The discovery of nuclear chain reactions need not bring about the destruction of mankind any more than did the discovery of matches. We only must do everything in our power to safeguard against its abuse.

~ Albert Einstein

What do we know about the nucleus?

Rutherford discovered
- Contains positively charged particles (protons).
- Held together by a strong force.

James Chadwick and the discovery of the neutron

Scientists in the early 1900’s knew that there was too much mass in the nucleus for it to be composed only of protons. In the 1930’s, Chadwick performed experiments with Beryllium emissions (neutrons) and showed that they were a neutral particle with a mass about the same as a proton. (Their presence could be identified by the momentum of recoiling charged particles)

Modeling the nucleus

All of the previously discovered rules still apply.
- Electric force law – protons will repel each other.
- Wave-particle duality – protons and neutrons will behave as waves of probability.
- Pauli exclusion principle – only one proton (or neutron) can be in each possible state.

Compare atomic and nuclear models

- Electron energy levels first determined experimentally by measuring discrete emission spectra.
- Rydberg recognized a pattern.
- This led to an understanding of the quantum behavior of electrons.
- Electron energies can now be calculated exactly using electric force laws and equations for wave behavior.
- Nuclear energy levels have been measured experimentally.
- Scientists are still looking for details of patterns.
- While there is a lot we do understand, there are still some holes.
- Because we still do not know the equation for the nuclear strong force, we cannot calculate exact values for proton and neutron energies.

The Strong Interaction

Characteristics of the strong interaction:
1. Very strong, attractive force. (about 100 times stronger than the electrical force under comparable circumstances)
2. Acts only over a short range, about the size of a nucleon or so. Beyond that, the forces are zero.
3. Only between nucleons

- protons
- neutrons

A proton and a neutron are not affected by strong: electrons, photons, neutrinos.

Isotopes are atoms with the same number of protons but different numbers of neutrons.

Hydrogen isotopes:
- $^1_1\text{H}$ (Deuterium)
- $^2_1\text{H}$ (Tritium)

(average weight = 1.0079)

Helium isotopes:
- $^3_2\text{He}$
- $^4_2\text{He}$

(average weight = 4.0026)

Energy (mass) per nucleon: Why does the graph go down so steeply at low atomic mass?

$E = mc^2$

P1: Why would the graph increase at large atomic mass?

The graph abruptly ends. What does this tell us about the range of the nuclear strong force?

Nuclear energy:
- How does the mass of a proton in a hydrogen atom compare to the mass of a proton in a helium atom?
- How do the nuclear potential energies compare?
- How do nuclear forces explain this?
Combining two small nuclei to make a larger one gives off energy. Because nuclei are positively charged, you need either extremely hot reactants or large confining forces.

**Fusion**

Where do we get deuterium? $^2\text{H}$
- Seawater 0.015%

Where do we get tritium? $^3\text{H}$
- not much available in nature
  But we can make it, with accelerators!

Raw Material for Fusion

$$^6\text{Li} + ^1\text{n} \rightarrow ^4\text{He} + ^1\text{H}$$

**Yah but...**

- How do we get the hydrogen nuclei close enough for the strong force to make them stick?
  - hit together hard enough
  - temperature required? 30-100 million degrees
  - must be dense, close
  - What kind of container are you going to use?
    - Magnetic field? 1950 needed 400,000 x better.
    - Haven't reached break-even yet

**No confinement**

**Gravitational confinement**

**Confinement using magnetic fields: Tokamak**
the facility is very large, the size of a sports stadium
the fuel target is very small, the size of a BB-gun pellet
the laser system is very powerful, equal to 1,000 times the electric generating power of the United States, heats & compresses fuel
each laser pulse is very short, a few billionths of a second

Some Good News and Some Bad News for Fusion

Fuel is plentiful, in sea water
Clean – no atmospheric pollution
No danger of an accident
We can’t do it yet
Neutrons from fusion may cause equipment to become radioactive
No funding to pursue now (world – wide economy)

Another way to do nuclear energy
How does the mass of a proton in a uranium atom compare to the mass of a proton in an iron atom?
How do the nuclear potential energies compare?
How do nuclear forces explain this?

