Introduction to Nuclear and Particle Physics

Short History of the beginnings

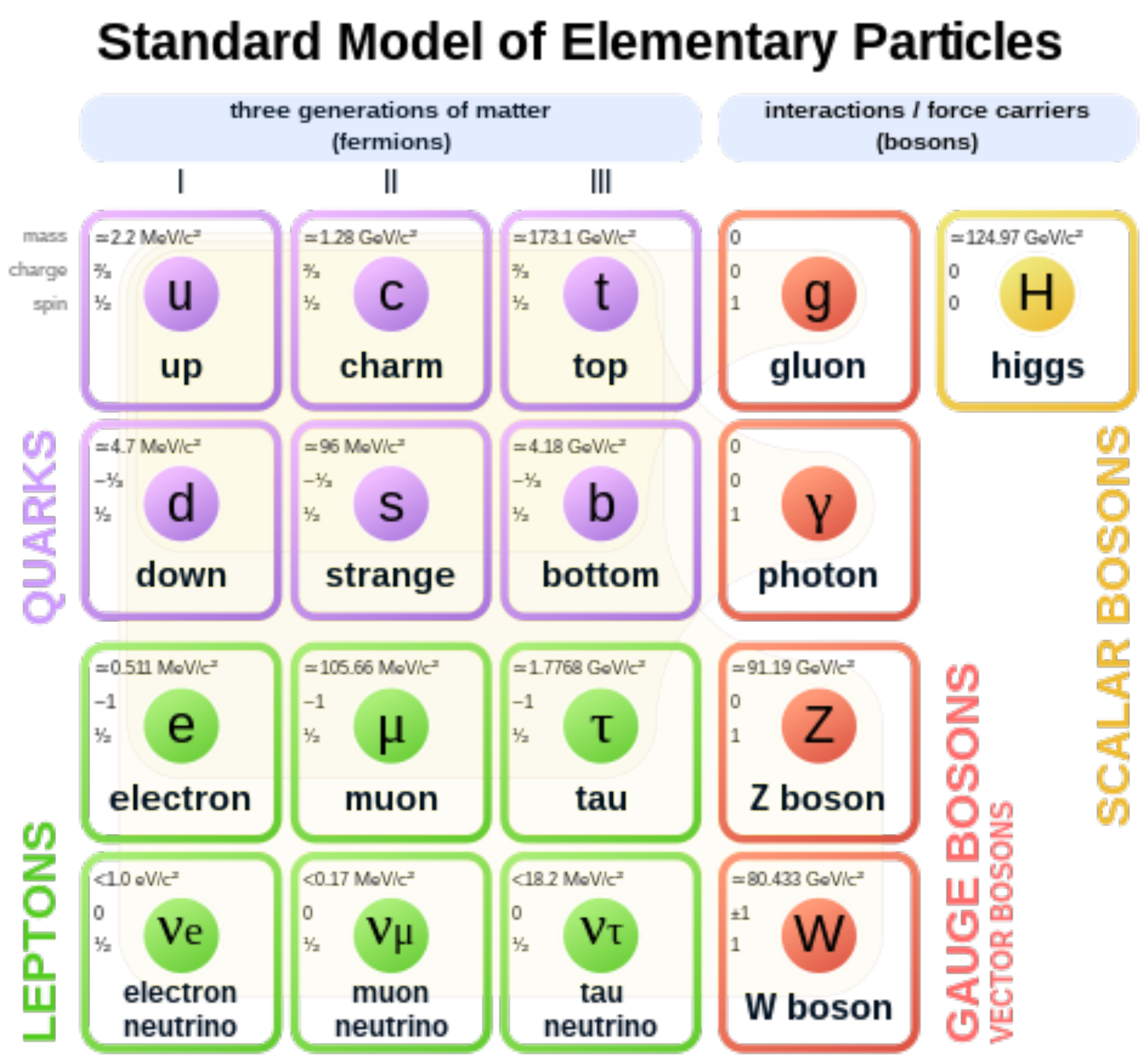
Helga Dénes 2022 Yachay Tech

hdenes@yachaytech.edu.ec

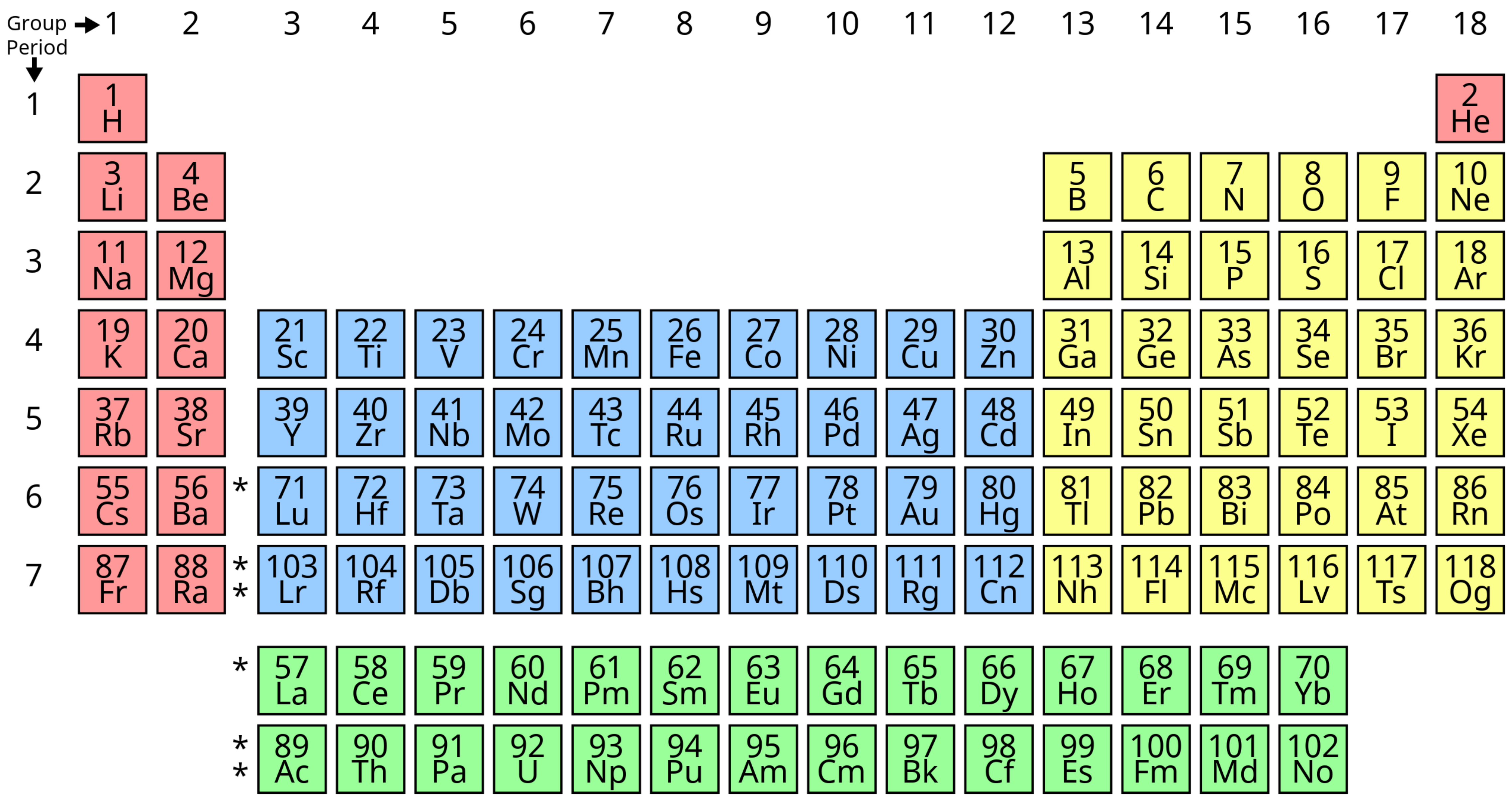
What is the difference?

Nuclear Physics deals with processes related to or affecting the nuclei of atoms.

Particle Physics deals with the most elemental particles like Fermions and Bosons.



https://en.wikipedia.org/wiki/Standard_Model



https://en.wikipedia.org/wiki/Periodic_table

What is the difference?

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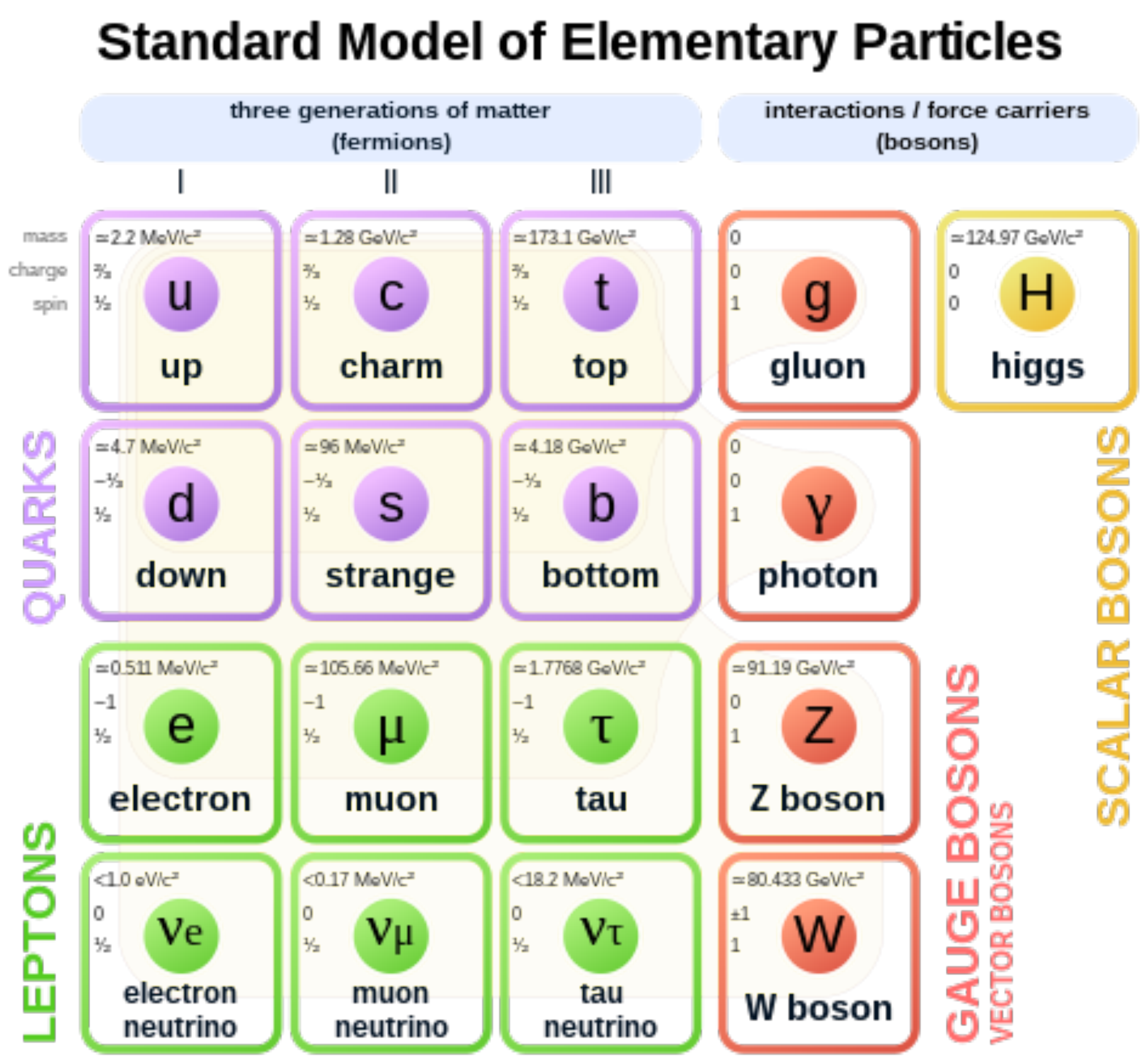
Nuclear Physics no unified theory, theory for bits and pieces

Particle Physics unified theory called standard model based on quantum field theory (quantum mechnics + relativity)



