Introduction to Nuclear and Particle Physics

Short Introduction

Helga Dénes 2024 S2 Yachay Tech

hdenes@yachaytech.edu.ec

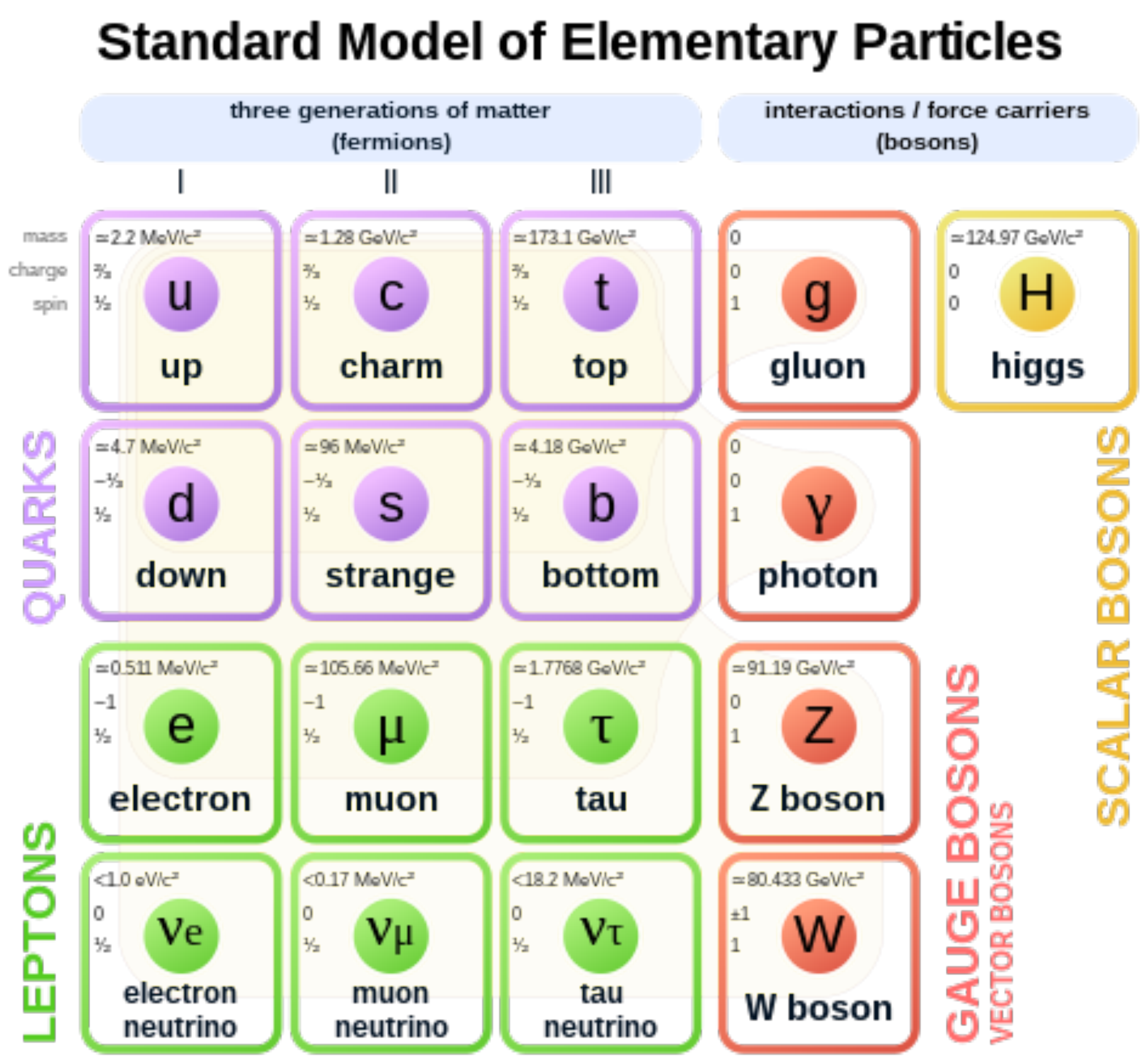
What is the difference?

What is the difference between nuclear and particle physics?

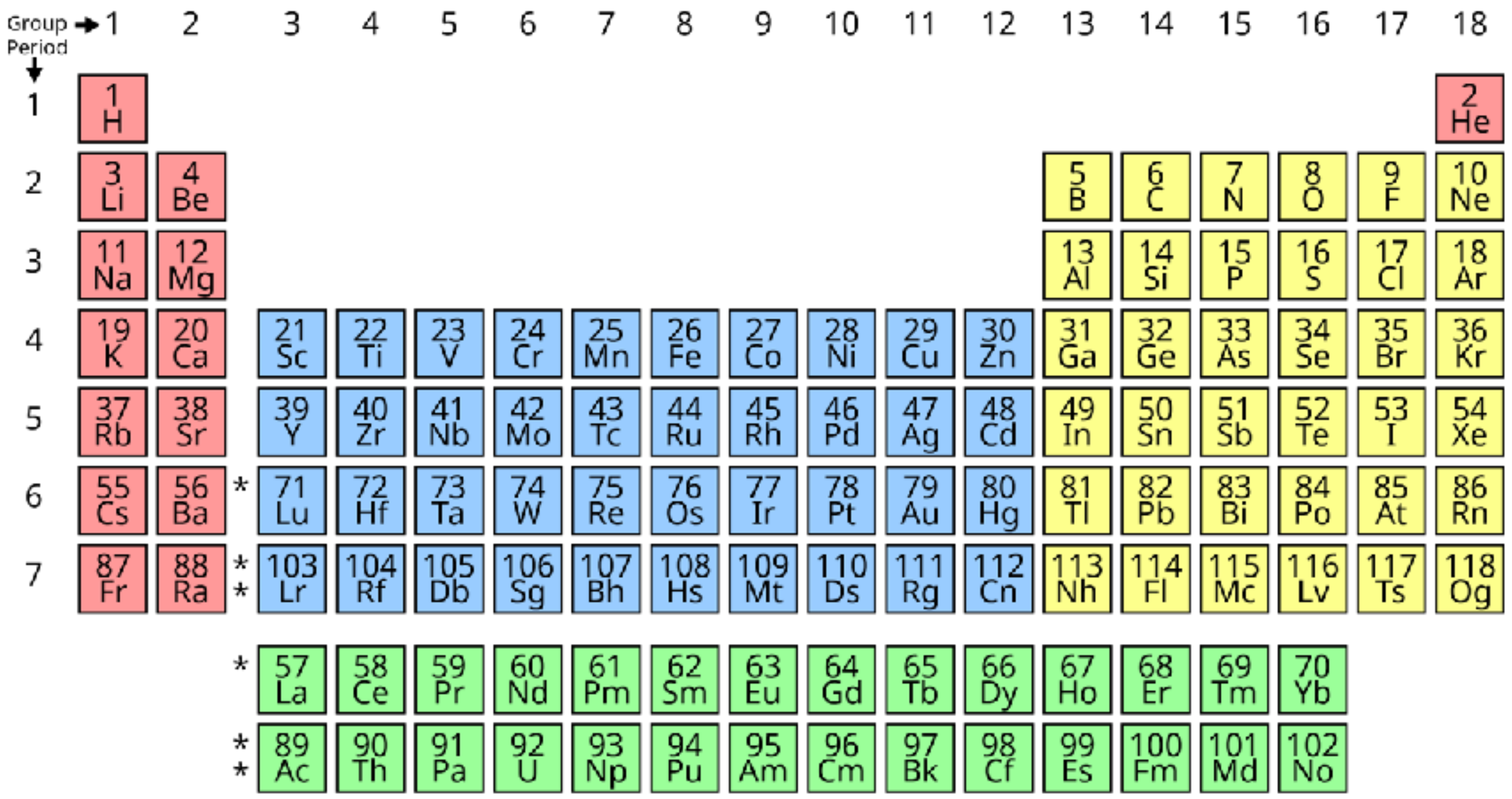
What is the difference?

