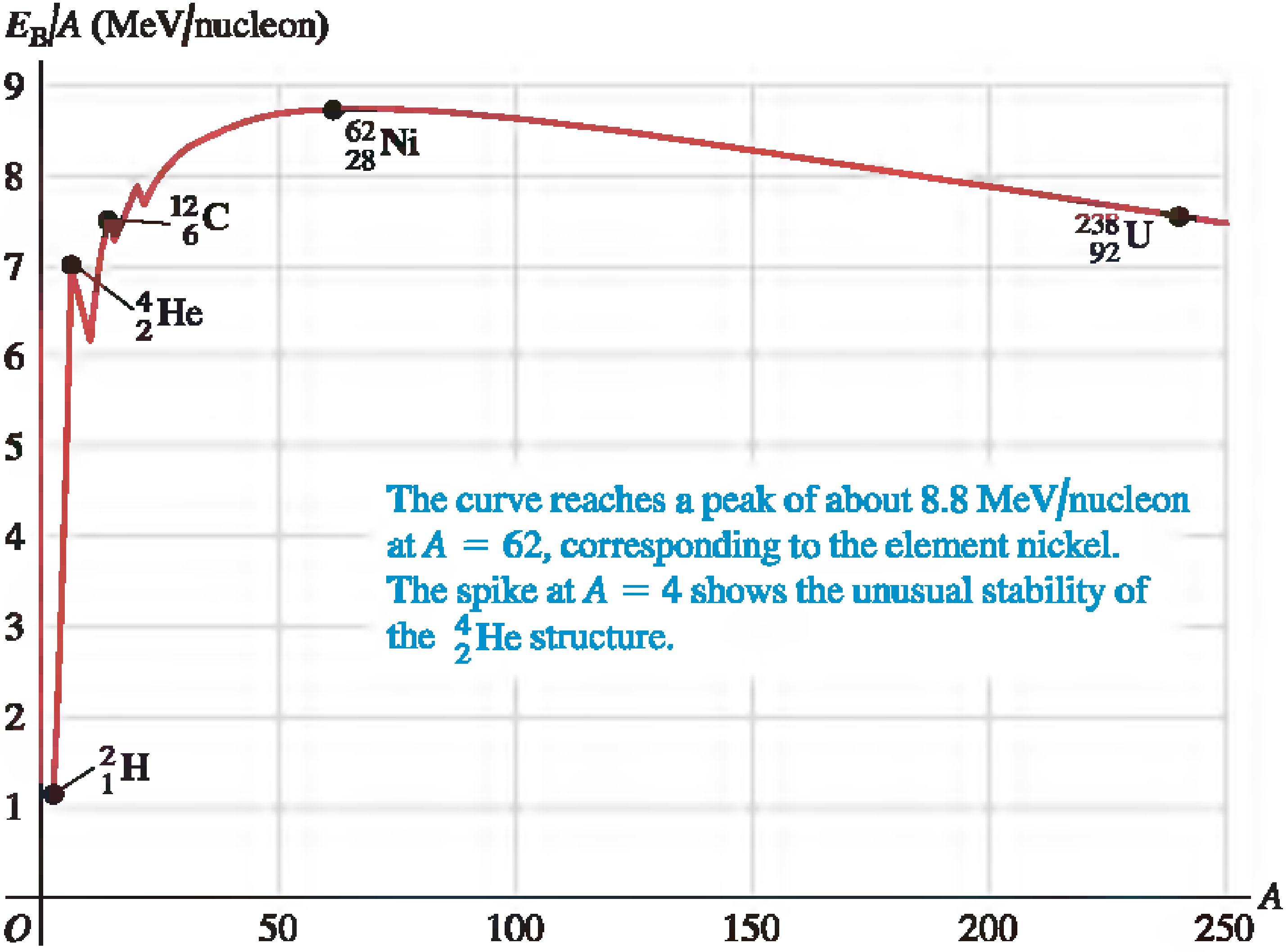
- The **binding energy $\mathbf{E_B}$** : the magnitude of the energy by which the nucleons are bound together.

- Total **rest energy $\mathbf{E_0}$** of the separated nucleons is greater than the rest energy of the nucleus.

- The rest energy of the nucleus : $E_0 - E_B$

- The binding energy for a nucleus containing Z protons and N neutrons :

$$\boxed{E_B = (Zm_p + Nm_n - {}^{A}_{Z}M)c^2}$$



The curve reaches a peak of about 8.8 MeV/nucleon at $A = 62$, corresponding to the element nickel. The spike at $A = 4$ shows the unusual stability of the $^{4}_{2}$He structure.

PROBLEM 1

Because it has the highest binding energy per nucleon of all nuclides, Ni (Z=28;A=62) may be described as the most strongly bound. Its neutral atomic mass is 61.928349 u. Find its mass defect. its total binding energy, and its binding energy per nucleon.

SOLUTION

We use $Z = 28$, $M_H = 1.007825$ u, $N = A - Z = 62 - 28 = 34$, $m_n = 1.008665$ u, and ${}^{A}_{Z}M = 61.928349$ u

$$\boxed{E_B = (Zm_p + Nm_n - {}^{A}_{Z}M)c^2}$$

$$E_B = (0.585361\ \mathrm{u})(931.5\ \mathrm{MeV/u}) = 545.3\ \mathrm{MeV}$$

It would require a minimum of 545.3 MeV to pull a ${}^{62}_{28}\mathrm{Ni}$ nucleus completely apart into 62 separate nucleons. The binding energy *per nucleon* is $\frac{1}{62}$ of this, or 8.795 MeV per nucleon.

