Waves

A traveling disturbance consisting of coordinated vibrations that transmit energy with no net movement of the matter.

Source: some kind of disturbance from the state of equilibrium.

Propagation: due to some properties of the medium such as elasticity.

What happens?

Flick of hand produces a disturbance. This disturbance travels down the rope.

What happens if we continue to move hand up & down?

Disturbances travel in form of vibrations, but no matter is moved along the rope, just energy.

Examples of waves:

- Mechanical waves
  - Ripples on water, surface waves on water
  - Vibrating strings
  - Seismic waves (during earthquakes)
  - Sound

- Electromagnetic waves
  - Radio waves, Microwave, Infrared, Light, UV, X, γ

And there are more to come...

Transverse and longitudinal waves

Transverse: disturbances are perpendicular to propagation

Longitudinal: disturbances are parallel to propagation

Example of a wave pulse on a rope.

Example of a longitudinal wave:
Some properties of waves:

**QUESTION:** I generate waves on a rope. As I increase the displacement of my hand...

1. The wave will travel faster.
2. There will be no difference.
3. The wave will be "bigger".

The disturbance will be bigger: The **AMPLITUDE** will be larger.

Amplitude: The maximum displacement of points in a wave. Measured from zero (equilibrium position).

Amplitude "depends" on the source, but may change in the medium (damping).

**QUESTION:** If I swing my hand up & down faster...

1. The wave will travel faster.
2. The wave will have larger amplitude.
3. None of the above.

Answer 3: The speed of the wave is unaffected by how fast I wiggle my hand up & down. What is affected is the **FREQUENCY**.

The number of oscillations per second in a wave at any point along the wave.

Frequency is a property of the **SOURCE** only.

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**Example:** If the string is 1 m long and its mass is 5g. The tension is 100 N. Find the speed of wave propagation:

\[ v = \sqrt{\frac{F}{\rho}} = \sqrt{\frac{100 \text{ N}}{\rho}} = \sqrt{\frac{100 \text{ N}}{0.005 \text{ kg/m}}} = 141.4 \text{ m/s} \]

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**Speed of the wave - speed of the wave propagation**

Speed of the wave is a property of the **medium**.

In mechanical waves it depends on the elasticity of the medium.

1. Waves in the string: \[ v = \sqrt{\frac{F}{\rho}} \]
   where \( \rho \) = \( \frac{m}{L} \) linear mass density

2. Waves in the air (sound):
   \[ v = \sqrt{\frac{p}{\rho}} \]
   where \( p \) - pressure, \( \rho \) - density
   for air: \( v = 343 \times \sqrt{T} \) where \( T \) is in °C

3. Seismic waves:
   \[ v = \sqrt{\frac{B}{\rho \rho}} \]
   where \( B \) - bulk modulus, \( \rho \) - density

4. In general:

**WAVELENGTH, \( \lambda \):**

The distance between two equivalent points in a wave, e.g. the distance between two adjacent peaks or two adjacent valleys.

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**How long does it take for each point along the wave wiggle up & down once?**

\( \rightarrow \) **PERIOD**

**How far has the wave moved in one PERIOD?**

**ANSWER:**

One Wavelength
Amplitude and Wavelength:

Which wave has the largest amplitude? Which wave has the largest wavelength?

QUESTION:
I increase the frequency of a wave traveling on a rope (keeping everything else unchanged). What happened to the wavelength and the speed of the wave?

1. The wavelength increased, but the speed stayed the same.
2. The wavelength stayed the same, but the speed increased.
3. The wavelength decreased, but the speed stayed the same. ✓
4. Both the wavelength and the speed stayed the same.

So, if the wave travels one wavelength, \( \lambda \), in a time equal to the period, \( T \), how fast is it going?

\[ v = \frac{d}{t} = \frac{\lambda}{T} \]

Wavelength is a function of speed and frequency.

Frequency = \( f = \frac{1}{T} \)

Relationship between frequency, wavelength and the speed of the wave:

\[ v = f \lambda \]

Speed of a wave:
The speed of a wave depends on things like forces, mass per unit length etc., but not typically on the frequency. If the frequency changes, the wavelength must change to keep the velocity the same.

Example:
A wave on a rope travels at 2 m/s. I wiggle one end of the rope at a frequency of 1 Hz. What is the wavelength of the resulting wave?

\[ v = f \lambda \]
\[ \lambda = \frac{v}{f} = 2 \text{ m} \]

Wave Propagation: "How waves move"

- REFLECTION
- DIFFRACTION
- INTERFERENCE
Waves are reflected when they encounter a sudden change in the medium through which they travel. Examples:
- Mirror
- Satellite dish
- Echo

What happens when two waves meet?