Particle Physics deals with the most elemental particles like Fermions and Bosons. (Smaller size scales, typically higher energies)

Nuclear Physics deals with processes related to or affecting the nuclei of atoms. (Larger size scales)



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

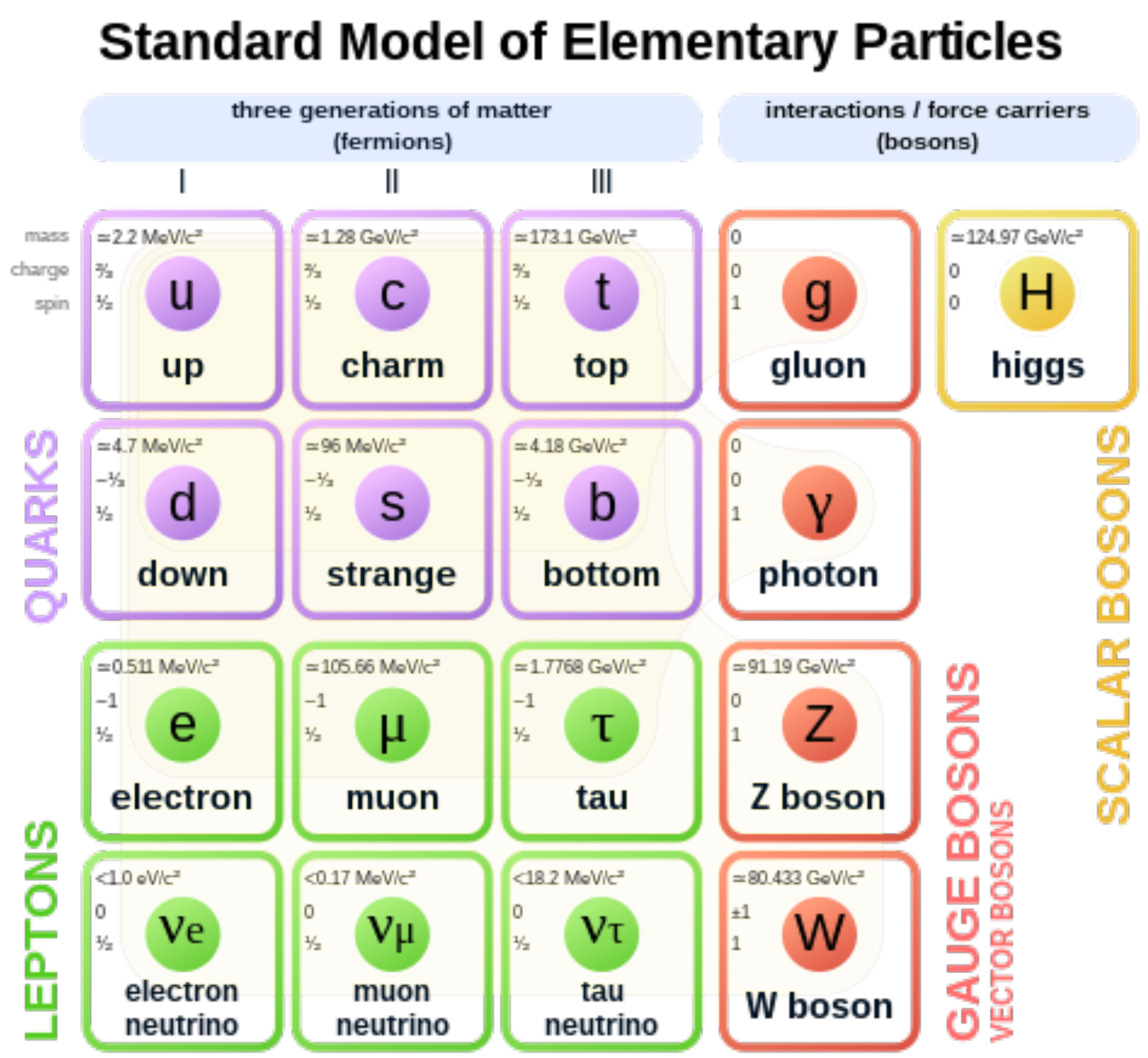


https://en.wikipedia.org/wiki/Periodic_table

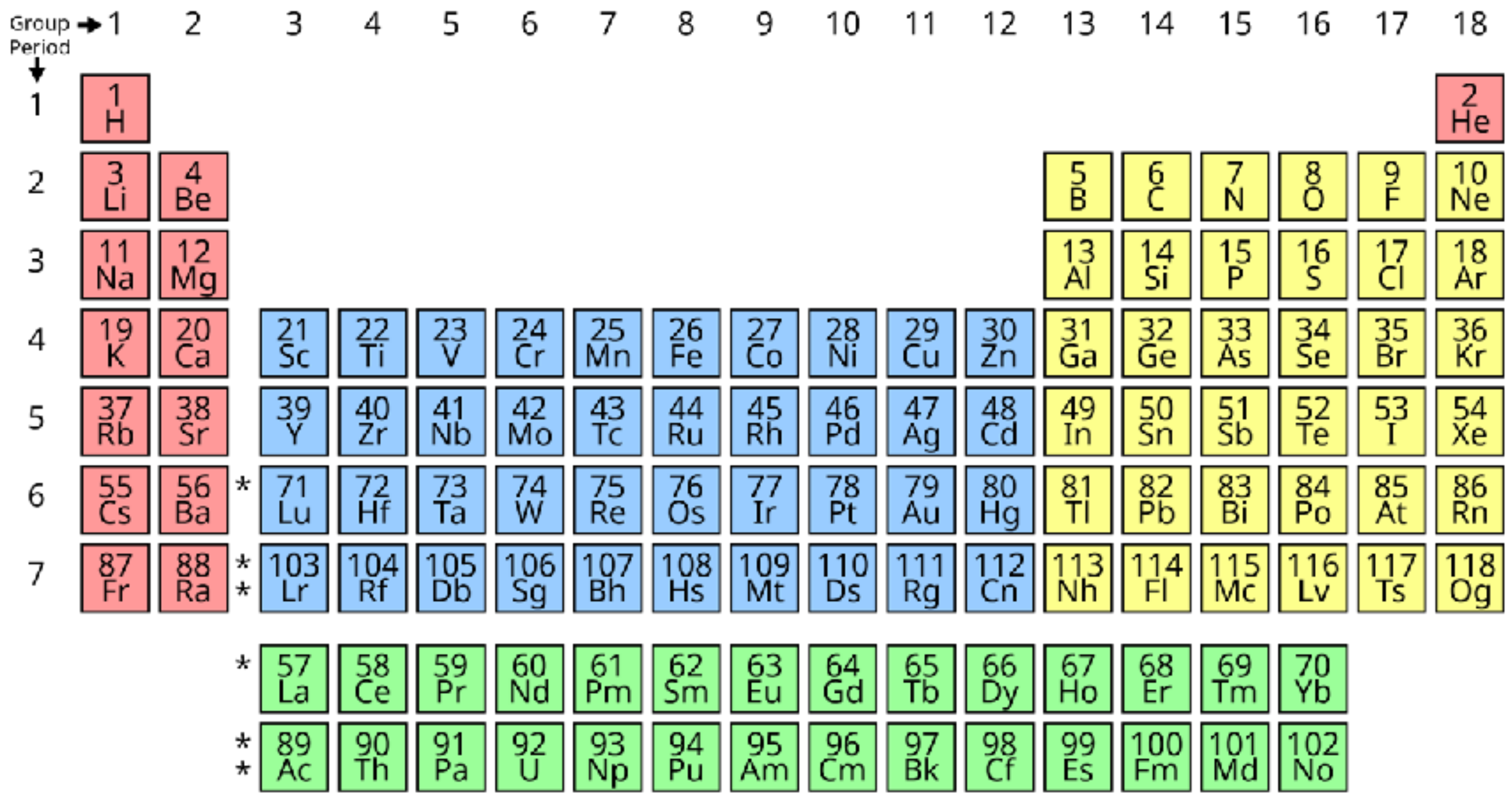
What is the difference?