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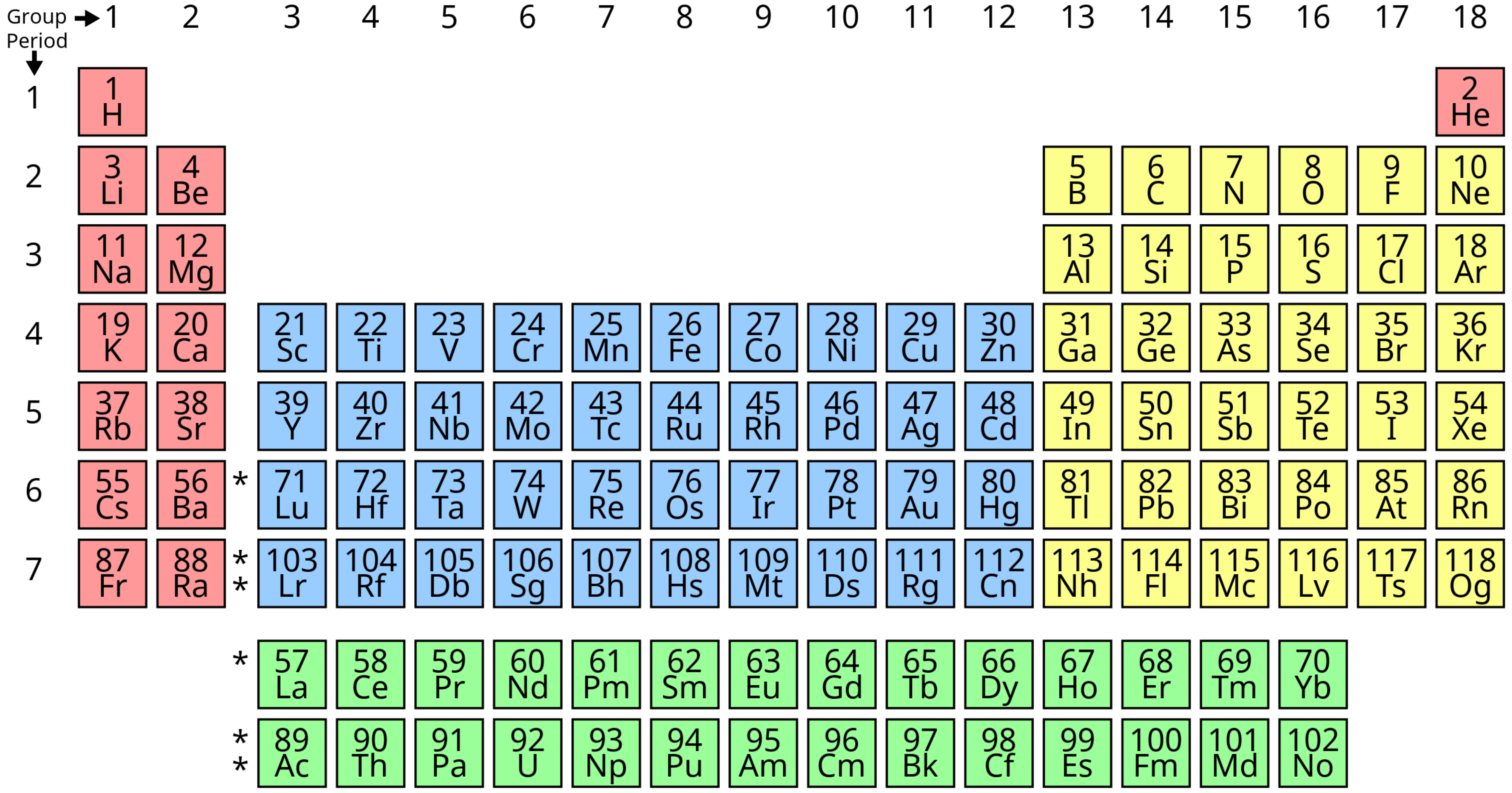

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Relevance

What applications can you think of?

Relevance

What applications can you think of?

- describing elementary particles, atoms,
- understanding cosmology, the interior of stars
- Radio carbon dating
- Nuclear power plants
- medical applications (e.g. imaging)
- etc.

The concept of atoms

Already in ancient Greece, Democritus theorised that matter can be subdivided until a fundamental particle is reached. He called this fundamental particle the atom.

This theory of atomism was a theory up until the 19th century, when concrete evidence started to emerge.

Mendeleev’s periodic table classified the atoms of different elements based on their properties.
-> This inspired the drive to understand the basic properties of atoms.

The start of Nuclear Physics

- 1896 Becquerel discovered that certain atoms are radio active, when uranium salts accidentally fogged a photographic plate.

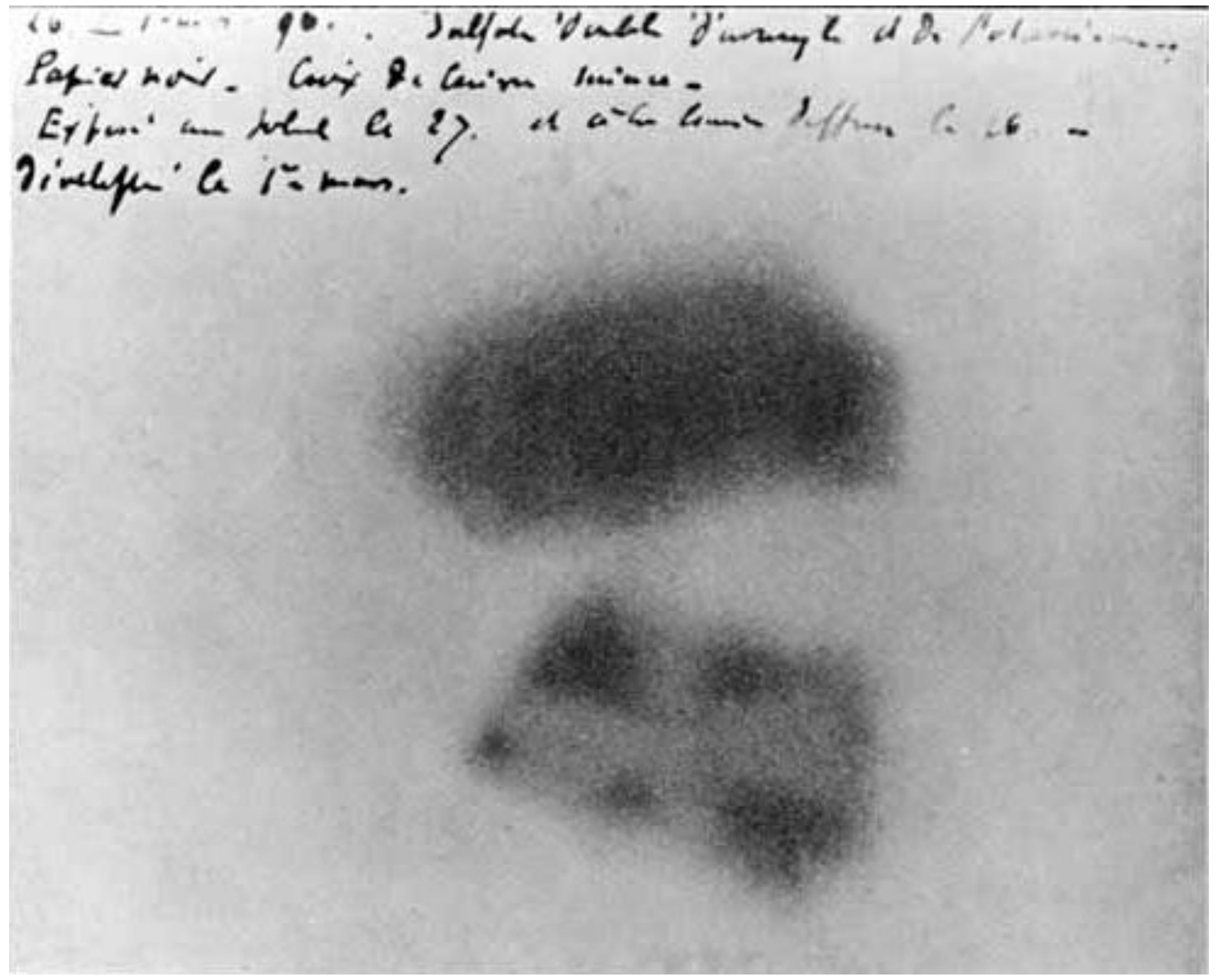
- **Radioactivity:** some chemical elements spontaneously emit radiation

- Marie and Piere Curie further researched the topic of radio activity and in 1897 discovered several radio active elements (polonium and radium).

- There were two distinct types of radiation discovered, named by Rutherford α and β rays.
  - β rays are electrons and
  - α rays are doubly ionised helium atoms.

  - In 1900 Villard discovered a third type of decay that involved the emission of photons, referred to in this context as γ rays.

Becquerels photographic plate with the uranium salt mark.



https://en.wikipedia.org/wiki/Henri_Becquerel

The start of Nuclear Physics

- Question, where do the atom get the energy to produce these rays? At this moment the theory was that atoms are the smallest units of matter.
- Rutherford showed in 1900 that the intensity of the radiation emitted from a radioactive source was not constant, but reduced by a factor of two in a fixed time that was characteristic of the source, but independent of its amount. This is called its **half-life**.
- In 1902, together with Soddy, Rutherford proposed the **transformation theory**, according to which the atoms of any radioactive element decay with a characteristic half-life, emitting radiation, and in so doing are transformed into the atoms of a different chemical element.
- In 1897 J.J. Thomson established the nature of ‘cathode rays’, radiation that had been observed to occur when an electric field was established between electrodes in an evacuated glass tube.
  - These were free electrons (e),
  - Thomson measured their mass and charge -> atoms contained electrons

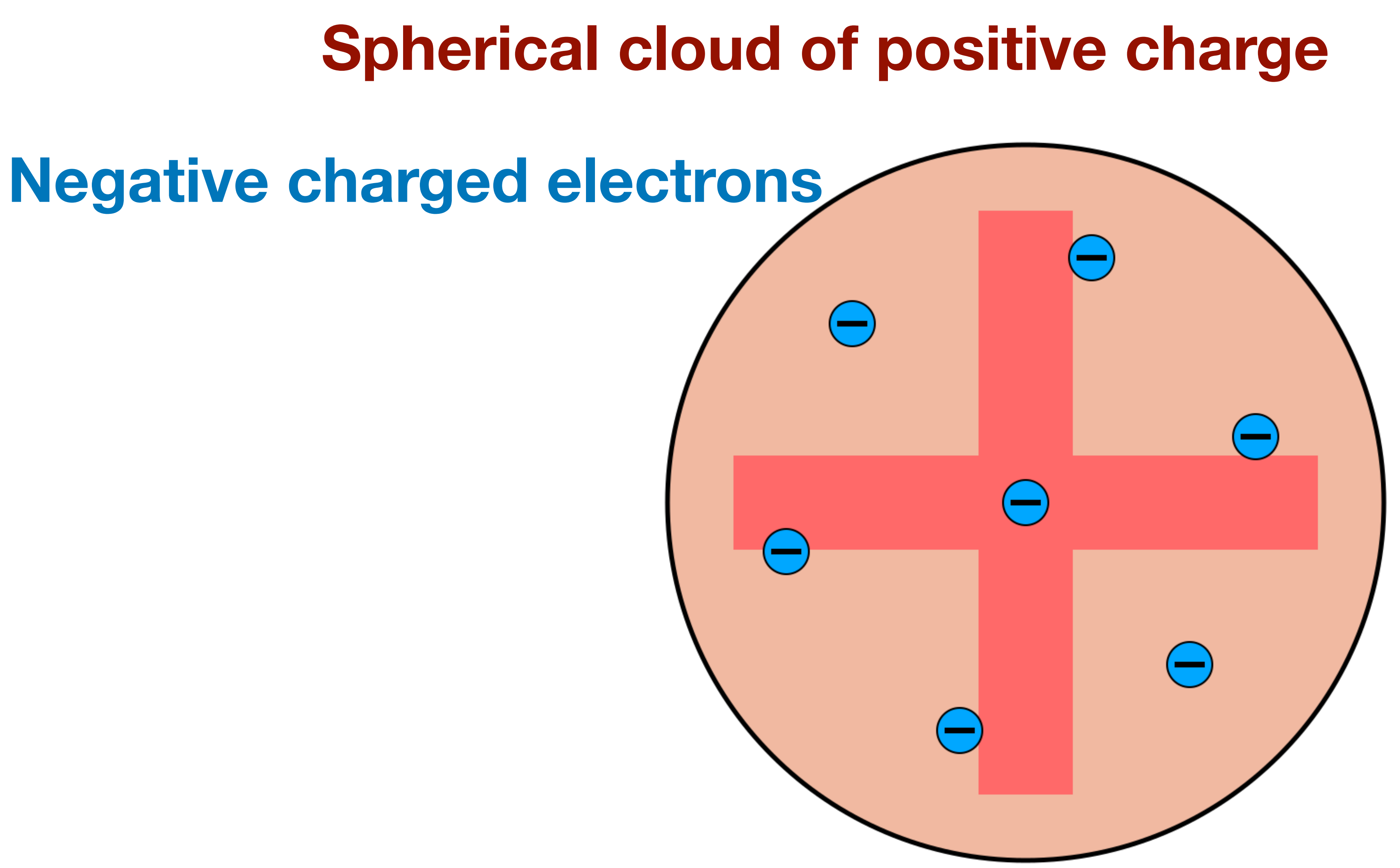
The Plum pudding model of the atom

- Based on the discovery of electrons inside atoms Thompson proposed the **plum pudding model** for the atom in 1903

- The plum pudding model has electrons surrounded by a volume of positive charge, like negatively charged "plums" embedded in a positively charged "pudding".

