Introduction to Elementary Particles

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Contents

- General overview of particle physics
- Historical discovery of various kinds of elementary particles
- Interactions: how do particles interact with one another?
- How are elementary particles produced?
- How are elementary particles detected?

❑ General overview of Particle physics

General overview of Particle physics

- Particle physics is the study of the ultimate constituents of matter and the laws governing of their interactions
- Method of study particle physics:
  - ➢Experimental methods
  - ➢Theoretical methods

Approaches to Particle Physics

Experimental	Theoretical
Large Accelerators	Empirical Analysis
Detectors	Model Building
Precision Measurements	Numerical Computation
Cosmological Data	Mathematical Foundations

Experimental method

- **Large accelerators**
  - Particles collide together at very high speed → very high energy collisions → provide information of particles
  - "Particle phyiscs" is thus sometimes called "high energy physics"
  - Uncertainty principle:
    - Δp is large for small Δx
    - ΔE is large for small Δt
  - Relativity: $E = mc^2$: large mass particles need high energies to be created

  -> need accelerators to study short range distance effects.
- **Detectors:**
  - desinged to measure as much physical information as possible: mass, spin, charge, energy, …

Experimental method

- **Precision measurements:**
  - Mashing particles together in high-energy collisions does not always provide enough and precise information of particles.
  - For example: interations of neutrinos with other kinds matter (electrons, nuclei) do not require high energy and the probability of occuring interactions is very low.
  - Need for sensitive detectors to pick out the signal from the noisy background
  - Other purposes of experiments to search for new physics.

- **Cosmological data:**
  - The early universe was an environment of a hot plasma of all kinds of particles
  - With very high average temperature, observations from cosmology can provide us with useful and important information about particle physics

Theoretical method

- **Emprical analysis**:
  - One of main missions of particle physics is to analyze the data
  - From experiments, raw data is converted into usable information such as masses or lifetimes of particles.
  - Theorists make use of the information to seek new patterns in the data, to critique existing analysis, and to suggest new experiments.
  - Data analysis with an enormous volume requires:
    - a huge computational infrastructure
    - a very sophisticated level of data processing and programming skill

Theoretical method

- **Model buiding**
  - Propose a model for how nature works at the subatomic level
  - Make a clear set of assumptions about the particle content, the interactions between the particles, …
  - The difference between a theory and a model:
    - Theory: basic mathematical frame work used for describing physics: quantum mechanics, Yang-Mills theory, Special relativity…
    - Model: a particularization of a theory to a specific context: quark model, standard model,…
- **Theories to describe motion of particles**:
  - ***Classical mechanics***: describe object of everyday life
  - ***Special relativity***: for objects that travel very fast
  - ***Quantum mechanics***: for objects that are very small
  - ***Quantum field theory***: for object that are very fast and very small

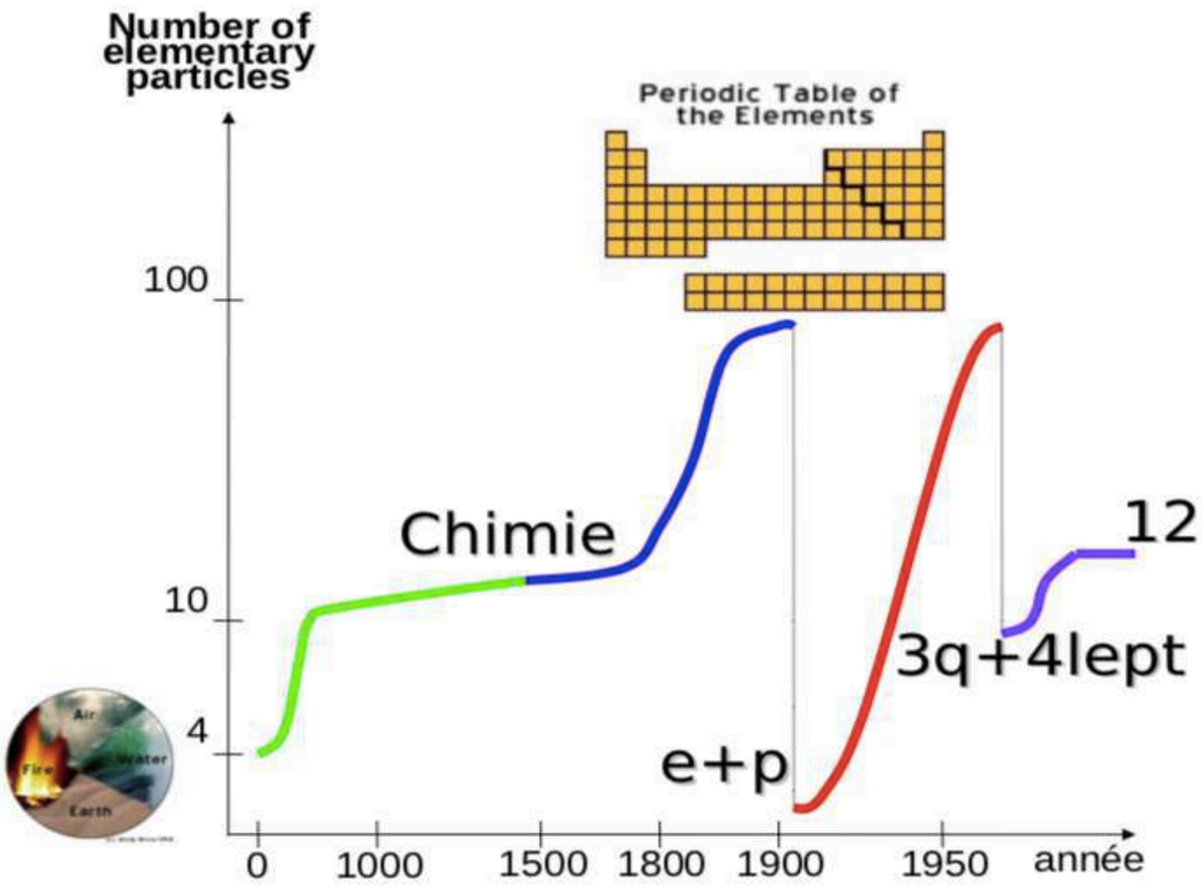
Theoretical method

- **Numerical computation**
  - ➢Many problems in particle physics cannot be solve theoretically. We need to use computers to deal with these problems.
  - ➢The calculations are simply to big or too long for any person or a group of people.
  - ➢Numerical computation is thus used to solve problems/equations with as few approximation as possible.

- **Mathematical foundations**
  - ➢Mathematical structure of particle physics and its model.
  - ➢Examples: String theory, theory of standard model, QCD,….

❑ Historical discovery of elementary particles

Number of particles during history



4 elements :

Ether, mercury, sulfur, salt

1789 Lavoisier : 33 élts

1868 Mendeleïev

1897 electron

1917 proton

1932 neutron et e^+

1937 muons

1947 pions, quark

1964 quark theory

1974 quark c

1975 lepton

1977 quark b

1994 quark t

2000 neutrino

❑ Historical discovery of elementary particles

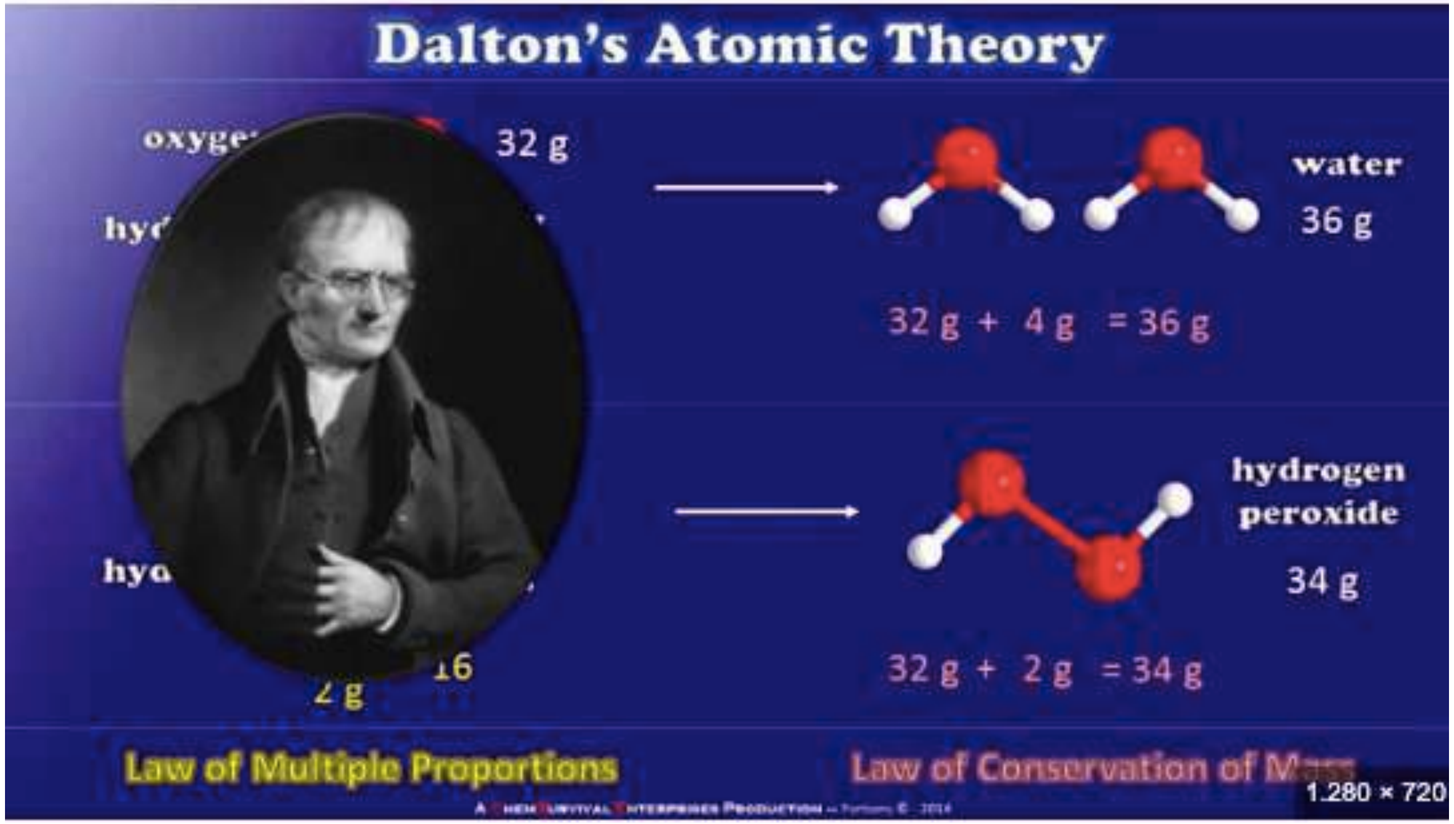
- ➢The classical era (1897 - 1932): *The Structure of the Atom*
- ➢The Photon *(1900 - 1924)*
- ➢Neutrinos (1930 - 1962)
- ➢The Standard Model

The Structure of the Atom

- Our modern, scientific understanding of the structure of matter begins with the chemist John Dalton:

https://www.youtube.com/watch?v=OUoV--CuLDA

➢All matter is made of atoms, which are indivisible.
➢All atoms of a given element are identical in mass and properties.
➢Compounds are combinations of two or more different types of atoms.