Fission
Breaking one extremely large nucleus into two smaller ones gives off energy.
Free neutrons from one fission can trigger another fission, creating a chain reaction.
This reaction is easy to control simply by changing the number of neutrons that are absorbed by inert atoms.
This reaction produces isotopes not normally found in nature.

Fission Process

Fission Reactor
Fissile material (fuel rods) $^{239}\text{U},\,^{235}\text{Pu}$
Moderator
Slow neutrons down
Control rods
Absorb extra neutrons
Problems
radioactive waste
fuel is rare
fuel can be misappropriated for weapons
mistakes are costly
Current applications for fission reactors

Some Good News and Some Bad News for Fission

- a natural fuel exists $^{235}\text{U}$ — ore is 0.7% $^{235}\text{U}$, rest is $^{238}\text{U}$, but hard to separate, also - you can make fuel (breeder reactor).
- Not much fuel needed.
- Lots of energy (shows up in energy of fragments)
- Public now fears it (half life of 30 years or more, $^{90}\text{Sr},^{137}\text{Cs}$)
- Breeder technology difficult - US has given up, but not France, Japan, Russia
- Some danger from accidents.
- What do you do with the waste?

When you look in more detail, what do you see? Why don’t all possible isotopes occur naturally?

Missing isotopes

We don’t see something we would expect to see … not all combinations of protons and neutrons occur. We don’t even find byproducts of naturally occurring fission. Why not?

Nature favors the state with the most disorder.

Radioactive Decay

The missing isotopes must change into atoms with less nuclear potential energy (mass).
The energy will be released as heat.
Any change must obey all of the laws

Radioactive decay

Important laws
Conservation of mass-energy … The total mass-energy before is the same as the total mass-energy after the decay. Things decay into atoms with less mass so that energy can be released.
Conservation of Charge … the total number of positive - negative charges before and after the reaction must be the same.
## Radioactive decay

Alpha decay – A nucleus emits 2 protons and 2 neutrons (a helium nucleus).

Beta decay – A proton changes into a neutron or vice versa

Gamma decay – Protons or neutrons shift energy levels and emit a photon.

## Nuclear Structure

- Electrostatic force (repulsion). It increases with Z since it is long range.
- Neutrons added to compensate.
- Too many neutrons, starts to beta decay.
- Too many protons, starts to alpha decay

**Bottom Line:** some isotopes are unstable and unstable isotopes are “radioactive.”

## Ionizing Radiation

The particles released in decay carry a lot of energy
- often a million times typical molecular binding energies
- danger to living cells
  - damage RNA or DNA causing death of cells or mutations
  - disrupt metabolic processes
  - cells with high activity seem more prone to damage than others (cancer therapy)

## Geiger Counter

The energetic particle from a nucleus ionizes gas molecules. A shower of electrons is collected on the wire and causes a small current. This current is observed by the counter. **Demo**

## Nuclear process are high energy

*Can knock electrons out of molecules*
- make them glow
- watch dials – radium excites powder, (the alpha decay)
- dial painters got cancer

## Marie Curie (1867-1934)

* Her thesis was on charge conductivity in air due to Becquerel’s rays from uranium.
* She proposed that they came from the nucleus itself and looked at other elements.
* She and Pierre chemically separated elements in pitchblende and ore (some from Utah). Three years to isolate 1/10 gram of radium chloride.
* Discoverer of radioactive elements polonium and radium in pitchblende.
* First person to win 2 Nobel prizes (physics 1903, chemistry 1911)
Alpha Decay
1. Alpha particles are known to be helium nuclei. Travel only a short range in materials (1-2 inches).

2. Example:
\[ ^{226}\text{Ra} \rightarrow ^{222}\text{Rn} + ^{4}\text{He} \]
(conservation of mass number)
(conservation of charge)

3. These alpha particles were the “bullets” for Rutherford and Chadwick (neutron).

Beta Decay
Example:
\[ ^{14}_6\text{C} \rightarrow ^{14}_7\text{N} + 0\cdot\text{e} \]
Must have mass-energy conservation!
Must have charge conservation!