INTERFERENCE!

Destructive Interference

Constructive Interference

“destructive”

“constructive”

DIFFRACTION

An opening in a room acts as a “point source” sending waves in all directions - causing the wave to “bend”
The Doppler effect: dependence of the wavelength on the motion of the source relative to the observer.

Finalize general properties of waves:
1. Main characteristics of waves: f, v, λ, A, T.
2. Frequency f is a "property" of the source.
3. Wave speed is a "property" of the medium.
4. Every point perturbed by the wave becomes a source for another wave.
5. All perturbations that we discuss are linear. Therefore, we have the superposition principle. Wave properties or features as interference are the consequence of this principle.

Sound
- SOUND is a (longitudinal) pressure wave in air, any gas, liquid, or solid.
- The amplitude of sound waves are very small compared to the atmospheric pressure: \( \Delta P / P \approx 0.00001 \)

SPEED OF SOUND:
- Depends on elasticity (forces between atoms or molecules) and density
- For ideal gases depends on the mass of atom or molecule and temperature.
- Speed of sound in air is about \( v = 343 \text{ m/s (768 mph)} \)
- In air at room temperature \( 20^\circ \text{C} \) \( v = 343 \text{ m/s} \)

Example: If the time between the lightning and a thunder is 3 s, how far is the T-storm? The air temperature 75°F.
1. Convert to Kelvin: \( T = 273.15 + \frac{5}{9} \times (75 - 32) = 297^\circ \text{K} \)
2. Calculate the speed of sound: \( v = 20.1 \times \sqrt{297} = 346.4 \text{ m/s} \)
3. Calculate the distance: \( d = v \times t = 346.4 \times 3 = 1040 \text{ m} \)

Waveform = graph of the pressure variations in air versus time
- Pure tone: sound with a sinusoidal waveform, single \( \lambda \).
- Complex tone: repeats itself (periodic), but multiple \( \lambda \)'s - a superposition of pure tones
- Noise - irregular
What is the frequency of this sound wave?
1. It cannot be determined.
2. 0.025 Hz
3. 0.05 Hz
4. 40 Hz
5. 20 Hz

What is the wavelength of this sound wave (T = 293 K)?

Period \( T = 0.05 \) sec \( \Rightarrow f = 1/T = 20 \) Hz

\[ v = 20.1 \times \sqrt{293} = 344.1 \text{ m/s} \]

\[ \lambda = \frac{v}{f} = \frac{344.1}{20} = 17.2 \text{ m} \]

How is sound produced?
- Any object vibrating in air will produce pressure waves:
  - Vibrating strings, plates, membrane...
- Standing waves in 'wind' instruments

Frequency depends on length of string or pipe etc. = resonance frequency.
Higher "modes" can be generated by blowing harder.

How do these perceptions correspond to physical attributes of sound?

Production of sound:
- Frequency
- Amplitude
- Complexity (spectrum)

Perception of sound:
- Pitch
- Loudness
- Tone quality

Amplification: resonator "boxes"
Select (filter) and amplify certain harmonics to produce a complex (or pure) sound.
Resonance in open pipes:

One end open: organ and wind instruments

Both ends open (Our music Bloogles are like these.)

Sound level: Measured in decibel (dB)
If amplitude is 10x bigger, the decibel level is increased by 20 dB.
90 dB sound has 10x the amplitude of 70 dB sound.

Loudness = Perception of loudness

0 dB - threshold of hearing
1 dB - minimal loudness change detectable by ears
10 dB difference = sounds twice as loud
120 dB - threshold of pain
If you add two sounds of the same loudness, the resultant loudness increases by 3 dB
(sound of 50 dB) + (sound of 50 dB) = (sound of 53 dB)
(Loudness also depends on frequency. Ears are most sensitive around 1000 – 5000 Hz.)

Sound Propagation
• Sound becomes weaker further away from a sound source.
By how much?
Energy is conserved, but sound is spreading over an area ~ d^2.
Energy ~ Amplitude^2
Energy per unit area ~ 1/d^2
Therefore: Amplitude ~ 1/d
PITCH

"How high a low a sound is"
Which physical quantity is pitch due to?
1. Amplitude
2. Frequency ✓
3. Speed of sound
4. Shape of waveform

PITCH:
A sound with a higher frequency will sound "higher", a sound with a lower frequency will sound "lower".

Why do CD players have a range of 20 - 20,000 Hz, when musical instruments range from 50 - 5000 Hz only?