3 Nuclear Reactions

- **Nuclear reactions** : Rearrangements of nuclear components that result from a bombardment by a particle

$$A + B \rightarrow C + D$$

- Several conservation laws **: The classical conservation principles for charge, momentum, angular momentum, and energy (including rest energies)**

EXAMPLE : $^{4}_{2}\mathrm{He} + {}^{14}_{7}\mathrm{Na} \rightarrow {}^{17}_{8}\mathrm{O} + {}^{1}_{1}\mathrm{H}$

Conservation of charge : 2 + 7 = 8 + 1

Conservation of nucleon number A : 4 +14 = 17 + 1

- **Reaction energy :**

$$\boxed{Q = \underbrace{(M_A + M_B - M_C - M_C)}_{\Delta m\text{ : mass defect}}c^2}$$

PROBLEM 2

When lithium ${}^{7}_{3}\mathrm{Li}$ is bombarded by a proton, two alpha particles (${}^{4}_{2}\mathrm{He}$) are produced. Find the reaction energy.

SOLUTION

$${}^{1}_{1}\mathrm{H} + {}^{7}_{3}\mathrm{Li} \rightarrow {}^{4}_{2}\mathrm{He} + {}^{4}_{2}\mathrm{He}$$

$$M_A + M_B - M_C - M_D = 0.018623\ \mathrm{u}$$

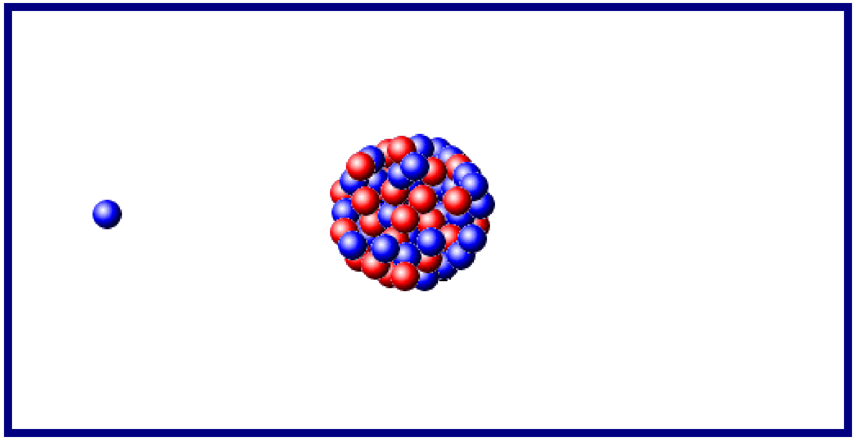
$$Q = (0.018623\ \mathrm{u})(931.5\ \mathrm{MeV/u}) = 17.35\ \mathrm{MeV}$$

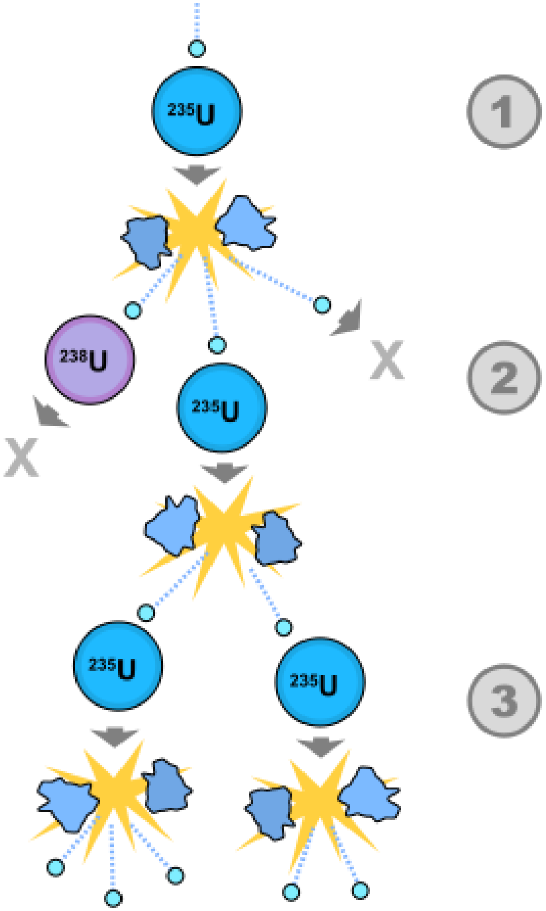
3.1 Fission Reactions

- **Nuclear fission** is a decay process in which an unstable nucleus **splits into two fragments** of comparable mass.

EXAMPLE : $^{235}_{92}\mathrm{U} + ^{1}_{0}\mathrm{n} \rightarrow ^{235}_{92}\mathrm{U} \rightarrow ^{144}_{56}\mathrm{Ba} + ^{89}_{36}\mathrm{Kr} + 3^{1}_{0}\mathrm{n}$

- **Chain Reactions** : Fission of a uranium nucleus, triggered by neutron bombardment, releases other neutrons that can trigger more fissions





PROBLEM 3

Calculate the energy released in the fission reaction

$$ {}^{235}_{92}\mathrm{U} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{140}_{54}\mathrm{Xe} + {}^{94}_{38}\mathrm{Sr} + 2\,{}^{1}_{0}\mathrm{n} $$

You can ignore the initial kinetic energy of the absorbed neutron. The atomic masses are ${}^{235}_{92}\mathrm{U}$, 235.043923 u; ${}^{140}_{54}\mathrm{Xe}$, 139.921636 u; and ${}^{94}_{38}\mathrm{Sr}$, 93.915360 u.

