Chapter 30

Nuclear Physics
Atomic Nuclei

- Rutherford’s discovery of the atomic nucleus caused scientists to ask how the nucleus was put together.
- Every nucleus is composed of particles called protons and neutrons.
- Different elements have different numbers of these two particles in the nuclei.
- The protons and neutrons in most nuclei are bound together very tightly.
  - Generally, can be treated as a simple, unbreakable particle in chemical reactions or atomic spectra.
Nuclear Reactions

• In a **nuclear reaction**, a nucleus breaks apart or is assembled
• These reactions can release very large amounts of energy
Structure of the Nucleus

- Nuclei are composed of \textit{nucleons} – protons and neutrons
- Proton
  - $m_p = 1.673 \times 10^{-27}$ kg
  - Positively charged
  - Charge is $+e$
- Neutron
  - $m_n = 1.675 \times 10^{-27}$ kg
  - Electrically neutral
Atomic Number

- Every nucleus can be specified by the numbers of protons and neutrons it contains.
- The number of protons is called the atomic number.
  - Symbolized by Z.
  - Each element has a particular and unique number of protons.
  - Therefore, each has a characteristic value of Z.
- Z also equals the number of electrons in an atom.
  - Since atoms are electrically neutral, the number of electrons will equal the number of protons.
The number of neutrons is symbolized by $N$
- The value of $N$ for a particular element can vary
- The **mass number**, $A$, is the sum of the number of protons and neutrons
  - $A = Z + N$
- Notation: $^{A}_{Z}X$
  - $X$ is the symbol for the element
- Example: $^{4}_{2}He$
  - The element is He
  - The mass number, $A$, is 4
  - The atomic number, $Z$, is 2
  - Therefore, there are 2 neutrons in the nucleus
Isotopes

- Elements with various numbers of neutrons are called **isotopes**
  - All isotopes of a particular element will have the same number of protons and electrons
    - Same Z, but different N
  - The chemical properties are determined by the bonding electrons, so the chemical properties of different isotopes of a given element are essentially identical
- Example: $^3_2\text{He}$, $^4_2\text{He}$, $^6_2\text{He}$
Isotopes and Atomic Mass

• The **atomic mass** of an atom is the mass of the nucleus plus Z electrons
• The atomic masses of different isotopes are different
• The periodic table contains an average value of the atomic mass for each element based on the *natural abundance* of each isotope
• The value listed in the periodic table is the mass in grams of 1 mole of atoms
Rutherford’s Scattering Experiment

• In a scattering experiment, a projectile particle is fired at a target particle
• Rutherford’s observation that some alpha particles were “backscattered” implies a very massive nucleus
  • They were scattered back in the direction from which they came
• The experiment can be explained in terms of conservation of momentum and energy in an elastic collision
Size of the Nucleus

- Rutherford’s experiment treated the alpha particles as very small particles.
- They could pass through the atom or be scattered over a large range of directions.
- It showed the alpha particle is smaller than the size of the atom itself.

Section 30.1
Size of the Nucleus, cont.

- Most nuclei have an approximately spherical shape.
- The radius, \( r \), depends on the number of nucleons it contains.
  \[
  r = r_0 A^{1/3} \text{ or } A = \left(\frac{r}{r_0}\right)^3
  \]
- \( r_0 \approx 1.2 \text{ fm} = 1.2 \times 10^{-15} \text{ m} \)
Potential Energy

- Since the protons in the nucleus are charged particles, they have a potential energy associated with them.
  \[
  PE = \frac{k(+e)(+e)}{r^2} = 2 \times 10^{-13} \text{ J} \approx 1 \text{ MeV}
  \]

  - This is very large compared to the typical atomic-scale energy of around 10 eV.
  - This is much larger than the energies associated with electrons, molecules, and chemical reactions.
Forces in the Nucleus

- The protons in the nucleus repel one another with a large force.
- To make the nucleus stable, there must be another even stronger force acting to attract them.
- This force is called the **strong force**.
- The strong force attracts any two nucleons to each other.
Strong Force

THE STRONG FORCE ACTS BETWEEN ANY TWO NUCLEONS

Two neutrons are attracted to each other by the strong force.

A neutron and a proton are attracted by the strong force.

The total force between two protons is the sum of the electric and strong forces.