P2: What element is X?
Where did the electron come from?

1.\text{neutron} \rightarrow 1.\text{proton} + 0.\text{electron}
2.\text{n} \rightarrow 1.\text{p} + 0.\text{e}

\(\beta\) particle has greater penetration than alpha.

Beta Decay (continued)
\[ ^{14}_6\text{C} \rightarrow ^{14}_7\text{N} + 0\cdot\text{e} \]
mass-energy missing in these exp’ts something else emitted besides 0\cdot\text{e}
Strange critter called \textit{neutrino}
“neutrino” = 0\text{neutrino}
- discovery of new elementary particle took 20 yrs (1959) - it has 0 charge & very little mass!
- hardly any interaction with matter. Go through the sun almost as if not there.

Beta Decay Summary
1. Beta particle (known to be an electron) and neutrino (ν) are emitted.
2. Example:
\[ ^{14}_6\text{C} \rightarrow ^{14}_7\text{N} + 0\cdot\text{e} + 0\cdot\nu \]
important to carbon dating

Forces
The force responsible for holding the nucleus together is 1) electromagnetic force 2) strong force 3) weak force 4) gravitational force

P3: The effect of the weak force is to 1) hold the nucleus together 2) change a proton into a neutron or vice versa 3) force the protons apart

Gamma Decay
1. Gamma rays are now known to be high energy photons.
2. Example
\[ ^{87}_36\text{Kr} \rightarrow ^{2}_Z\text{X} + 0\gamma \text{gamma ray} \]

P4: What is the element X here?
Half-life

Important Examples

$^{14}\text{C} \rightarrow 1^{\text{He}} + \, _{0}^{1}\text{e} + \, \text{neutrino} \, \text{(half-life of 5730 years)}$

$^{40}\text{K} \rightarrow 1^{\text{He}} + \, 2^{\text{Ar}} + \, \text{neutrino} \, \text{(half-life of 1.3 billion years)}$

Each half-life, half of the remaining atoms are left undecayed.

- One half-life $\rightarrow \frac{1}{2}$
- Two half-lives $\rightarrow \frac{1}{2} \times \frac{1}{2} = \frac{1}{4}$
- Three half-lives $\rightarrow \frac{1}{2} \times \frac{1}{2} \times \frac{1}{2} = \frac{1}{8}$

If the original number of atoms is known, the age of the sample can be determined by the fraction of atoms left.

This process is known as radioactive dating

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**P2: What is the half-life of this isotope?**

A sample of radioactive gas is produced. After 20 minutes, only $\frac{1}{4}$ of the original gas remains. What is the half life of the gas?

- a) 5 minute
- b) 10 minutes
- c) 15 minutes
- d) 20 minutes

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**P6: A sample of radioactive material with a half-life of 6 hours sits for a day (24 hrs). How much of the original material remains?**

- a) A half
- b) A quarter
- c) An eighth
- d) A sixteenth

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**Half-life experiment**

Demo: roll of sugar cubes

Case 1: Decay when you roll a 1.

For your first roll the probability of a decay is $\frac{1}{6} \approx 17\%$.

**P7:** After your first roll what is the probability of a decay?

After your second roll?

What is the half life for this radioactive material?

Case 2: Decay when you roll a 1, 2, or 3, probability of decay is 50%.
Radioisotope dating

$^{14}\text{C}$ concentration in organic material is used to date fairly recent previously living things.

$^{14}\text{C} \rightarrow ^{14}\text{N} + \beta^- + \text{neutrino}$ (half-life of 5730 years)

$^{40}\text{Ar}$ concentrations in rocks can be used to date older igneous rock samples.

$^{40}\text{K} + \beta^- \rightarrow ^{40}\text{Ar} + \text{neutrino}$ (half-life of 1.3 billion years)

Applications of carbon dating: Shroud of Turin

The Shroud of Turin

95% certainty that linen of shroud dates from no earlier than 13th century AD