SOLUTION

$$ \Delta m = M\left({}^{235}_{92}\mathrm{U}\right) - M\left({}^{140}_{54}\mathrm{Xe}\right) - M\left({}^{94}_{38}\mathrm{Sr}\right) - m_{\mathrm{n}} $$

$$ \Delta m = 235.043923\ \mathrm{u} - 139.921636\ \mathrm{u} - 93.915360\ \mathrm{u} - 1.008665\ \mathrm{u} = 0.1983\ \mathrm{u} $$

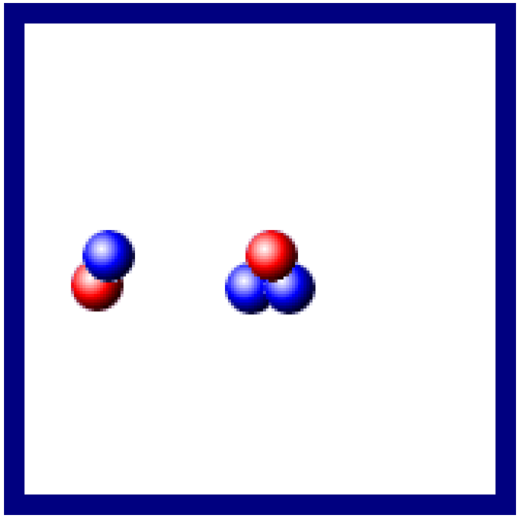
$$ E = (\Delta m)c^2 = (0.1983\ \mathrm{u})(931.5\ \mathrm{MeV/u}) = 185\ \mathrm{MeV}. $$

3.2 Nuclear Fusion

- In a nuclear fusion reaction, two or more small light nuclei come together, or fuse. to form a larger nucleus.
- Fusion reactions release energy for the same reason as fission reactions: The binding energy per nucleon after the reaction is greater than before.

EXAMPLE : ${}_{1}^{2}\mathrm{H} + {}_{1}^{1}\mathrm{H} \rightarrow {}_{2}^{3}\mathrm{He} + \gamma$

- Atoms have this much energy only at extremely high temperatures : thermonuclear reactions.



PROBLEM 4

Two deuterons fuse to form a triton (a nucleus of tritium, or ${}^{3}_{1}\mathrm{H}$) and a proton. How much energy is liberated?

SOLUTION

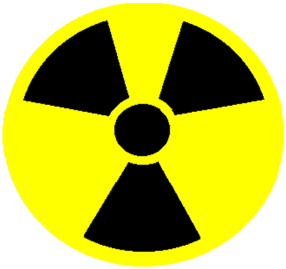
$${}^{2}_{1}\mathrm{H} + {}^{2}_{1}\mathrm{H} \rightarrow {}^{3}_{2}\mathrm{He} + \mathrm{p}$$

$$\begin{aligned} Q &= [2(2.014102\ \mathrm{u}) - 3.016049\ \mathrm{u} - 1.007825\ \mathrm{u}] \\ &\quad \times (931.5\ \mathrm{MeV/u}) \\ &= 4.03\ \mathrm{MeV} \end{aligned}$$

4. Radioactivity

- Among about 2500 known nuclides, fewer than 300 are stable. The others are unstable structures that decay to form other nuclides by emitting particles and electromagnetic radiation, a process called **radioactivity**.
- The time scale of these decay processes ranges from a small fraction of a microsecond to billions of years.

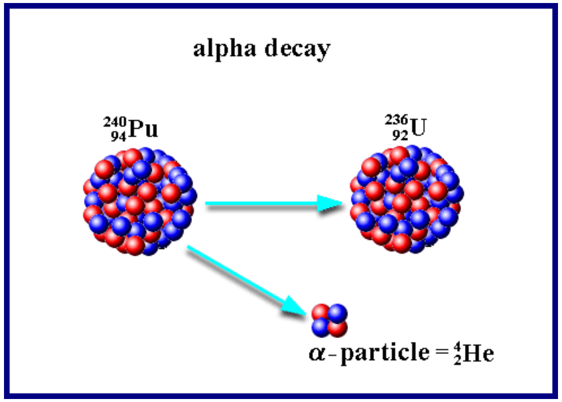
The international sign for radioactivity

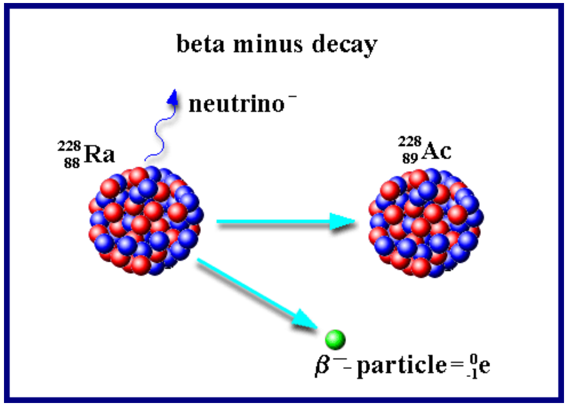


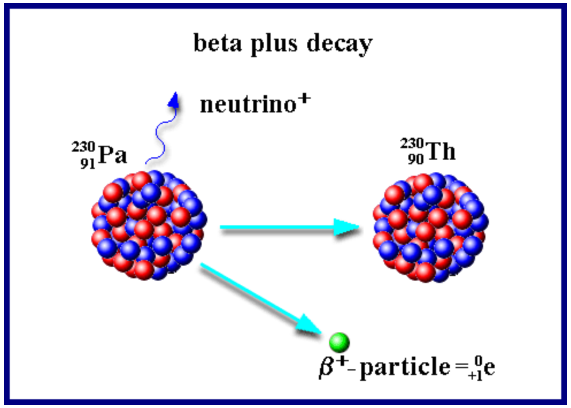
- When unstable nuclides decay into different nuclides, they usually emit **alpha** (α) or **beta** (β) particles:

Alpha particle is a ^{4}He nucleus, a beta-minus particle (β^-) is an electron, beta-plus particle (β^+) is a positron (antiparticle of electron)

$$^A_ZX \rightarrow {}^4_2He + {}^{A-4}_{Z-2}Y \;;\; ^A_ZX \rightarrow {}^0_{-1}e + {}^A_{Z+1}Y \;;\; ^A_ZX \rightarrow {}^0_1e + {}^A_{Z-1}Y$$


alpha decay


beta minus decay


beta plus decay

EXAMPLE :

What nuclide is produced in the following radioactive decays?