- Pairs of protons, pairs of neutrons, and protons and neutrons all attract via the strong force
- If only two protons are involved, the electric force is greater in magnitude than the strong force
  - A nucleus containing just two protons is not stable

Section 30.1
The strong force has an approximately constant magnitude when the nucleons are about 1 fm apart.

The force is negligible when the distance is greater.

The strong force does not play any role in binding electrons.
Stability in the Nucleus

- Neutrons are essential for the stability of the nucleus.
- A neutron placed between two protons will add an attractive force that overcomes the Coulomb repulsion.
  - It will also increase the distance between the protons and decrease the Coulomb force.

The strong force attracts these protons to a neutron located between them.
Stability in the Nucleus, cont.

• The number of neutrons generally increases as the atomic number increases
  • As more and more protons are added to the nucleus, more and more neutrons are needed to keep the protons sufficiently separated so that the Coulomb force does not cause the nucleus to fly apart
• Adding too many neutrons eventually results in an unstable nucleus
• This is explained by the quantum theory of the nucleus called the **nuclear shell model**
  • There are energy levels of nucleons inside a nucleus, similar to the energy levels of electrons within an atom

Section 30.1
Mass and Energy Scales

- Electric potential energy of protons in a nucleus is on the order of MeV
- The potential energy associated with the strong force is negative and also on the order of MeV
- The rest energy of the proton and neutron can be found from $E = mc^2$
  - $E_p = 938$ MeV
- Mass can be expressed in units of energy/c$^2$
  - $m_p = 938$ MeV/c$^2$
- Mass can also be expressed in atomic mass units [u]
  - $1 \text{ u} = 1.66 \times 10^{-27} \text{ kg} = 931.5$ MeV/c$^2$
### Properties of Particles

#### TABLE 30.1 Properties of the Proton, Neutron, and Electron

<table>
<thead>
<tr>
<th>Particle</th>
<th>Charge</th>
<th>Mass (kg)</th>
<th>Mass (atomic mass units(^a = \text{u}))</th>
<th>Mass (MeV/c(^2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proton</td>
<td>+(e)</td>
<td>(1.6726 \times 10^{-27})</td>
<td>1.0073</td>
<td>938.27</td>
</tr>
<tr>
<td>Neutron</td>
<td>0</td>
<td>(1.6749 \times 10^{-27})</td>
<td>1.0087</td>
<td>939.57</td>
</tr>
<tr>
<td>Electron</td>
<td>−(e)</td>
<td>(9.109 \times 10^{-31})</td>
<td>(5.486 \times 10^{-4})</td>
<td>0.5110</td>
</tr>
</tbody>
</table>

\(^a\)1 u corresponds to 931.5 MeV/c\(^2\).
Radioactivity

• Some nuclei are unstable and decay spontaneously into two or more particles
• This process is called \textit{radioactive decay}
  • The term \textit{radioactivity} refers to the process in which a nucleus spontaneously emits either particles or radiation
• When a nucleus decays, it can emit particles or photons
• The decay products were originally called \textit{alpha}, \textit{beta} and \textit{gamma}
  • Generally all are called “radiation” even though only gamma is actually a form of electromagnetic radiation
Alpha Particles

• An alpha particle is composed of two protons and two neutrons
  • This is a He nucleus and is denoted as $^4_2\text{He}$
• The alpha particle generally does not carry any bound electrons, so it has a charge of $+2e$
Alpha Particles, cont.

- Decays follow patterns similar to chemical reactions
  - Parent nucleus $\rightarrow$ daughter nucleus + alpha particle
    - The daughter nucleus and the alpha particle are collectively known as *decay products*
- Example of a nuclear decay that produces an alpha particle:
  \[
  \frac{226}{88} Ra \rightarrow \frac{222}{86} Rn + \frac{4}{2} He
  \]
- The number of nucleons is conserved
- The numbers of protons and neutrons are separately conserved

Section 30.2
Beta Particles

- There are two varieties of beta particles
  - Negatively charged particle is an electron
  - Positively charged particle is a **positron**
    - The antiparticle of the electron
    - Except for charge, identical to the electron
- Electrons and positrons have the same mass
- They are both point charges
Beta Particles, cont.