Range of human hearing: Maximum 20 - 20,000 Hz

Tone quality is determined by the actual waveform of the sound. For accurate representation of the sound higher frequencies are needed. "High fidelity"

QUESTION:
You are a designer for a new concert hall. Which wave effects do you have to take into account?
1. Reflection
2. Diffraction
3. Interference
4. All of the above ✓
5. None of the above
6. These things have nothing to do with sound.

Sounds of instruments etc. are due to Complex waveforms = combination of waves of several frequencies.

Lowest frequency = "Fundamental", determines pitch

Higher frequencies = "Harmonics", determine tone quality. Frequencies of harmonics are whole number multiples of the fundamental frequency.
**Answer:** All of the above

**Example:** Reflection

Which path takes the most time?

1. Path 1
2. Path 2
3. Path 3
4. Path 4
5. They all take the same amount of time.

The goal: deliver the same complex sound to all places.

**Multiple Reflection lead to reverberation.**

Reverberation - good and bad:
- Amplifies the sound
- Makes it more uniform
- Can make echo or multiple sounds

**ELECTROMAGNETISM**

1. A moving charge, an electric current, or changing electric field induce a magnetic field
2. A changing magnetic field induces an electric field.
3. The electric charge is the source of electric and magnetic fields
4. Electric and magnetic fields are related with each other
   - Maxwell equations - complete picture of electro-magnetism
   - Predicted Electro-Magnetic waves
   - Light - EM wave
   - James Clerk Maxwell (1831 – 1879)

**Electromagnetic Waves**

Wave: A traveling disturbance consisting of coordinated vibrations that transmits energy but not matter.

EM waves:
1. Source of EM waves
2. What oscillates?
3. EM waves propagation

I disturb the electric field by moving charges back and forth. What happens?

- The moving charge creates an oscillating electric field and an oscillating magnetic field.
- The oscillating magnetic field produces a new changing electric field opposing the original electric field.
- The oscillating electric field will produce a new opposing magnetic field.

An oscillating (accelerating) charge is a source of EM wave.

- EM wave is transverse - E and B fields are mutually perpendicular and both perpendicular to the direction of propagation
- Both E and B fields oscillate in phase
- EM wave propagates with speed of light
- does not need a medium

What kind of wave is an electromagnetic wave?

1. Transverse Wave
2. Longitudinal wave
3. Neither
Differences between EM waves and mechanical waves:
- EM waves are really two (coupled) waves: an electric field and a magnetic field wave.
- EM waves do not require a medium and can travel through vacuum.

SPEED of EM waves:
In vacuum: \( c = 299,792,458 \text{ m/s} \)
\( c = 300,000 \text{ km/s} = 186,000 \text{ miles/s} \)
In a medium they are slower
\( c_{\text{med}} = \frac{c}{n} \quad n \text{ – index of refraction} \)

A radio station transmits EM waves with frequency 100 MHz. What is the wavelength of the EM waves?

\[ f = 100 \text{ MHz} = 100 \times 10^6 \text{ Hz} = 100,000,000 \text{ Hz} \]
\[ v = \frac{c}{\lambda} \]
\[ \lambda = \frac{c}{f} = \frac{300,000,000 \text{ m/s}}{100,000,000 \text{ Hz}} = 3 \text{ m} \]
Or alternatively:
\[ \lambda = \frac{c}{f} = 3 \times 10^8 \text{ m/s} / 10^8 \text{ Hz} = 3 \text{ m} \]

**RADIO WAVES:**
EM Waves with
\[ f = 100 \text{ ... } 10^9 = 1,000,000,000 \text{ Hz} \]
\( \lambda = 3000 \text{ km} \ldots 0.3 \text{ m} \)
Can be generated directly by moving charges back and forth (changing electric field) in an antenna.
- Radio: AM = 700 – 1400 kHz, FM = 88 – 108 MHz
- TV
- Emissions from Planets and stars

**MICROWAVES:**
EM waves with
\[ f = 10^9 \text{ ... } 10^{12} \text{ Hz} \]
\( \lambda = 30 \text{ cm} \ldots 0.3 \text{ mm} \)
Can be generated by very sophisticated electronics and antennas.
- Communication: Satellites
- Radar
- Cooking your food
- MRI

**Very Large Array, New Mexico**
Radar:
Microwaves bounce off metallic objects (Reflection). Measure time it takes to reach object and return.

If it takes 20 microseconds for the signal to return, how far away is the airplane?

\[ 20 \, \mu s = 20 \times 10^{-6} \, s = 0.00002 \, s \]
\[ d = \frac{c \cdot t}{2} = \frac{(300,000 \, \text{km/s})(0.00002 \, s)}{2} = 3 \times 10^5 \, \text{km/s} \times 2 \times 10^{-5} \, s / 2 = 3 \, \text{km} \]

Venus' surface measured by radar:

Microwave oven:
Water molecules have are electric dipoles.