The Structure of the Atom

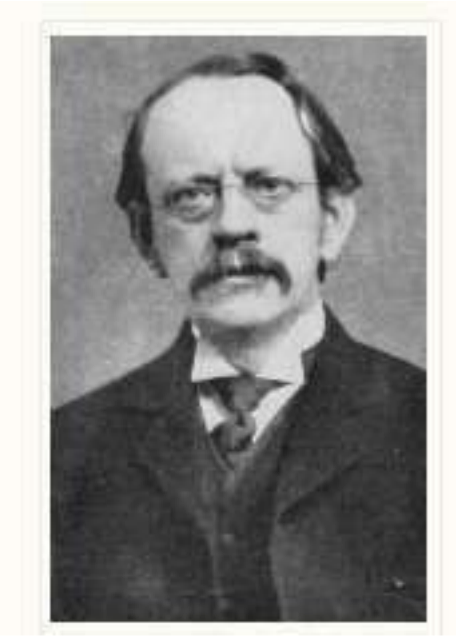
- In 1867: A fuller picture came with Mendelev's arrangement of the elements in the pattern known as the *periodic table*
- By Mendelev's time, it had long been understood that elements are made of ***atoms*** (meaning "indivisible").
- The order in the periodic table suggests a structure to the atoms:
  - The elements are labelled by two numbers:
    - The atomic number Z
    - The atomic weight A

The Structure of the Atom: *periodic table*

Group → / Period ↓	1	2	3		4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H																		2 He
2	3 Li	4 Be												5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg												13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc		22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y		40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	57 La	*	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	89 Ac	**	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Nh	114 Fl	115 Mc	116 Lv	117 Ts	118 Og
				*	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu	
				**	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr	

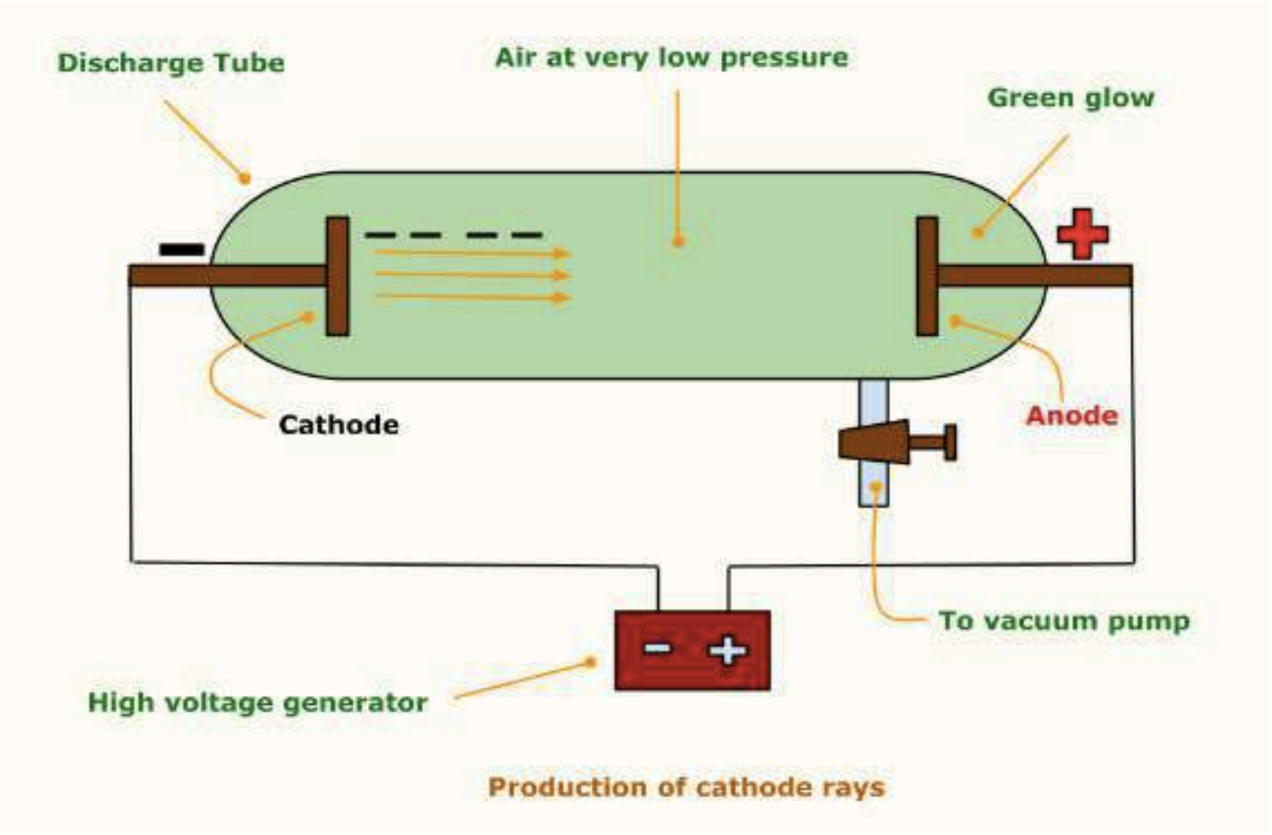
The Structure of the Atom: *electron discovery*

- 30 years later … in 1897: JJ Thomson discovered the particle that we now call the ***electron*** in Cathode Ray Tube (CRT) experiment



J. J. Thomson
Nobel Prize in 1906
for discovering the elementary particle electron

- Electron is Nagative charge
- e/m = -1.76×10^{8} C/gram
- Electron is approximately 2000 times lighter than hydrogen

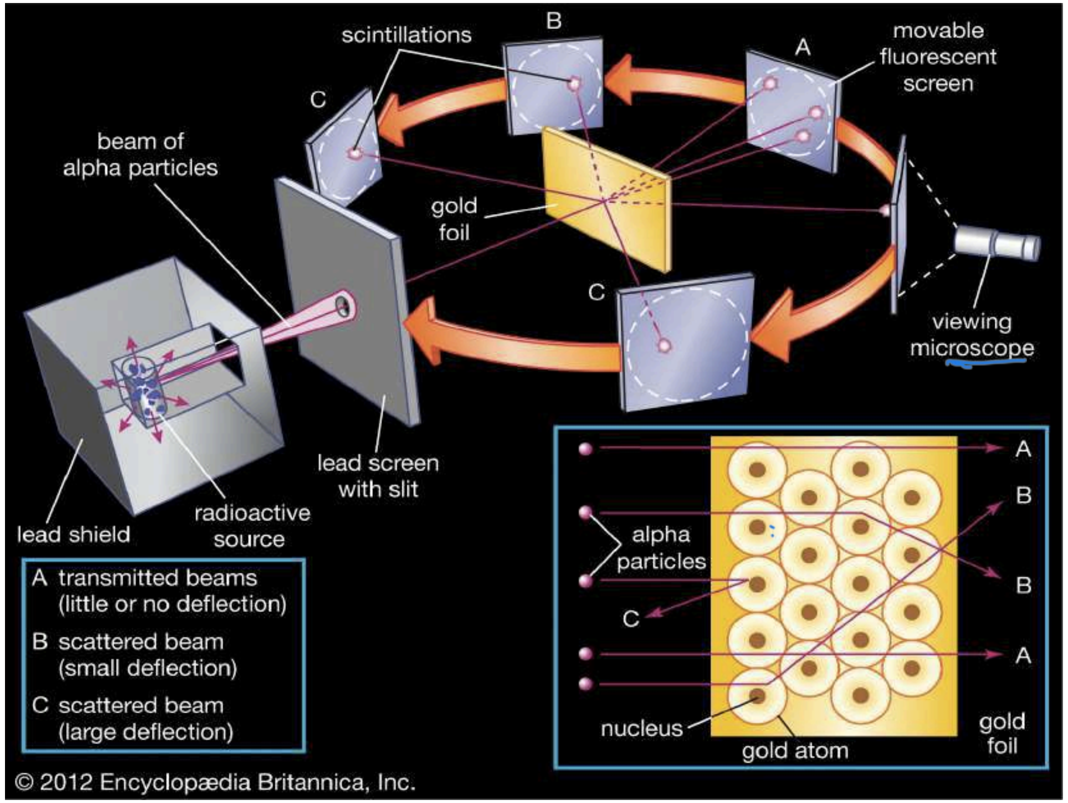


The Structure of the Atom: *proton discovery*

- In 1911, … Ernest Rutherford and his colleagues unravel the full structure of the atom:

Ernest Rutherford
Nobel Prize in Chemistry in 1908
for his work in radioactivity

- Most of the atom mass and its entire positive charge are confined in a small core → ***nucleus***
- The positively charged particle is called ***proton***.
- Most of the volume of an atom is empty space.
- The number of negatively charged electrons dispersed outside the nucleus is same as number of positively charge in the nucleus

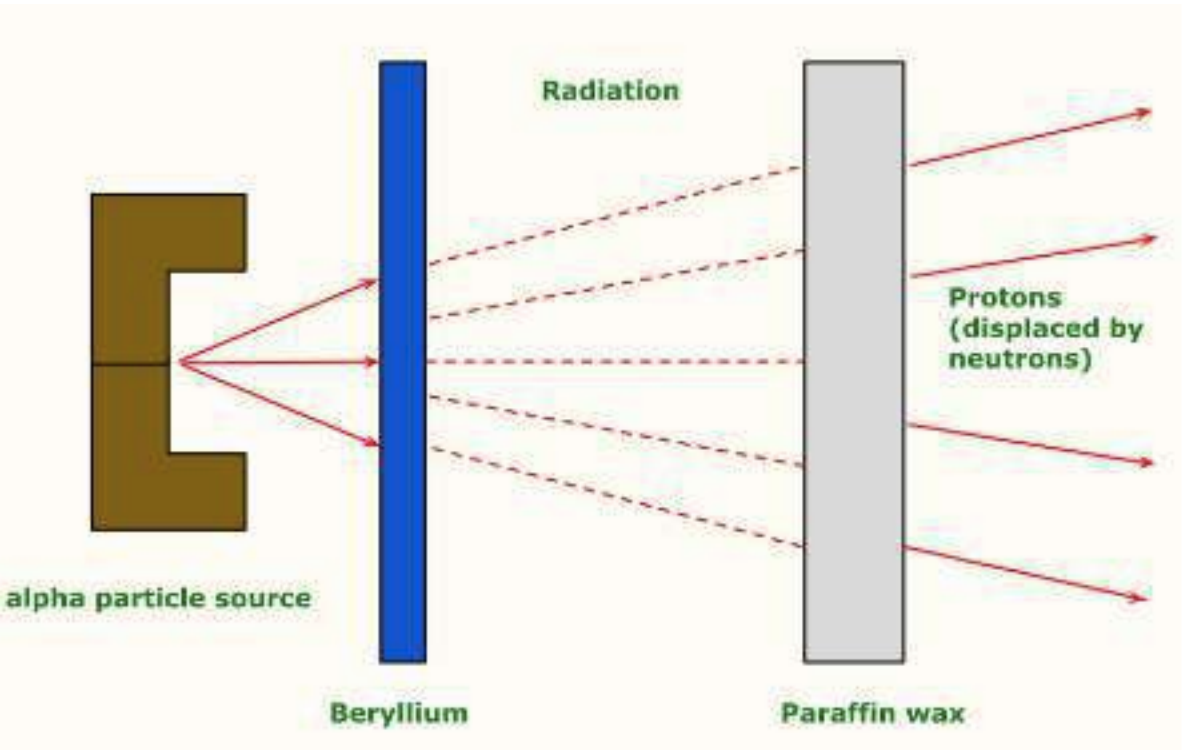


The Structure of the Atom: *neutron discovery*

- In 1932: Discovery of neutron (by James Chadwick):

James Chadwick
(a student of Rutherford)
Nobel Prize in Physics in 1935
for discovery of neutron

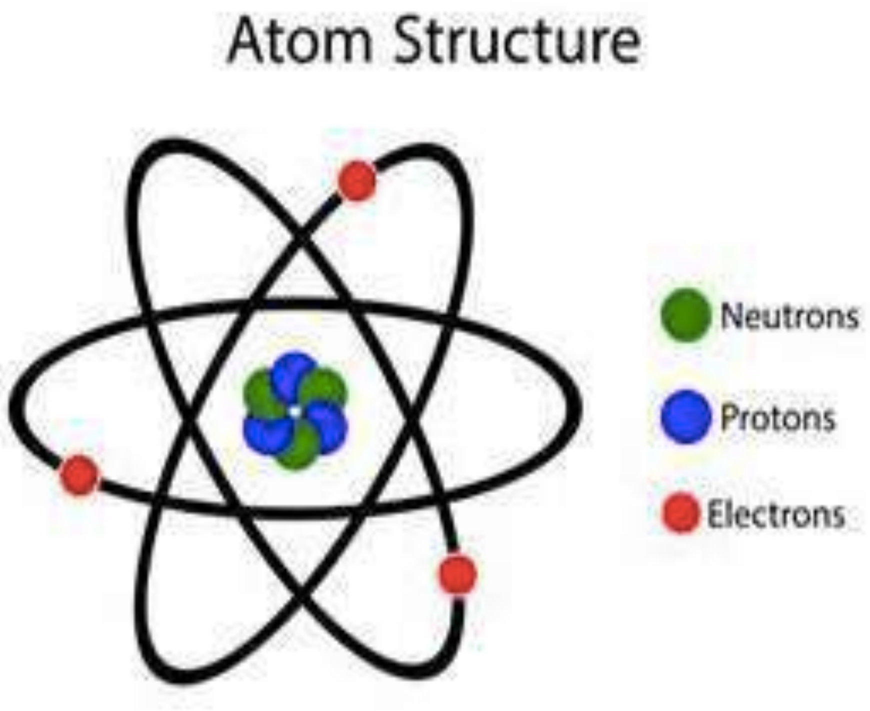
- The atomic model offered by Rutherford is not complete
- Various experiments showed that mass of the nucleus is approximately twice than the number of proton
- Chadwick discovered the existence of a new particle which is ***charge less and has similar mass to proton***



$${}^{9}_{4}Be + {}^{4}_{2}\alpha \longrightarrow [{}^{13}_{6}C] \longrightarrow [{}^{12}_{6}C] + {}^{1}_{0}n$$

The Structure of the Atom

- Each atom consists of a nucleus, surrounded by a some what blurry cloud of electrons.
- The nucleus itself is comprised of two further particles, the proton and neutron.
- The atomic number Z counts the number of protons in the nucleus;
- The atomic weight A counts (roughly) the combined number of protons and neutrons.



Discovery of the photon (1900-1926)

- The photon is a very “morden” particle, that is “***particle of light***” or “***light quantum***”
- The first idea was suggested by Max Planck in 1900 when attempting to explain the so-called blackbody spectrum for the electromagnetic radiation emitted by a hot object.

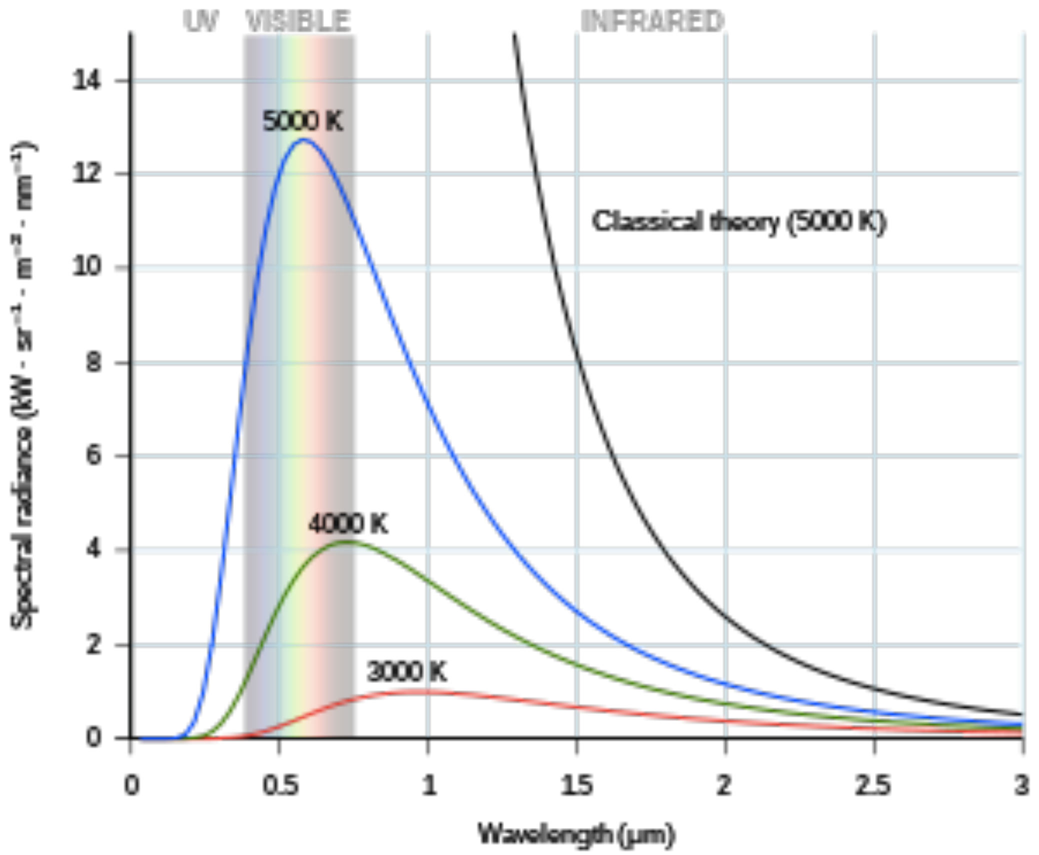
Max Planck’s assumption

➢Electromagnetic radiation is quantized as a package of energy:

$$E = hf$$

➢where f is the frequency of the radiation and h is the Planck constant used to fit the data.