- Decays follow this pattern
  - Parent nucleus $\rightarrow$ daughter nucleus + beta particle + antineutrino
Beta Particles, final

- Example of a nuclear decay that produces a beta particle:
  \[ _6^\text{14}C \rightarrow _7^\text{14}N + e^{-1} + \bar{\nu} \]
- The number of nucleons is conserved
  - A neutron is converted to a proton
- Electric charge is conserved
Gamma Decay

- Gamma decay produces photons
- Decays produce the following pattern
  - Parent nucleus $\rightarrow$ daughter nucleus + gamma ray
- Example of a nuclear decay that produces a gamma ray:
  $^{14}_7N^* \rightarrow ^{14}_7N + \gamma$
  - The asterisk denotes that the nucleus is in an excited state

Section 30.2
Gamma Rays and Energy Levels

- The excited nucleus can emit gamma rays with many different energies
  - Depends on which excited and final states are involved
- Typical gamma rays have energies from about 10 keV to 100 MeV or higher
Gamma Rays vs. X-rays

- Gamma rays and X-rays are both portions of the electromagnetic spectrum
- Their energy ranges overlap
- By convention, the distinction is based on the origin of the radiation
  - Gamma rays are produced in nuclear reactions
  - X-rays are generated by processes involving atomic electrons
Conservation Rules

• Conservation of mass-energy
  • The total energy at the start of the decay must equal the total energy at the end of the decay
  • You must also account for the conversion of mass to energy and energy to mass

• Conservation of momentum

• Conservation of electric charge
  • The total number of charged particles may change, but the total amount of charge will not

• Conservation of nucleon number

Section 30.2
Radioactive Decay Series

• When a nucleus undergoes a radioactive decay, it may be converted into another type nucleus
  • If the process involves alpha or beta emissions
• The decay reactions often continue through numerous steps
• Eventually, a stable daughter nucleus is produced
Decay Series, Example

- The original parent nucleus is $^{238}_{92}U$ and the final product is $^{\text{206}}_{82}Pb$.
- Beta decays are indicated by horizontal arrows to the right.
  - The number of protons increases by 1.
- Diagonal arrows represent alpha decays.
  - Reduces the proton number by two and the neutron number by two.

Section 30.2
• The alpha particle consists of two protons and two neutrons
  • The total mass of the individual particles is 4.0320 u
  • The mass of the actual alpha particle is 4.0015 u
• The difference is due to the binding energy of the alpha particle, \( E_{\text{binding}} = (\Delta m)c^2 \)
• For the alpha particle, \( \Delta m = -0.0305 \text{ u} \) and \( E_{\text{binding}} = -28.4 \text{ MeV} \)
• The alpha particle has a lower energy than a collection of separated protons and neutrons
• The alpha particle is therefore more stable than the collection and will not spontaneously decay

Section 30.2
Energy in a Nuclear Reaction

- Total mass before = 226.0234 u
- Total mass after = 226.0202 u
- $E_{\text{reaction}} = -4.8$ MeV
- This energy is typically released as kinetic energy of the products
- To conserve momentum, the products are emitted in opposite directions

Section 30.2
Half-life

- Individual nuclei decay one at a time, at random times
  - It is not possible to predict when a particular nucleus will decay
  - This randomness is a feature of quantum theory
- The probability for decay can be given
- The probability is specified in terms of the *half-life* of the nucleus, $T_{1/2}$
- Assume an initial number of nuclei, $N_0$, are present in a sample at $t = 0$
- At time $t = T_{1/2}$, half of the nuclei will have decayed

Section 30.2
Half-life, cont.

- At time $t = 2 \, T_{1/2}$, there will be $N_0 / 4$ nuclei remaining.
- This decay curve is described by an exponential function.
- The decay constant, $\lambda$, is defined so that

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

Section 30.2
In terms of the decay constant, the half-life is

\[ T_{1/2} = \frac{\ln 2}{\lambda} \approx \frac{0.693}{\lambda} \]

A large decay constant means a short half-life and a small decay constant means a long half-life.

Values for half-life vary widely.

