Mitglied der Helmholtz-Gemeinschaft

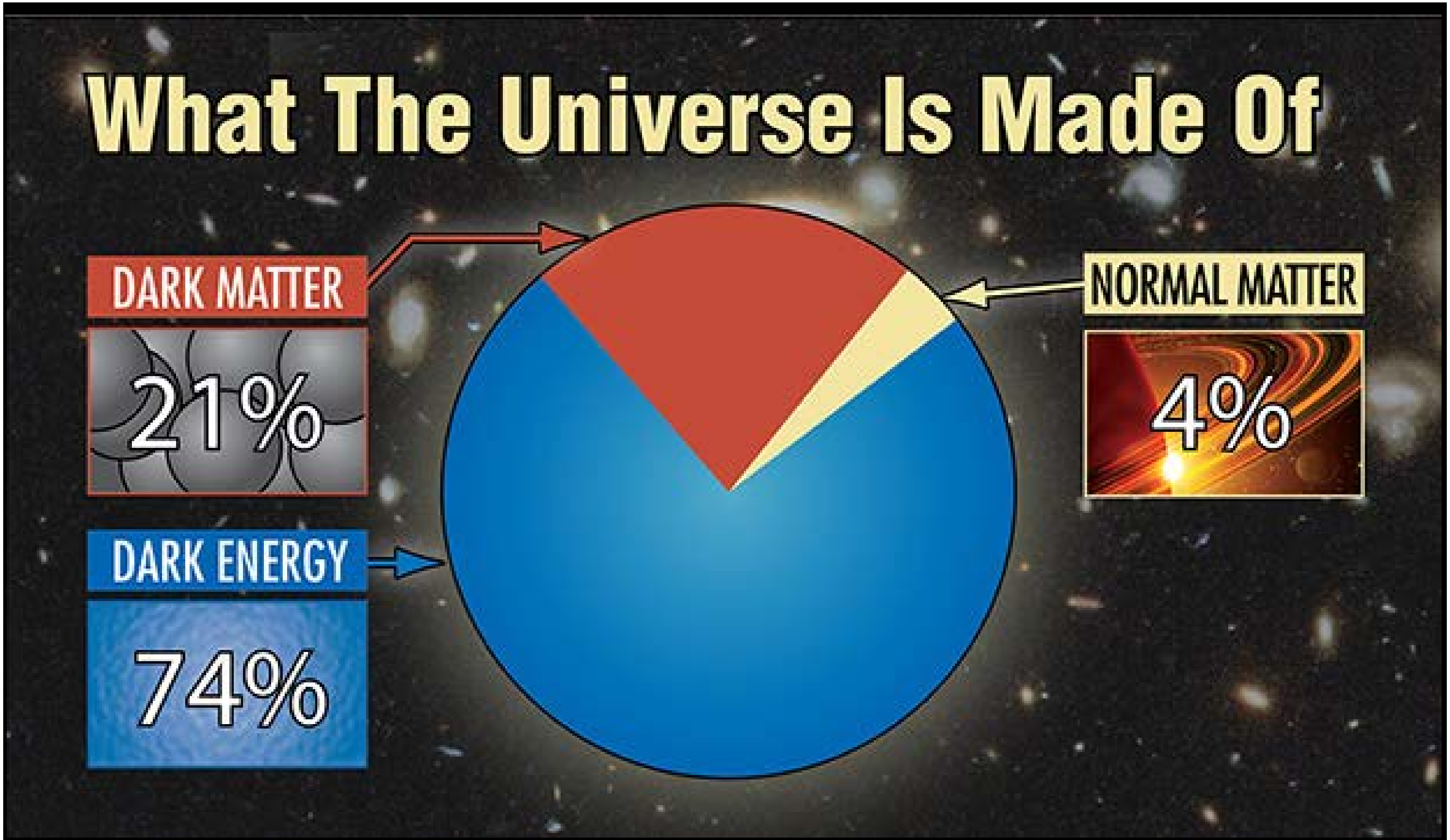
JÜLICH FORSCHUNGSZENTRUM

2nd Autumn Lectures – Tbilisi 2015