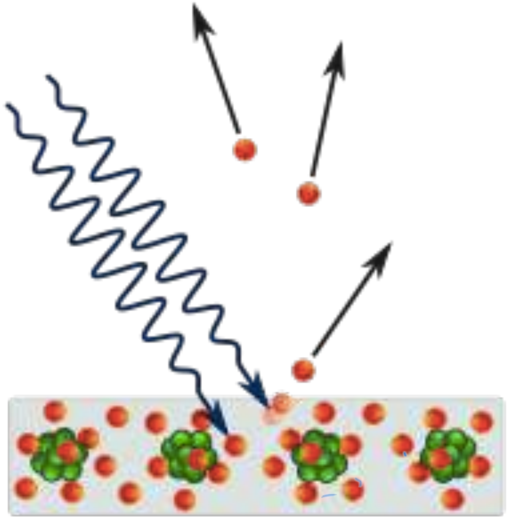
➢The quantization was due to a peculiarity in the emission process.



Discovery of the Photon *(1900 - 1924)*

- **Einstein, in 1905:**
  - Quantization was a feature of the electromagnetic field itself
  - Quantization was not related to emission mechanism.
  - Used Planck's idea of quatization and his formula to explain *photoelectric effect:*
    - When electromagnetic radiation strikes a metal surface, an imcoming light quantum hits an electron in metal, giving up its energy *hf*
    - The electron thus emerges with an energy *E*

$$E \leq hf - w \quad (w \text{ is work function})$$

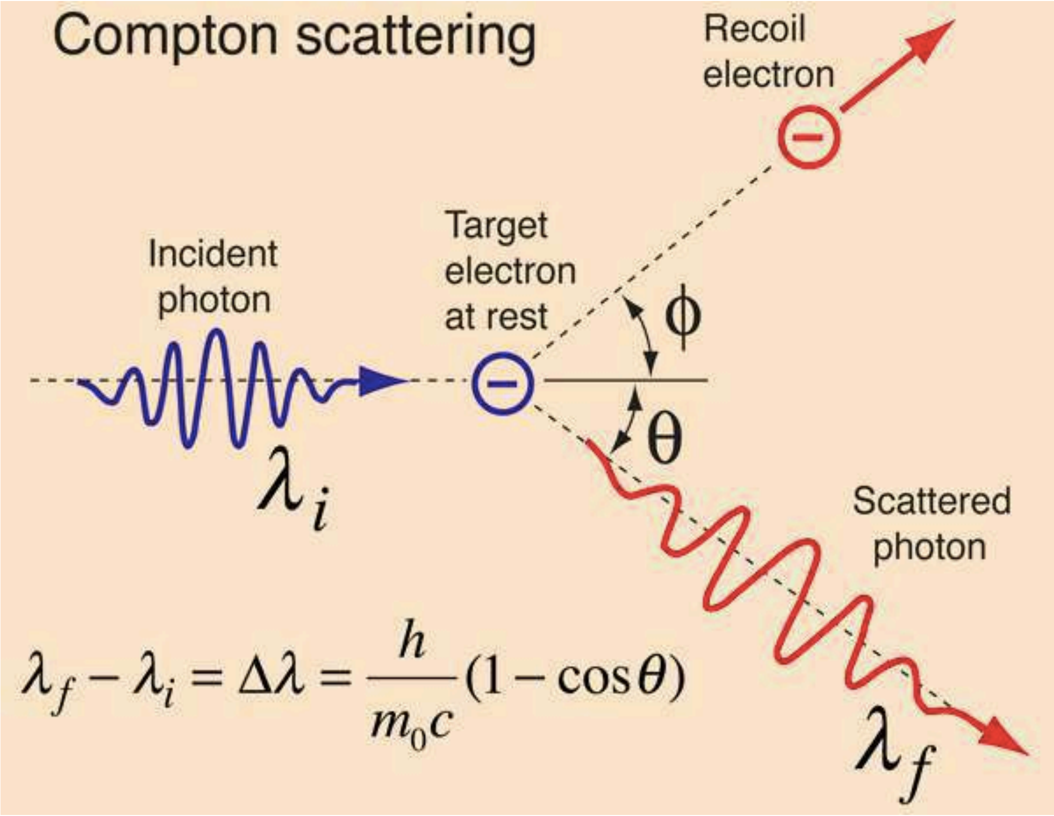


Photoelectric effect

The Photon *(1900 - 1924)*

Experimental confirmation by A. H. Compton (1923)

- The validity of the energy and momentum conservation laws convinced most skeptics of the reality of light quanta.
- The relation between the change in frequency of the photon and the scattering angle is very simply calculable in the photon picture, and agrees perfectly with experiment;



Einstein remarked (in 1924)

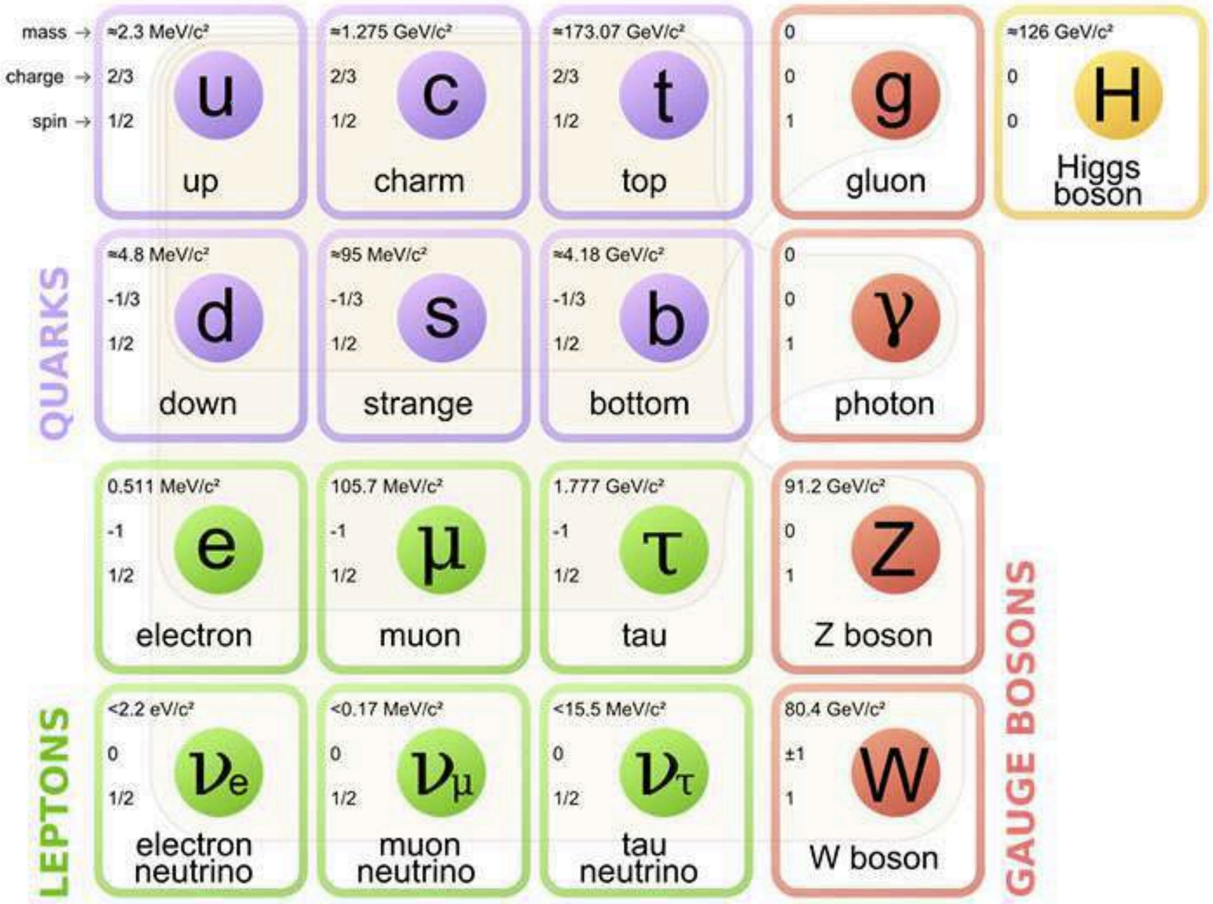
"*The positive result of the Compton experiment proves that radiation behaves as if it consisted of discrete energy projectiles, not only in regard to energy transfer but also in regard to Stosswirkung (momentum transfer).*"

Compton wavelength for the target electron

$$\frac{h}{m_e c} = \frac{hc}{m_e c^2} = \frac{1240\ eV\ nm}{0.511\ MeV} = .00243\ nm$$

The Standard Model

- All matter is made of three kinds of elementary particles: leptons, quarks and mediators:
  - 6 leptons (and 6 anti-leptons) falls in 3 generations
  - 6 flavors of quarks (and 6 anti-quarks) also fall in three generations
  - 4 mediators for 4 types of interactions



Classification of particles

- Every type of particle falls into one of two classes called
  - Fermions: No two particles can occupy the same quantum state → *Pauli exclusion principle.*
  - Bosons: No *Pauli exclusion principle.*
- Mathematical picture:
  - Fermion: $\psi(x_1, x_2) = -\psi(x_2, x_1)$ --> *probability amplitude to find the two particles at positions x_1 and x_2*
  - Bosons: $\psi(x_1, x_2) = \psi(x_2, x_1)$
- Particles:
  - Fermions: *electrons, quarks and neutrinos* → All the matter particles in the universe
  - Bosons: All the force carrying particles are bosons

Spin

- Particles have an inherent angular momentum that we call *spin*
- *Spin* is a quantum mechanical property
- Like many phenomena in the atomic world, spin is quantised

$$s = 0,\ \frac{1}{2}\hbar,\ \hbar,\ \frac{3}{2}\hbar,\ 2\hbar, \ldots$$

- Each particle in nature has a spin with a value taken from this list.
- Pauli: the spin determines whether a particle is a boson or fermion:
  - Particles with integer spin are bosons.
  - Particles with half-integer spin are fermions.