**TABLE 30.2 Half-lives of Nucleons and Some Important Nuclei**

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>Half-life</th>
</tr>
</thead>
<tbody>
<tr>
<td>n (a free neutron)</td>
<td>10.4 min</td>
</tr>
<tr>
<td>(^1\text{H}) (a proton)</td>
<td>Stable</td>
</tr>
<tr>
<td>(^2\text{H}) (deuterium)</td>
<td>Stable</td>
</tr>
<tr>
<td>(^3\text{H}) (tritium)</td>
<td>12.33 yr</td>
</tr>
<tr>
<td>(^{14}\text{C})</td>
<td>5730 yr</td>
</tr>
<tr>
<td>(^{60}\text{Co})</td>
<td>5.27 yr</td>
</tr>
<tr>
<td>(^{123}\text{I})</td>
<td>13.2 h</td>
</tr>
<tr>
<td>(^{222}\text{Rn})</td>
<td>3.82 days</td>
</tr>
<tr>
<td>(^{226}\text{Ra})</td>
<td>1600 yr</td>
</tr>
<tr>
<td>(^{235}\text{U})</td>
<td>(7.04 \times 10^8) yr</td>
</tr>
<tr>
<td>(^{238}\text{U})</td>
<td>(4.47 \times 10^9) yr</td>
</tr>
</tbody>
</table>
Measuring Radioactivity – Activity

- The “strength” of a radioactive sample is measured using a property called its activity.
- This can be measured with a Geiger counter.
- The activity is proportional to the number of nuclei that decay in one second.

Section 30.2
Geiger Counter

- Invented by Hans Geiger
  - Student of Rutherford
- Detects the passage of a fast-moving particle through a gas
- The particle ionizes the gas and a current flows between the central wire and the walls
- Current comes as short pulses, giving the “clicks”
Measuring Radioactivity – Units

• A common unit of activity is the Curie (Ci)
  • $1 \text{ Ci} = 3.7 \times 10^{10} \text{ decays / s}$
  • In practice, a sample with this activity would be very dangerous
  • Most studies or medical uses involve activities of millicuries or microcuries

• The official SI unit of activity is the Becquerel (Bq)
  • $1 \text{ Bq} = 1 \text{ decay / s}$
Nuclear Stability

- To be stable, a nucleus containing two or more protons must contain neutrons.
- The dashed line in the plot indicates $N = Z$.
- Low-mass nuclei tend to have equal numbers of protons and neutrons.
- Heavy nuclei will contain more neutrons than protons.
Nuclear Stability, cont.

- The He nucleus is stable because the neutrons can “sit” between the protons and hold the nucleus together.
- Adding another proton produces the need for more neutrons to keep the protons apart and provide the needed strong force.
- As the number of protons grows, more neutrons are needed.

Section 30.3
Nuclear Binding Energy

• For stable nuclei, the mass of a nucleus containing N neutrons and Z protons is less than the total mass of N isolated neutrons plus Z isolated protons.

• The mass difference is connected to the binding energy of the nucleus through $E = mc^2$.

• The binding energy can be found by finding the mass of the nucleus and then subtracting the mass of the same numbers of isolated protons and neutrons.

• The most stable nuclei are those with the largest binding energy.
  • Near Fe and Ni with $A \approx 60$
Nuclear Binding Energy, Graph

Section 30.3
Nuclear Fission

• Radioactive decay can be induced by a collision between two nuclei or by the collision of a neutron with a nucleus

• An important example occurs when $^{235}U$ collides with a neutron:

\[ ^1_0 n + ^{235}_{92}U \rightarrow ^{130}_{56}Ba + ^9_{36}Kr + 3^1_0 n \]

• This type of reaction is called *nuclear fission*, the main products are two nuclei, both roughly half the size of the original parent nucleus

Section 30.3
Features of Fission Reactions

• There can be many different possible reaction products
• The reaction produces more free neutrons than it uses
  • These free neutrons can then induce fission in other nearby uranium nuclei, creating a chain reaction
• The reaction releases energy
  • The extra binding energy is released in the form of gamma rays and through the kinetic energies of the particles produced
Factors Influencing the Reaction

- Natural uranium is more than 99% $^{238}\text{U}$ which does not readily undergo fission
  - Natural uranium is enriched to increase the concentration of $^{235}\text{U}$
  - This is a difficult engineering process
- If the piece of uranium is small, many of the nuclei are close enough to the surface that many of the released neutrons escape before inducing another fission event
  - The critical mass is the minimum amount of nuclear fuel material needed to sustain a chain reaction
Energy from Fission

- The binding energy per nucleon of $^{235}_{92}U$ is about -7.6 MeV
- For many of the products, the binding energy is about -8.5 MeV
- The difference is -0.9 MeV
- Since there are 235 nucleons, the total energy per nucleus is about 210 MeV
- For one gram of pure $^{235}_{92}U$, this would correspond to a total energy of about $9 \times 10^{10}$ J
  - For comparison, one gram of TNT releases about 4200 J
Nuclear Power Plants

• Nuclear fission is used in a controlled way in nuclear power plants.