Structure of Matter (SoM) Part 1

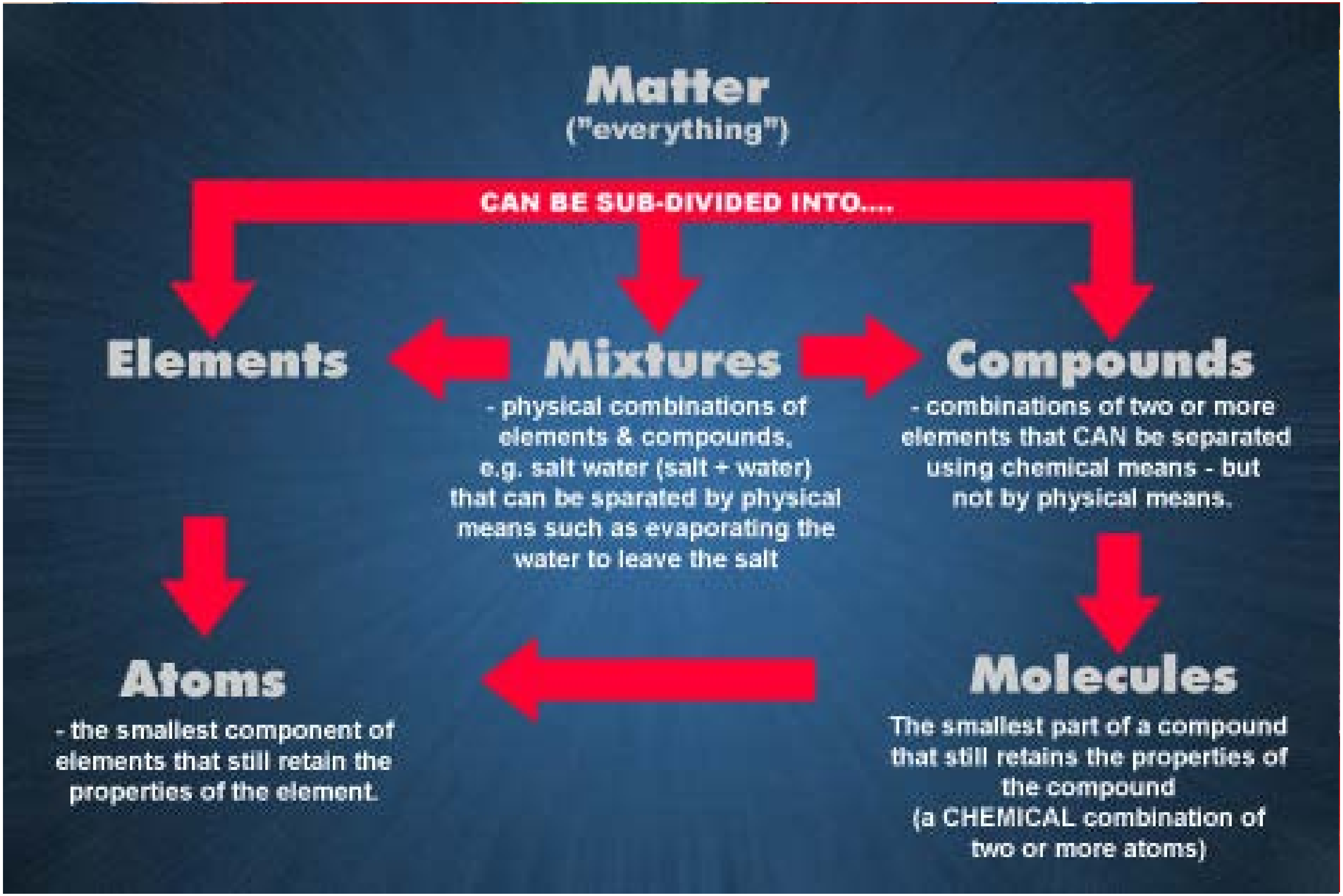
October, 2015 | Hans Ströher (Forschungszentrum Jülich)