- The model tried to explain:
  - that electrons are negatively charged particles and
  - that atoms have no net electric charge.

- Could account for the stability of atoms, but gave no explanation for the discrete wavelengths observed in the spectra of light emitted from excited atoms.



https://commons.wikimedia.org/wiki/File:Plum_pudding_model.svg

Gold foil experiment

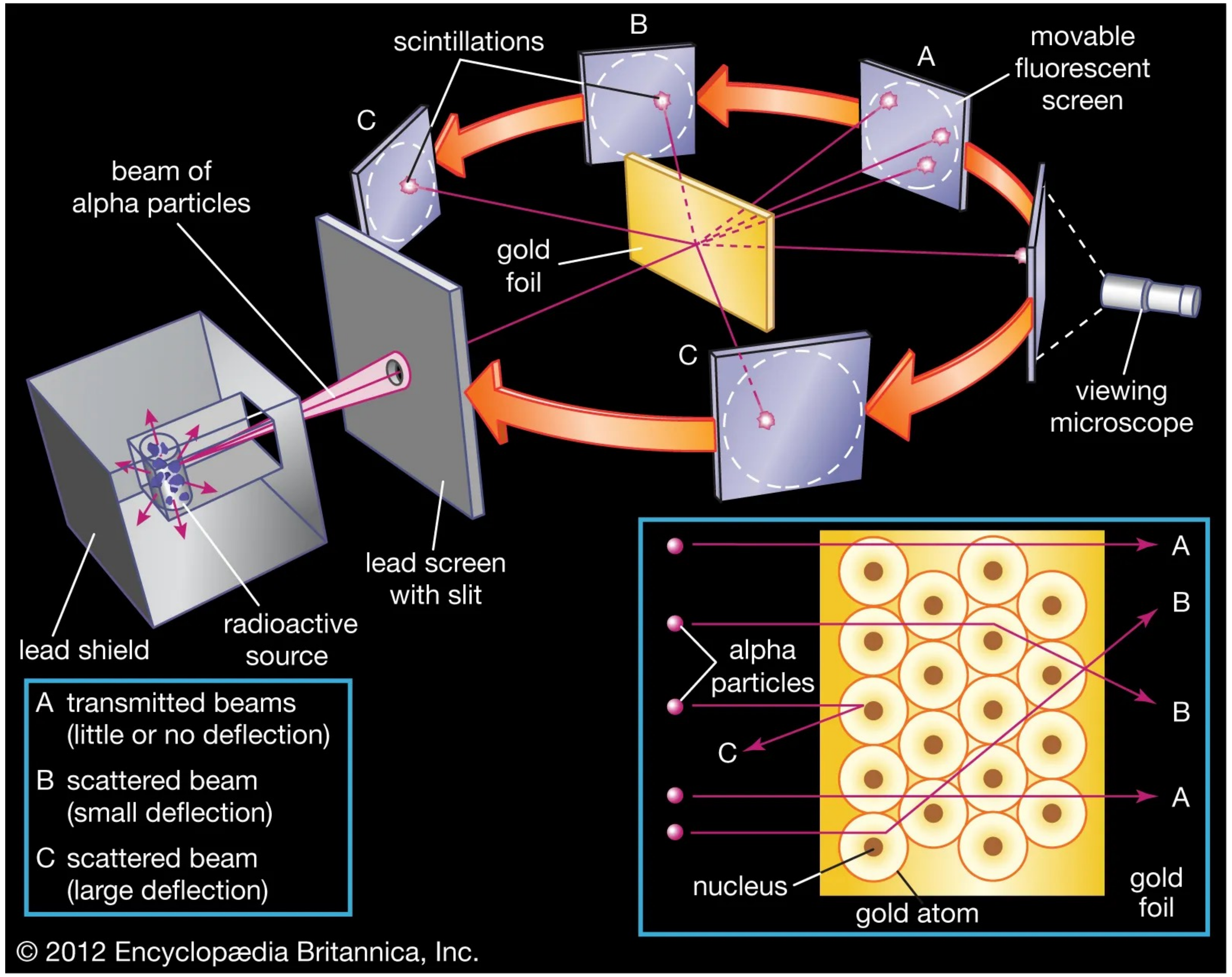
- By Rutherford, Marsden and Geiger

- A piece of gold foil was hit with α particles, which have a positive charge.

- In the Thomson model, most of the α particles would pass through the foil, with only a few suffering deflections through small angles

- Most alpha particles went right through. This showed that the gold **atoms were mostly empty space**.

- Some particles had their paths bent at large angles.
  - The only way this would happen was if t**he atom had a small, heavy region of positive charge inside it.**



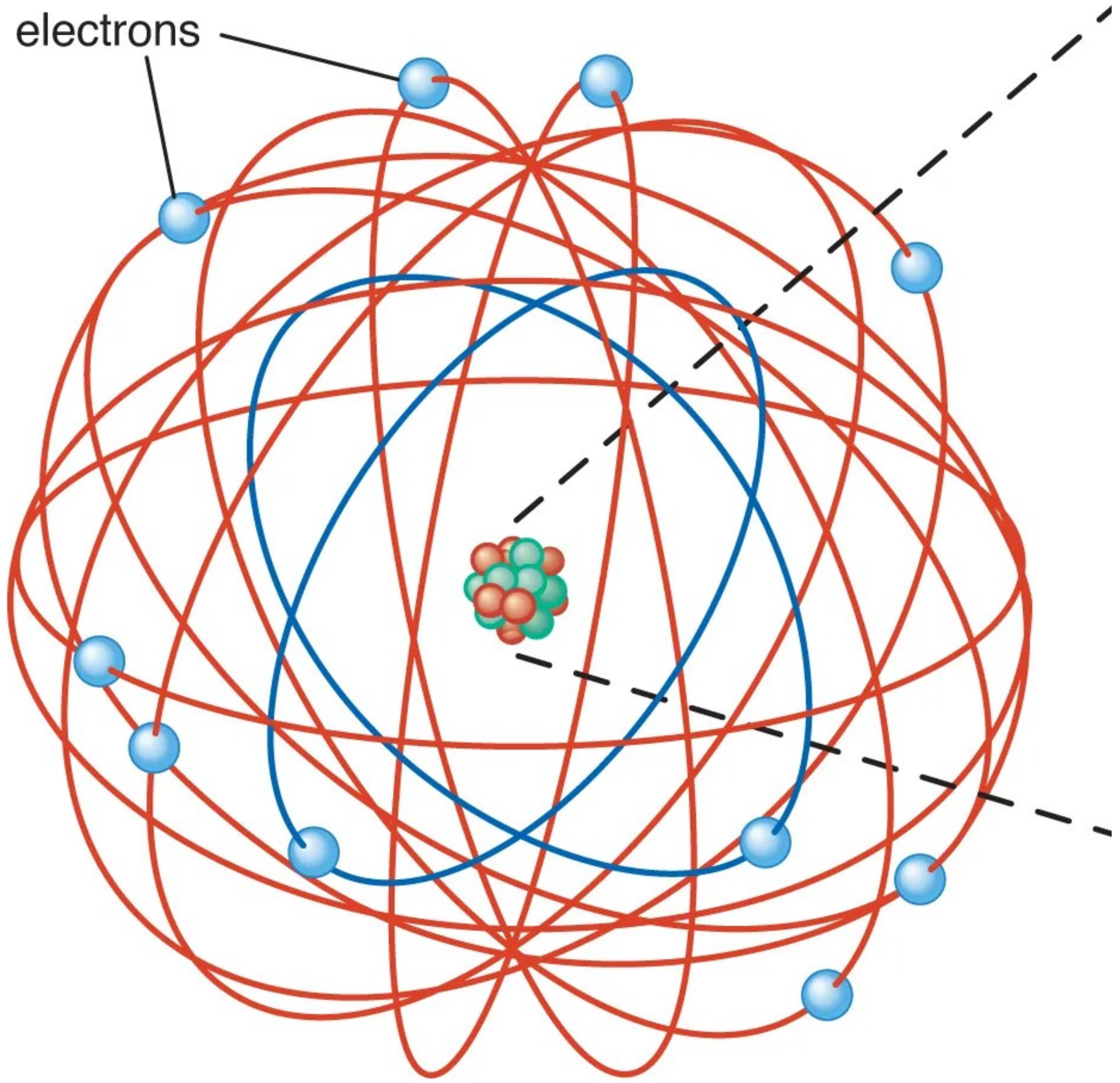
Encyclopedia Britanica

The nuclear model of the atom

- 1911 Rutherford proposed the existence of an atomic nucleus.

- Rutherford's nuclear model described the atom as a tiny, dense, positively charged core called a nucleus, in which nearly all the mass is concentrated, around which the light, negative constituents, called electrons, circulate at some distance, much like planets revolving around the Sun.

- Antonius Van den Broek made the proposal that the atomic number of an atom is the total number of units of charge present in its nucleus.



Encyclopedia Britanica

The Bohr-Rutherford model

- In 1913 Moseley proved with experiments that Van den Broek's proposal was right.
  - He demonstrated that the **charge on the nucleus is +Ze, where the integer Z was the atomic number of the element** concerned, and implying Z orbiting electrons for electrical neutrality.
  - the foundation of a physical explanation of Mendeleev's periodic table
  - predicted the existence of seven unknown chemical elements, which were later discovered.

- The Rutherford model was further developed by Bohr (**Bohr-Rutherford model**)
  - The motion of the electrons is confined to a set of **discrete orbits**. This model could explain the discrete nature of the observed electromagnetic spectra when excited atoms decayed, because photons of a definite energy would be emitted when electrons moved from one orbit to another

- However, radioactivity is still not explain by this model

The neutron

Until 1932 it was believed that the nucleus consisted of A protons and A-Z nuclear electrons, to make up the Ze net positive charge. However there were problems with this idea, as it did not match expectations from quantum mechanics:

- the nuclear electrons would need to be bound to the protons with a very strong force, for which there was no evidence.
- The nucleus has a size of 10^{-14}m. For the electrons to be confined in this space would need to have a momentum distribution of ~ 20MeV/c. But the distributions observed from electrons from beta decay are around 1MeV/c.
- The spin of the nucleus is not consistent with the added spins of the proton and electron
- The magnetic momentum of the nucleus is not consistent with the expectation

Discovery of the Neutron

- The problem was solved in 1932 by the discovery of the neutron by Chadwick.
- His work followed earlier experiments by Iréne Curie (the daughter of Pierre and Marie Curie) and her husband Frédéric Joliot. They had observed that neutral radiation was emitted when α particles bombarded beryllium, and later work had studied the energy of protons emitted when paraffin was exposed to this neutral radiation.
- Chadwick refined and extended these experiments and demonstrated that they implied the existence of an **electrically neutral particle of approximately the same mass** $(0.1\%$ larger$)$ **as the proton, called the neutron (n).**
- The discovery of the neutron led immediately to the correct formulation of nuclear structure, in which an isotope of atomic number Z and mass number A is a bound state of Z protons and A–Z neutrons. There are no electrons bound inside nuclei.

Terminology for Nuclear physics

- The nuclear species is characterised by the total amount of electric charge in the nucleus (+Ze) and by it's total number of mass units (Z).
  - **Z is the atomic number** and e is the magnitude of the electric charge.
- The fundamental **positively charged particle in the nucleus is the proton**.
- The simplest nucleus consists of 1 proton (Hydrogen).
- A nucleus of atomic number Z contains Z protons and Z positive charge.
  - A neutral atom contains Z electrons.
- The mass of the electron is much smaller ($m_p \sim 2000\ m_e$) than the mass of the proton and can often be ignored nor the mass of the atom.
- The **atomic mass number (A)** of a nuclear species is the nearest integer to the mass ratio between the nuclear mass and the fundamental mass unit.
  - **The fundamental mass unit is defined to be nearly that of the proton**
- For nearly all nuclei A is greater than Z, by about a factor of two or more.