Hydrogen, positive
Oxygen, negative

Water molecules rotate. When heated, they rotate more vigorously.

If we apply a changing electric field to the water, it will be forced to rotate, increasing its kinetic energy.

... and its temperature!

INFRARED

EM waves with

\[ f = 10^{12} - 4 \times 10^{14} \, \text{Hz} \]
\[ \lambda = 0.3 \, \text{mm} - 0.75 \, \mu \text{m} (750 \, \text{nm}) \]

Emitted by warm objects, lasers, LEDs

- Heat radiation
- Remote controls
- Some Wireless devices
- Lasers
- Fiber-optic communication

Infrared Photography:
VISIBLE LIGHT:
EM waves with

\[ f = 4 \times 10^{14} \text{ Hz} \ldots 7.5 \times 10^{14} \text{ Hz} \]
\[ \lambda = 750 \text{ nm} \ldots 400 \text{ nm} \]

Very narrow range of EM waves which happens to be detectable by human eyes.

- Seeing
- Optics
- TV
- Photography

ULTRAVIOLET
EM waves with

\[ f = 7.5 \times 10^{14} \ldots 10^{18} \text{ Hz} \]
\[ \lambda = 400 \text{ nm} \ldots 0.3 \text{ nm} \]

Emitted by the sun, very hot objects

- Tanning
- Lithography to make computer chips

X RAYS
EM waves with

\[ f = 10^{16} \ldots 10^{20} \text{ Hz} \]
\[ \lambda = 30 \text{ nm} \ldots 0.3 \text{ pm} \]

Made by bombarding a target with electrons.
Can travel through matter almost unhindered.

- X-ray imaging
- X-ray diffraction

Materials with "heavier" atoms in them stop x-rays more efficiently. For example Calcium in Bone.
Since X-rays have wavelength the size of atoms, they can reveal atomic structure of crystals and molecules.

For example:
Structure of DNA

How are X-rays generated?

Electron gun

Electrons

Target

X-rays

GAMMA (γ) RAYS
EM waves with
\[ f = 3 \times 10^{19} \ldots > 10^{23} \text{ Hz} \]
\[ \lambda = 10 \text{ pm} \ldots < 3 \text{ fm} \]

Emitted by nuclear processes, such as radioactivity

BLACKBODY RADIATION
Bodies emit heat radiation that depends on their temperature.

Wien's law

\[ \lambda_{\text{max}} = \frac{0.0029}{T} \]

Color of stars is due to their temperature

Rigel: \( T = 10,000 \) K

Betelgeuse: \( T = 3,200 \) K

Sun: \( T = 5,800 \) K

Cosmic background radiation
Blackbody radiation of universe discovered in 1965

Arno Penzias and Robert Wilson

Robert Dicke

T = 2.7326 K, microwave radiation
\[ \lambda = 0.0029/2.7326 = 0.00106 \text{ m} = 1.06 \text{ mm} \]
**Passage of the EM waves through the atmosphere**

**Ionosphere**
- Ions high up (~90 km) in the atmosphere can reflect certain radio waves (shortwave).

**Ozone layer**
- At about 20–40 km above sea level: High concentration of ozone ($O_3$).
- Stops UV light, protects life on earth.

**Ozone hole:** Certain pollutants can reduce the amount of ozone in the ozone layer (CFCs).

**Greenhouse effect**
- Certain gases ($H_2O$, $CO_2$, $CH_4$) reflect or absorb infrared radiation, keeping heat from escaping into space.
  - Keeps it about 35o higher than without.
  - Important for life conditions.
  - Regulates temperature on Earth.
  - Responsible for high temperature on Venus (460o C) – runaway greenhouse effect.
  - Global warming.

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- At about 20–40 km above sea level: High concentration of ozone ($O_3$).
- Stops UV light, protects life on earth.

**Ozone hole:** Certain pollutants can reduce the amount of ozone in the ozone layer (CFCs).

Do not confuse ozone problem with the greenhouse effect.
**BLACKBODY RADIATION**

Bodies emit heat radiation that depends on their temperature.

**Stefan’s law**

\[ P \sim T^4 \]

The power of EM radiation emitted by an object is proportional to the fourth power of its temperature (K).

**Wien’s law**

\[ \lambda_{\text{max}} = \frac{0.0029}{T} \]

**Light:**
- Light is an electromagnetic wave with frequencies in the range of $4 \times 10^{14}$ to $7.5 \times 10^{14}$ Hz.
- In air & vacuum, wavelengths range from 450 nm to 750 nm, where 1 nm = 1 billionth of a meter.
- Color is determined by frequency (wavelength).
- White light is a mixture of all colors.
- In vacuum, the speed of light is $3 \times 10^8$ m/s.