• Safely is always a major concern at a nuclear fission reactor.
  • All reactors are designed with extensive safety features.
  • The latest designs include passive safety features that do not require operator action or electronic feedback to deal with emergency situations.
• **Fuel rods** contain $^{235}_{92}U$ that can be added or removed from the core while the reactor is operating

• **Control rods** contain materials that absorb neutrons
  • They can be inserted or removed from the core to control the number of free neutrons and adjust the fission rate
• Moderator circulates through the core
  • Often water
  • One function is to slow down the neutrons to increase the probability they will induce a fission event
  • It also carries away heat to a separate steam engine where a generator converts it to electrical energy
• This heat engine operates according to the laws of thermodynamics
  • Including needing a cold reservoir
Fusion Reactions

- In **nuclear fusion**, two nuclei join together to produce one new particle.
- An example reaction:
  \[ ^6_3 Li + ^6_3 Li \rightarrow ^{12}_6 C + \text{energy} \]
- This energy is in the form of gamma rays plus the kinetic energy of the carbon nucleus.
- The energy released is about 2.5 MeV / nucleon.
  - This is more energy per nucleon than fission.
Fusion and the Sun

• Nuclear fusion is the process that powers stars
• Hydrogen nuclei are fused to form helium nuclei
  • Heavier elements can also be formed by fusion
• Fusion reactions can take place in the Sun due to the high temperatures and pressures in the core
  • To produce fusion on Earth, you have to give the nuclei high speeds and keep them close together
  • Experimental designs for fusion power plants are being built
Biological Effects

• The biological effects of radioactivity result from the way the decay or reaction products interact with atoms and molecules.

• The typical binding energy of an electron in an atom is on the order of 10 eV.

• The energy released in a nuclear reaction is typically several MeV.

• If one of the particles collides with an atomic electron, there is enough energy to eject the electron from the atom or break a chemical bond in molecules.
Amount of Damage

- The amount of damage that a particular particle is capable of doing is difficult to predict.
- Some of the complications include:
  - Type of particle
    - Alpha, beta and gamma radiation all have different masses and charges and therefore interact with tissue in different ways.
  - The amount of kinetic energy carried by a particle varies.

Section 30.4
• **Radiation absorbed dose – rad**
  - 1 rad is the amount of radiation that deposits $10^{-2}$ J of energy into 1 kg of absorbing material
    - The unit accounts for both the amount of energy carried by the particle and the efficiency with which the energy is absorbed

• **Relative biological effectiveness – RBE**
  - This measures how efficiently a particular type of particle damages tissue
  - This accounts for the fact that different types of particles can do different amounts of damage even if they deposit the same amount of energy
Measuring Damage, cont.

• RBE value tends to increase as the mass of the particle increases

• **Röntgen Equivalent in Man – rem**
  - Dose in rem = (dose in rad) x RBE
  - This combines the amount and effectiveness of the radiation absorbed

**TABLE 30.3 Relative Biological Effectiveness (RBE) for Different Types of Radiation**

<table>
<thead>
<tr>
<th>Radiation</th>
<th>RBE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alpha particles</td>
<td>10–20</td>
</tr>
<tr>
<td>Beta particles</td>
<td>1.0–1.7</td>
</tr>
<tr>
<td>Gamma rays and X-rays</td>
<td>1.0</td>
</tr>
<tr>
<td>Slow neutrons</td>
<td>4–5</td>
</tr>
<tr>
<td>Protons</td>
<td>5</td>
</tr>
<tr>
<td>Fast neutrons</td>
<td>10</td>
</tr>
<tr>
<td>Heavy ions</td>
<td>20</td>
</tr>
</tbody>
</table>