Part 1 – Atoms – Introduction



Lecture is only about these 4% …

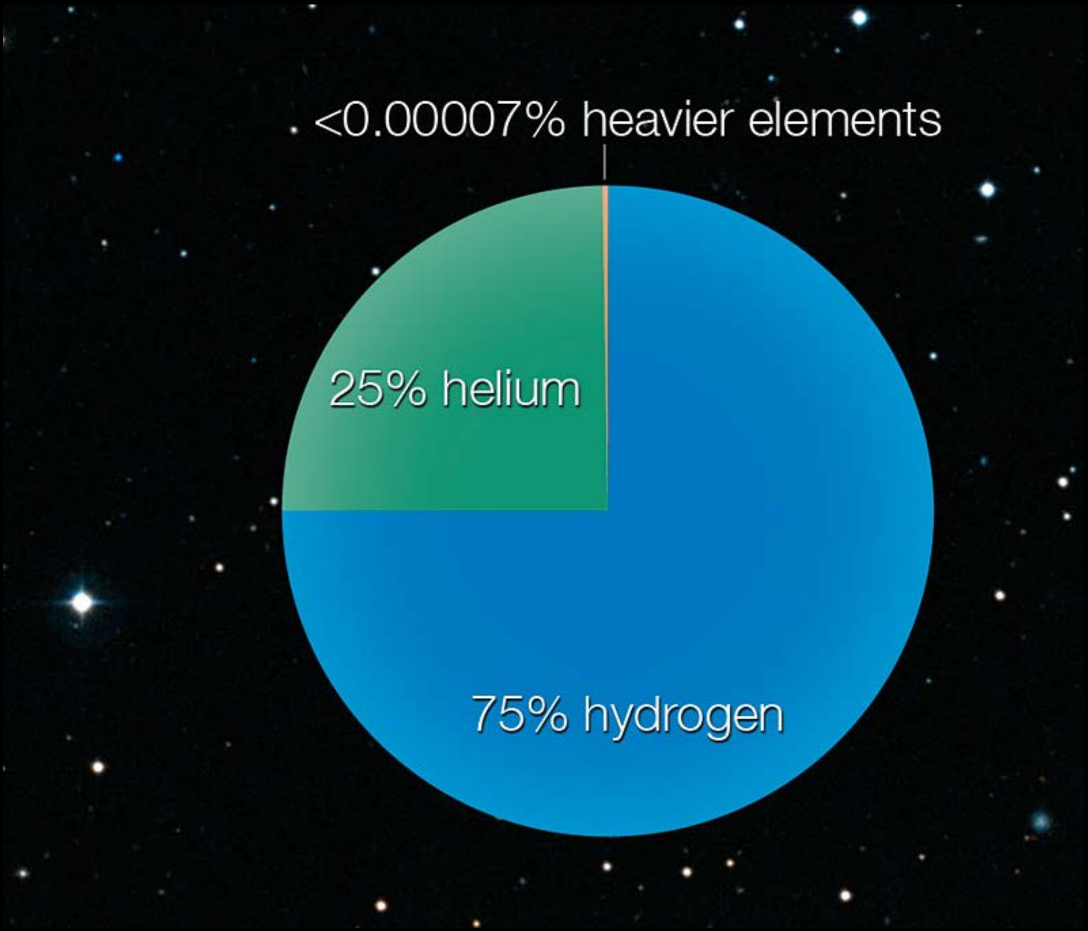
Part 1 – Atoms – Introduction



Part 1 – Atoms – Introduction

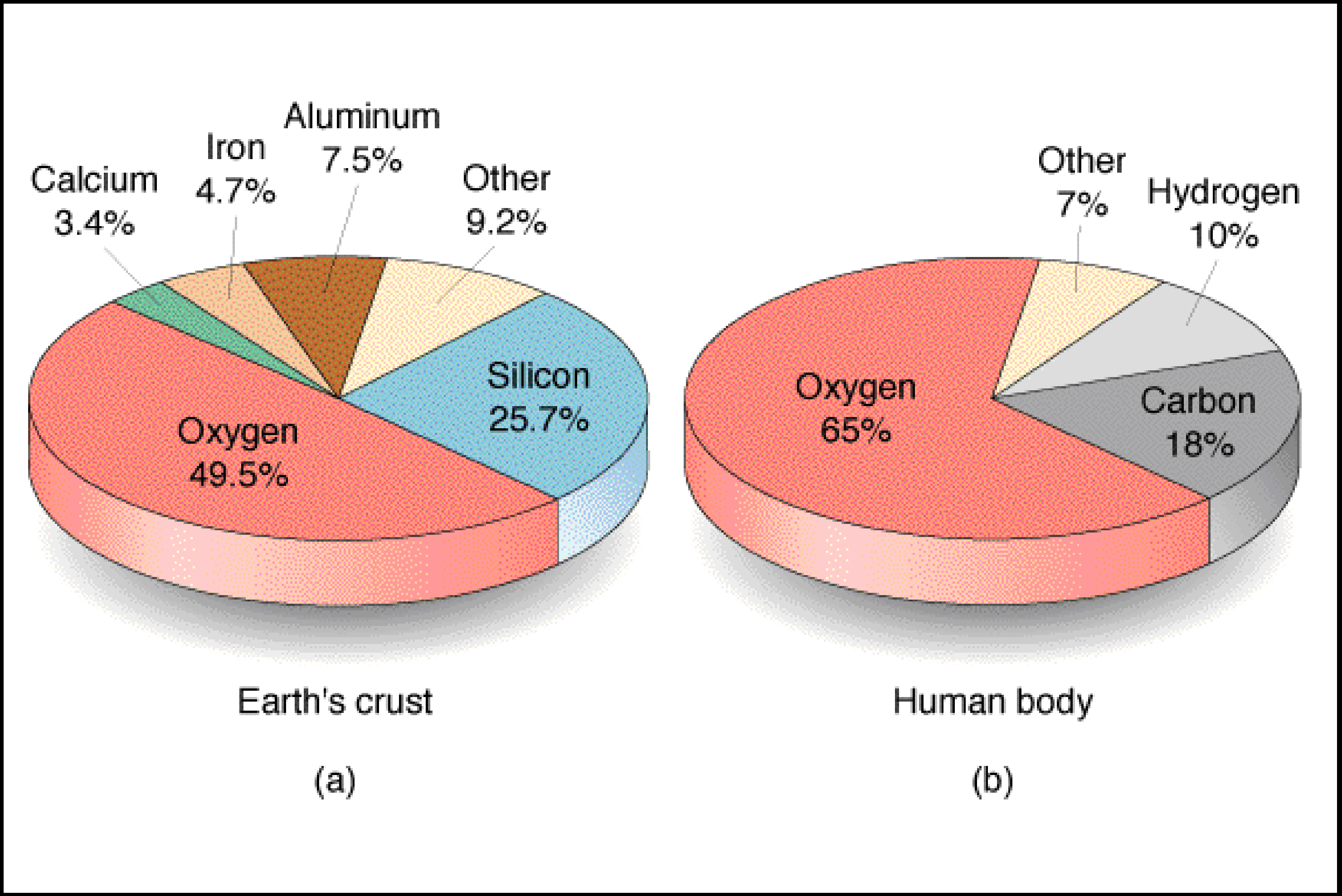
All matter is composed of **atoms**, the different kinds being known as **(chemical) elements**.

- There are 114 (+ x) elements identified, but only a few dozen are found in biological systems.