**DIFFRACTION:**

Light passing through a very narrow slit will spread out.

Every point reached by the wave (including those in the slit) becomes a source of waves.

The resultant signal at any point is a result of interference from all directly arriving waves.

**INTERFERENCE:** summation of waves - superposition principle

- **Destructive Interference:** Waves in opposite phases
- **Constructive Interference:** Waves in the same phase
**Two slit interference**

Summation of waves with different paths:
- for a maximum the difference in paths has to be the integer number of wavelengths
- for a minimum – half integer

**Interference effects: thin films**

Some wavelengths interfere destructively, some constructively

**Electromagnetic waves:**

Do the E & M vectors always have to point in the same direction?
1. Yes
2. No

**Polarization**

Answer: No, in most light the E-vector points in random directions.

Polarized light, e.g. laser light:

Unpolarized light can be polarized by
- Reflection
- Passing through a polarization filter (polaroid)

Note: B field direction and magnitude is always related to the E field’s direction and magnitude
**Diffuse reflection:**
Reflection off rough surfaces - most common. Most light we see is diffuse reflected light.

**LCD Displays**
No signal - transparency because of correct rotation of polarization

**Reflection: Specular reflection**
Specular reflection - depends on the reflecting surface only - all rays are reflected similarly
- the surface is flat enough
- Depends on the wavelength - the shorter the wavelength, the better quality mirror is required for to obtain the specular reflection

**The Law of Reflection:**
The angle of incidence equals the angle of reflection.

**Colored Objects:**
- Reflect only some frequencies of light and absorb others.
If an object appears red, it
Reflects red and absorbs other colors such as blue, yellow, green, etc.
REFLECTION, plane mirror

When you look into a mirror, what is reversed?
1. Nothing is reversed.
2. Left and Right are reversed.
3. Up and Down are reversed.
4. Front and Back are reversed.

http://perg.phys.ksu.edu/vqm/laserweb/Java/MirrImge/Imageme1.htm

One-way mirrors

Normally, part of light is reflected and the rest is transmitted.

Curved mirrors

Concave mirror

An image from a convex mirror – always virtual, always smaller than the object.

Van Eyck: "The Arnolfini couple"

Convex mirror

Concave mirror – virtual image if the object is closer than the focus.
Concave mirror - real image if the object is farther than focus

Real image reduced & inverted

Curved Mirrors Application: TELESCOPES

Hubble space telescope
Tiny error in mirror, repaired in 1993
2.4 m mirror, too flat on one edge by 1/50th of the width of a single human hair

Why?
1. The pencil actually bends when in contact with water.
2. It's some kind of interference effect.
3. It's a magic trick.

Aberrations:
Spherical aberration
REFRACTION!

When light enters a medium it slows down.

Now assume light hits a boundary (= interface) between two media under an angle:

What happens?

1. Some of it reflects off the interface.

2. Some gets transmitted, but how?

Analogy: Car leaving road and entering mud

Because the right wheel slows down first, the car rotates.

Light does the same thing when it crosses the interface between two different media:

= REFRACTION

LAW OF REFRACTION:

A light ray bends towards the normal when it enters a transparent medium in which light travels slower. It bends away from the normal if it enters a medium in which light travels faster.

Which way is faster for the light, 1 or 2?

Glass into air

Air into glass
How to explain the pencil in water?

It increases to some maximum angle (critical angle), at which something strange happens: the light does not come out from the more dense medium. If this angle is exceeded: it is completely reflected – total internal reflection.

TOTAL INTERNAL REFLECTION
Happens after exceeding the CRITICAL ANGLE
Application:
Optical fiber

LENSES AND IMAGES:
Recall: Light rays can be focused by a curved mirror. They can also be focused by using refraction:

Opposite case:

Lenses:
- Combinations of concave and convex surfaces, utilizing refraction to manipulate light

Focal point
Focal length
Two convex surfaces = biconvex lens
How does it work?

Converging Lens

Diverging Lens

Biconcave Lens

How does it work?

Law of Refraction:
A light ray bends towards the normal when it enters a transparent medium in which light travels slower.
It bends away from the normal if it enters a medium in which light travels faster.

Which way is faster for the light, 1 or 2?
Lenses are used to form images of objects. How they do that can be determined by "ray tracing".

**Example:**

In this case light re-converges and projects a real image that is inverted.

Another example: What’s different??