(a) α decay of $^{239}_{94}Pu$

(b) β^- decay of $^{24}_{11}Na$

(c) β^+ decay of $^{15}_{8}O$

SOLUTION

$$^{239}_{94}\mathrm{Pu} \rightarrow {}^{4}_{2}\mathrm{He} + {}^{235}_{92}\mathrm{U}$$

$$^{24}_{11}\mathrm{Na} \rightarrow {}^{0}_{-1}\mathrm{e} + {}^{24}_{12}\mathrm{Mg}$$

$$^{15}_{8}\mathrm{O} \rightarrow {}^{0}_{+1}\mathrm{e} + {}^{15}_{7}\mathrm{N}$$

• Radioactive Decay Rates

- *N*(*t*) : the (very large) number of radioactive nuclei in a sample at time *t*,

dN(*t*) : the (negative) change in that number during a short time interval *dt*

\- *dN*(*t*)/*dt* is called the **decay rate or the activity** of the specimen.

Activity: becquerel (Bq) in SI or curie (Ci)

$$1\mathrm{Ci} = 3.70\times10^{10}\,\mathrm{Bq} = 3.70\times10^{10}\,\mathrm{decays/s}$$

$$-\frac{dN(t)}{dt} = \lambda N(t) \qquad \boxed{N(t) = N_0 e^{-\lambda t}}$$

λ **: decay constant**

- **The half-life $T_{1/2}$** is the time required for the number of radioactive nuclei to decrease to one-half the original number N_0

$$\boxed{T_{1/2} = \frac{\ln 2}{\lambda} = \frac{0.693}{\lambda}}$$

- **The mean lifetime T_{mean}** (generally called the lifetime)**:**

$$\boxed{T_{\text{mean}} = \frac{1}{\lambda} = \frac{T_{1/2}}{\ln 2}}$$

PROBLEM 5

The radioactive isotope ^{57}Co decays by electron capture with a half-life of 272 days. (a) Find the decay constant and the lifetime. (b) If you have a radiation source containing ^{57}Co, with activity 2.00 μCi, how many radioactive nuclei does it contain? (c) What will be the activity of your source after one year?

SOLUTION

$$T_{1/2} = (272 \text{ days})(86{,}400 \text{ s/day}) = 2.35 \times 10^{7} \text{ s.}$$

$$T_{\text{mean}} = \frac{T_{1/2}}{\ln 2} = \frac{2.35 \times 10^{7} \text{ s}}{0.693} = 3.39 \times 10^{7} \text{ s}$$

$$\lambda = \frac{1}{T_{\text{mean}}} = 2.95 \times 10^{-8} \text{ s}^{-1}$$

PROBLEM 5

The radioactive isotope ^{57}Co decays by electron capture with a half-life of 272 days. (a) Find the decay constant and the lifetime. (b) If you have a radiation source containing ^{57}Co, with activity 2.00 μCi, how many radioactive nuclei does it contain? (c) What will be the activity of your source after one year?

SOLUTION

$$-\frac{dN(t)}{dt} = 2.00\ \mu\text{Ci} = (2.00 \times 10^{-6})(3.70 \times 10^{10}\ \text{s}^{-1})$$

$$= 7.40 \times 10^{4}\ \text{decays/s}$$

$$N(t) = -\frac{dN(t)/dt}{\lambda} = \frac{7.40 \times 10^{4}\ \text{s}^{-1}}{2.95 \times 10^{-8}\ \text{s}^{-1}} = 2.51 \times 10^{12}\ \text{nuclei}$$

$$N(t) = N_0 e^{-\lambda t} = N_0 e^{-(2.95\times 10^{-8}\ \text{s}^{-1})(3.156\times 10^{7}\ \text{s})} = 0.394 N_0$$

$$(0.394)(2.00\ \mu\text{Ci}) = 0.788\ \mu\text{Ci}.$$

PROBLEM 6

The isotope ^{226}Ra undergoes a decay with a half-life of 1620 years.
What is the activity of 1.00 g of ^{226}Ra?
Express your answer in Bq and in Ci.

SOLUTION

$$\frac{dN}{dt} = \lambda N\ . \quad \lambda = \frac{\ln 2}{T_{1/2}} = \frac{\ln 2}{1620\ \text{yr}\left(3.15\times10^{7}\ \text{s/yr}\right)} = 1.36\times10^{-11}\ \text{s}^{-1}\ .$$

$$N = 1\ \text{g}\left(\frac{6.022\times10^{23}\,\text{atoms}}{226\ \text{g}}\right) = 2.665\times10^{25}\ \text{atoms}\ .$$

$$\frac{dN}{dt} = \lambda N = (2.665\times10^{25})(1.36\times10^{-11}\text{s}^{-1}) = 3.62\times10^{10}\ \text{decays/s} = 3.62\times10^{10}\,\text{Bq}$$

PROBLEM 7

We are given the following atomic masses:

U238 : 238.05079 u; He4: 4.00260 u

Th234 : 234.04363 u; H1: 1.00783 u; Pa237 : 237.05121u

(a) Calculate the energy released during the alpha decay of U238

(b) Show that U238 cannot spontaneously emit a proton; that is, protons do not leak out of the nucleus in spite of the proton-proton repulsion within the nucleus.