Spin

- The spins of all the known elementary particles in Nature:

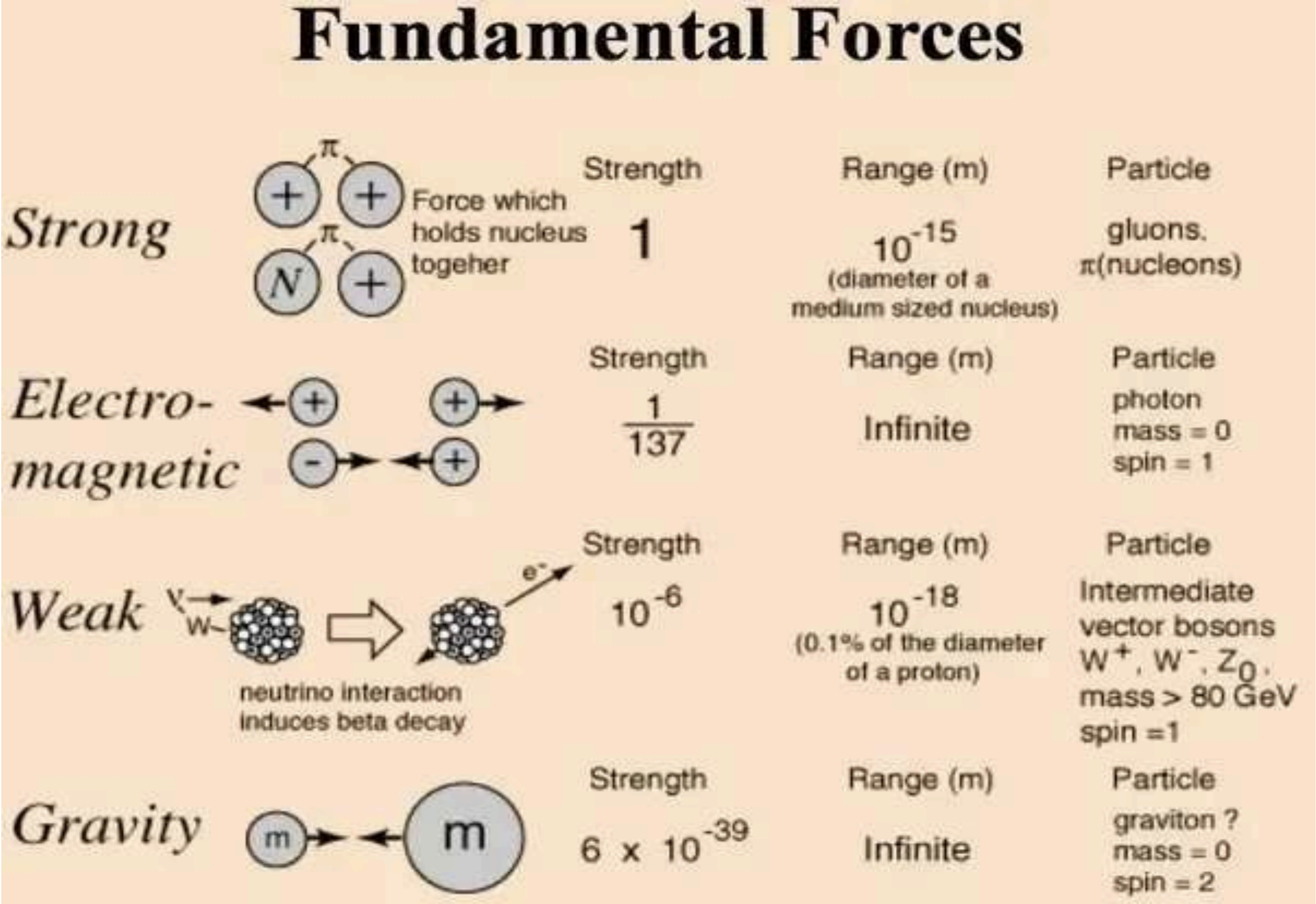
  - Spin 0: *The Higgs Boson*
  - Spin 1/2 : *All matter particles, i.e. the electron, muon and tau, together with the six types of quarks and three neutrinos*.
  - Spin 1: *The photon, gluon and W and Z bosons. In other words, the particles associated to electromagnetism and the weak and strong nuclear forces.*
  - Spin 2: *The graviton.*

❑ How do particles interact with one another?

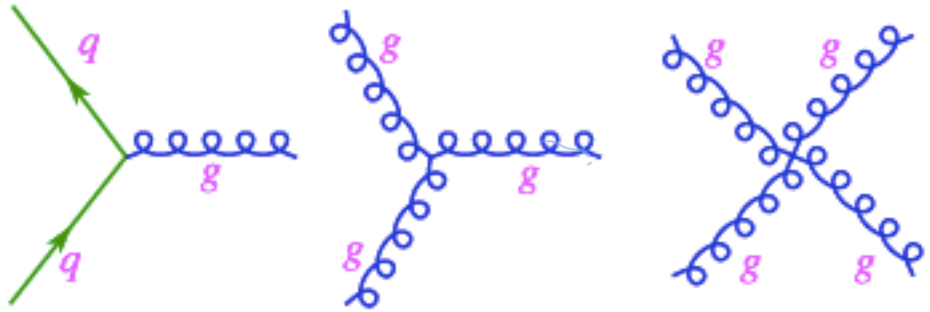
Interactions of elementary particles:

- Elementary particles are too small, it is hard to probe interactions between them.
- Indirectly, experimental information comes from three sources:
  - ***Scattering events***: fire one particle at another and record the results
  - ***Decays***: a particle spontaneously dis-integrates
  - ***Bound state***: two or more particles stick together as a composite object.

How do particles interact with one another?



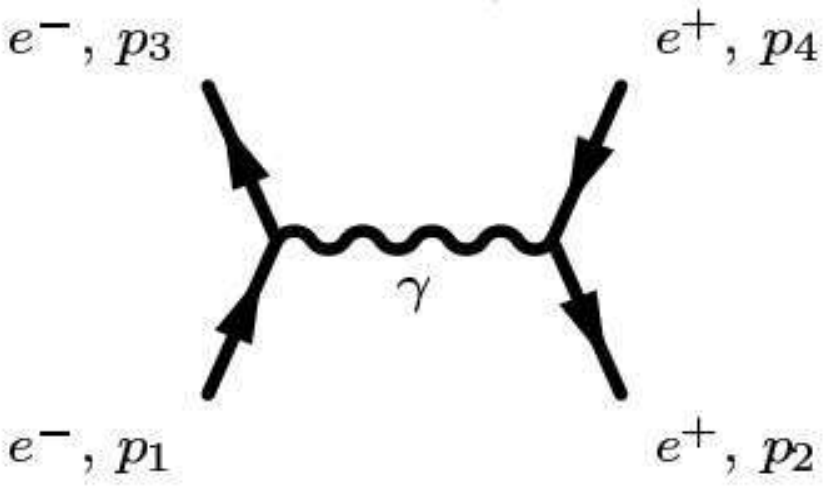
Strong interaction: *QuantumChromodynamics (QCD)*

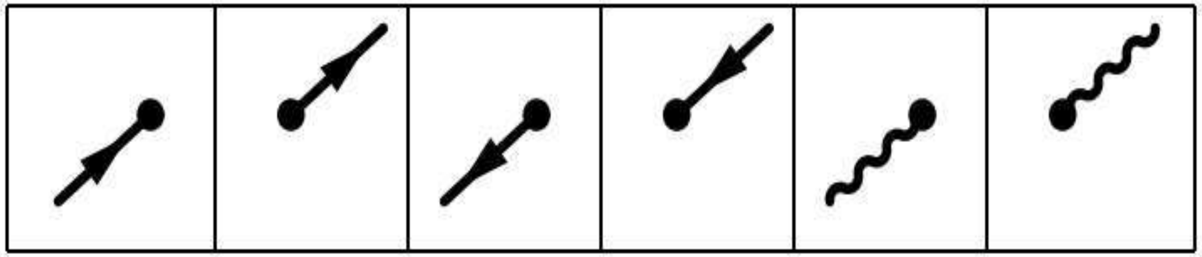


- There are two key features that distinguish QCD from QED:
  - ➢Quarks interact more strongly the further they are apart, and more weakly as they are close by – asymptotic freedom.
  - ➢Gluons interact with themselves
- Quark confinement: quarks can only exist in the form of colorless combinations → quarks are never found outside a hadron
- Quarks have charges of less than the fundamental charge, *e*

Electro-magnetic interaction:
Quantum electrodynamics (QED)

- QED is the oldest, the simplest, and the most successful of the dynamical theories.
- The Feynman for QED:

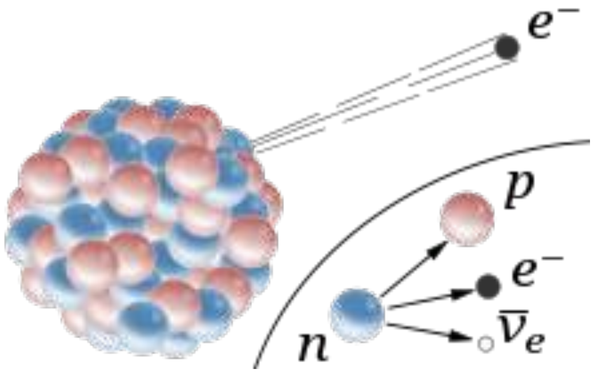


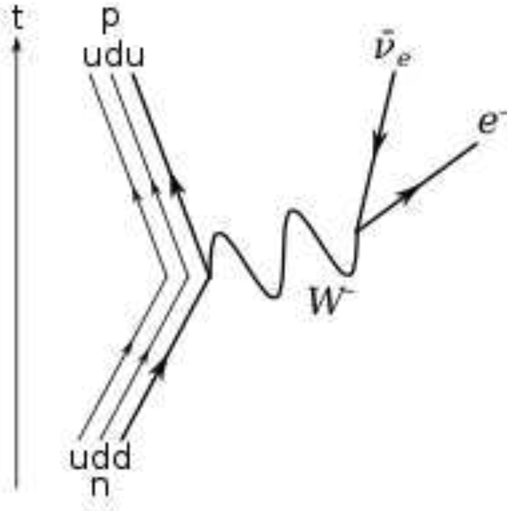


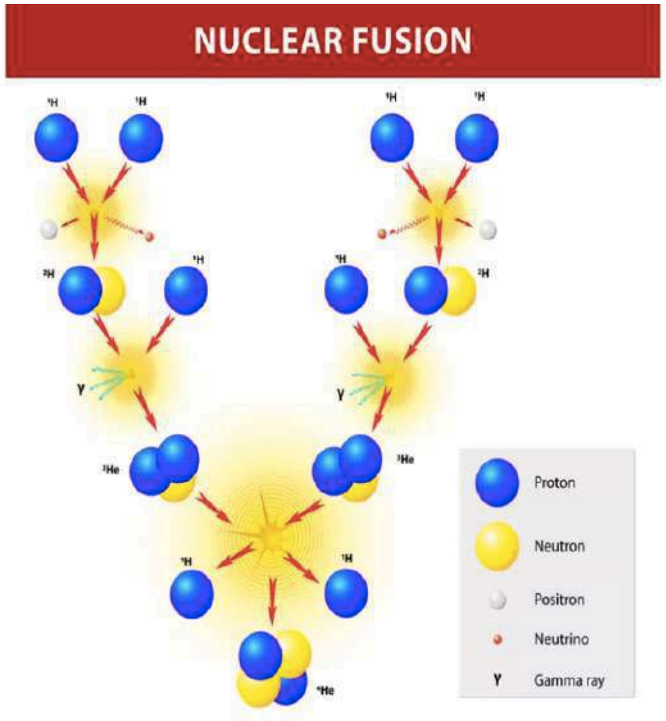
e^- in	e^- out	e^+ in	e^+ out	γ in	γ out
u	$\bar{u}$	$\bar{v}$	v	ϵ_μ	ϵ^*_μ

Weak interaction

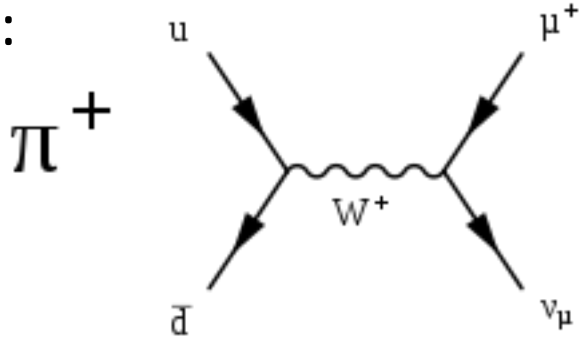
- The weak force is one of the four fundamental forces that govern all matter in the universe
- Beta decay:





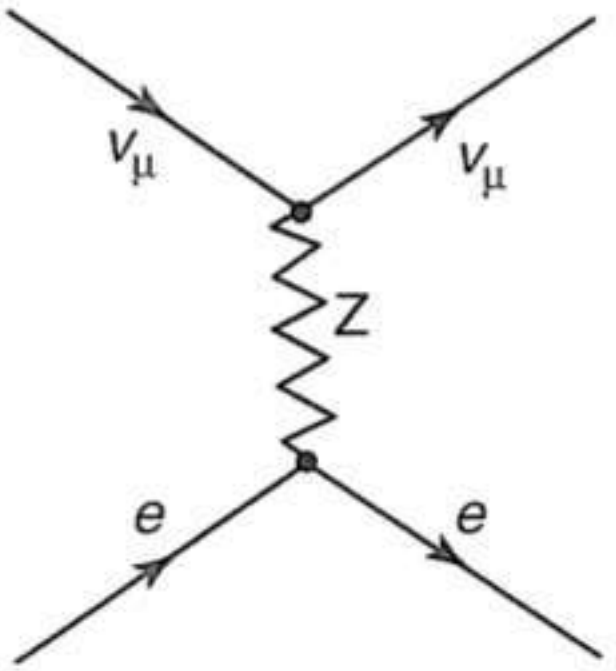


Pion decay:

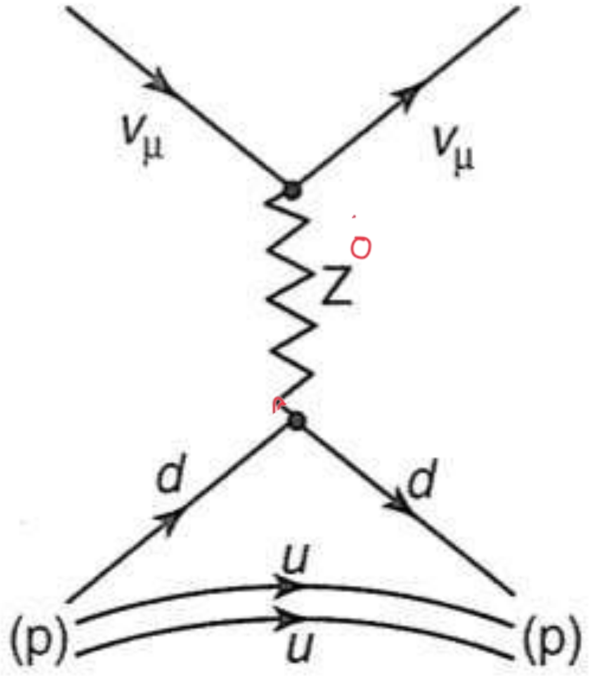


Weak interaction: neutral current

- Neutrino-electron scattering

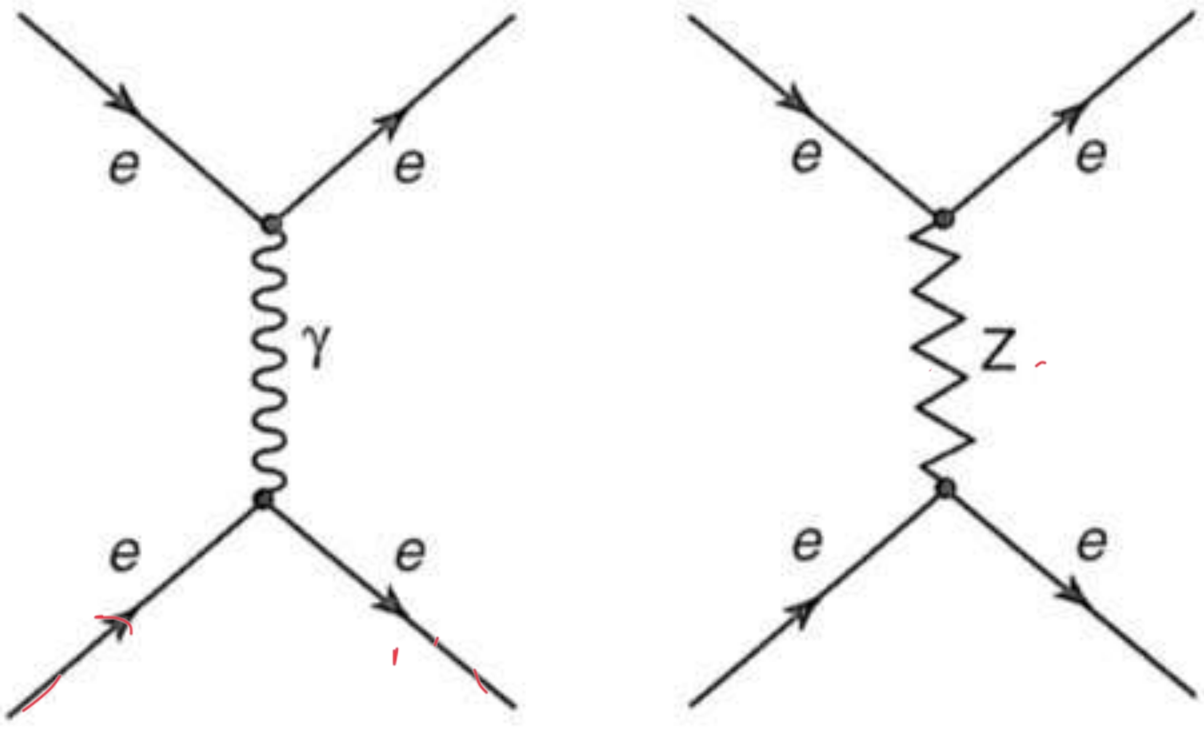


neutrino–proton scattering ($\nu_\mu + p \to \nu_\mu + p$)

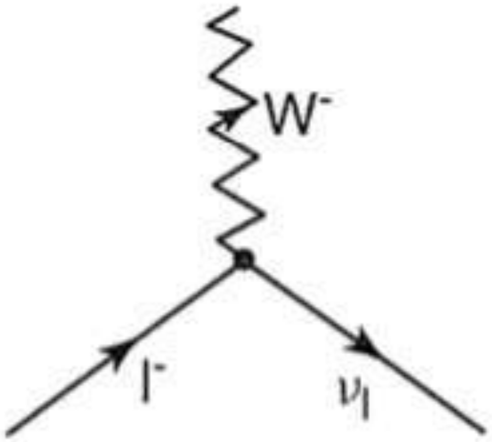


Weak interaction: Neutral current

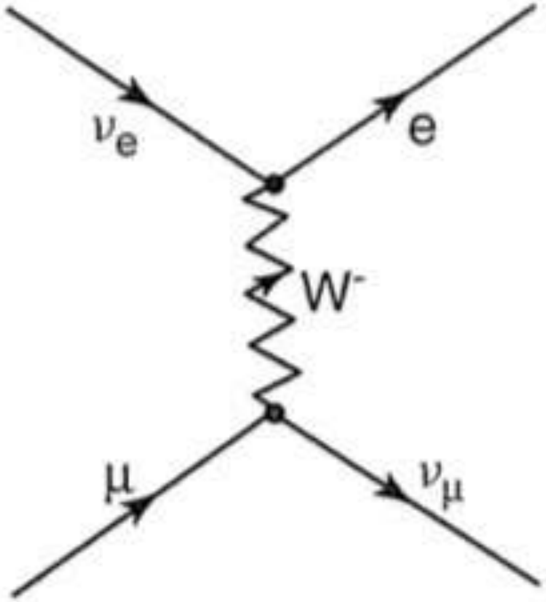
- Any process mediated by photon could also be mediated by Z.
- Thus, to observe a pure neutral weak interation → resort neutrino scatering.