The light rays are not converging, the lens is not projecting an image. Looking through the lens a **virtual** image appears. = Magnifier

Is the image in a camera real or virtual?

1. Real
2. Virtual

**Lens formula**

\[ p = \frac{sf}{s - f} \]

\( f \) = Focal length

\( s \) = Object distance

\( p \) = Image distance
Example:
In a slide projector a slide is located 11 cm from a lens with a 10 cm focal length. Where should the screen be located to get a sharp image?

\[ p = \frac{sf}{s-f} \]

\[ p = \frac{10 \times 11}{11-10} = \frac{110}{1} = 110 \text{ cm} = 1.1 \text{ m} \]

Example:
A magnifying glass has a focal length of 10 cm. You place a coin at 5 cm from the lens. Where is the image?

\[ p = \frac{sf}{s-f} \]

\[ p = \frac{5 \times 10}{5-10} = \frac{50}{-5} = -10 \text{ cm} \]

What does that mean?
1. There is no image
2. There is a real image
3. There is a virtual image

Magnification:

\[ M = \frac{-p}{s} \]

Example: Magnifier, \( s = 5 \text{ cm}, p = -10 \text{ cm} \)

\[ M = \frac{-(-10)}{5} = \frac{10}{5} = 2 \text{ Virtual upright image} \]

Example: slide projector, \( s = 11 \text{ cm}, p = 110 \text{ cm} \)

\[ M = \frac{-110}{11} = -10 \text{ What does that mean?} \]

Real, inverted image

Telescope, microscope, etc.
The object - first lens - first image - second lens - second image and so on.

The human eye

Focusing
Nearsightedness

DISPERSION

Refraction depends on wavelength of light (color)

In glass, shorter wavelengths travel slower than longer wavelengths.

Prism

Rainbow and halo are results of collective refraction and reflection:

Primary rainbow

Secondary rainbow

Halo effect

Blue Skies and Evening glow - Scattering of light
Discovery of radioactivity

- H. Becquerel, 1896 - discovery of natural radioactivity - some matter emits invisible radiation (Uranium salt)
- The emitted rays are not X-rays discovered earlier by Wilhelm Roentgen
- Marie and Pierre Curie explored newly found radiation, separated polonium and radium
- Discovery of radon by F.E. Dorn, 1900
- F. Soddy, A. Fleck, Antonius Van den Broek - Becquerel's found radioactivity is due to α-particle (charge +2) - helium nucleus
- Final contribution Moseley - X-ray characteristic spectra: charge of the nucleus = its atomic number

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Rutherford experiment

- Rutherford scattered α-particles on gold foil - first scattering experiment 1906-1909
- J.J. Thomson model "plum pudding" - there is certain density of matter - given enough energy a particles should get through being scattered by certain angles and having lost certain energy
- The results are quite unexpected:
  - most of α-particles go through hardly scattered at all, not losing energy
  - Some, very few, α-particles are scattered backwards
- He coined the word "proton", 1920.
- Was looking for the structure of α-particle
- Predicted neutron, discovered by James Chadwick, 1932

Consequences: structure - matter consists of extremely dense and small positively charged nuclei and electrons orbiting them. The distances between the nuclei are many times larger than their sizes (by a factor of about 10^5).

Rutherford continued scattering experiments after WW I - 1919

Nuclear Physics: Physics of the nucleus itself – 1921 – strong interactions!

Masses of components

<table>
<thead>
<tr>
<th>Component</th>
<th>Mass (10^-27 kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proton</td>
<td>1.673</td>
</tr>
<tr>
<td>Neutron</td>
<td>1.675</td>
</tr>
<tr>
<td>Electron</td>
<td>9.11</td>
</tr>
</tbody>
</table>

Because of the mass - energy equivalence, it is convenient to introduce different units for masses:

\[ E_0 = mc^2 \Rightarrow \frac{m}{u} = E_0 / c^2 \]

atomic mass unit = 1/12 of the most abundant C isotope

\[ 1u = \frac{1.66 \times 10^{-27} \times 9 \times 10^{19}}{1.6 \times 10^{-19}} = 932.6 \text{ MeV} \]

\[ m_{proton} = 938.3 \text{ MeV}/c^2 = 1.00730u \]

\[ m_{neutron} = 939.6 \text{ MeV}/c^2 = 1.00869u \]

\[ m_{electron} = 0.511 \text{ MeV}/c^2 = 0.00055u \]

Nuclear Definitions

- Nucleus: "made of" protons & neutrons = nucleons
- Mass number, A: Number of nucleons in nucleus
- Atomic Number, Z: Number of protons in nucleus, amount of positive charge, position on periodic table
- Neutron Number, N: Number of neutrons in nucleus

\[ A = Z + N \]

- Isotopes: Nuclei with same Z (same element), but different N & A.
- Isobars: Nuclei with same A (roughly same mass), but different Z (element) and N.