SOLUTION

(a) $^{238}_{92}U \rightarrow {}^{4}_{2}He + {}^{234}_{90}Th$

$$Q = (M_i - M_f)c^2 = 4.25 \text{ MeV}$$

(b) $^{238}_{94}U \rightarrow {}^{1}_{1}p + {}^{237}_{93}Pa$

$Q = -7.68$ MeV → **Must add 7.68 MeV**

PROBLEM 8

Consider the fusion reaction $^{2}H + {}^{2}H \rightarrow {}^{3}He + n$

(a) Estimate the barrier energy by calculating the repulsive electrostatic potential energy of the two ^{2}H nuclei when they touch.

(b) Compute the energy liberated in this reaction in MeV and in joules.

(c) Compute the energy liberated per mole of deuterium, remembering that the gas is diatomic, and compare with the heat of combustion of hydrogen, about 2.9 × 10^{5} J/mol.

SOLUTION

(a)

$$U = \frac{1}{4\pi\epsilon_0}\frac{e^2}{r} = (8.988\times10^{9}\ \mathrm{N\cdot m^2/C^2})\frac{(1.602\times10^{-19}\ \mathrm{C})^2}{2(1.51\times10^{-15}\ \mathrm{m})} = 7.64\times10^{-14}\ \mathrm{J} = 0.48\ \mathrm{MeV}$$

(b)

$$(3.510\times10^{-3}\ \mathrm{u})(931.5\ \mathrm{MeV/u}) = 3.270\ \mathrm{MeV}$$

$$(3.270\times10^{6}\ \mathrm{eV})(1.602\times10^{-19}\ \mathrm{J/eV}) = 5.239\times10^{-13}\ \mathrm{J}.$$

(c)

$$(6.022\times10^{23})(5.239\times10^{-13}\ \mathrm{J}) = 3.155\times10^{11}\ \mathrm{J/mol}.$$

PROBLEM 9

You are given the following neutral atomic masses:
^{226}Ra: 226.025403 u ; ^{222}Rn: 222.017571 u; ^{4}He: 4.002603 u
Show that alpha emission is energetically possible and that the calculated kinetic energy of the emitted a particle agrees with the experimentally measured value of 4.78 MeV.

SOLUTION

$$226.025403\ \mathrm{u} - (222.017571\ \mathrm{u} + 4.002603\ \mathrm{u}) = +0.005229\ \mathrm{u}$$

$$E = (0.005229\ \mathrm{u})(931.5\ \mathrm{MeV/u}) = 4.871\ \mathrm{MeV}$$

PROBLEM 10

Gold, ^{198}Au, undergoes β^- decay to an excited state of Hg. If the excited state decays by emission of a γ photon with energy 0.412 MeV, what is the maximum kinetic energy of the electron emitted in the decay? This maximum occurs when the antineutrino has negligible energy. (The recoil energy of the Hg nucleus can be ignored.
The masses of the neutral atoms in their ground states are
Au: 197.968225 u ; Hg:197.966752 u)

SOLUTION

The mass change is $197.968225 \text{ u} - 197.966752 \text{ u} = 1.473\times10^{-3} \text{ u}$

$$(1.473\times10^{-3} \text{ u})(931.5 \text{ MeV/u}) = 1.372 \text{ MeV}.$$

$$1.372 \text{ MeV} - 0.412 \text{ MeV} = 0.960 \text{ MeV}.$$

PROBLEM 11

Measurements indicate that 27.83% of all rubidium atoms currently on the earth are the radioactive 87Rb isotope. The rest are the stable 85Rb isotope. The half-life of 87Rb is 4.75×10^{10} y.
Assuming that no rubidium atoms have been formed since, what percentage of rubidium atoms were 87Rb when our solar system was formed 4.6×10^{9} y ago?

SOLUTION

Let *N* be the present number of 87Rb atoms.

$$0.2783 = N/(N + N_{85}).\ N = 0.3856N_{85}.$$

$$\frac{N_0}{N_0 + N_{85}} = \frac{Ne^{\lambda t}}{Ne^{\lambda t} + N_{85}} = \frac{(0.3855e^{\lambda t})N_{85}}{(0.3856e^{\lambda t})N_{85} + N_{85}} = \frac{0.3856e^{\lambda t}}{0.3856e^{\lambda t} + 1}.$$

$$e^{\lambda t} = e^{(1.459\times10^{-11}\ \mathrm{y}^{-1})(4.6\times10^{9}\ \mathrm{y})} = e^{0.16711} = 1.0694$$

$$\frac{N_0}{N_0 + N_{85}} = \frac{(0.3856)(1.0694)}{(0.3856)(1.0694) + 1} = 29.2\%.$$

PROBLEM 12

The ratio of 14C to 12C in living matter is measured to be 1.3×10^{-12} at the present time. A 12.0-g sample of carbon produces 180 decays/min due to the small amount of 14C in it.

From this information, calculate the half-life of 14C.