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

Nuclear Physics no unified theory, theory for bits and pieces



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



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

Relevance

What applications can you think of?

Relevance

Some examples for applications:

- Describing elementary particles, atoms,
- Understanding cosmology, the interior of stars
- Radio carbon dating
- Nuclear power plants
- Powering submarines
- Emergency lights in buildings
- medical applications (e.g. imaging)
- etc.

The start of Nuclear Physics

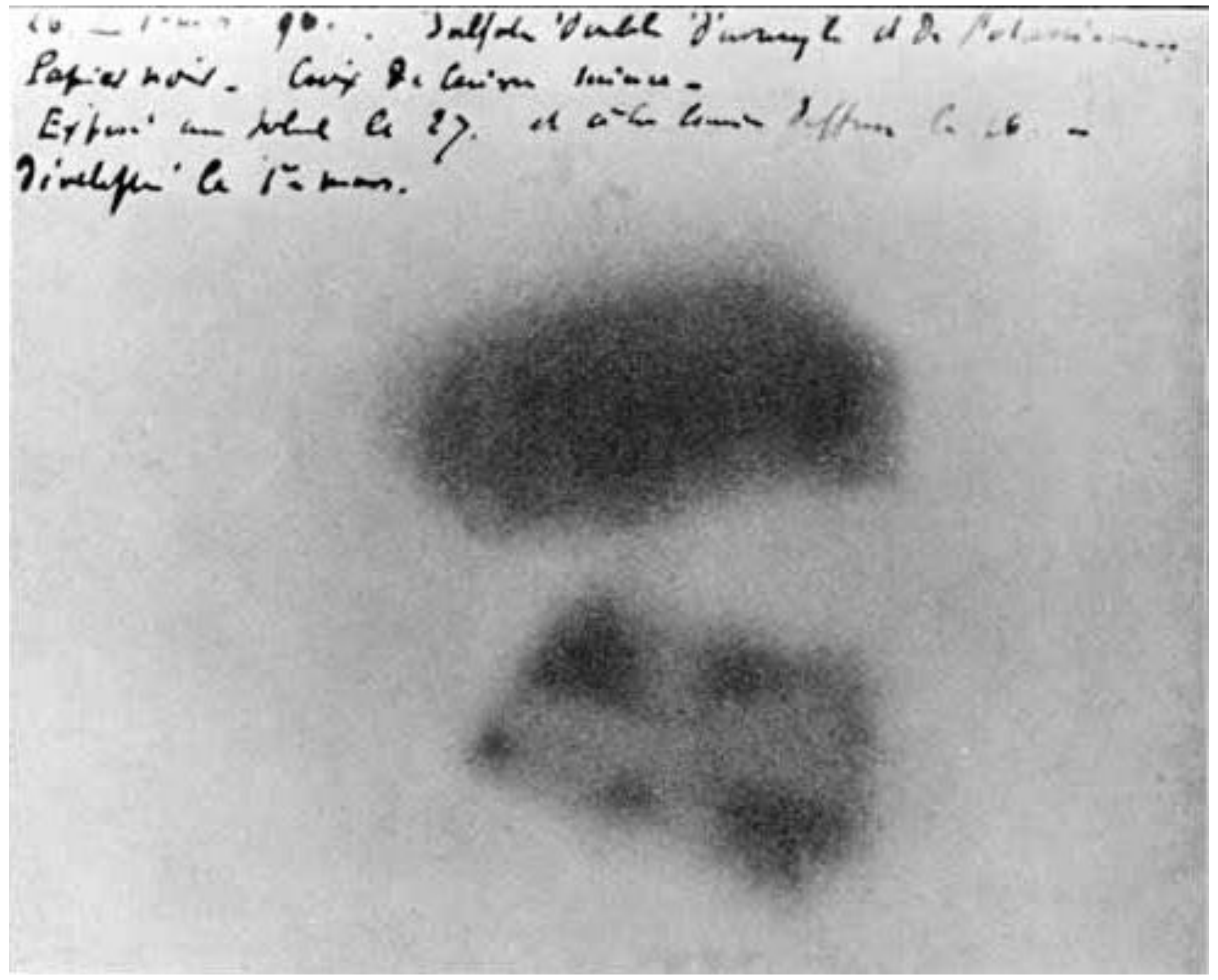
- 1896 Becquerel discovered that certain atoms are radio active, when uranium salts accidentally fogged a photographic plate.

- **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).

  - **How many radio active decays are there?**

Becquerels photographic plate with the uranium salt mark.



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

The start of Nuclear Physics

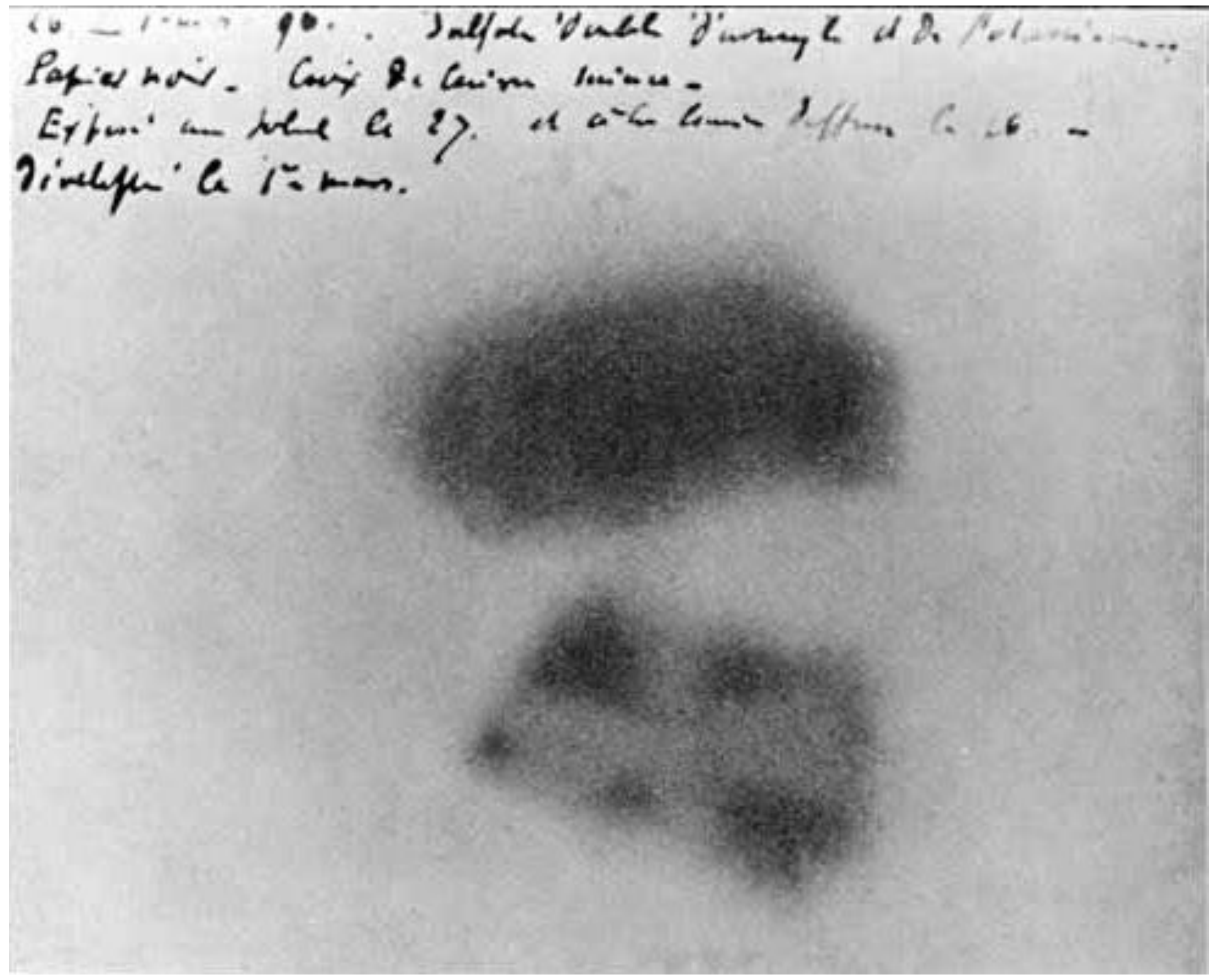
- 1896 Becquerel discovered that certain atoms are radio active, when uranium salts accidentally fogged a photographic plate.