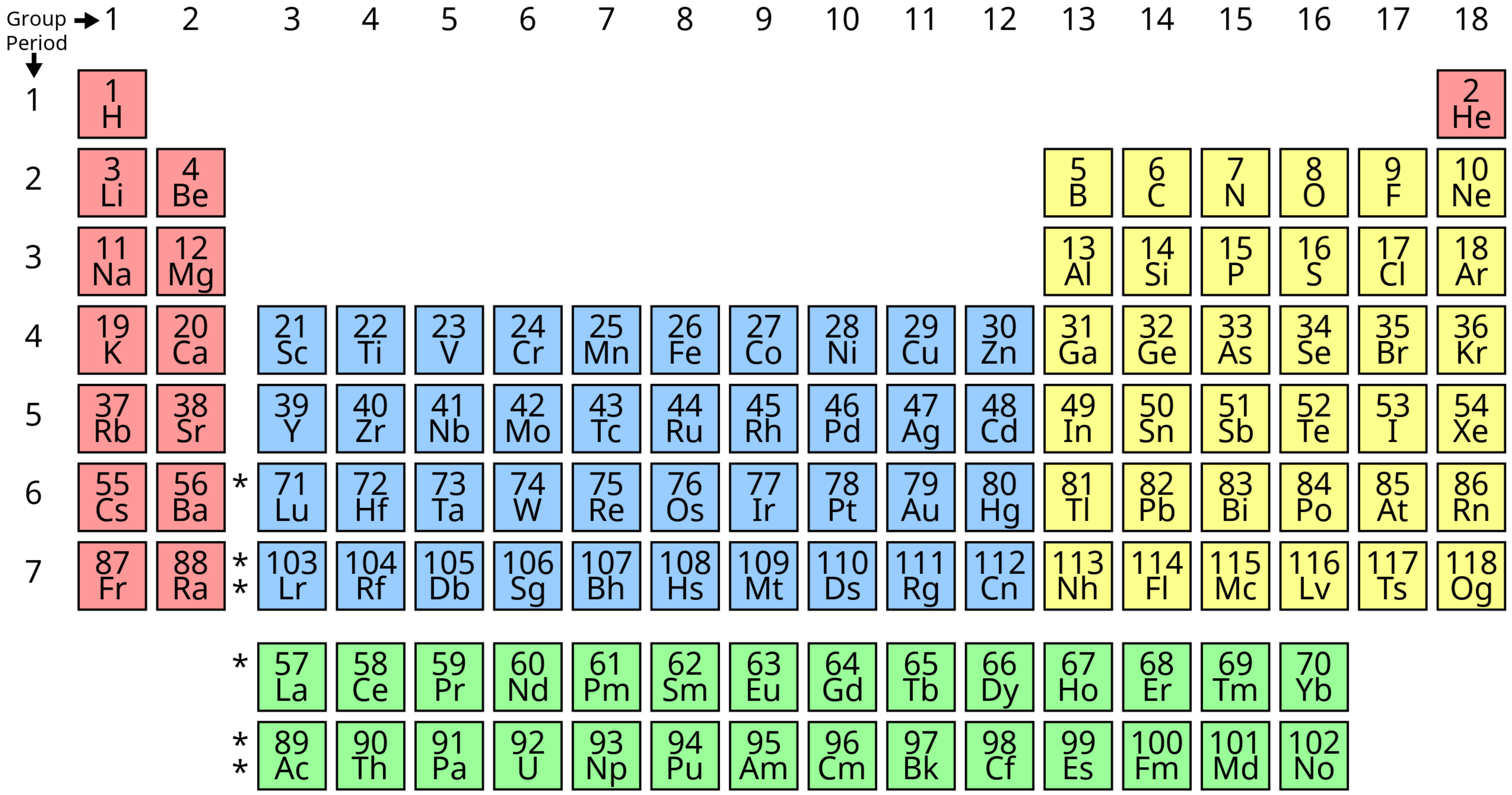
Terminology for Nuclear physics

A nucleus has Z protons and A-Z neutrons. To indicate a specific nuclear species or nuclide we use: $^{A}_{Z}X_{N}$

Where A is the atomic mass number, Z is the atomic number (number of protons) and N is the number of neutrons.

Some examples are: $^{1}_{1}H_{0}$, $^{238}_{92}U_{146}$, $^{56}_{26}Fe_{30}$.

Nucleons: is a term for the nuclear particles, the proton and the neutron.



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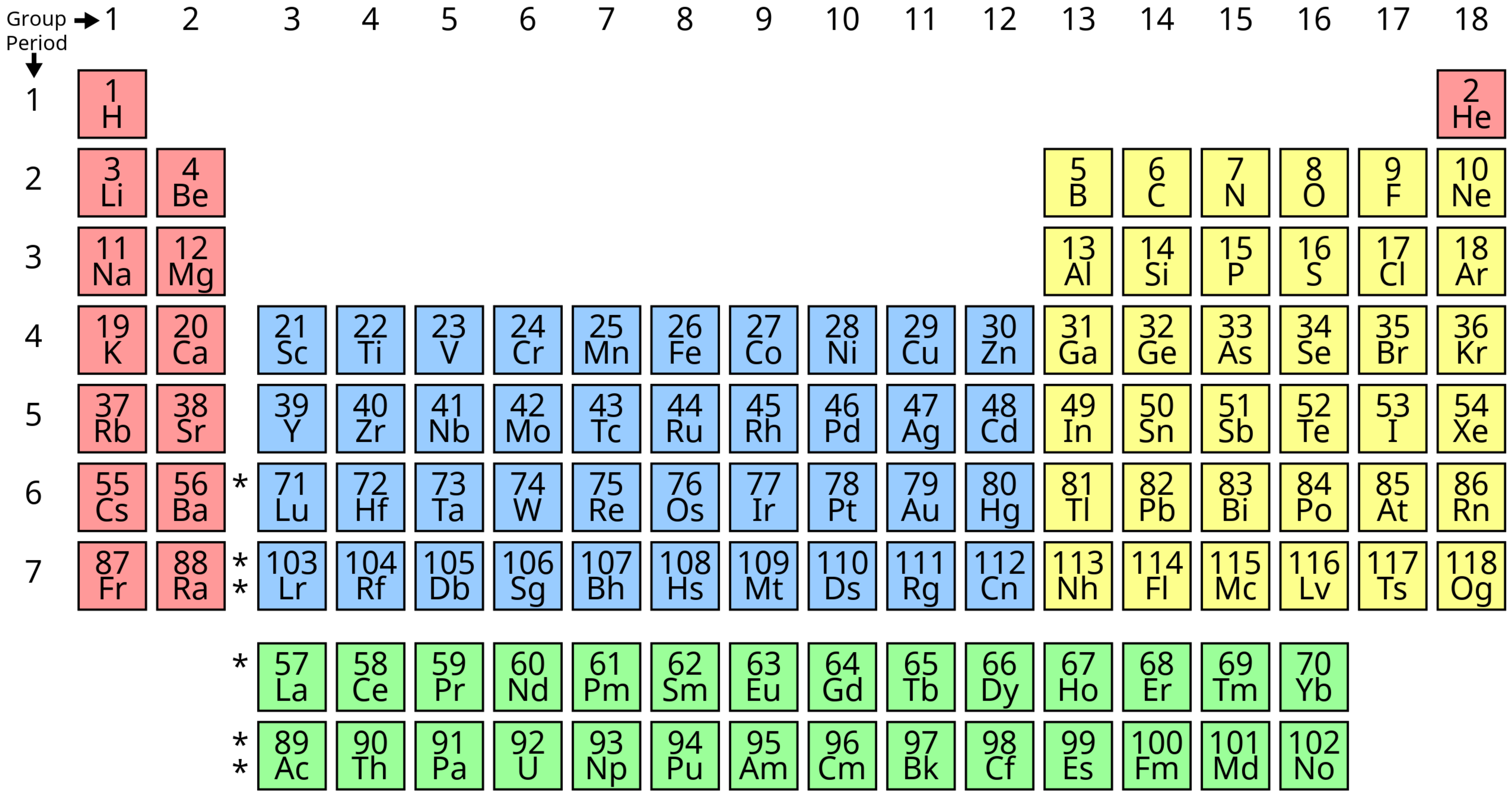
Terminology for Nuclear physics

$$^{A}_{Z}X_{N} \qquad\qquad ^{1}_{1}H_{0},\ ^{238}_{92}U_{146},\ ^{56}_{26}Fe_{30}.$$

- Note that the chemical symbol and the atomic number are redundant. All Hydrogen atoms have 1 proton and all iron atoms have 26 protons.
- In a similar way A and N are redundant, since we can infer N from A (N = A -Z).
- This means that the most common way to represent nuclear species is: **^{1}H, ^{228}U, ^{56}Fe.** However when dealing with nuclear reactions and decay it is useful tu use Z and N.



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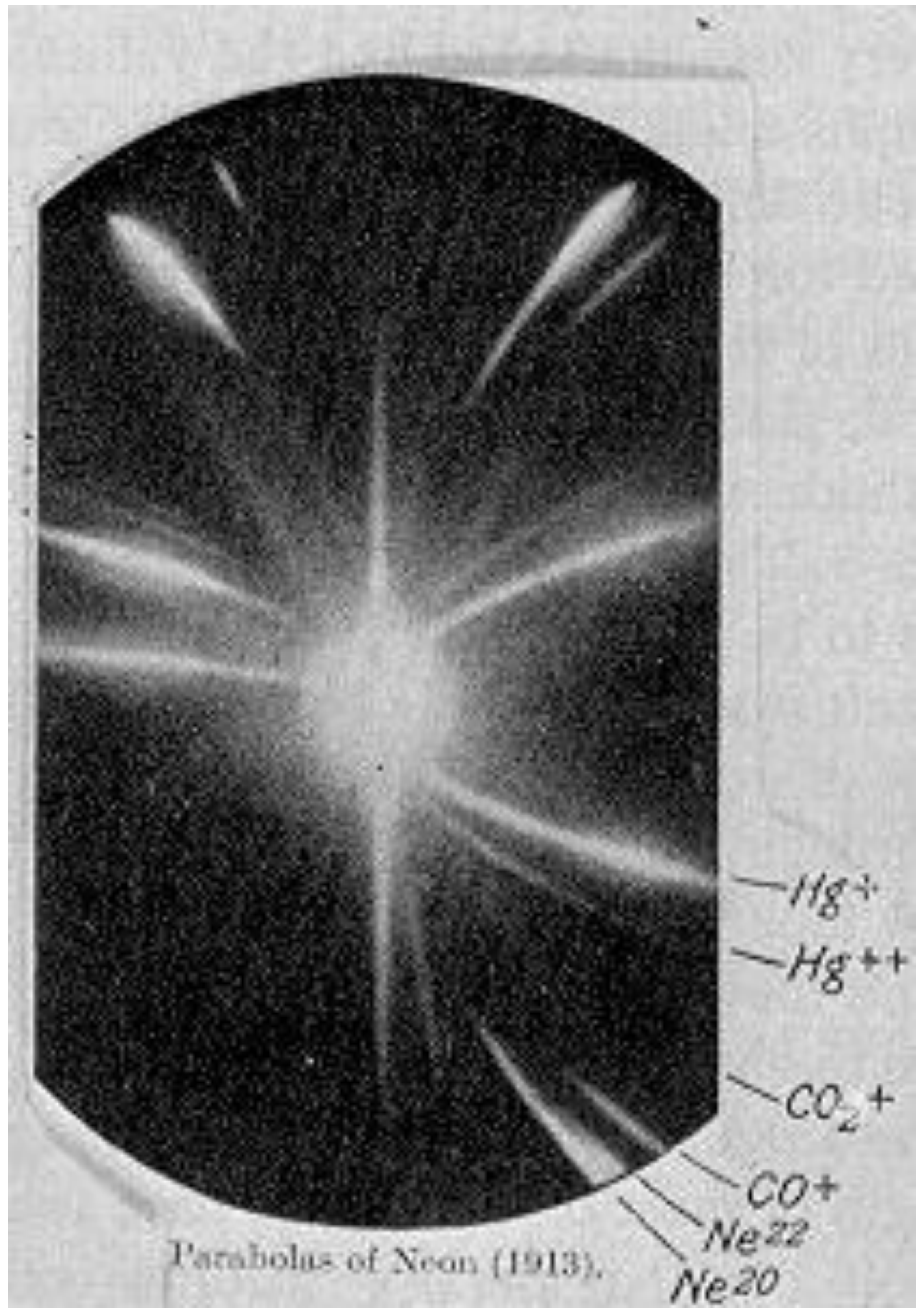
Isotopes

- In 1913 Soddy showed that a **given chemical element often contained atoms with different atomic masses (A)** but but the same number of protons (e.g. they have different numbers of neutrons). He called this isotopism and the members of such families isotopes.
- Isotopes of the same element have **similar chemical properties, but different atomic masses and physical properties.**
- A neutral atom has the same number of electrons as protons. Thus different isotopes of a given element all have the same number of electrons and share a **similar electronic structure**. Because the **chemical behavior of an atom is largely determined by its electronic structure**, different isotopes exhibit nearly identical chemical behavior.
  - (from the Greek roots isos ("equal") and topos ("place"), meaning "the same place", suggested by Margaret Todd)

photographic plate with the separate impact marks for the two isotopes of neon: neon-20 and neon-22.