Universe: Hydrogen and Helium

Part 1 – Atoms – Introduction



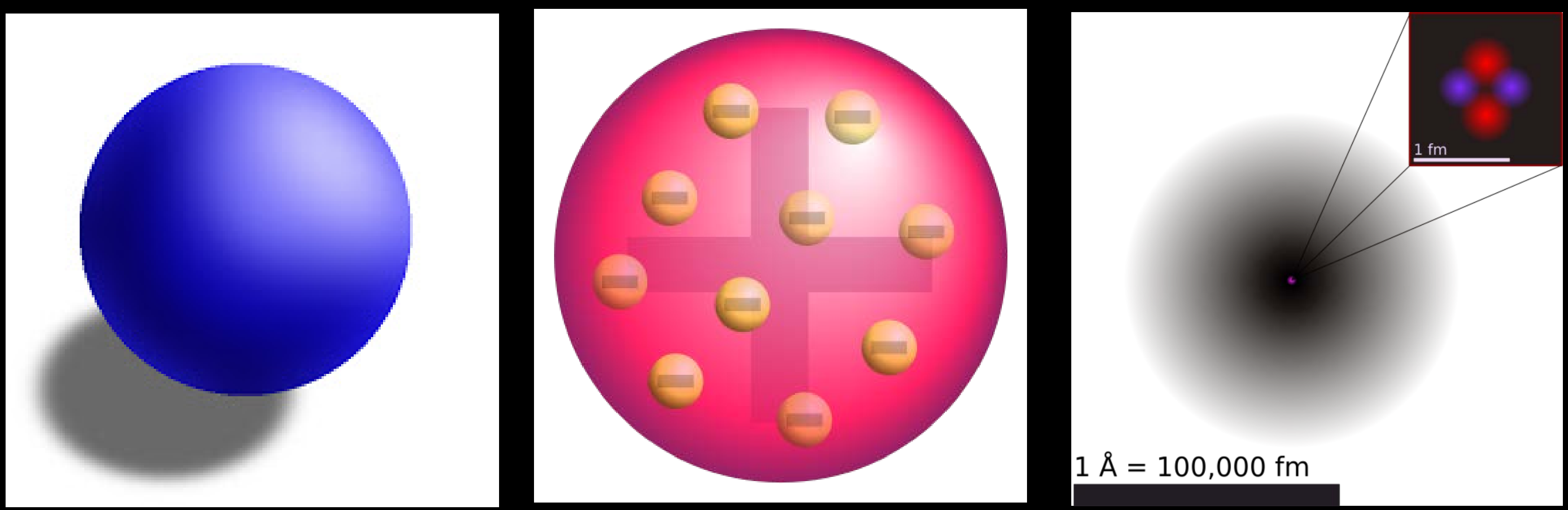
Abundances (Weight)

Part 1 – Atoms – Introduction

All atoms are constructed similarly:

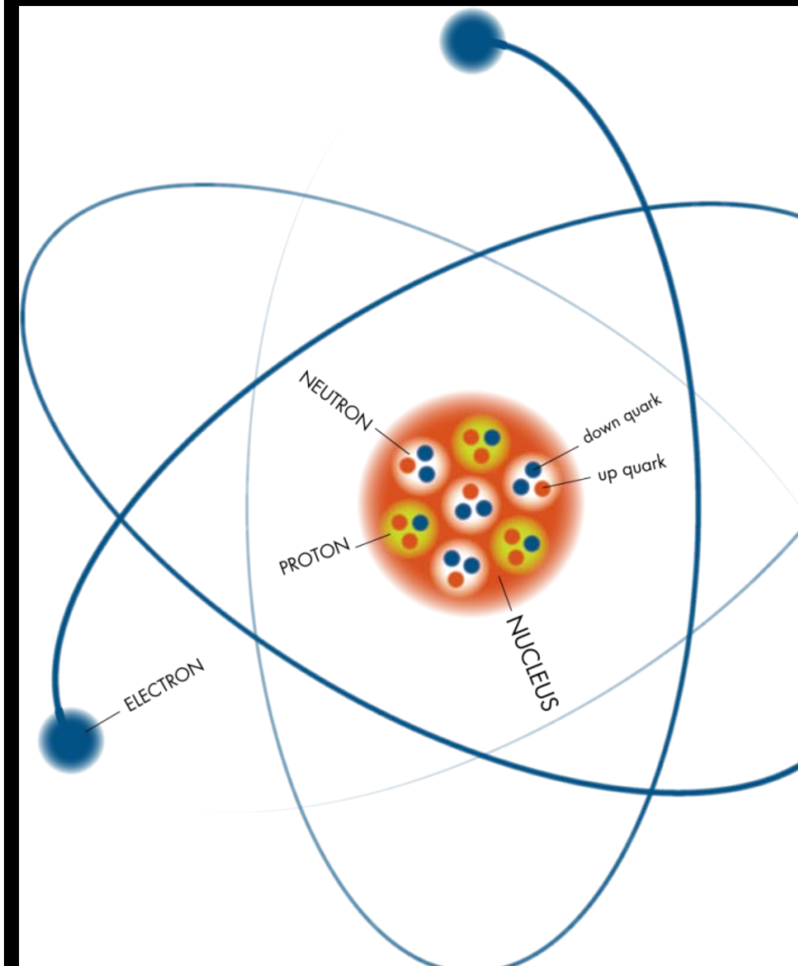
- There is a **nucleus** with **protons** (particles with a positive electrical charge, p) and **neutrons** (neutral particles, n).
  [Exception: H nucleus has no neutrons.]
- Shells of **electrons** (particles with negative charge) surround the nucleus. Neutrons and protons are approx. 1800 times heavier than electrons.
- In its elemental ("neutral") state, an atom has **equal numbers of protons and electrons**.
- The **atomic number** of an element is the number of protons in the nucleus. It determines the chemical nature of the element.
- The **atomic mass** of an element is (approximately) the sum of the masses of protons, neutrons, and electrons present.

