Lecture 3: Matter

Reading: Section 5-7

Key Ideas

Fundamental Particles
- Matter and Anti-matter

Structure of Atoms
- Nucleus of protons & neutrons orbited by electrons
- Elements, Isotopes, & Radioactivity
- Ionization

Structure of Molecules

State of Matter
- Effects of temperature

Range of Ordinary Matter

- Fundamental particles (quarks & leptons)
- Subatomic particles: protons, neutrons, & electrons
- Single atoms (hydrogen, helium, gold, etc.)
- Simple molecules (O_2, H_2O)
- Macromolecules (DNA, complex polymers)
- Macroscopic objects (rocks, people, planets …)

Ordinary matter is mostly in the form of atoms and molecules

Fundamental & Subatomic Particles

<u>Protons and neutrons</u>
- Made of up quarks
- Proton – 2 up and 1 down quarks
- Neutron – 1 up and 2 down quarks

<u>Electrons</u>

A zoo of other particles, such as neutrinos, pions, D mesons, etc. which are of vast interest to particle physicists

Matter and Anti-matter

Each particle has an “anti-particle”.

This “anti-particle” has

the same mass as the particle
the opposite charge (if possible)

Proton – Anti-proton
Neutron – Anti-neutron
Electron-Positron

When matter and anti-matter encounter each other, they annihilate and produce energy.

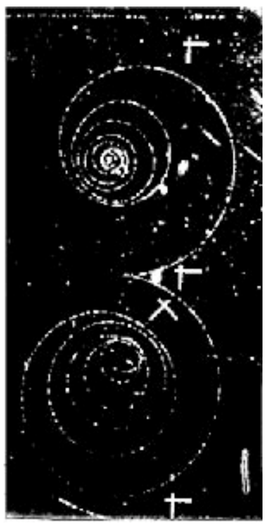

Image of electron & positron in bubble chamber under a magnetic force

Same mass, opposite charge

Apparently appear out of nowhere

Energy & Matter

E=mc^2

Matter can be turned into energy, for example electron and positron can annihilate.

Energy can be turned into matter, for example two photons can combine to create an electron-positron pair.

How much energy is needed per photon to make an electron-positron pair?

Use equations:
$E = mc^2$ and $E = \dfrac{hc}{\lambda}$

Find λ=0.0006 nanometers

This is a gamma-ray. Very energetic!

Atoms

Nucleus of heavy subatomic particles:

- Proton: positively charged
- Neutron: uncharged (neutral)

Electrons orbiting the nucleus:

- Negatively charged particles
- $1/1836^{th}$ the mass of a proton

Atoms are mostly empty space:

- Only 1 part in 10^{15} of space is occupied
- The rest of the volume is threaded by electromagnetic fields

Chemical Elements

Distinguish atoms into *Elements* by the *number of protons* in the nucleus.

<u>Atomic Number:</u>

- 1 proton=Hydrogen
- 2 protons=Helium
- 3 protons=Lithium … and so on

Numbers of electrons = Numbers of protons for neutral atoms

Periodic Table: See Box 5-5 in your book

Some Abbreviations

Hydrogen – 1 proton – "H"
Helium – 2 protons – "He"
Carbon – 6 protons – "C"
Nitrogen – 7 protons – "N"
Oxygen – 8 protons – "O"
Iron – "Fe"

Known Elements

- 117 elements are currently known
- 87 are metals
- 11 are gasses
- 2 occur as liquids (Bromine & Mercury)
- 26 are natural radioactive elements
- 24 are only made in particle accelerators (on Earth)

In addition, each element can have a number of different *isotopes*.

Top Ten Most Abundant Elements

10) Sulfur
9) Magnesium
8) Iron
7) Silicon
6) Nitrogen
5) Neon
4) Carbon
3) Oxygen
2) Helium
1) Hydrogen

Explaining the formation of the elements is one of the triumphs of modern astrophysics.

Isotopes

A given element can have many *isotopes*

Same number of *protons*
Different number of *neutrons*

<u>Example:</u> Carbon Isotopes
^{12}C has 6 protons and 6 neutrons
^{13}C has 6 protons and 7 neutrons
^{14}C has 6 protons and 8 neutrons

Chemically *identical*, but *different masses*

Radioactivity

If a nucleus has too many or too few neutrons, it is unstable to radioactive decay

Examples

$^{3}H \rightarrow {}^{3}He + e^{-} + \nu_e$
$^{14}C \rightarrow {}^{14}N + e^{-} + \nu_e$

Free neutrons are unstable

$n \rightarrow p + e^{-} + \nu_e$

Ionization

Neutral atoms have the same number of electrons orbiting the nucleus as there are protons in the nucleus.
Ionized atoms have unequal numbers of electrons and protons. Usually there are fewer electrons than protons, because one or more electrons have been knocked out.
Notation for different ionization states:
He for neutral helium
He^{+} for singly ionized helium (2 protons, 1 electron)
He^{++} for doubly ionized helium (2 protons, 0 electrons)

Molecules

<u>Two or more atoms</u> held together by electromagnetic forces

Examples of common molecules
H_2O – water
CO – carbon monoxide
CO_2 – carbon dioxide
O_3 – ozone
NH_3 – ammonia

Binding Energies

Some forms of matter are more tightly bound than others. It takes more energy to pry them apart.

From lowest to highest binding energy:

- Molecules
- Atoms
- Nuclei
- Protons and Neutrons

Temperature

Temperature is a measurement energy content of an object

Solids:

Higher temperature means higher average vibrational energy per atom or molecule

Gases:

Higher temperature means more average kinetic energy (faster speeds) per atom or molecule.

Cold to Hot

In cold conditions, even particles that are weakly bound can survive, such as molecules and neutral atoms.

As the environmental gets hotter, molecules break apart into atoms, atoms become ionized, etc. and in the most extreme cases, protons & neutrons dissolve into quarks. The energy to break them apart comes from the other rapidly moving particles slamming into them or from energetic photons heating the material.

Atoms and Molecules

An atom of certain element can be changed into a different element through nuclear processes.

A molecule can be changed through chemical processes (changing the bounds between the atoms)

It takes much less energy for chemical reactions than for nuclear reactions (molecules are much less tightly bound)

Nuclear reactions are important in stars and will be the focus of most of our discussions of reactions. Chemical reactions are important in cooler regions, such as star forming clouds.

Another example of the difference between molecules or atoms: poisoning with arsenic and cyanide.