Some examples?

More details on isotopes: https://en.wikipedia.org/wiki/Isotope

Isotopes

Some examples?

Examples are:

- ^{1}H, **hydrogen** with only a proton in the nucleus, and ^{2}H called deuterium, which has a proton and a neutron
- **Chlorine** has two stable naturally occurring isotopes ^{35}Cl and ^{37}Cl. Chlorine also has many usable isotopes that are produced in nuclear reactions and are radioactive, or radioisotopes.
- Common isotopes of **carbon** include ^{12}C, ^{13}C, and ^{14}C. These types of atoms have 6, 7, and 8 neutrons respectively. ^{12}C is the most common carbon isotope in nature. ^{14}C is famously used in archaeological radioactive dating, using its half life.
- In most types of nuclear power production, a specific isotope of **uranium**, ^{235}U, is used. This is the only naturally occurring fissile nucleus found on Earth (although people have made other fissile isotopes of plutonium). In nature, uranium exists as a mixture of ^{238}U, ^{235}U, and ^{234}U. ^{238}U is by far the most common. The uranium used for nuclear power in most nuclear reactors is processed to have a higher ratio of ^{235}U to the other isotopes than normally occurs in nature. This process is called "enriching" uranium.

https://energyeducation.ca/encyclopedia/Isotope

Isotones and Isobars

Isotones are nuclides with the **same number of neutrons (N)** but different numbers of protons. e.g. stable isotones with N =1 are ^{2}H and ^{3}He

(The term was formed by the German physicist K. Guggenheimer by changing the "p" in "isotope" from "p" for "proton" to "n" for "neutron")

Isobars are nuclides with the **same number of A.** Examples are ^{3}He and radioactive ^{3}H; ^{40}S, ^{40}Cl, ^{40}Ar, ^{40}K, ^{40}Ca.

(The term originates from the Greek word isos, meaning "equal" and baros, meaning “weight”, suggested by Alfred Walter Stewart)

Two **molecules that differ only in the isotopes** of their atoms are called **isotopologues.**

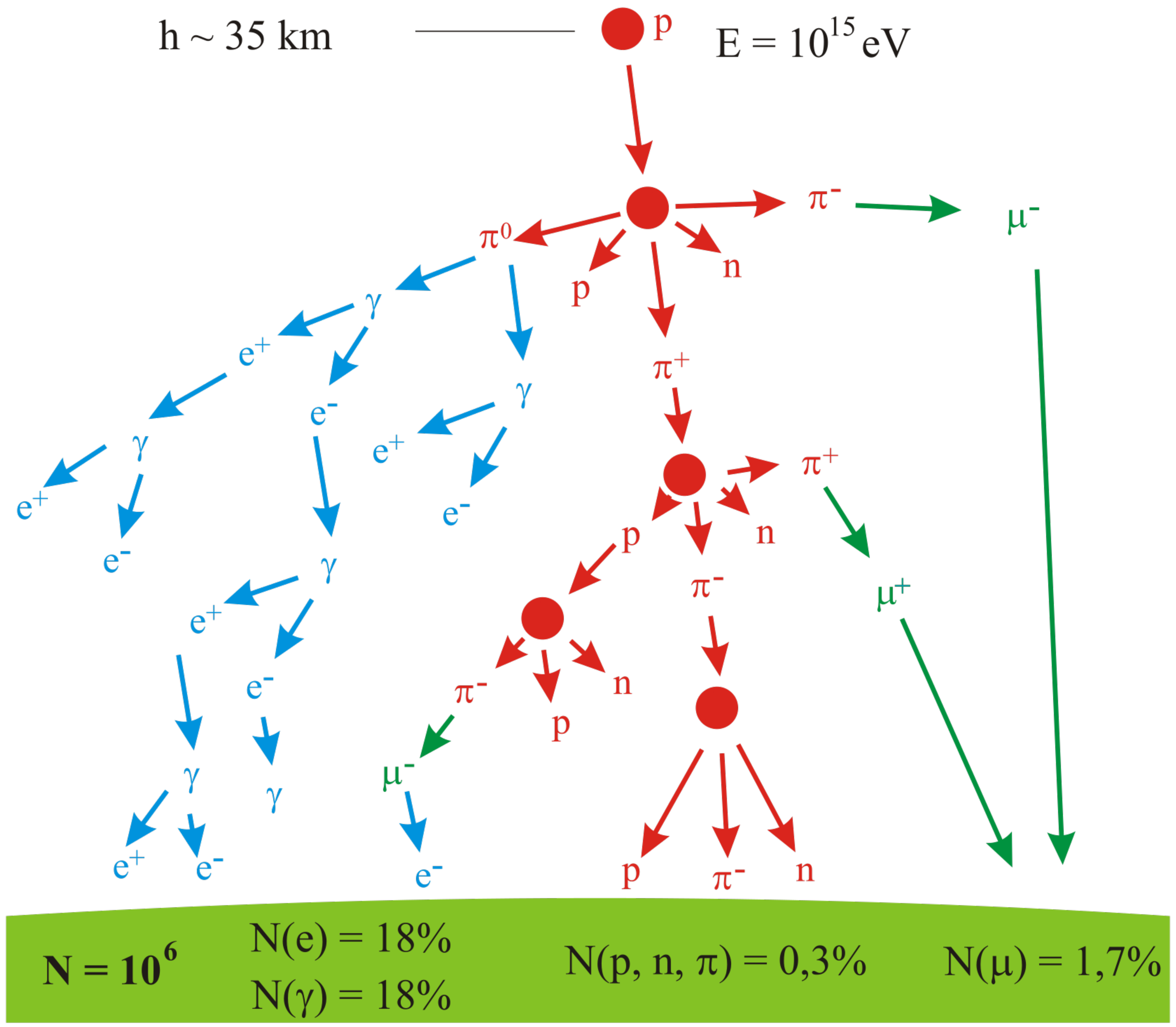
Current understanding

- By **1932 physicists had arrived at a model of the nucleus** in which an isotope of atomic number Z and mass number A is a bound state of Z protons and A–Z neutrons.
- Later workers, including Heisenberg applied quantum mechanics to the nucleus, now viewed as a collection of neutrons and protons, collectively called nucleons.
- The force binding the nucleus is not the **electromagnetic force that holds electrons in their orbits**, but a much stronger force that does not depend on the charge of the nucleon (i.e. is charge-independent) and with a very short effective range. This **binding interaction is called the strong nuclear force**.
- In addition, there is a third force, much weaker than the electromagnetic force, called the **weak interaction, responsible for β decays**, where neutrinos as well as electrons are emitted.
- These ideas form the essential framework of our understanding of the nucleus today.
- Nevertheless, there is still no single theory that is capable of explaining all the data of nuclear physics and different models are used to interpret different classes of phenomena.

The start of Particle Physics

- The simple picture of the atom was quickly expanded, because of the discovery of many **new subatomic particles**, initially in cosmic rays and later in experiments using particle accelerators.
- divided into two types:
  - **primaries,** which are high-energy particles, mostly protons, incident on the Earth's atmosphere from all directions in space
  - **secondaries**, which are produced when the primaries collide with nuclei in the Earth's atmosphere, with some reaching the surface.
- It was among these secondaries that the new particles were discovered, mainly using a detector devised by C.T.R. Wilson, called the **cloud chamber**.

Cosmic ray shower. First proton collides with a particle in the air creating pions, protons and neutrons.



https://en.wikipedia.org/wiki/Air_shower_(physics)

Cloud chamber

- A cloud chamber is a vessel filled with **air almost saturated with water vapour** and fitted with an expansion piston.
- When the vessel was suddenly expanded, the air was cooled and became supersaturated.
- **Droplets were then formed preferentially along the trails of ions left by charged particles passing through the chamber**.
- Immediately after the expansion, the chamber was illuminated by a flash of light and the tracks of droplets so revealed were photographed before they had time to disperse.

- The use of these chambers in cosmic ray studies led to many important discoveries, including, in 1932, the detection of antiparticles.

The original cloud chamber of C.T.R. Wilson at the Cavendish Lab, Cambridge England.

https://en.wikipedia.org/wiki/Cloud_chamber

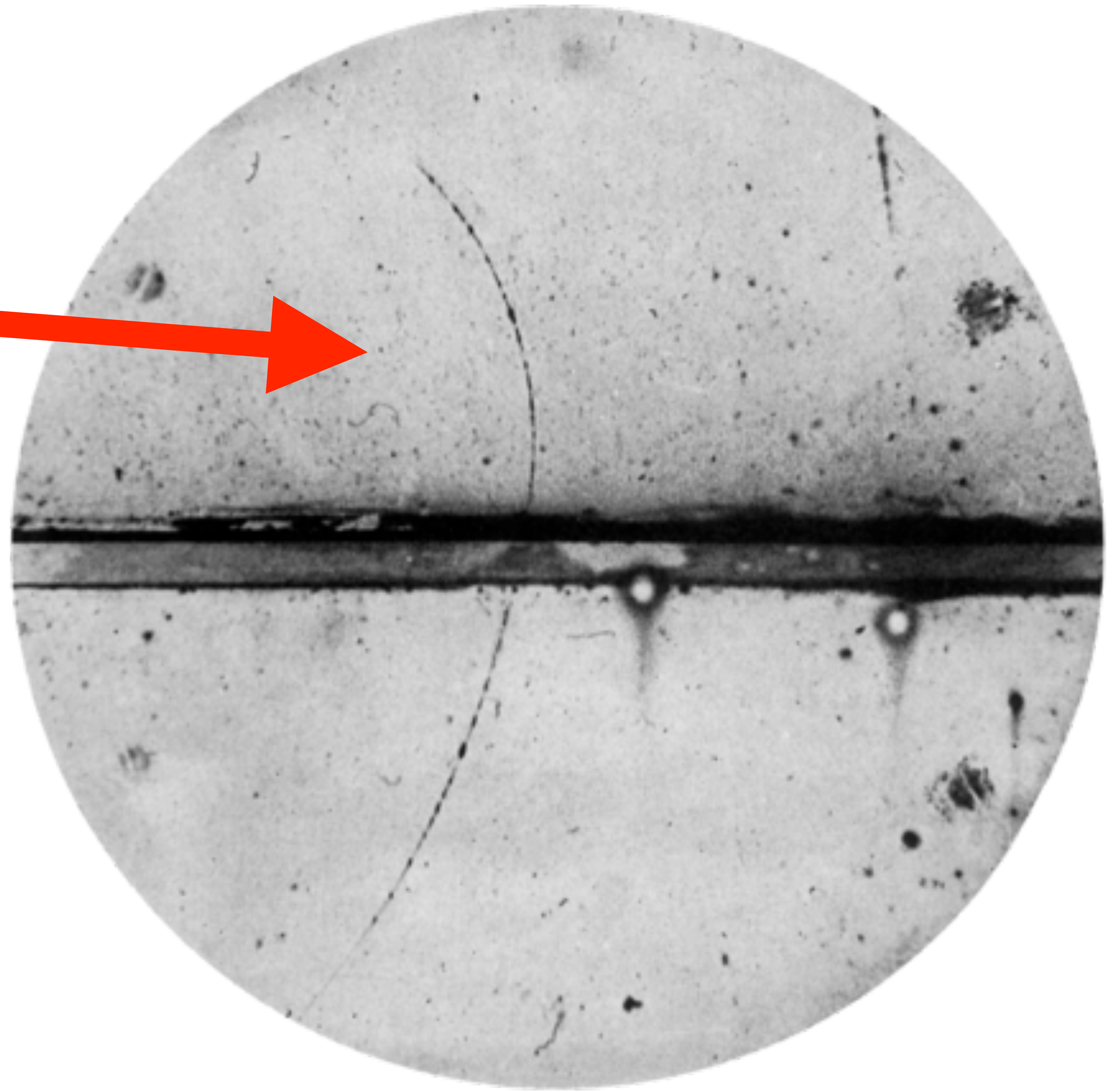
Which particle was this?