- **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**
  - **α rays are doubly ionised helium atoms.**
- In 1900 Villard discovered a third type of decay involving rays:
  - **γ rays are photons**

Becquerels photographic plate with the uranium salt mark.



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

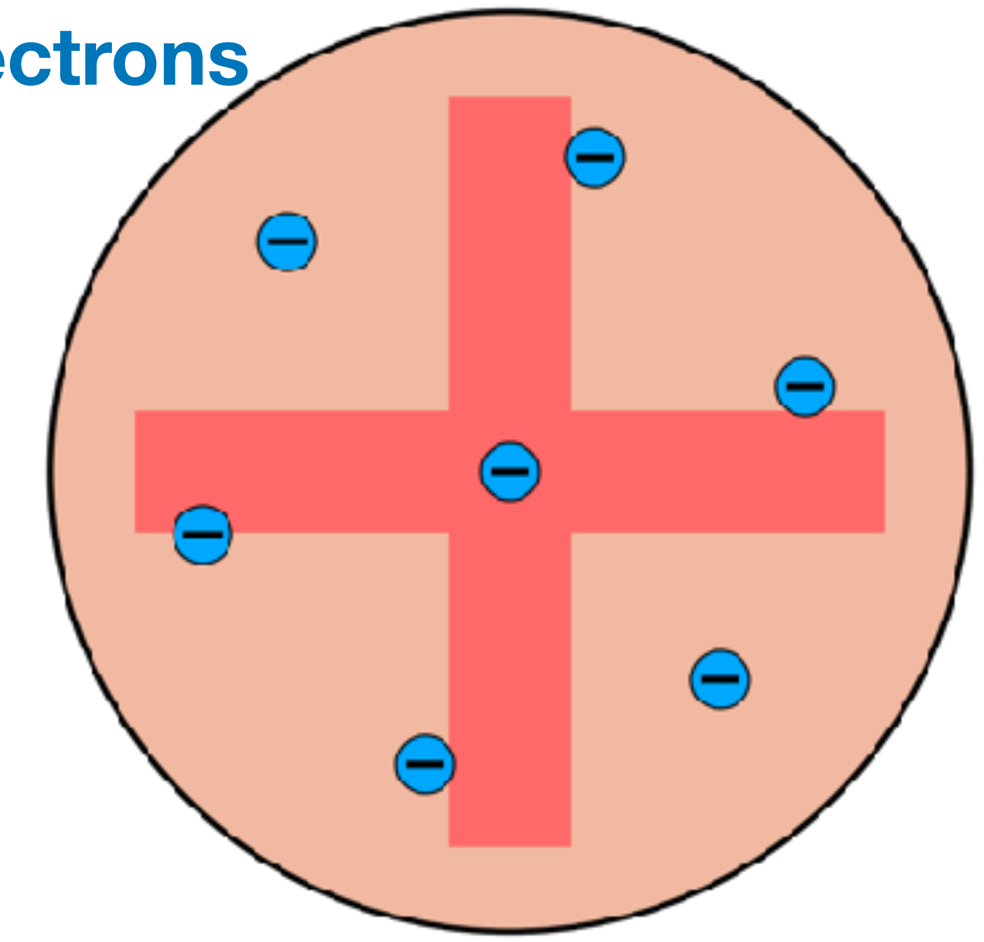
The Plum pudding model of the atom

- 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.**

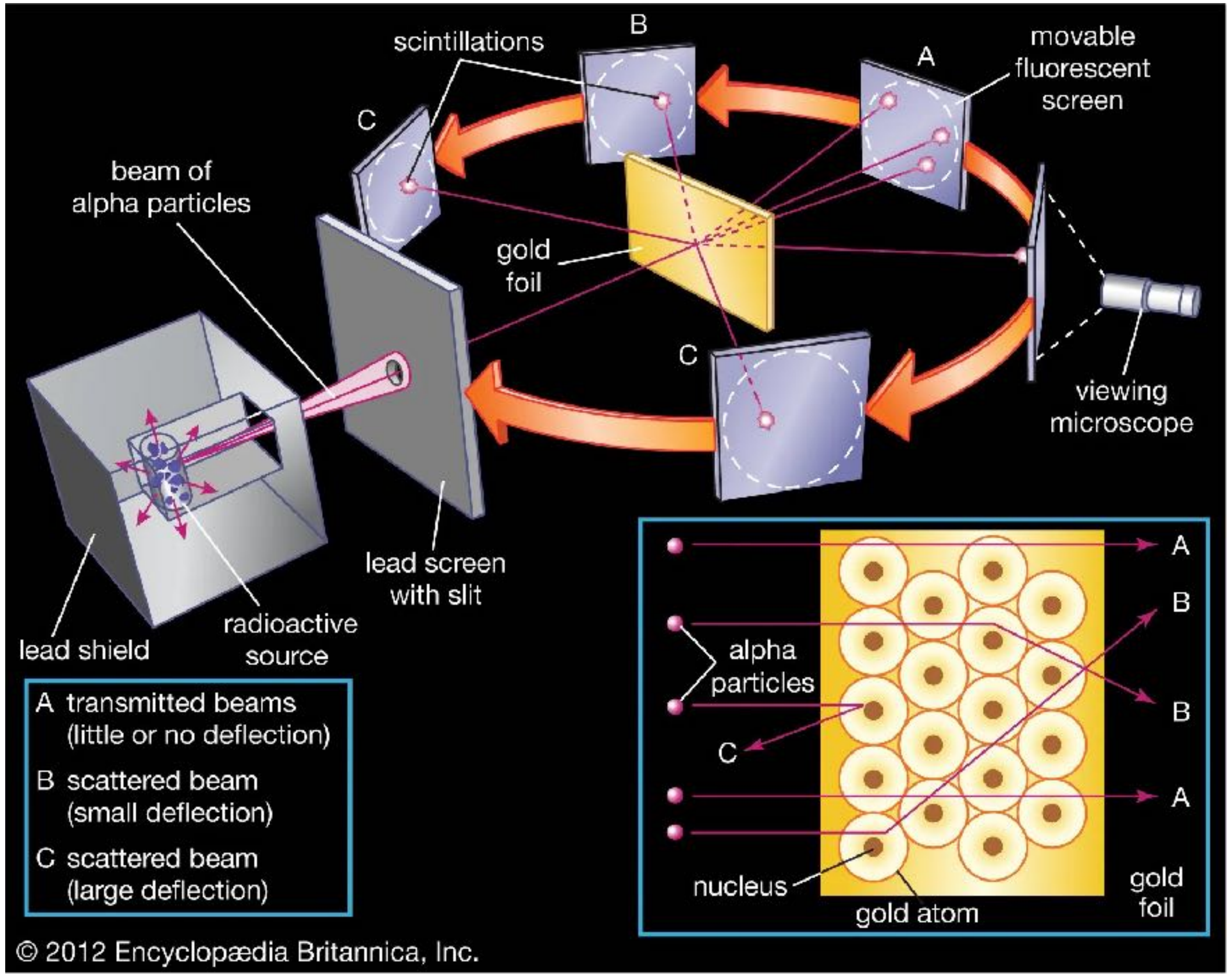
- Could account for the stability of atoms, but gave no explanation for the discrete wavelengths observed in the spectra of light emitted from excited atoms.