SOLUTION

$$N_{\text{tot}} = nN_{\text{A}} = mN_{\text{A}} / M = (12.0\times10^{-3}\ \text{kg})(6.022\times10^{23}\ \text{atoms/mol})/(12.011\times10^{-3}\ \text{kg/mol})$$

$$\text{N}_{\text{tot}} = 6.016\times10^{23}\ \text{atoms, so } (1.3\times10^{-12})(6.016\times10^{23}) = 7.82\times10^{11}\ \ \text{carbon-14 atoms}$$

$$\Delta N / \Delta t = -180\ \text{decays/min} = -3.00\ \text{decays/s}$$

$$\Delta N / \Delta t = -\lambda N; \qquad \lambda = \frac{-\Delta N / \Delta t}{N} = 3.836\times10^{-12}\ \text{s}^{-1}$$

$$T_{1/2} = (\ln 2) / \lambda = 1.807\times10^{11}\ \text{s} = 5730\ \text{y}$$

PROBLEM 13

The unstable isotope ^{40}K is used for dating rock samples. Its half-life is 1.28×10^{9} y .

(a) How many decays occur per second in a sample containing $1.63 \times \mathrm{lO}^{-6}$g of ^{40}K?

(b) What is the activity of the sample in curies?

SOLUTION

(a)

$$\lambda = \frac{0.693}{T_{1/2}} = \frac{0.693}{(1.28\times10^{9}\ \text{y})(3.156\times10^{7}\ \text{s/1 y})} = 1.715\times10^{-17}\ \text{s}^{-1}$$

$$N = \frac{1.63\times10^{-9}\ \text{kg}}{40\ \ \text{u}} = \frac{1.63\times10^{-9}\ \text{kg}}{40(1.66054\times10^{-27}\ \text{kg})} = 2.454\times10^{16}.$$

$$|\,dN/dt\,| = \lambda N = (1.715\times10^{-17}\ \text{s}^{-1})(2.454\times10^{16}) = 0.421\ \text{decays/s}$$

(b)

$$|\,dN/dt\,| = (0.421\ \text{decays/s})(1\ \text{Ci}/(3.70\times10^{10}\ \text{decays/s})) = 1.14\times10^{-11}\ \text{Ci}$$

PROBLEM 14

The nucleus ^{15}O has a half-life of 122.2 s; ^{19}O has a half-life of 26.9 s. If at some time a sample contains equal amounts of ^{15}O and ^{19}O, what is the ratio of ^{15}O to ^{19}O

(a) after 4.0 minutes and

(b) after 15.0 minutes?

SOLUTION

(a)

$$\frac{2^{-240/122.2}}{2^{-240/26.9}} = 2^{(240)\left(\frac{1}{26.9}-\frac{1}{122.2}\right)} = 124.$$

(b) the ratio is 7.15×10^{7}.

PROBLEM 15

A bone fragment found in a cave believed to have been inhabited by early humans contains 0.21 times as much ^{14}C as an equal amount of carbon in the atmosphere when the organism containing the bone died. Find the approximate age of the fragment.

SOLUTION

$$N / N_0 = 0.21$$

$$0.21 = e^{-\lambda t} \text{ so } \ln(0.21) = -\lambda t \text{ and } t = -\ln(0.21)/\lambda$$

$$\lambda = 1.209\times10^{-4}\ \text{y}^{-1} \text{ for } {}^{14}\text{C}. \quad \text{Thus } t = \frac{-\ln(0.21)}{1.209\times10^{-4}\ \text{y}} = 1.3\times10^{4}\ \text{y}.$$

PROBLEM 16

The ratio of U235 to U238 in natural uranium deposits today is 0.0072. What was this ratio 2.0 × 10^9 y ago?

The half-lives of the two isotopes are 7.04 × 10^8 y and 44.7 × 10^8 y, respectively.

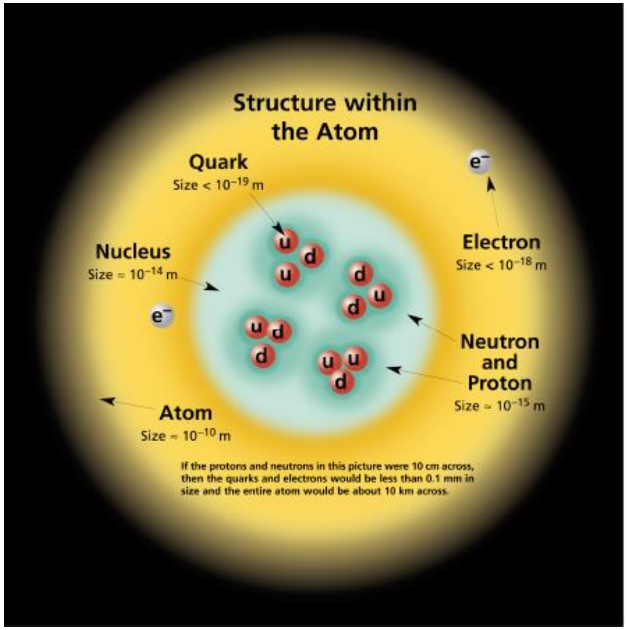
SOLUTION

$$\frac{N_5(t)}{N_8(t)} = \frac{N_5(0)}{N_8(0)} e^{-(\lambda_5 - \lambda_8)t}.$$

$$\frac{N_5(0)}{N_8(0)} = \frac{N_5(t)}{N_8(t)} e^{(\lambda_5 - \lambda_8)t}.$$

$$\frac{N_5(0)}{N_8(0)} = \frac{N_5(t)}{N_8(t)} e^{(\lambda_5 - \lambda_8)t} = (0.0072)(e^{1.66}) = 0.0379 \approx 3.8\%.$$

5 Fundamental Particles. Quarks



More than 30 long-lived particles and antiparticles have been detected experimentally.