Notation for nuclei and particles:

Examples: Carbon: \[ ^{12}_{6}C \quad ^{14}_{6}C \]

Proton: \[ ^{1}_{1}P \]
Neutron: \[ ^{1}_{0}N \]
Electron: \[ ^{0}_{-1}e \]
Several remarks about nuclei

- We say that nuclei are "made of" nucleons – protons and neutrons.
- This is not quite so – the nucleons (although are the building blocks) are not the same as bare protons and neutrons: a bare neutron is not stable – it decays in about 887 seconds!
- There are more effects like magic numbers, stable and unstable isotopes that are not just a straight consequence of the protons and neutrons being together.
- The strong force is needed to keep the nucleus together and overcome electrostatic repulsion.

RADIOACTIVITY

= Radioactive Decay

Some isotopes are unstable: too many neutrons, too few neutrons, too heavy.

These nuclei will transform into more stable nucleus.

In the process the nucleus will emit particles:

Alpha (α): Helium nucleus, \(^{4}\text{He}\)

Beta (β): Electron, \(\text{e}^-\)

Gamma (γ): electromagnetic radiation, gamma photon

Penetration of radiation

Radiation loses energy (scatters) and is then absorbed.

In general, the larger the energy is, the smaller is the cross section.

The damage is done in interaction - at smaller energies.

Alpha Decay

Very heavy nuclei (Z>82) decay by emitting an alpha particle.

Example:

\[
^{238}_{94}\text{Pu} \rightarrow ^{234}_{92}\text{U} + ^{4}_{2}\text{He}
\]

Beta Decay

In Beta decay a neutron is spontaneously converted to a proton and an electron.

Example:

\[
^{14}_{6}\text{C} \rightarrow ^{14}_{7}\text{N} + ^{0}_{1}\text{e}
\]

Question:

Radium-226 decays via an alpha decay. What does it decay to?

1. Radon (Rn 222), Z = 86
2. Radon (Rn 230), Z = 86
3. Thorium (Th 222), Z = 90
4. Thorium (Th 230), Z = 90
QUESTION:
Consider the following reaction. Which isotope are we starting with?

\[ ^{131}_{53}\text{I} \rightarrow ^{131}_{54}\text{Xe} + ^{0}_{-1}e + \nu \]

1. Cesium (Cs), Z=55, A=130
2. Cesium (Cs), Z=55, A=131
3. Cesium (Cs), Z=55, A=132
4. Iodine (I), Z=53, A=132
5. Iodine (I), Z=53, A=131
6. Iodine (I), Z=53, A=132

What's that?
In order to ensure energy conservation, another particle has been predicted by W. Pauli in 1930 (before the discovery of neutron). It has been discovered only in 1955 by F. Reines and C. Cowan.

- This particle is a neutrino. It is almost massless, has no charge and moves with almost the speed of light, very weakly interacts with matter...

Gamma Decay
Nuclei can be excited, just like electrons in an atom. They will emit a gamma photon and revert back to the ground state.

\[ ^{87}_{38}\text{Sr}^* \rightarrow ? + \gamma \]

Beta+ decay
- Positron – the anti-particle of an electron – same mass and spin, but the charge is the same, but opposite sign
- Positron was predicted by P.A.M. Dirac in 1930 and discovered by C. Anderson in 1932.
- Many elements undergo a so-called β⁺ decay emitting a positron (e⁺).

\[ ^{22}_{11}\text{Na} \rightarrow ^{22}_{10}\text{Ne} + ^{0}_{1}e + \nu \]

Radioactivity and Energy
Particles emitted during radioactive decay have kinetic energy ⇒ Heat
- Responsible for keeping the earth’s core molten ⇒ continental drift, volcanism
- Used in some thermoelectric generators for space missions.

But where does this energy come from?
- Binding energy is negative!
- Each spontaneous decay works in such a way that the binding energy of the products is larger than the BE of the initial nucleus – the total energy of the nucleus is reduced and an excess of energy is expelled as kinetic energy of products
**Half-Life**

Not all radioactive isotopes decay at the same rate.

Measured by **half-life**: Time in which half of original material has decayed.

Note: "decaying" isotopes don't disappear, they just transform into a different isotope.

**Example:**

Half-life = 1 day
1 g radioactive isotope initially
How much is left after one day?
Answer: ½ gram

**Question:** How much is left after 1 additional day?

1. Nothing, since the other $\frac{1}{2}$ g has now decayed as well.
2. $\frac{1}{4}$ gram
3. $\frac{1}{2}$ gram

Answer: $\frac{1}{4}$ gram.
The half-life is always the time it takes for $\frac{1}{2}$ of the original amount to decay, whatever the initial amount may be.