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.
- 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 **the atom had a small, heavy region of positive charge inside it.**



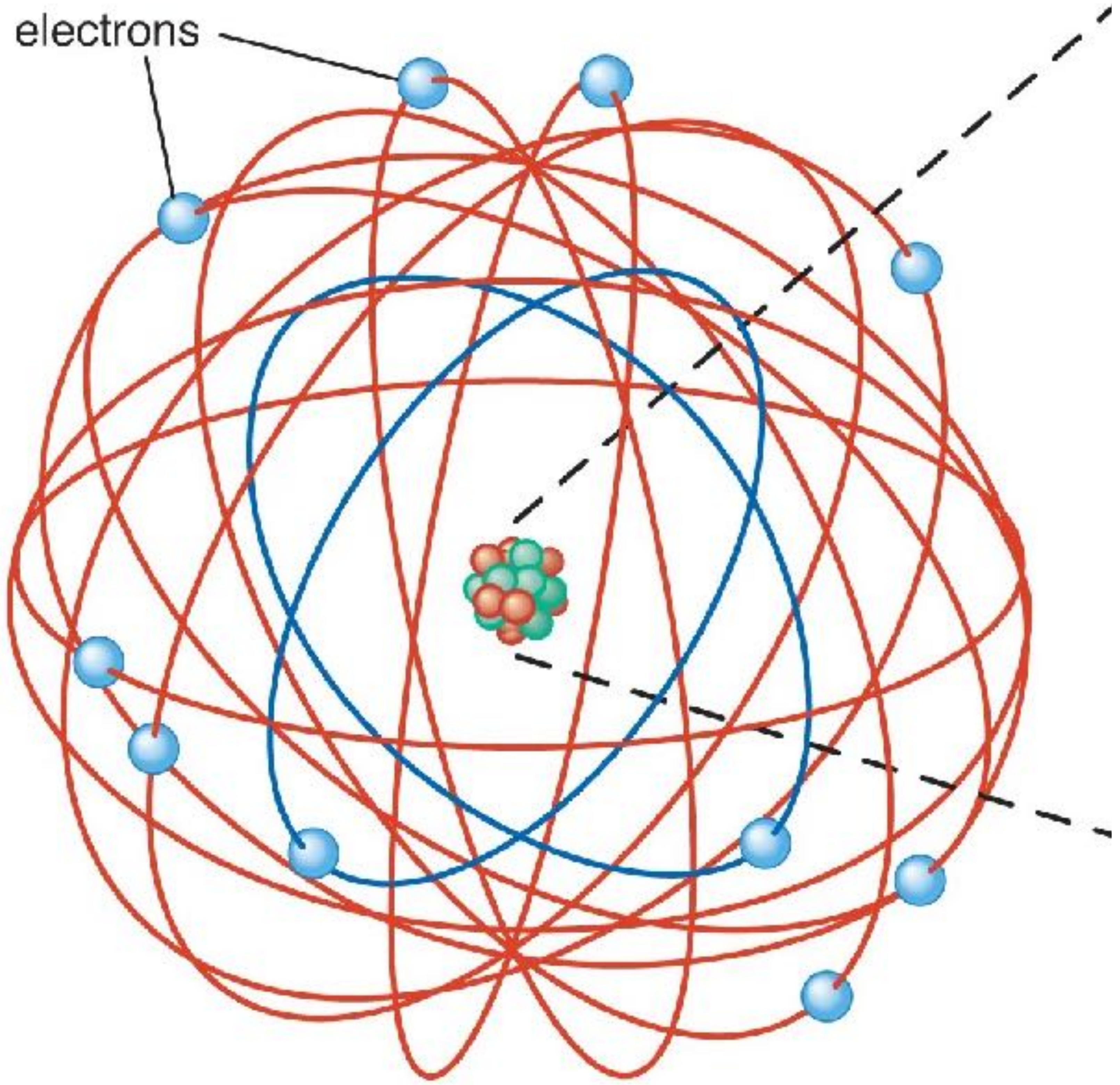
Encyclopedia Britanica

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 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

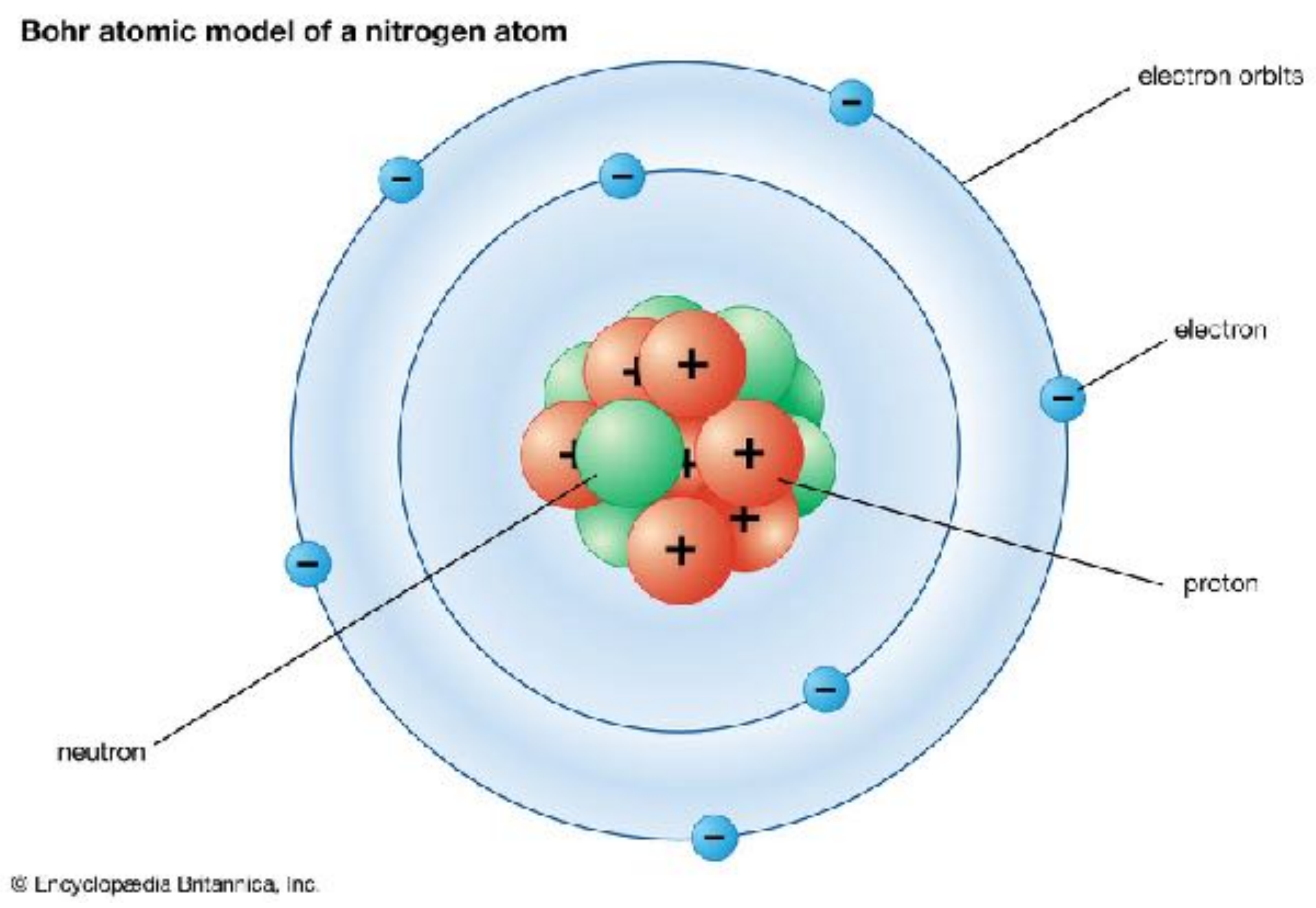
- In 1913 Moseley proved with experiments that:
  - The **charge on the nucleus is +Ze, where the integer Z was the atomic number of the element**, and implying Z orbiting electrons for electrical neutrality.
  - The foundation of a physical explanation of Mendeleev's periodic table
  - Also predicted 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