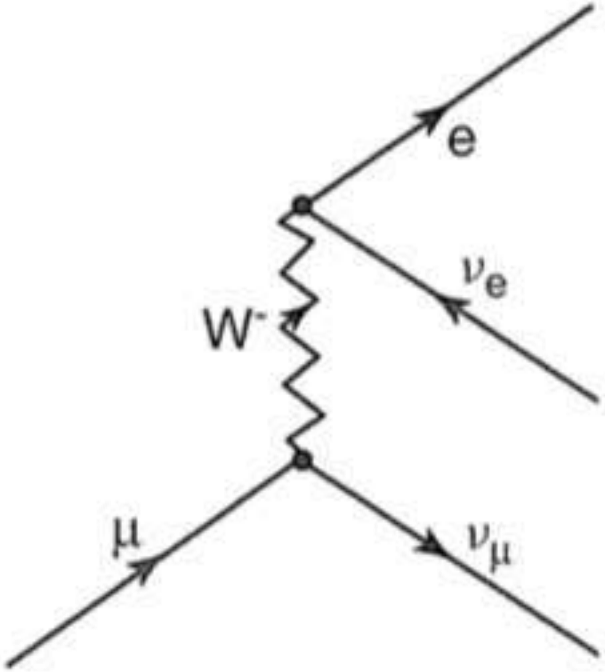
Weak interaction: Charge current of leptons



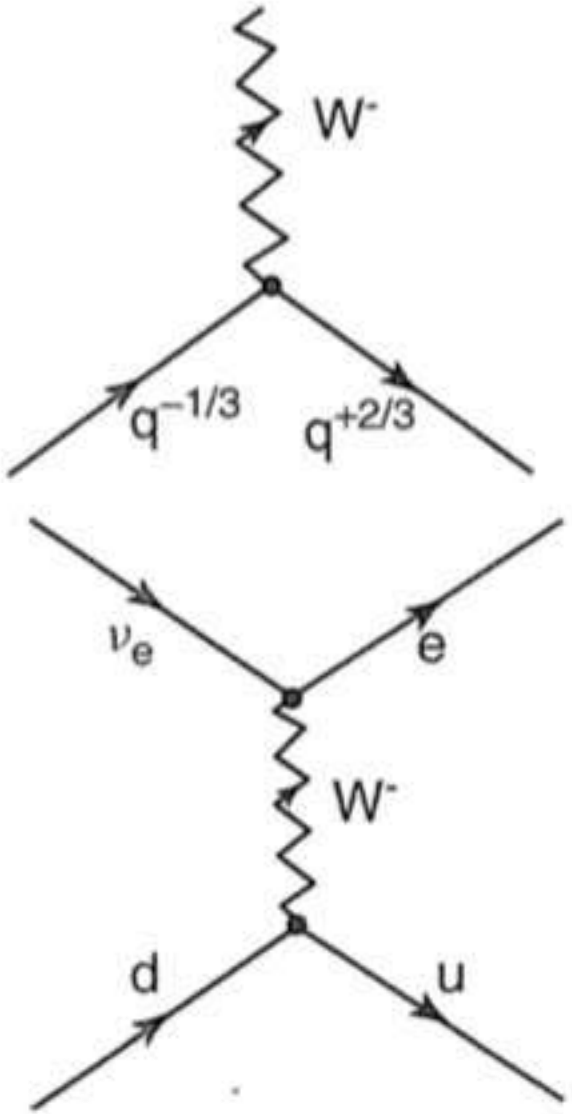
$$\mu^- + \nu_e \rightarrow e^- + \nu_\mu$$

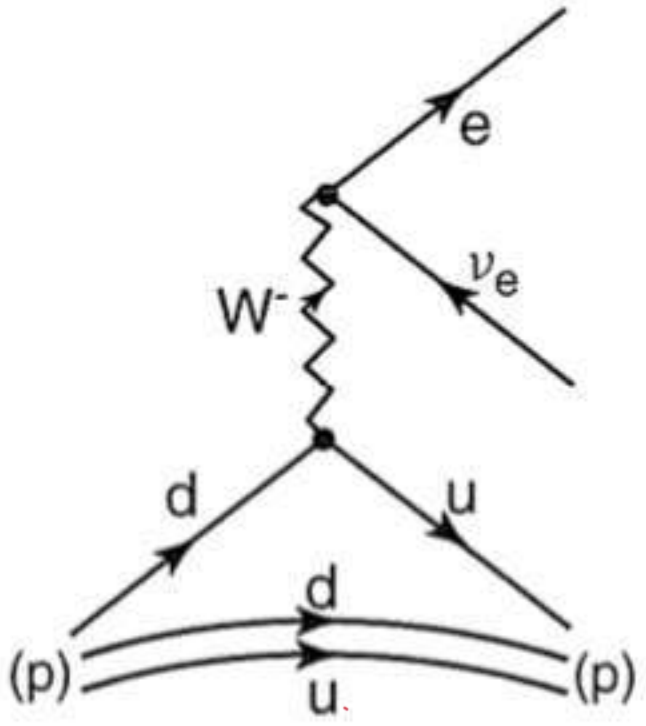


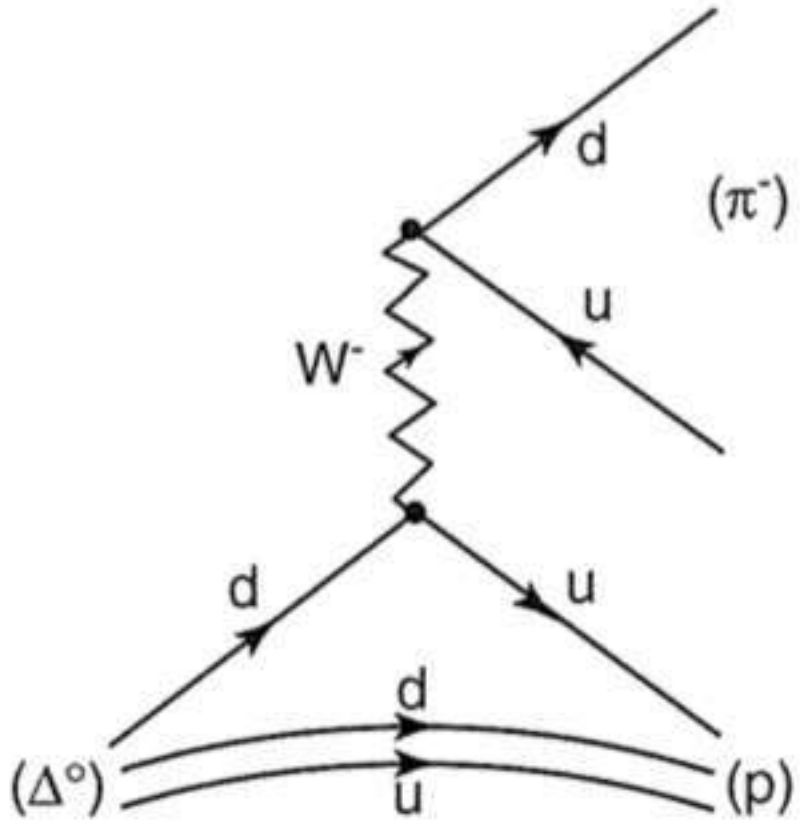
$$\mu^- \rightarrow e^- + \nu_\mu + \overline{\nu}_e:$$



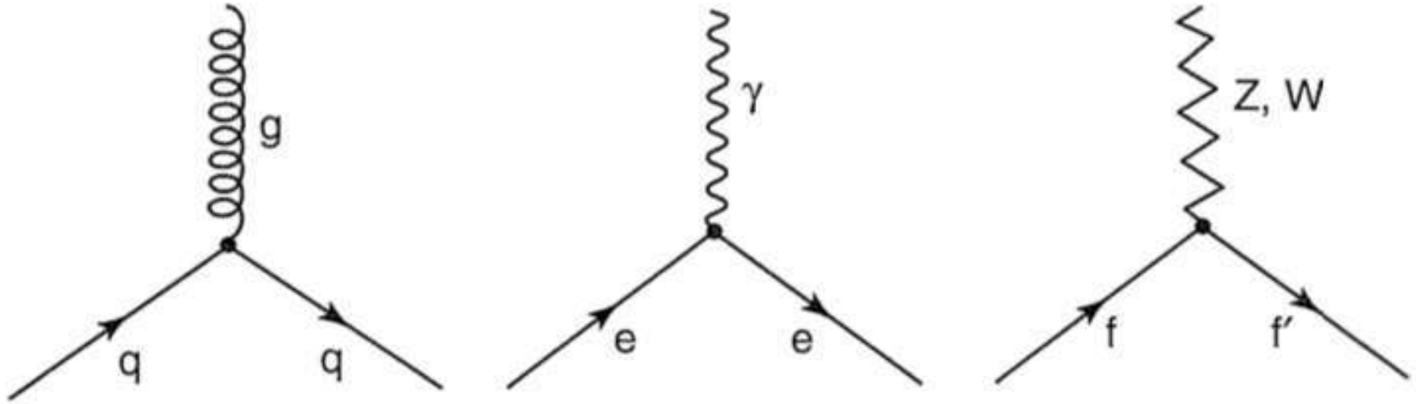
Weak interaction: Charge current with quarks







Decays and Conservation law



- *Charge*: all three interactions conserve electric charge
- *Color*: The electromagnetic and weak force don't affect color. The strong interaction conserves color at the vertex.
- *Baryon number*: 1 for baryon and -1 for anti-baryon and zero for everything else.
- *Lepton number*: there is no mixing between leptons so electron number, muon number and tau number are separately conserved!
- *Flavor*: conserved at strong and EM vertex but not weak vertex.