**How is this possible?**

Quantum mechanics: We can not predict how long a single nucleus will be stable. We can only predict the probability that it will decay in a certain time.

**Half-life:** Time interval during which nucleus has 50% chance to decay.

**Radioactive Dating**

Since half-lives are fixed they can be used to date things as long as we know the initial ratio of isotopes.

**Example:** Carbon dating

C-14 is produced in the upper atmosphere by bombardment of nitrogen by cosmic rays:

\[ ^{14}\text{N} + p \rightarrow ^{14}\text{C} + \gamma \]

C-14 decays with a half-life of 5,730 years back into nitrogen:

\[ ^{14}\text{C} \rightarrow ^{14}\text{N} + \frac{1}{2}e \]
Carbon Dating

As we breathe, we continuously add carbon to our body that has a certain (very small) percentage of C-14.

Therefore the C-14/C-12 ratio is fixed as long as an organism is alive.

Once the organism dies, no new carbon is added and C-14 content goes down.

Half of the C-14 will be gone after 5,700 years, \( \frac{3}{4} \) will be gone after 11,400 years etc.

Radioactive dating:

Carbon dating good for up to 40,000 years on organic materials (bones, wood).

Dating of rocks: Uranium-Lead, Potassium-Argon, Rubidium-Strontium, can date rocks back to billions of years

Note: you do not need to know how much of the original isotope was there in the first place. Example: Rubidium-Strontium "isochrones".

Time scales

Age of an average human: \( 8 \times 10^3 \) years

Age of human civilization: \( 5 \times 10^3 \) years

Age of upright walking human species: \( 2 \times 10^6 \) years

Age of first known life: \( 3.7 \times 10^9 \) years

Age of the Earth: \( 4.55 \times 10^9 \) years

Age of universe: \( 1.37 \times 10^{10} \) years

Artificial nuclear reactions

Radioactive isotopes occur naturally

But they can also be made artificially by bombarding nuclei with particles:

\[
\begin{align*}
^{238}_{92}U + {}^1_{0}n &\rightarrow ^{239}_{92}U \\
^{239}_{92}U &\rightarrow ^{239}_{93}Np + {}^0_{1}e \\
^{239}_{93}Np &\rightarrow ^{239}_{94}Pu + {}^0_{1}e
\end{align*}
\]

Irene and Frederic Joliot - Curie, 1934

Making nuclear fuel for reactors.

Making use of binding energy

Mass and Energy are equivalent:

\[ E = mc^2 \]

Binding energy - mass difference:

\[
\begin{align*}
m_{\text{protons}} &= 938.3 \text{ MeV/c}^2 \\
m_{\text{neutrons}} &= 939.6 \text{ MeV/c}^2 \\
m_{\text{electron}} &= 0.511 \text{ MeV/c}^2
\end{align*}
\]

\[ m_p = 4.00 \text{ u} = 3,730.3 \text{ MeV/c}^2 < 3,755.8 \text{ MeV/c}^2 \]

Binding Energy = 25.5 MeV

\[ m_{\text{Pu}} = 55.85 \text{ u} = 52,085.7 \text{ MeV/c}^2 < 52,583.8 \text{ MeV/c}^2 \]

Binding Energy = 498.1 MeV

Nuclear binding energy per nucleon

Fe has the largest binding energy per nucleon - the most desired position for a nucleus: lower fuse, higher decay
Nuclear Fission:
Very heavy nuclei can be broken up into more stable (larger binding energy), smaller nuclei if bombarded by neutrons.

Each time a U-235 nucleus undergoes fission, it releases three more neutrons.

These neutrons can hit other U-235 nuclei and split them, releasing 9 more neutrons... 27 neutrons... 81 neutrons... 243... 729... 2,187... 6,561... 19,683...

Chain reaction!

Fission can also be controlled...
Use low concentration of U-235, U-238 does not fission, but is much more abundant.

Fission of U-235 is more efficient of neutrons are slow. Use "moderator" (carbon, water) to slow down neutrons.

Atomic bombs

Fusion in stars

H → He → C, O, Ne → O, Ne, Na → Si, S → Fe

Fe is the heaviest element produced by fusion; more heavy elements are produced during supernova explosions - similarly to the production of elements in neutron irradiation.
Nuclear Fusion

H + H → He + e^+ + ν

"proton-proton chain"

Tokamak

Temperature required is 1-3 × 10^8 K

ITER - 2005