Cloud chamber

Cloud chamber photograph used to prove the existence of the positron. Observed by C. Anderson.

Track of a charged particle (positron)
The track is curved due to the presence of a magnetic field.

The first antiparticle discovered.



https://en.wikipedia.org/wiki/Cloud_chamber

Pions

- in 1934 Hideki Yukawa had predicted the existence of mesons as the force carrier particle of the strong nuclear forces.
  - The range of the nuclear force required the mesons to have **a mass of around one seventh of the proton** mass (meson means middle weight)
  - while the charge independence of the nuclear force required there to be **three charge states**, +e, – e and zero, respectively.
- During the search for these particles in cosmic ray secondaries, Anderson and Neddermeier discovered new subatomic particles in1936. These were initially thought to be mesons, but are now known to be particles called **muons**.
- Muons are rather like heavy electrons and, like both electrons and neutrinos, do not interact via the strong force that holds the nucleus together.
- Charged particles with suitable properties were finally detected in 1947. These particles were later named from mesons to **pions**. It also turned out that this particle is not the force carrier, but a lepton.
- The birth of particle physics as a new subject is considered to be 1947 with the discovery of pions and of strange particles by cosmic ray groups at Bristol and Manchester Universities, respectively.

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The neutrino

- In 1914 Chadwick discovered the continuous β - decay spectrum.
- At that time, nuclear decays were all viewed as a parent nucleus decaying via α, β, or γ decay to give a daughter nucleus plus either an alpha particle, an electron or a photon, respectively.
  - As each possibility would be a two-body decay, energy and momentum conservation implies that the emitted particle would have a unique energy, depending on the masses of the parent and daughter nucleons, which would be the same for all observed decays of a given type.
  - However, when Chadwick measured the energies of the electrons from samples of nuclei he found that the electrons emitted in a given β-decay process had a continuous energy distribution.

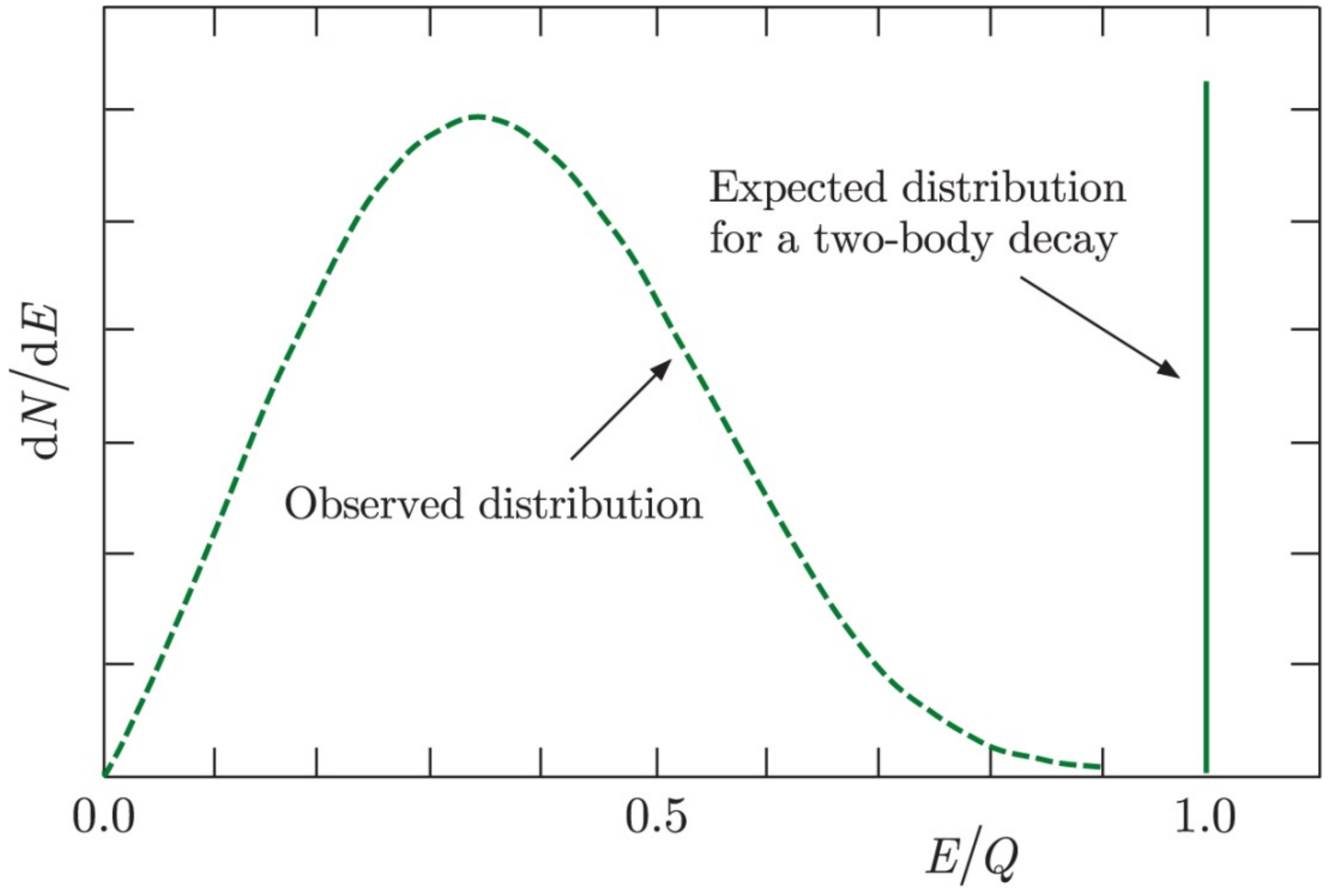


Figure 1.1 The observed electron energy distribution $\mathrm{d}N/\mathrm{d}E$ in β decay (dashed line) as a function of E/Q, where E is the kinetic energy of the electron and Q is the total energy released. Also shown is the expected energy distribution if β decay were a two-body process (solid line).

The neutrino

- In 1930 Pauli proposed that an **additional neutral particle** was emitted in β decays and shared the energy released with the electron.
- This particle had to be **very light**, since the most energetic electrons in the observed continuous distribution carried off almost all the energy released in the decay.
- Fermi proposed to call this particle the **neutrino.**
- Traces of a neutral particle, like the neutrino also showed up in cosmic ray experiments, in the pion and muon decay.
- Detecting the neutrino was extremely difficult since it only interacts with matter very weakly. Modern detectors are large water tanks or inside antarctic ice.
- Now we know:
  - Beta decay: $n \rightarrow p + e^- + \bar{\nu}_e$.
- Pion decay:
$$\pi^+ \to \mu^+ + \nu_\mu$$
$$\pi^- \to \mu^- + \bar{\nu}_\mu$$
- Muon decay:
$$\mu^+ \to e^+ \; \nu_e \; \bar{\nu}_\mu$$
$$\mu^- \to e^- \; \bar{\nu}_e \; \nu_\mu \, .$$

There are 3 types of neutrinos, the electron neutrino, the muon neutrino and the tau neutrino. They can also transform between each other, which is called neutrino oscillation.

Quarks

- Further work using cloud chambers to detect cosmic ray secondaries led to the discovery in 1947 by Rochester and Butler of new particles, named **kaons**, which was totally unexpected.
  - Kaons were almost immediately recognised as a completely new form of matter, because they had supposedly **'strange' properties**.

- Other strange particles with similar properties were discovered, and in 1953 it was realised that these properties were precisely what would be expected if they were **hadrons with nonzero values of a**n hitherto unknown **quantum number, given the name strangeness** by Gell-Mann, which was conserved in strong and electromagnetic interactions, but not necessarily conserved in the so-called weak interactions responsible for β decay.

- Non-strange particles like the pions and nucleons have zero values of strangeness.

Quarks

- Gell-Mann, and independently Zweig suggested that **hadrons were composed of more fundamental particles called quarks (q)**, together with their antiparticles.
    - Three quarks were required at the time, denoted **u, d, and s**, with fractional electric charges +2e/3, –e/3, and –e/3, respectively.
- **Ordinary matter, i.e. protons and nucleons are composed of u and d quarks only,** while the strange particles also contain s quarks. The latter is called the strange quark and the strangeness quantum number merely reflects the number of strange quarks and/or antiquarks present.
- The 1950s also saw technological developments that enabled high-energy beams of particles to be produced in laboratories, and these rapidly replaced cosmic rays as the source of the high-energy particles required to create new particles in collisions.
- Cloud chambers were largely superseded by **bubble chambers**, a more efficient device in which charged particles were detected by the trail of bubbles left along their tracks through a superheated liquid, rather than droplets in a supercooled gas -> many new particles were discovered

Quarks

- evidence for the existence of quarks as real particles began to emerge in 1960's and 1970's from a series of experiments analogous to those of Rutherford and his co-workers, where high-energy beams of electrons and neutrinos were scattered from nucleons.
    - Analysis of the angular distributions of the scattered particles confirmed that the nucleons were themselves bound states of point-like charged entities, with properties consistent with those hypothesised in the quark model, including their fractional electric charges.
    - To satisfy the Pauli exclusion principle (no two particles can be bound in the same state) in addition to flavours (u, d, s) colours were assigned to quarks (red, green and blue).
    - Later three more types of quarks were discovered as well: charm, top, bottom (c, t, b)
    - This is essentially the picture today, **where elementary particles are considered to be a small number of fundamental physical entities,** including quarks, the electron, neutrinos, the photon and a few others, but no longer nucleons.

Hadrons

- In addition to the elementary particles of the standard model, the **bound states of quarks are called hadrons**.

- Nucleons are examples of hadrons, but there are several hundred more, most of which are unstable and decay by one of the three interactions.
  - For example, the charged pions $\pi^{\pm}$ decay via the weak interaction with a lifetime of about 10^{-8} s, while the neutral pion π^0 decays via the electromagnetic interaction with a lifetime of about 10^{-17} s.
- The existence of quarks was first inferred from the properties of hadrons, and they remain particularly important because free quarks are unobservable in nature.
  - To deduce properties of quarks we are forced to study hadrons.

Baryons and mesons

- Hadrons can be further subdivided into baryons and mesons.
- Every **baryon is composed of 3 quarks**, and every **antibaryon is composed of 3 antiquarks**.
  - All naturally occurring baryons are color neutral. Each of the three quarks in a baryon have different colours.
- Every **meson is composed of a quark and an antiquark.**