Discovery of 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 problem was solved in 1932 by the discovery of the neutron by Chadwick.
- Chadwick demonstrated 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 associated witch the charge (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.

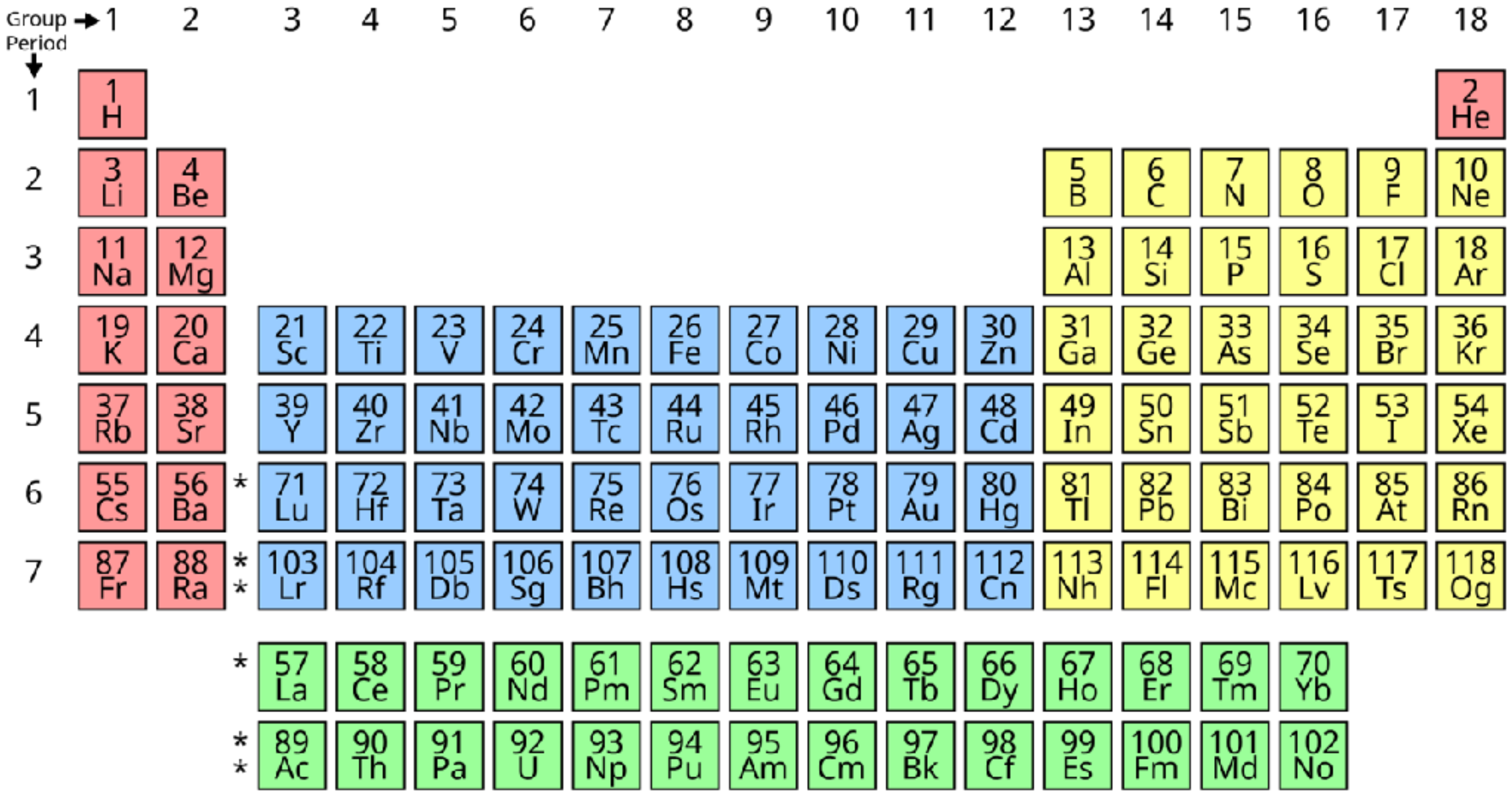
Group → / Period ↓	1	2		3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H																		2 He
2	3 Li	4 Be												5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg												13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca		21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 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	*	71 Lu	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	**	103 Lr	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
			*	57 La	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		
			**	89 Ac	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		

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

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 to use Z and N.