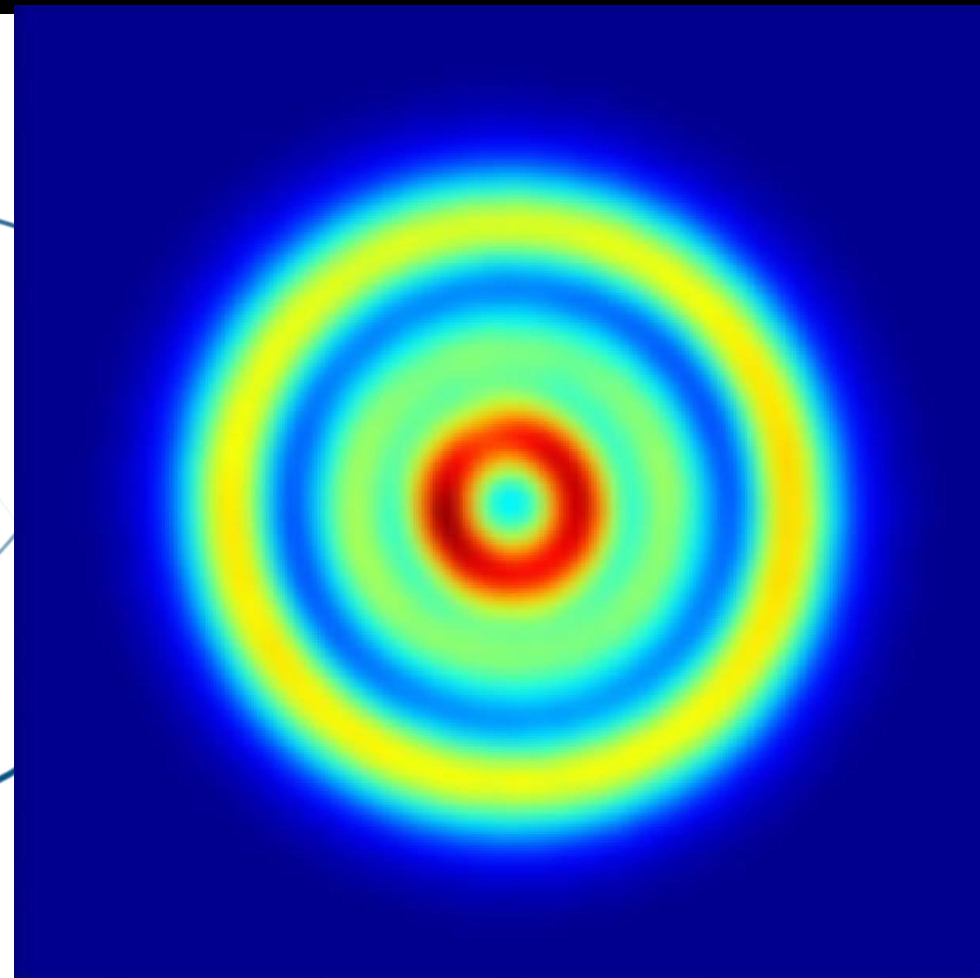
Part 1 – **Atoms** – Introduction



Models of the Atom

Part 1 – **Atoms** – Introduction





Atom = Nucleus (n, p) + Electrons

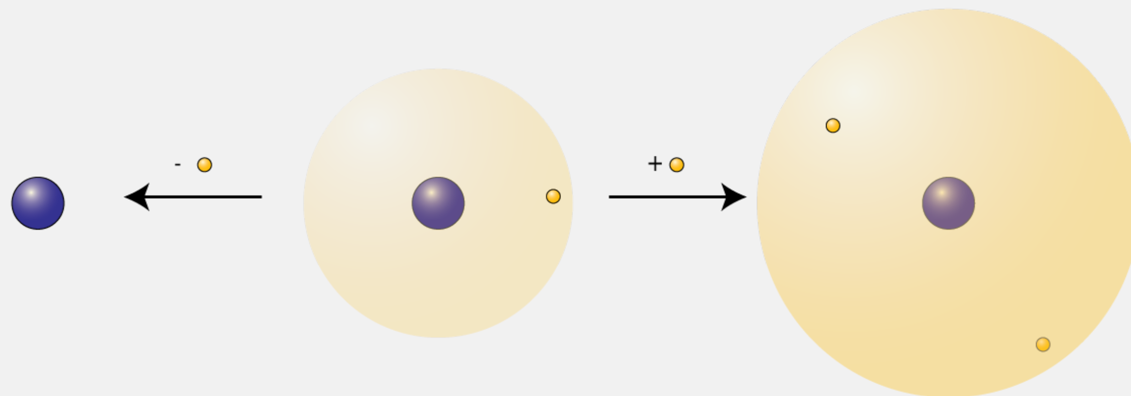
Part 1 – Atoms – Introduction

Atoms can gain or lose **electrons** without becoming unstable. Such a charged atom is called an **ion**.

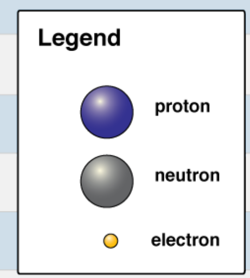
- An atom that gains electrons becomes negatively charged and is an **anion**; an atom that loses electrons becomes positively charged and is a **cation**.

Atoms do not ordinarily gain or lose **protons** of the nucleus; note that this would change them into a **different element**. However, this happens at the boarders of stability (see below); it can also be enforced by nuclear reactions (also possible for **neutrons**).