Q - electrical charge, S - strangness

The baryon decuplet

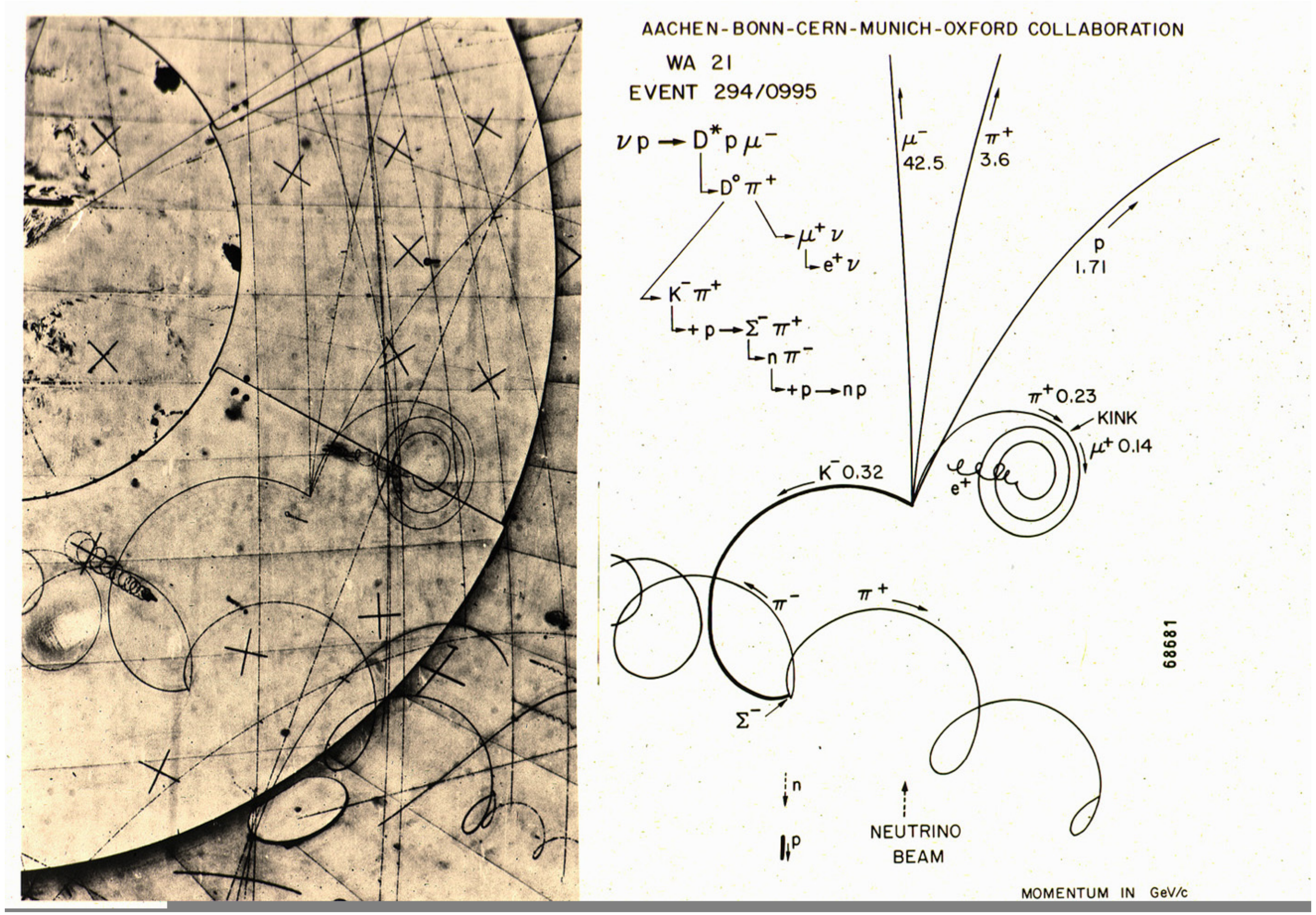
qqq	Q	S	Baryon
uuu	2	0	Δ^{++}
uud	1	0	Δ^{+}
udd	0	0	Δ^{0}
ddd	-1	0	Δ^{-}
uus	1	-1	Σ^{*+}
uds	0	-1	Σ^{*0}
dds	-1	-1	Σ^{*-}
uss	0	-2	Ξ^{*0}
dss	-1	-2	Ξ^{*-}
sss	-1	-3	Ω^{-}

The meson nonet

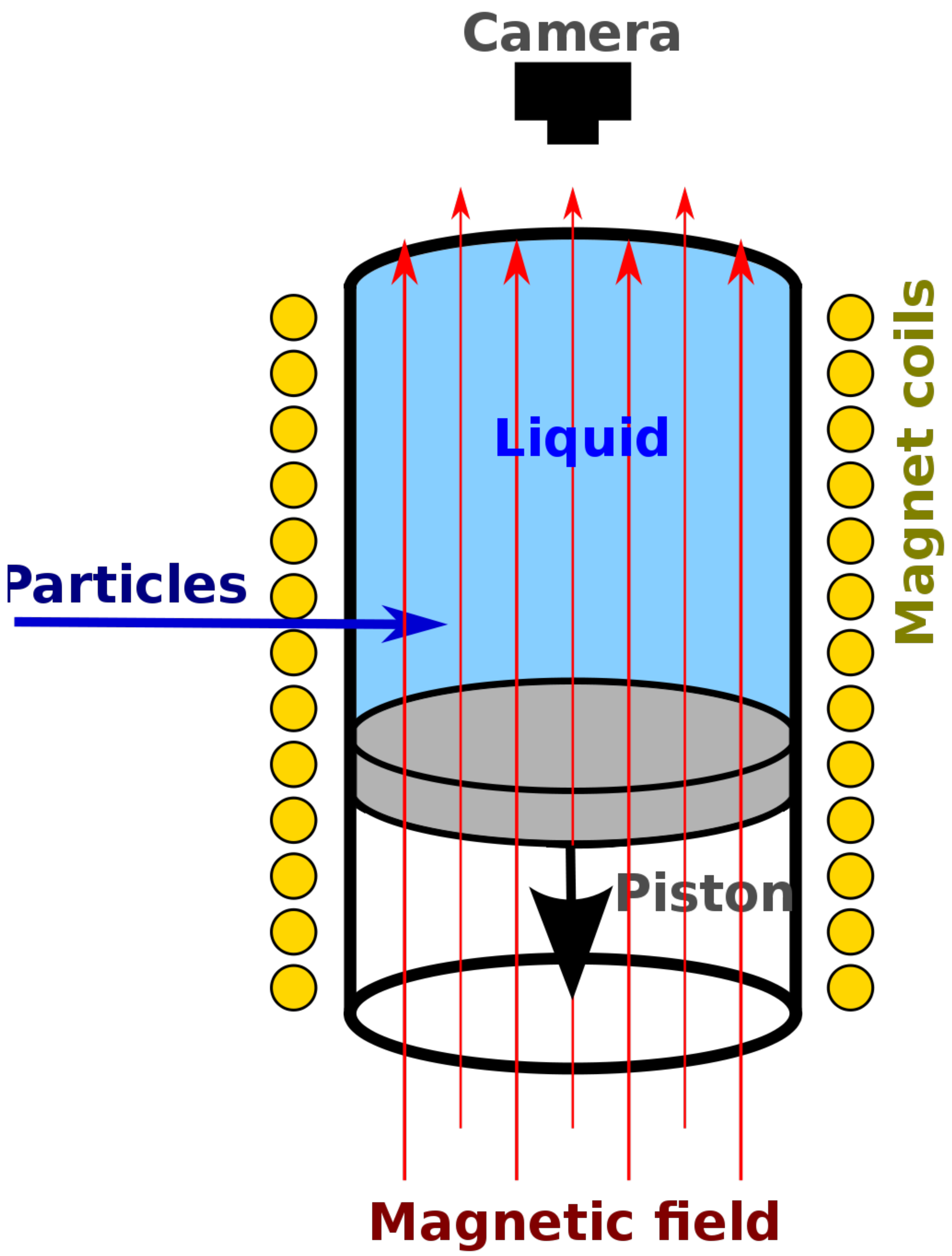
$q\bar{q}$	Q	S	Meson
$u\bar{u}$	0	0	π^0
$u\bar{d}$	1	0	π^+
$d\bar{u}$	-1	0	π^-
$d\bar{d}$	0	0	η
$u\bar{s}$	1	1	K^+
$d\bar{s}$	0	1	K^0
$s\bar{u}$	-1	-1	K^-
$s\bar{d}$	0	-1	$\overline{K}^0$
$s\bar{s}$	0	0	??

Bubble chamber

In this event a neutrino interacts with a proton producing an excited D meson



CERN: https://cds.cern.ch/record/39469



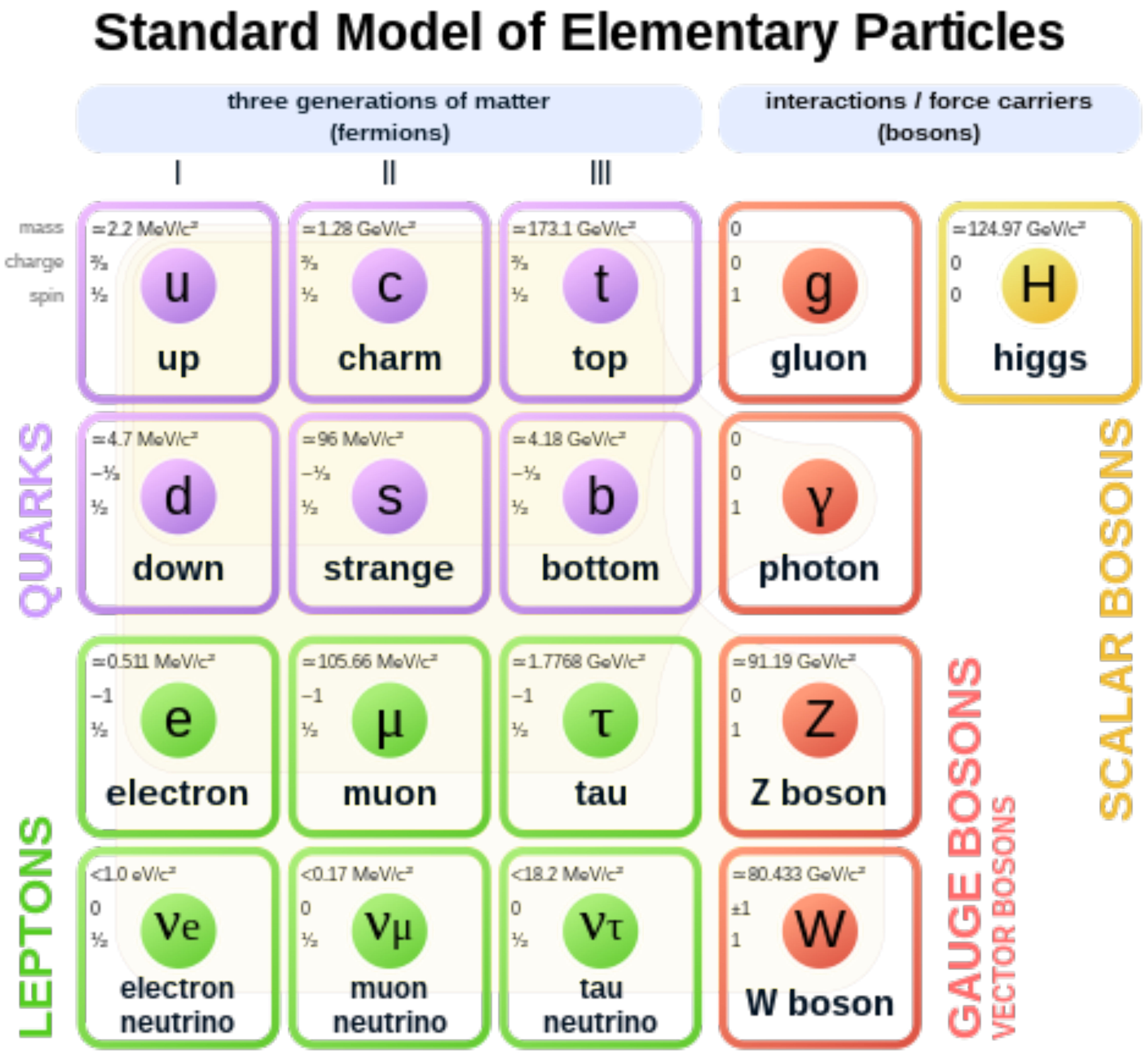
https://en.wikipedia.org/wiki/Bubble_chamber

Anti particles

- Constructing a quantum theory that is consistent with special relativity leads to the conclusion that for every charged particle of nature, there must exist an associated particle, called an antiparticle, with the same mass as the corresponding particle.
- This important prediction was first made by Dirac and follows from the solutions of the equation he postulated to describe relativistic electrons.
  - All charged particles have anti particles, whether the particle is an elementary particle or a hadron.
  - The neutron has an anti particle, however neither the photon γ nor the neutral pion π^0 has a distinct antiparticle.
- When brought together, particle–antiparticle pairs, each of mass m, can annihilate, releasing their combined rest energy $2mc^2$ as photons or other particles.
- There is a symmetry between particles and antiparticles, and **it is a convention to call the electron the particle and the positron its antiparticle**. This reflects the fact that **normal matter contains electrons rather than positrons**.

The standard model

- The standard model aims to explain all the phenomena of particle physics, except those due to gravity, in terms of the properties and interactions of a small number of elementary (or fundamental) particles, which are now defined as being point-like, without internal structure or excited states.
    - Particle physics thus differs from nuclear physics in having a single theory to interpret its data.
- An elementary particle is characterised by, amongst other things, its mass, its electric charge and its spin.