(An **antiparticle** has the same mass and spin as its associated particle, but the electromagnetic properties, such as charge and magnetic moment, are opposite in a particle and its antiparticle.
EX: electron and positron)

Hundreds of resonances particles have been observed.
In contrast with the relatively stable particles, a resonance particle is extremely short-lived (< 10^{-21} s).

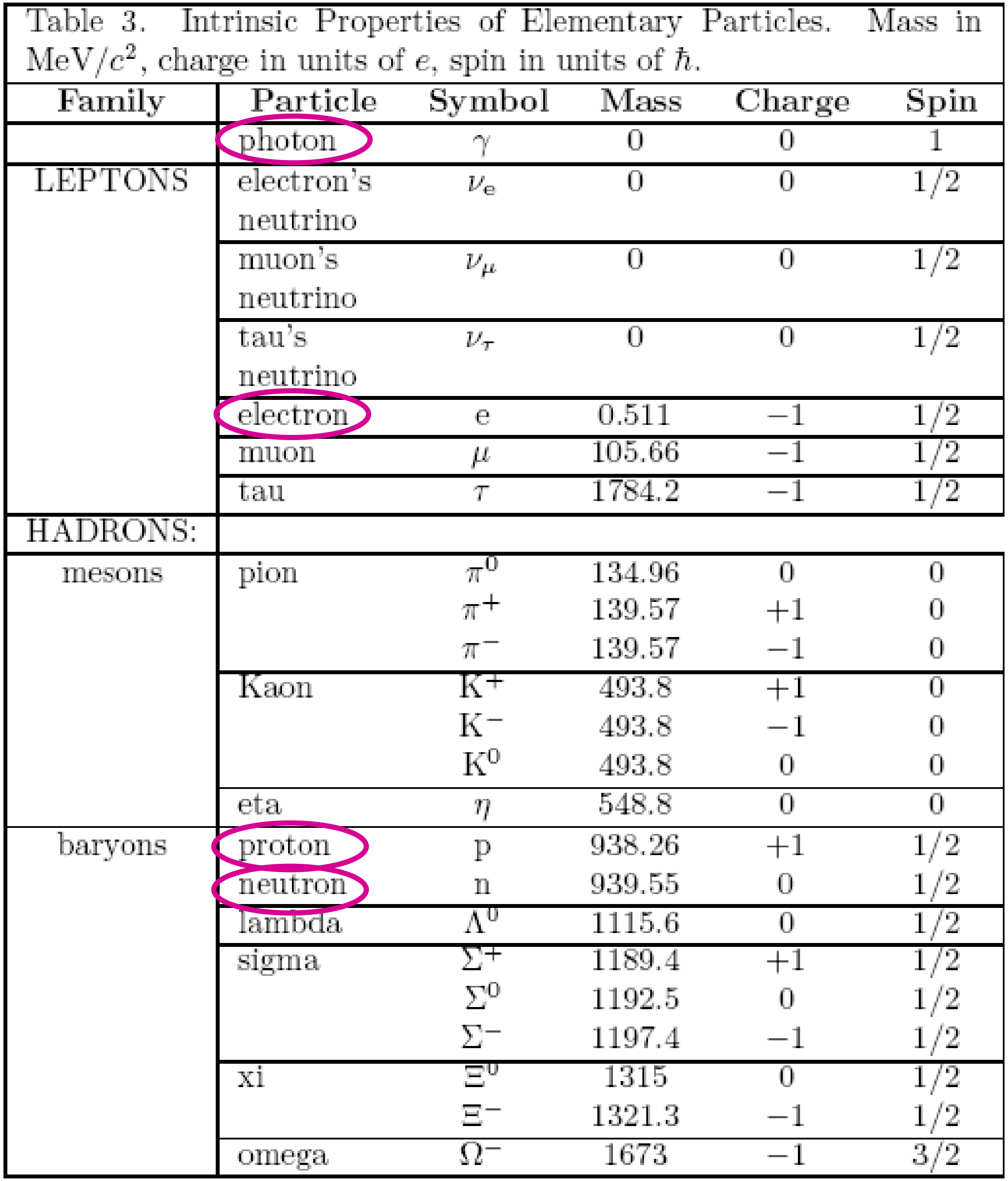


Table 3. Intrinsic Properties of Elementary Particles. Mass in MeV/c^2, charge in units of e, spin in units of $\hbar$.

Family	Particle	Symbol	Mass	Charge	Spin
	photon	γ	0	0	1
LEPTONS	electron's neutrino	ν_e	0	0	1/2
	muon's neutrino	ν_μ	0	0	1/2
	tau's neutrino	ν_τ	0	0	1/2
	electron	e	0.511	−1	1/2
	muon	μ	105.66	−1	1/2
	tau	τ	1784.2	−1	1/2
HADRONS:					
mesons	pion	π^0	134.96	0	0
		π^+	139.57	+1	0
		π^-	139.57	−1	0
	Kaon	K^+	493.8	+1	0
		K^-	493.8	−1	0
		K^0	493.8	0	0
	eta	η	548.8	0	0
baryons	proton	p	938.26	+1	1/2
	neutron	n	939.55	0	1/2
	lambda	Λ^0	1115.6	0	1/2
	sigma	Σ^+	1189.4	+1	1/2
		Σ^0	1192.5	0	1/2
		Σ^-	1197.4	−1	1/2
	xi	Ξ^0	1315	0	1/2
		Ξ^-	1321.3	−1	1/2
	omega	Ω^-	1673	−1	3/2