Part 1 – **Atoms** – Introduction



No. of protons	1	1	1
No. of electrons	0	1	2
Charge	+1	0	-1
Notation	H^+	H	H^-
Classification	cation	neutral (not an ion)	**anion**



Ion: N° Protons ≠ N° Electrons

Part 1 – **Atoms** – Introduction

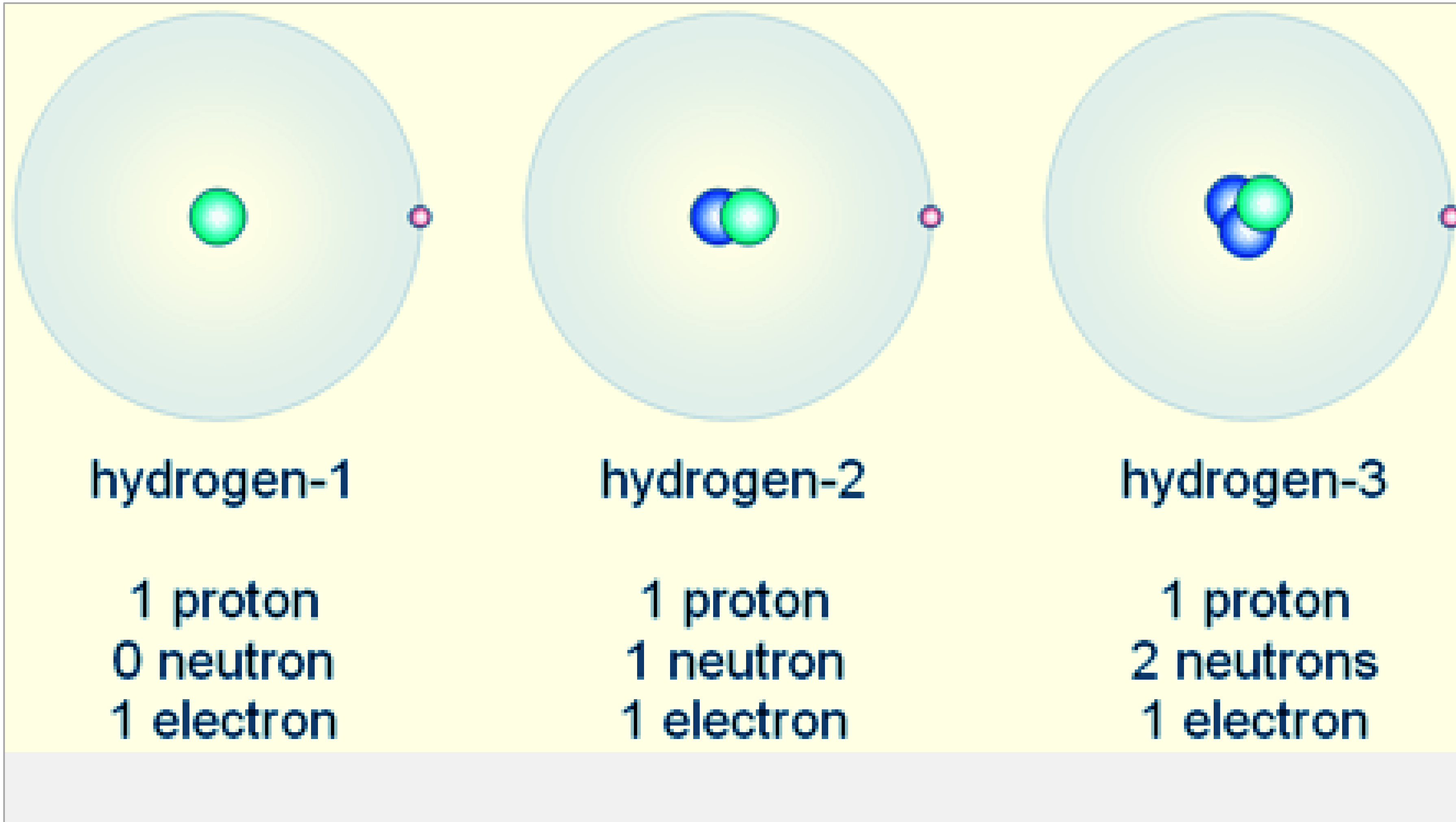
The **number of neutrons** in the nucleus can vary over a narrow range for an element.

- The different forms have identical chemical properties but slightly different masses. They are **isotopes**. Some are stable, but others are unstable (**radioactive isotopes**).
- The different isotopes of an element are indicated by placing a superscript before the symbol, where the superscript is the sum of the protons and neutrons.