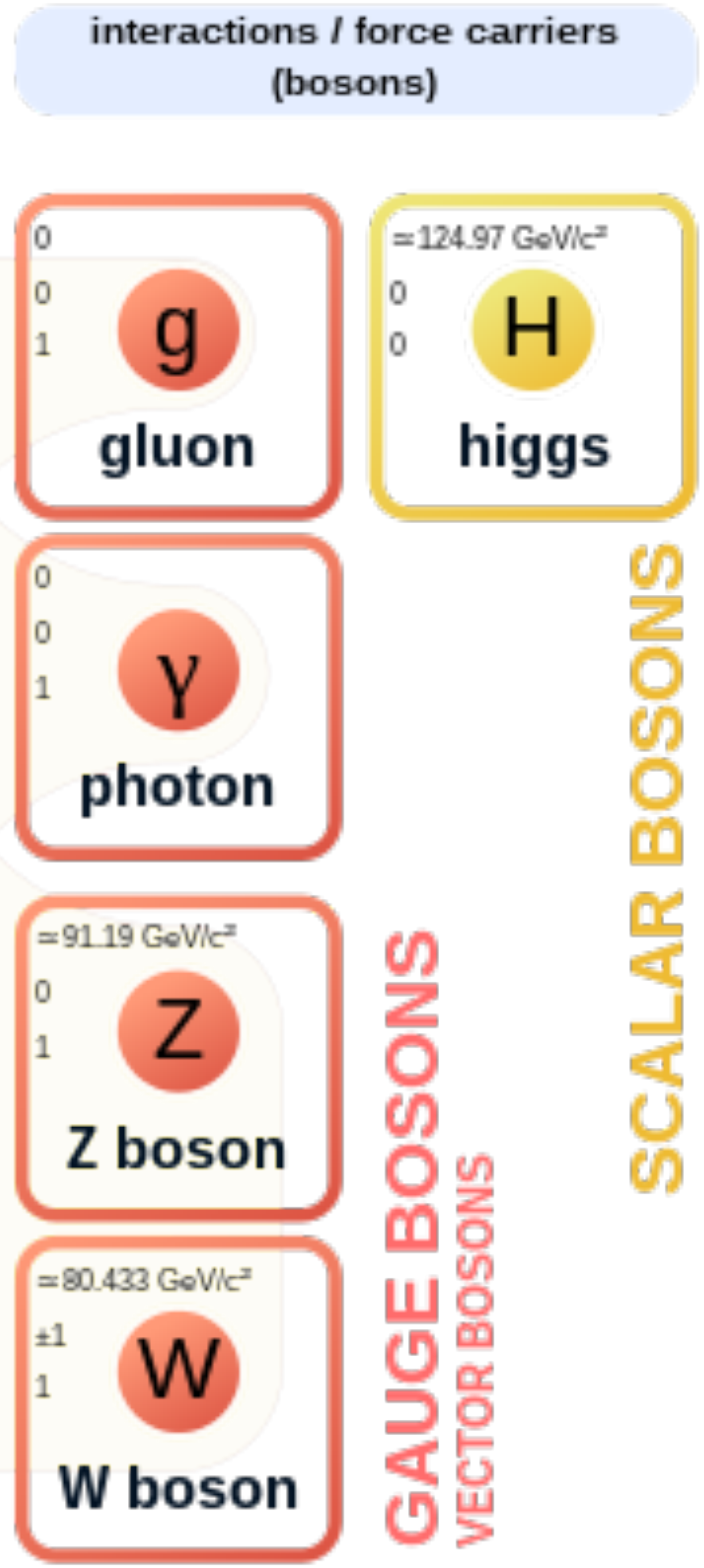


The standard model

  - **The spin** is a permanent angular momentum possessed by all particles in quantum theory, even when they are at rest. Spin has no classical analogue and is not to be confused with the use of the same word in classical physics, where it usually refers to the angular momentum of extended objects. The maximum value of the spin angular momentum about any axis is $S\hbar(\hbar \equiv h/2\pi)$, where h is Planck's constant and S is the spin quantum number, or spin for short.
- It has a fixed value for particles of any given type (for example S = 1/2 for electrons) and general quantum mechanical principles restrict the possible values of S to be 0, 1/2, 1, 3/2, ...
- Particles with **half-integer spin are called fermions** and those with **integer spin are called bosons**.
- There are two families of **elementary fermions** in the standard model:
  - the **quarks**, which interact via strong forces, and
  - the **leptons**, including electrons, muons, and neutrinos, which do not.
- In addition, there is a family of **spin-1 bosons**, which act as force carriers in the theory, and a **spin-0 particle, called the Higgs boson**, which plays a key role in understanding the origin of elementary particle masses within the theory.

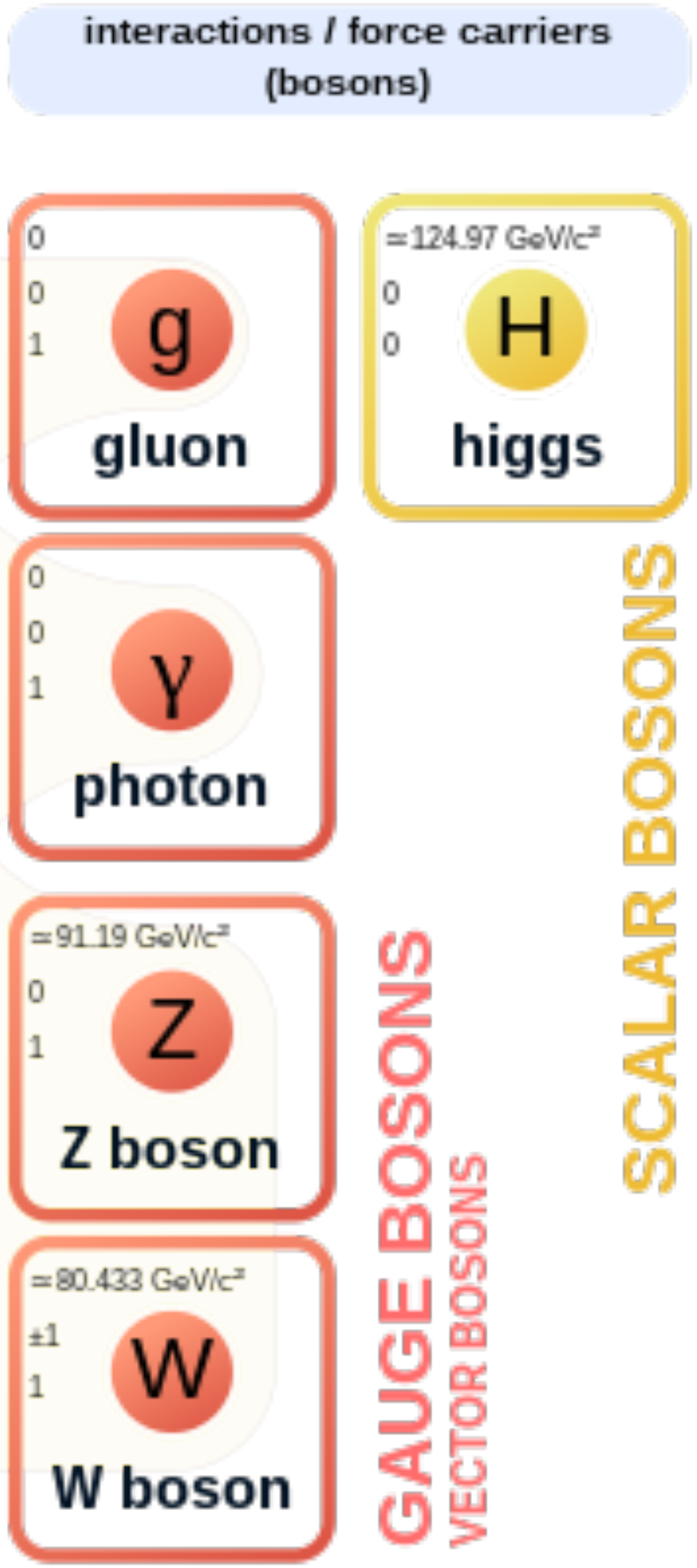
The standard model - forces

- Particles interact via four forces of nature.
- In decreasing order of strength, these are the
  - **strong interaction**, which binds the quarks together into hadrons;
  - **the electromagnetic interaction** between the charged leptons and quarks;
  - **the weak interaction** responsible for β decay; and
  - **gravity**.
- Although an understanding of all four forces will ultimately be essential in a complete theory, gravity is so weak that it can be neglected in nuclear and particle physics at presently accessible energies.



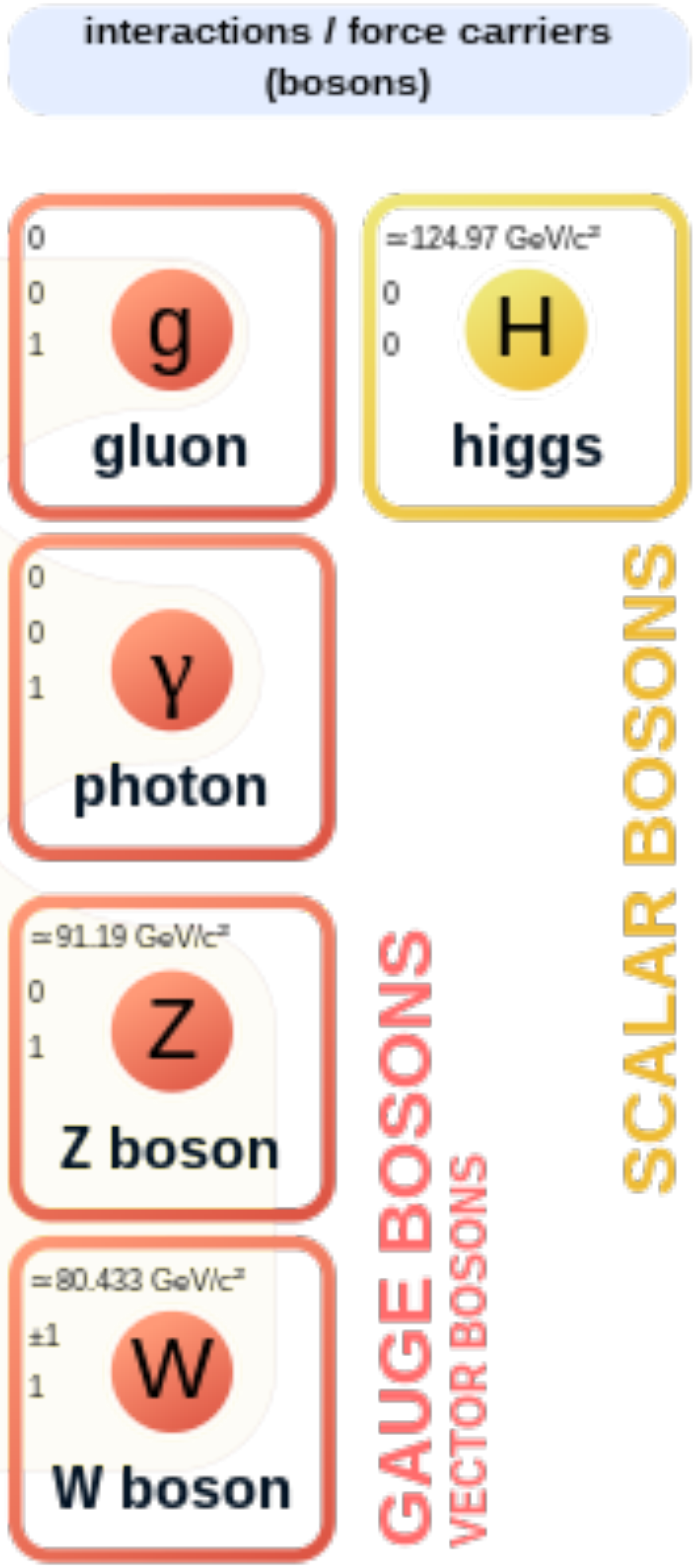
The standard model - forces

- In classical physics the electromagnetic interaction is propagated by electromagnetic waves, which are continuously emitted and absorbed. While this is an adequate description at long distances, at short distances the quantum nature of the interaction must be taken into account. In quantum theory, the interaction is transmitted discontinuously by the exchange of photons, which are members of the family of fundamental spin-1 bosons of the standard model.
- **Photons are referred to as the gauge bosons, or 'force carriers',** of the electromagnetic interaction.
  - The use of the word 'gauge' originates from the fact that the electromagnetic interaction possesses a fundamental symmetry called gauge invariance.
  - For example, Maxwell's equations of classical electromagnetism are invariant under a specific transformation of the electromagnetic fields, called a gauge transformation. This property is common to all the three interactions of nature



The standard model - forces

- The weak and strong interactions are also mediated by the exchange of spin-1 gauge bosons.
  - For the **weak interaction** these are the **W^+, W^-, and Z^0 bosons** with masses about 80–90 times the mass of the proton.
  - For the **strong interaction**, the force carriers are called **gluons**. There are eight gluons, all of which have zero mass and are electrically neutral.



Bonus reading recommendations

Robert T. Beyer, ***Foundations* of *Nuclear Physics*** - has a collection of the 13 most influential first publications on nuclear physics, in original language. There is one by Irene Currie in french and a few in German.