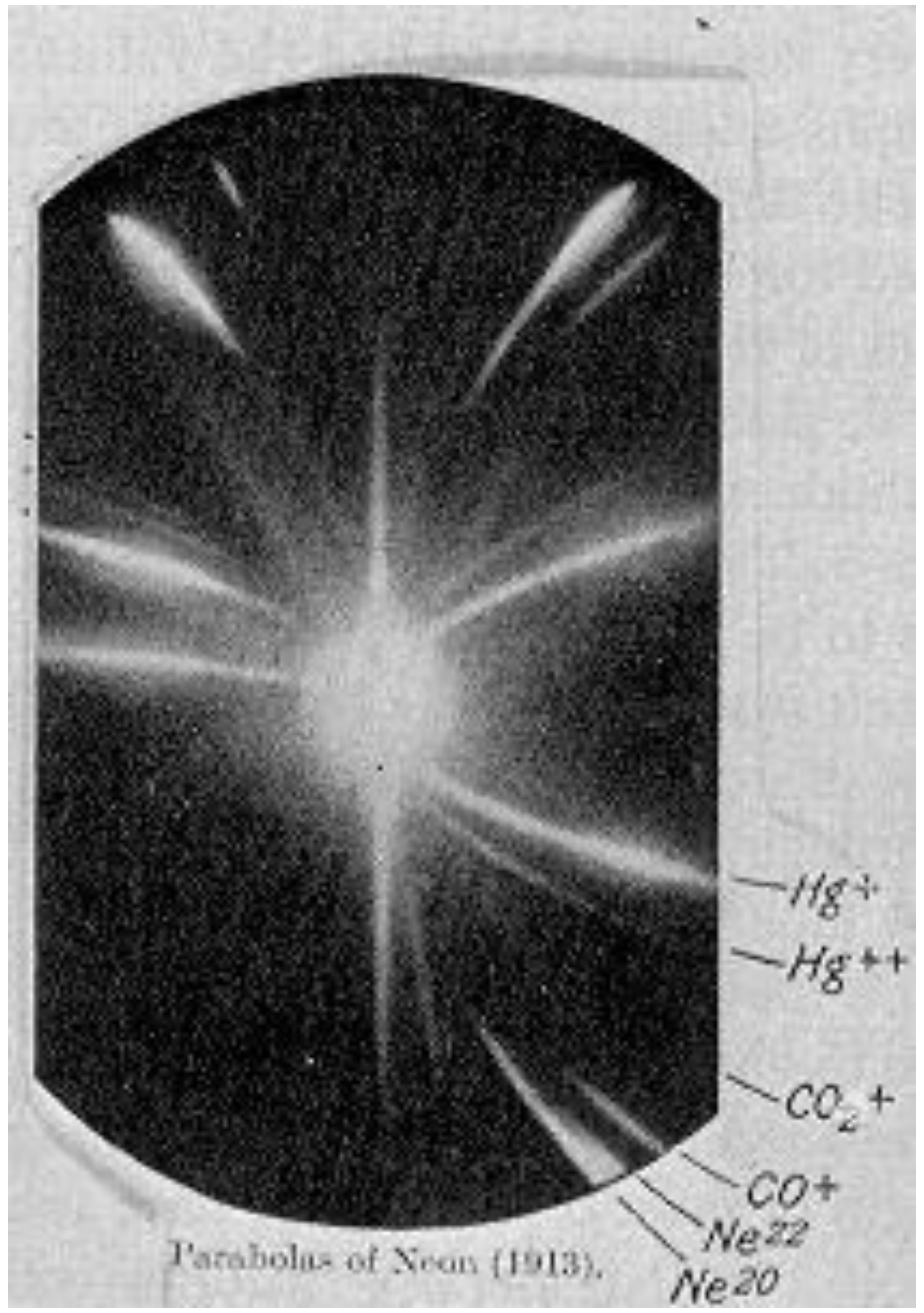
https://en.wikipedia.org/wiki/Periodic_table

Isotopes

- In 1913 Soddy showed that a **given chemical element often contained atoms with different atomic masses (A)** but the same number of protons (e.g. they have different numbers of neutrons). Such elements are called 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 behaviour of an atom is largely determined by its electronic structure**, different isotopes exhibit nearly identical chemical behaviour.

Some examples?

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



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.**

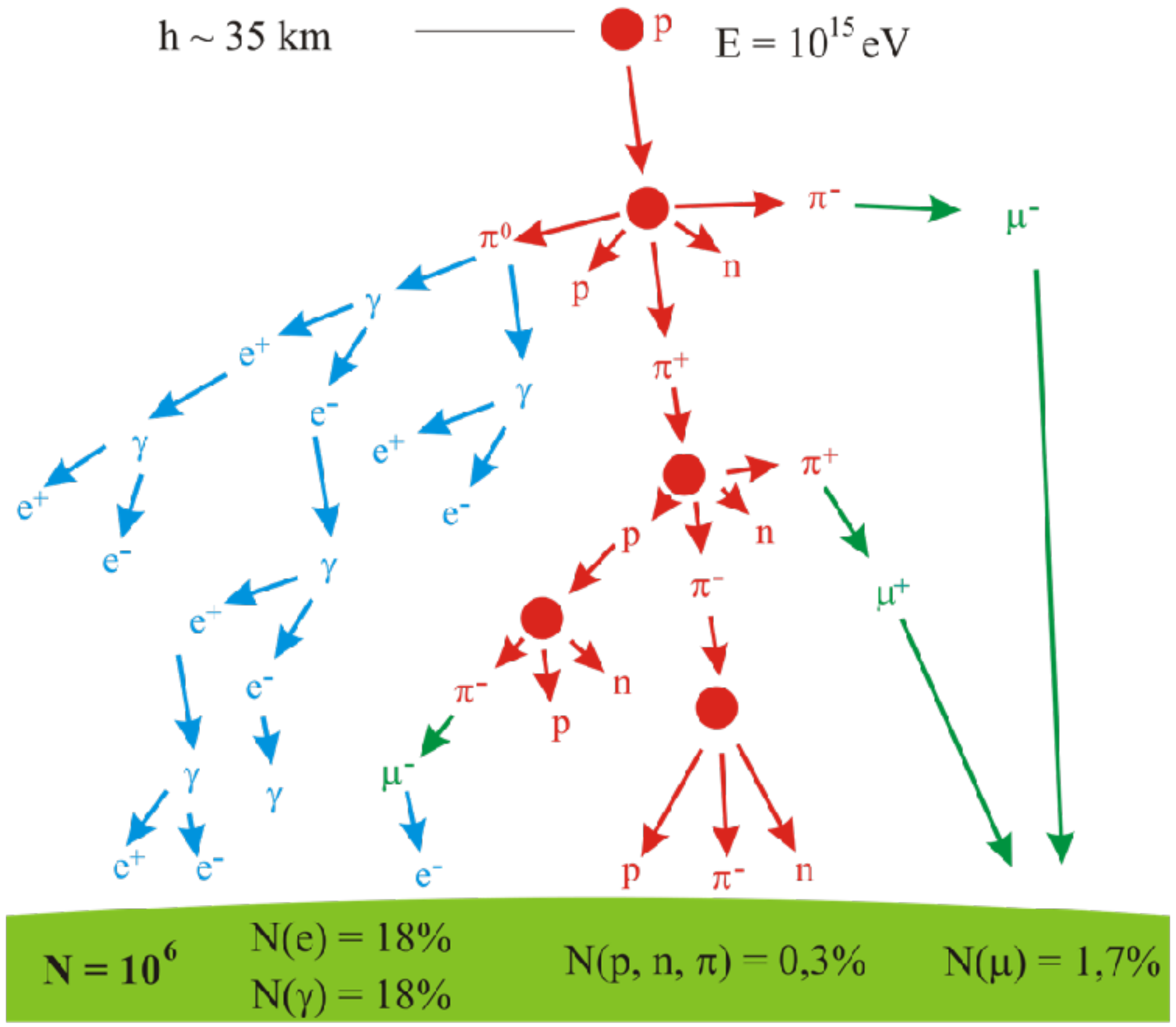
Current understanding

- 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.
- 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.

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)

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.
- Anderson and Neddermeier discovered new subatomic particles in 1936. These were initially thought to be mesons, but are now known to be particles called **muons**.
    - **Muons are leptons, and act like heavy electrons. They do not interact via the strong force.**
- Charged particles with suitable properties were finally detected in 1947. These particles were later named from mesons to **pions**.
- 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.

Strange particles

- Further work led to the discovery in 1947 by Rochester and Butler of new particles, named **kaons (K)**, 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 weak interactions responsible for β decay.

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 lead to the discovery of many new particles.