Section 30.4
Radiation Damage

• When the radiation dose is low, cells are sometimes able to repair the damage
  • Especially if the dose is absorbed over long periods of time
  • Generally, small amounts of radiation do not cause significant harm to living cells

• If the radiation dose is very large, cells can be completely destroyed

• At intermediate doses, cells survive but often malfunction as a result of the damage
  • A typical result is that the affected cells reproduce in an uncontrolled fashion, leading to cancer
Radiation damage is usually most severe for quickly dividing cells

- Many types of blood and bone marrow cells fall into the category
- Cancerous cells are also quickly dividing, so radiation can be used as a tool to selectively destroy cancer cells

The amount of damage can depend strongly on where the radiation source is located

- For example, an alpha particle outside the body will be stopped in the outer layer of skin and do relatively little damage
- If a person ingests an alpha particle it can do a great deal of damage to nearby cells

Section 30.4
**TABLE 30.4** Radiation Doses in Perspective (Typical Values)

<table>
<thead>
<tr>
<th>Activity</th>
<th>Dose (mrem)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Airline flight from New York City to Los Angeles</td>
<td>3</td>
</tr>
<tr>
<td>Dental X-ray</td>
<td>10</td>
</tr>
<tr>
<td>Chest X-ray</td>
<td>5–10</td>
</tr>
<tr>
<td>Mammogram</td>
<td>50–100</td>
</tr>
<tr>
<td>Approximate annual dose from natural background sources</td>
<td>300</td>
</tr>
<tr>
<td>Recommended maximum annual dose in addition to background dose</td>
<td>500</td>
</tr>
<tr>
<td><em>Apollo XVI</em> astronauts</td>
<td>500</td>
</tr>
<tr>
<td>1-in-30 risk of cancer</td>
<td>10,000</td>
</tr>
<tr>
<td>Radiation sickness possible</td>
<td>60,000</td>
</tr>
</tbody>
</table>
Radiation in Everyday Life

• For common medical procedures, the benefits usually outweigh the risk of exposure

• Natural exposure occurs from many sources
  • Cosmic rays – a collection of many different types of particles from outer space
  • Radon – produced by the decay of $^{238}\text{U}$ in rocks and soil
Radioactive Tracers

- A *radioactive tracer* is a chemical that contains radioactive nuclei.
- The movements of the tracer nuclei can be monitored by observing the radiation they emit through decay.
- Tracers are widely used in medicine and many other fields.
- Examples include:
  - Nuclear stress testing
  - PET scanning
  - Thyroid cancer fighting
Radiation and Cancer Treatment

- Radiation treatments are effective in treating many types of cancer
- Radioactive materials emit high energy electrons or gamma rays that kill nearby cancer cells
- Examples include
  - Breast cancer
  - Prostate cancer

Section 30.5
Carbon Dating

- Cosmic rays interacting with atmospheric nitrogen produce $^{14}\text{C}$
- $^{14}\text{C}$ is radioactive with a $T_{1/2} = 5730$ years
- Carbon dating is done by measuring the ratio of C-14 to C-12 and observing the decrease due to the decay of the $^{14}\text{C}$
MRI

- **Magnetic resonance imaging** (MRI) makes use of the magnetic properties of nuclei.
- Protons can have spin up or spin down states:
  - In a magnetic field, each state has a different energy.

![MRI Device Image](image-url)
The presence of a photon can be detected by observing the absorption of a photon that induces a transition to the higher energy state. The absorption occurs only if the separation between the energy levels matches the photon energy. An MRI magnet is designed so the energies match only at a particular spot within the body. The MRI signal gives the density of protons at that spot. By scanning this spot around the body, a three-dimensional image can be constructed.
New Conservation Law

• Nuclear physics reveals a new conservation law – conservation of nucleon number
  • All known nuclear reactions conserve the number of nucleons
  • Physicists don’t know why nucleon number is conserved
• Number conservation rules do not apply to all particles
  • For example, electron number is not conserved in all reactions
Quarks

- Nucleons are composed of particles called **quarks**
  - Determined by scattering experiments
- There are several different types of quarks
- All carry electric charge of $\pm e/3$ or $\pm 2e/3$
- Protons and neutrons are each composed of three quarks