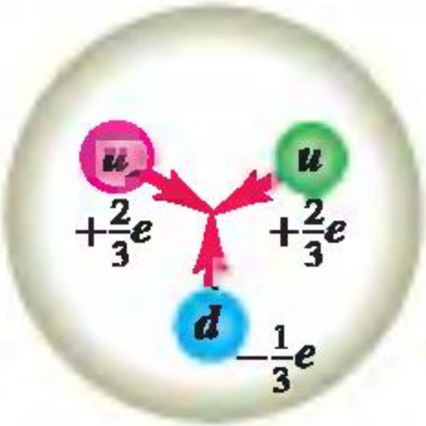
truly elementary particle (not composed of smaller entities)

composed of more basic particles (quarks)

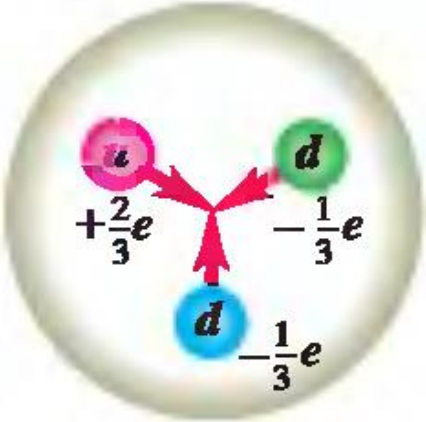
QUARKS MODEL (M. Gell-Mann and G. Zweig, 1963)

Hadrons are built from six quarks (u, d, s, c, b, t)
and their six **antiquarks** ($\bar{u}$, $\bar{d}$, $\bar{s}$, $\bar{c}$, $\bar{b}$, $\bar{t}$).

u : up,
d : down
s : strange
c : charm
b : bottom
t : top



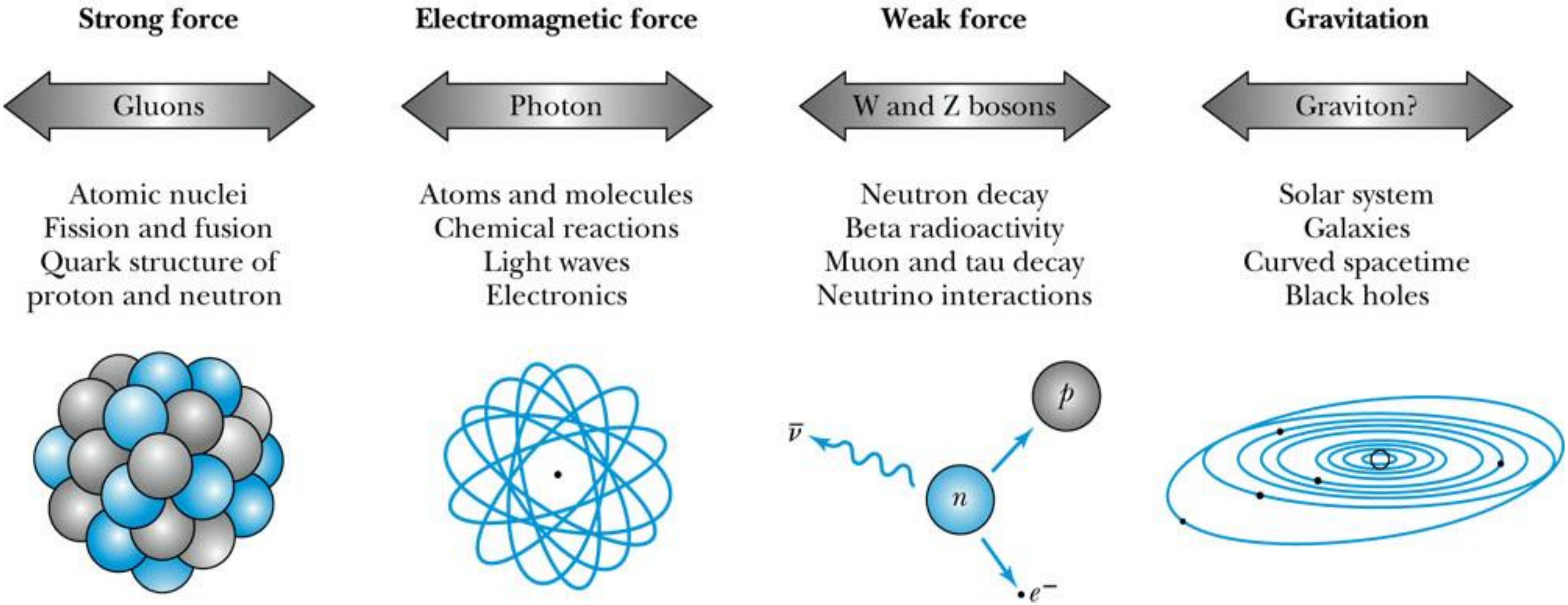
Proton (p)



Neutron (n)

proton quark content : (uud)
antiproton quark content : ($\bar{u}$, $\bar{u}$, $\bar{d}$)
neutron quark content : (udd)
antineutron quark content : ($\bar{u}$, $\bar{d}$, $\bar{d}$)

The Fundamental Interactions



Strong force	**Electromagnetic force**	**Weak force**	**Gravitation**
Gluons	Photon	W and Z bosons	Graviton?
Atomic nuclei Fission and fusion Quark structure of proton and neutron	Atoms and molecules Chemical reactions Light waves Electronics	Neutron decay Beta radioactivity Muon and tau decay Neutrino interactions	Solar system Galaxies Curved spacetime Black holes

The Standard Model

Three families of particles:

(1) the six leptons, which have no strong interactions;

(2) the six quarks, from which all hadrons are made;

(3) the particles that mediate the various interactions. These mediators are :

Gluons for the strong interaction among quarks, Photons for the electromagnetic interaction,

$W^{\pm}$ and Z^0 particles for the weak interaction

Graviton for the gravitational interaction.