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,
  - 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.**

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 colour 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

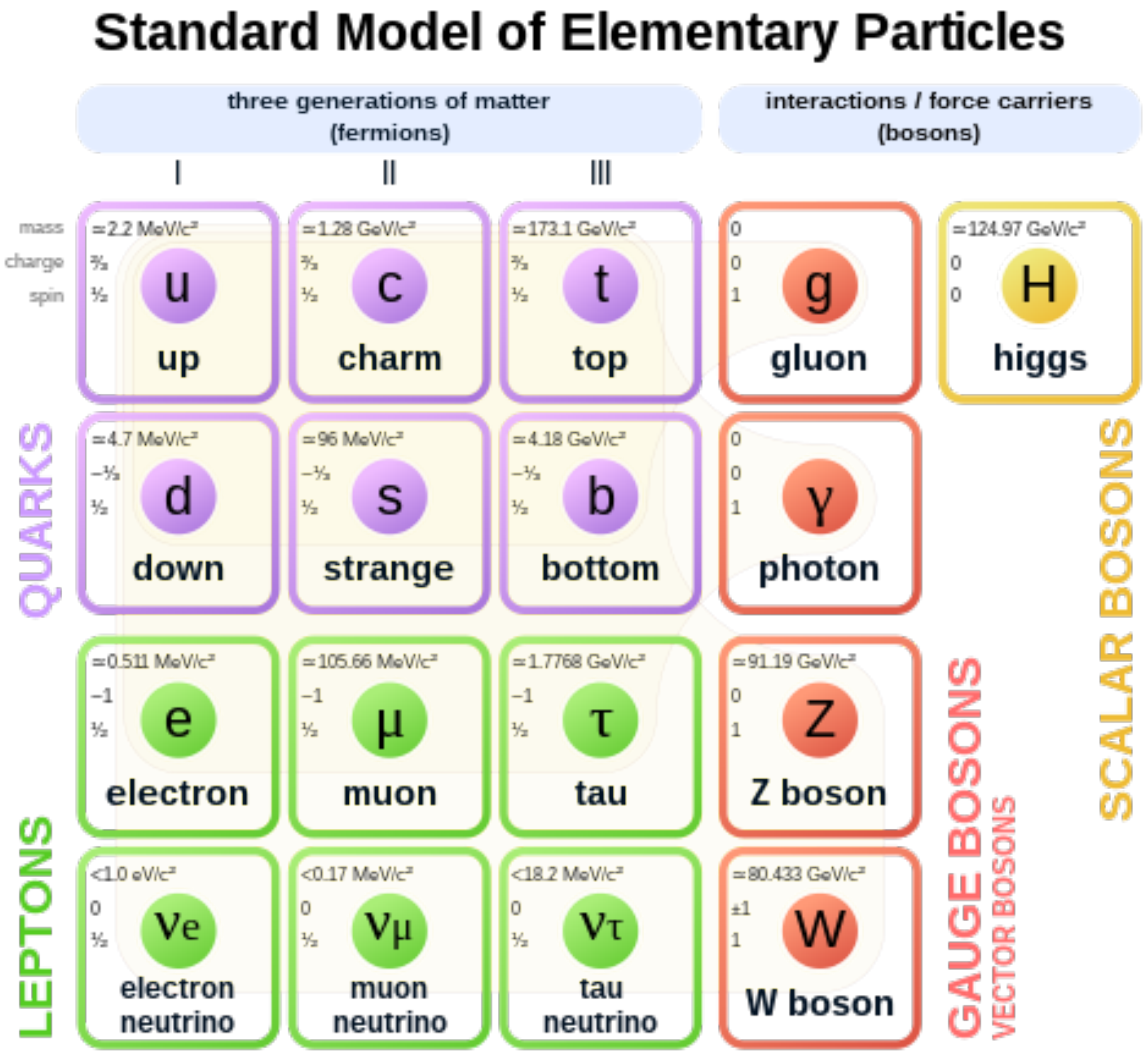
$q\bar{q}$	Q	S	Meson
$u\bar{u}$	0	0	π^{0}
$u\bar{d}$	1	0	π^{+}
$d\bar{u}$	-1	0	π^{-}
$d\bar{d}$	0	0	η
$u\bar{s}$	1	1	K^{+}
$d\bar{s}$	0	1	K^{0}
$s\bar{u}$	-1	-1	K^{-}
$s\bar{d}$	0	-1	$\overline{K}^{0}$
$s\bar{s}$	0	0	??

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 and spin as the corresponding particle, but with the opposite charge and opposite quantum numbers.
- 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 and the neutrino have anti particles, 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.**



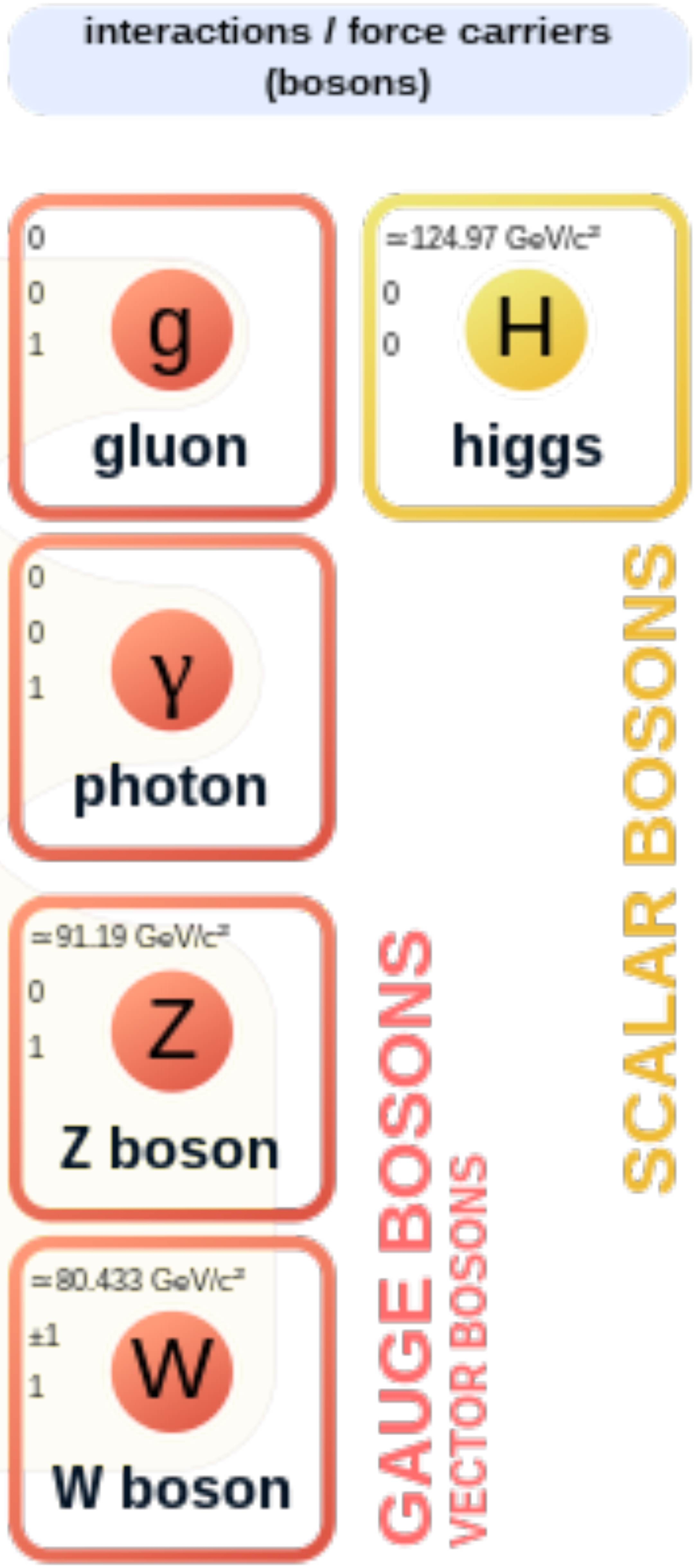
The standard model

- **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.

- 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 $0, 1/2, 1, 3/2, \ldots$.
- 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.
- Two types of bosons:
  - **spin-1 bosons**, which act as force carriers,
  - and a **spin-0 particle, called the Higgs boson**, which plays a key role in understanding the origin of elementary particle masses.

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 quantum theory, the electromagnetic 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 weak and strong interactions are also mediated by the exchange of spin-1 gauge bosons.
  - For the **weak interaction** these are the $\mathbf{W^+}$**,** $\mathbf{W^-}$**, and** $\mathbf{Z^0}$ **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.