Example:

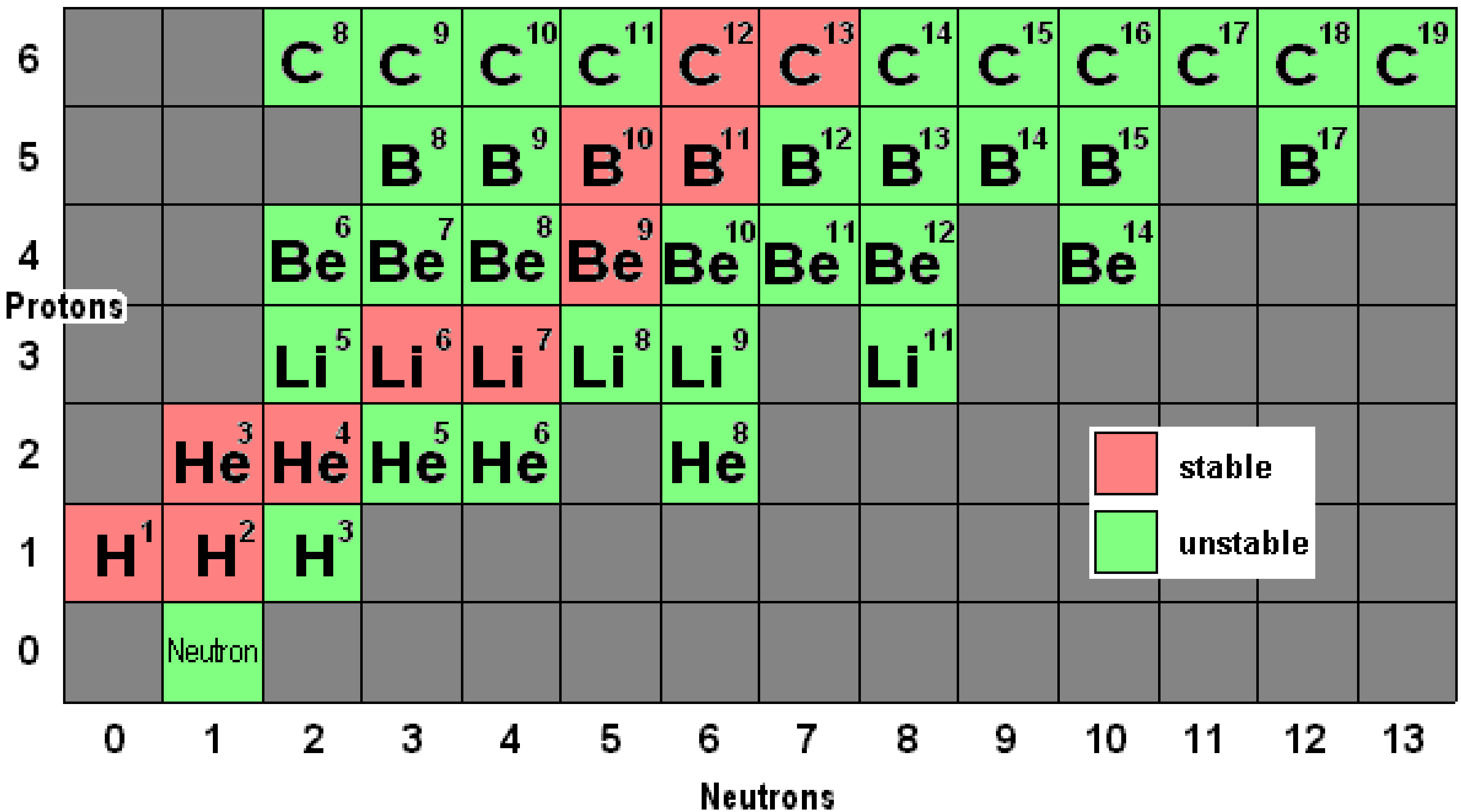
^{1}H, ^{2}H, and ^{3}H are the three isotopes of hydrogen, the first being by far the most common. ^{3}H is not stable but “radioactive”:
it decays into ^{3}He, an electron and an anti-neutrino (→ more later)

Part 1 – **Atoms** – Introduction



Isotopes: Atoms equal N° p but different N° n

Part 1 – **Atoms** – Introduction



Part of the „Table of Isotopes“

Part 1 – **Atoms** – Introduction

The number of **electrons in the outer shell** of an element largely determines how it behaves chemically.

- Atoms with the same number of electrons in the outer shell show many similarities. This enables the construction of a **periodic table of the elements**.
- The building principle behind is the "**Pauli (Exclusion) Principle**" which states that any two electrons of an atom must not be identical (in all of the "quantum numbers").