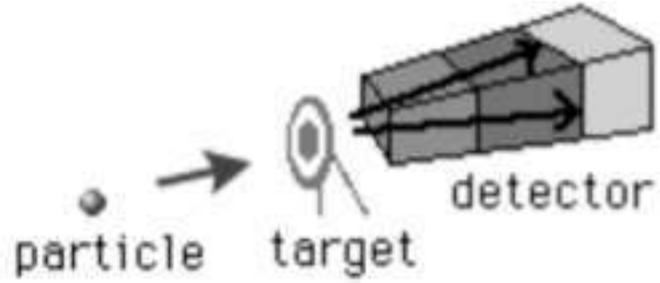
❑ How are elementary particles produced?

How are elementary particles produced?

- ***Electron***: heating up a piece of metal, and electrons come boiling off
- ***Proton***: can be produced by ionozing hydrogen. In case protons are used as a target, a tank of hydrogen is essentially a tank of protons (electrons are so light that an energetic incident particle will knock them out of the way).
- ***For more exotic particles***: produced from three main sources: cosmic rays, nuclear reactors and particle accelerators
  - ***Cosmic rays***: high-energy protons coming from outer space bombard with the Earth containing atoms in the upper atmosphere → produce showers of secondary particles (mostly muons and neutrinos). Disadvantages of this source: low rate and uncontrollable.
  - ***Nuclear reactors***: When radioactive nucleus disintegrates, it may emit a variety of particles (neutrons, neutrinos, alpha, beta and gamma rays).
  - ***Particle accelerators***: electrons and protons are accelerated to high energy, and smashed into a target. This can generate intense secondary beams of positrons, muons, pions, kaons, B-mesons, antiprotons, and neutrinos.

❑ How are elementary particles detected?

How are elementary particles detected?



- After the collision of a particle beam with some target (or another beam) detection of what happens becomes the key task.
- In order to do this, the particle must leave some imprint of its presence, which is made possible by the fact that particles ultimately transfer energy to the medium they are traversing – if not, we'd never observe them!
- There are many kinds of particle detectors: Geiger counter, Cloud chambers, Buble chambers, Drift chambers, Photographic emulsions, Cerenkov counters, Scintilators, Photomultipliers, …

More about Photons

Properties of a Photon

- Photon has no mass and no electric charge.

Natural Processes Emitting Photons

- When a charge is accelerated, it emits synchrotron radiation.
- During molecular, atomic, or nuclear transitions to a lower energy level, photons of various energies are emitted.
- In quantum field theory, the photon is an exchange particle in QED interactions, emitted from electron-positron annihilation.

Some Technological Applications Using Effects of Photons

- **Photomultiplier tube (PMT):** A detector of light that converts incident photons into an electric signal using the photoelectric effect.
- **Semiconductor charge-coupled device (CCD) chips:** An incident photon generates a charge on a microscopic capacitor that can be detected.
- **Geiger–Müller counter:** Used for detecting and measuring ionizing radiation such as alpha rays, beta rays, and gamma rays. Photons ionize gas molecules in the device, causing a detectable change in conductivity.

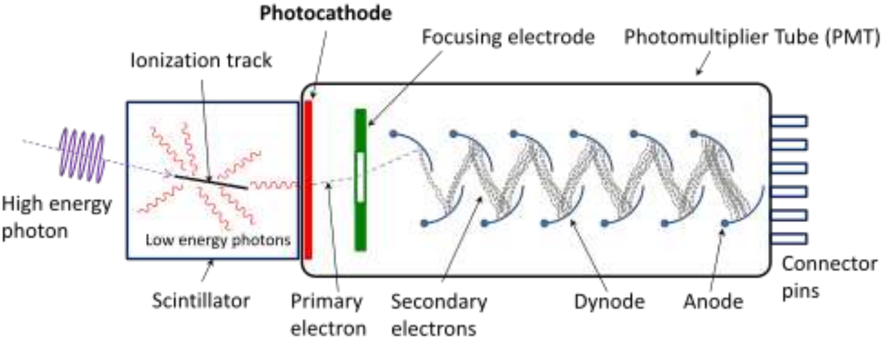
Introduction to PMT

- A highly sensitive vacuum tube that converts light into an electrical signal.
- Used in applications requiring detection of very low light levels.
- Examples: Medical imaging, particle physics, fluorescence spectroscopy.
- **Customizable Production:** PMTs can be manufactured in small quantities and tailored for specific applications.

Photomultiplier

Basic Working Principle of PMT

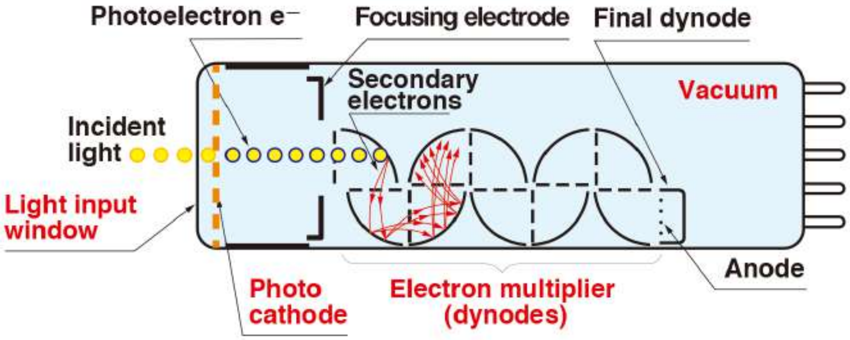
- **Photoelectric Effect:** Light photons strike a photocathode, releasing electrons.
- **Electron Multiplication:** Dynodes amplify the number of electrons.
- **Signal Collection:** Anode collects the multiplied electrons and generates a measurable signal.



Construction of PMT

Key Components:

- Photocathode (converts photons to electrons)
- Series of dynodes (amplifies electrons)
- Anode (collects electrons, producing an output current)
- Vacuum glass tube (ensures proper operation)



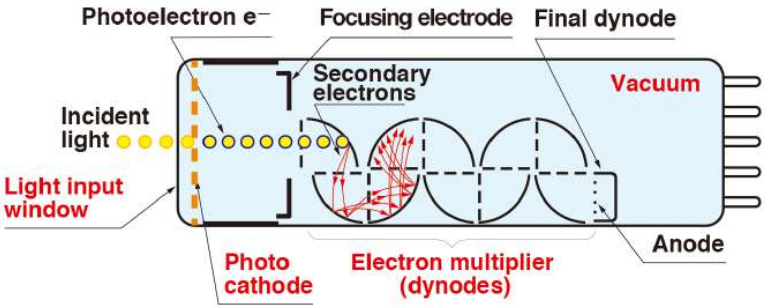
Materials Used in PMTs

Light Input Window Materials:

- Borosilicate glass; Quartz glass (UV-transmitting); and MgF_2 crystal

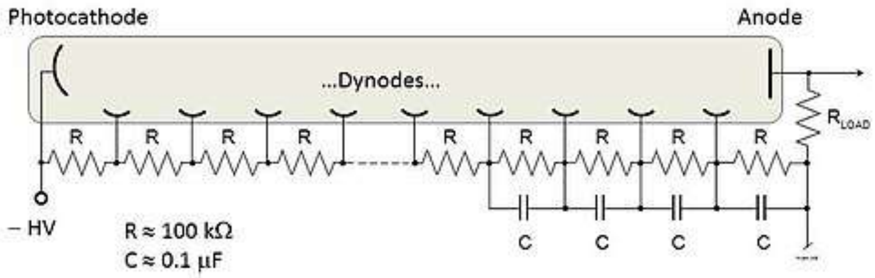
Photocathode Types:

- Bialkali (visible light region)
- Multialkali (extends to near-infrared)
- Alkali-halide (UV light detection)
- GaAs, InGaAs (sensitivity from UV to near-infrared)



Electron Multiplication Process

- **Dynodes:** Successive dynodes increase electron count via secondary emission.
- **Multiplication Factor:** Each dynode stage multiplies the number of electrons.
- **Gain:** Typically $10^6 - 10^8$, depending on the number of dynodes.



The Role of Vacuum in PMTs

- PMTs rely on the external photoelectric effect, where electrons are released into a vacuum upon photon impact.
- High-performance photocathodes require a vacuum environment for optimal electron emission.
- A vacuum prevents signal interference, allowing detection of low-level light with high sensitivity.

Advantages and Disadvantages of PMT

Advantages:

- Extremely high sensitivity
- Fast response time
- Wide spectral range

Disadvantages:

- Sensitive to magnetic fields
- Requires high voltage ($\sim$1000V)
- Prone to noise (dark current, thermal noise)

Applications of PMTs

- **Medical Imaging:** PET scans, scintillation detectors.
- **High-energy Physics:** Particle detectors.
- **Astronomy:** Detection of cosmic rays.
- **Spectroscopy:** Fluorescence and Raman spectroscopy.

Facility name	**Kamiokande** *(From 1983 to 1996)*	**SuperKamiokande** *(From 1996 to present)*	**HyperKamiokande** *(In planning stage)*
Type No.	R1449	R3600	R12860
Collection efficiency	40 % to 50 %	70 %	90 %
e^- transit time spread	8.0 ns	5.5 ns	2.4 ns

Summary of PMT

- PMTs are highly sensitive light detectors based on electron multiplication.
- They are widely used in scientific and industrial applications.
- Despite some limitations, ongoing research is improving their performance.

Future Trends in PMT Technology

- Improved quantum efficiency with new photocathode materials.
- Integration with digital electronics for real-time data processing.
- Development of hybrid photodetectors combining PMT and solid-state technology.

Thank you for your attention!

References

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