Part 1 – **Atoms** – Introduction

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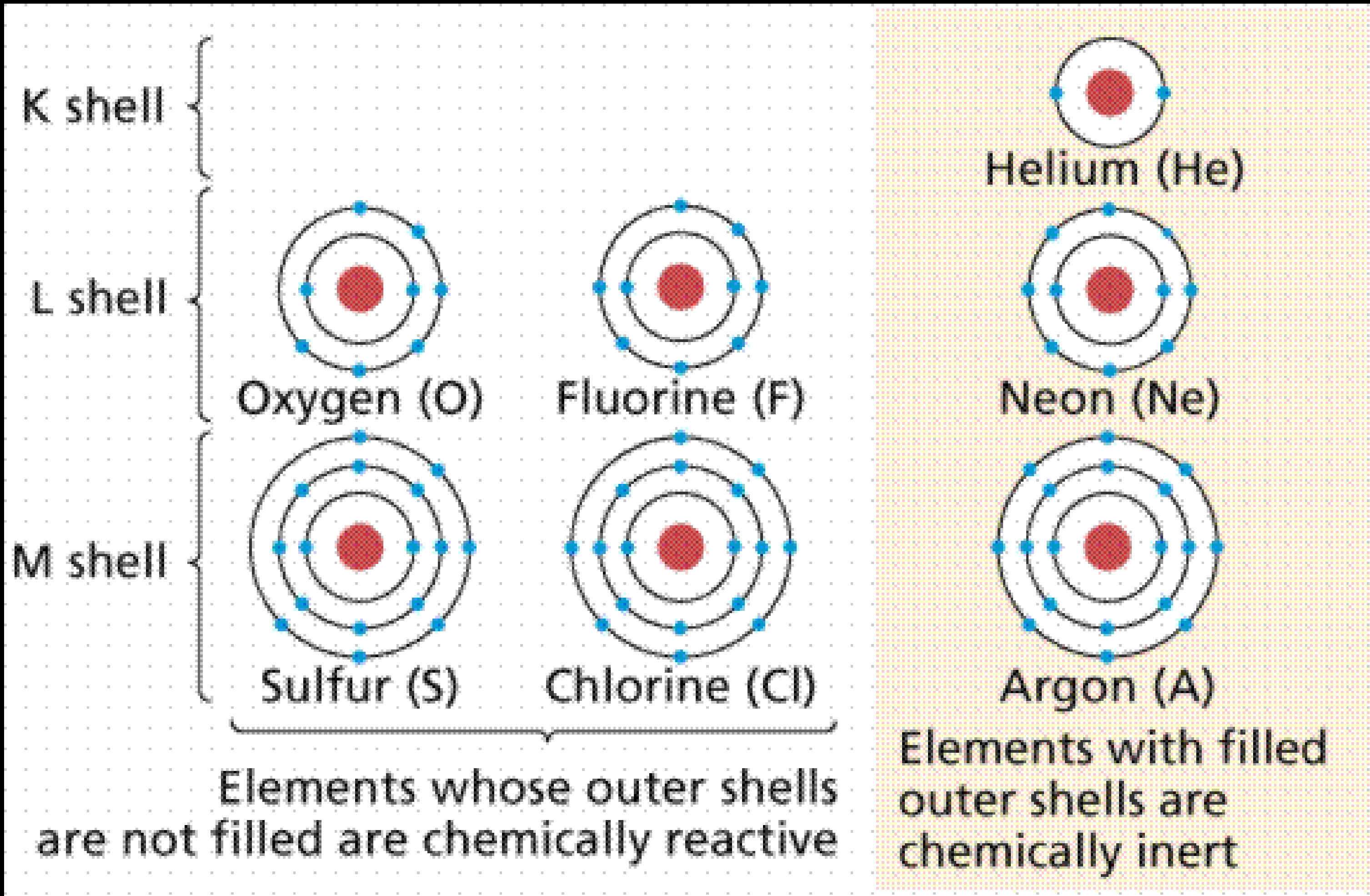
Key: Atomic # / Symbol / Exact Name

1 H Hydrogen																		2 He Helium
3 Li Lithium	4 Be Beryllium												5 B Boron	6 C Carbon	7 N Nitrogen	8 O Oxygen	9 F Fluorine	10 Ne Neon
11 Na Sodium	12 Mg Magnesium												13 Al Aluminum	14 Si Silicon	15 P Phosphorus	16 S Sulfur	17 Cl Chlorine	18 Ar Argon
19 K Potassium	20 Ca Calcium		21 Sc Scandium	22 Ti Titanium	23 V Vanadium	24 Cr Chromium	25 Mn Manganese	26 Fe Iron	27 Co Cobalt	28 Ni Nickel	29 Cu Copper	30 Zn Zinc	31 Ga Gallium	32 Ge Germanium	33 As Arsenic	34 Se Selenium	35 Br Bromine	36 Kr Krypton
37 Rb Rubidium	38 Sr Strontium		39 Y Yttrium	40 Zr Zirconium	41 Nb Niobium	42 Mo Molybdenum	43 Tc Technetium	44 Ru Ruthenium	45 Rh Rhodium	46 Pd Palladium	47 Ag Silver	48 Cd Cadmium	49 In Indium	50 Sn Tin	51 Sb Antimony	52 Te Tellurium	53 I Iodine	54 Xe Xenon
55 Cs Cesium	56 Ba Barium	*	71 Lu Lutetium	72 Hf Hafnium	73 Ta Tantalum	74 W Tungsten	75 Re Rhenium	76 Os Osmium	77 Ir Iridium	78 Pt Platinum	79 Au Gold	80 Hg Mercury	81 Tl Thallium	82 Pb Lead	83 Bi Bismuth	84 Po Polonium	85 At Astatine	86 Rn Radon
87 Fr Francium	88 Ra Radium	* *	103 Lr Lawrencium	104 Rf Rutherfordium	105 Db Dubnium	106 Sg Seaborgium	107 Bh Bohrium	108 Hs Hassium	109 Mt Meitnerium	110 Ds Darmstadtium	111 Rg Roentgenium	112 Cn Copernicium		114 Fl Flerovium		116 Lv Livermorium		

*	57 La Lanthanum	58 Ce Cerium	59 Pr Praseodymium	60 Nd Neodymium	61 Pm Promethium	62 Sm Samarium	63 Eu Europium	64 Gd Gadolinium	65 Tb Terbium	66 Dy Dysprosium	67 Ho Holmium	68 Er Erbium	69 Tm Thulium	70 Yb Ytterbium
* *	89 Ac Actinium	90 Th Thorium	91 Pa Protactinium	92 U Uranium	93 Np Neptunium	94 Pu Plutonium	95 Am Americium	96 Cm Curium	97 Bk Berkelium	98 Cf Californium	99 Es Einsteinium	100 Fm Fermium	101 Md Mendelevium	102 No Nobelium

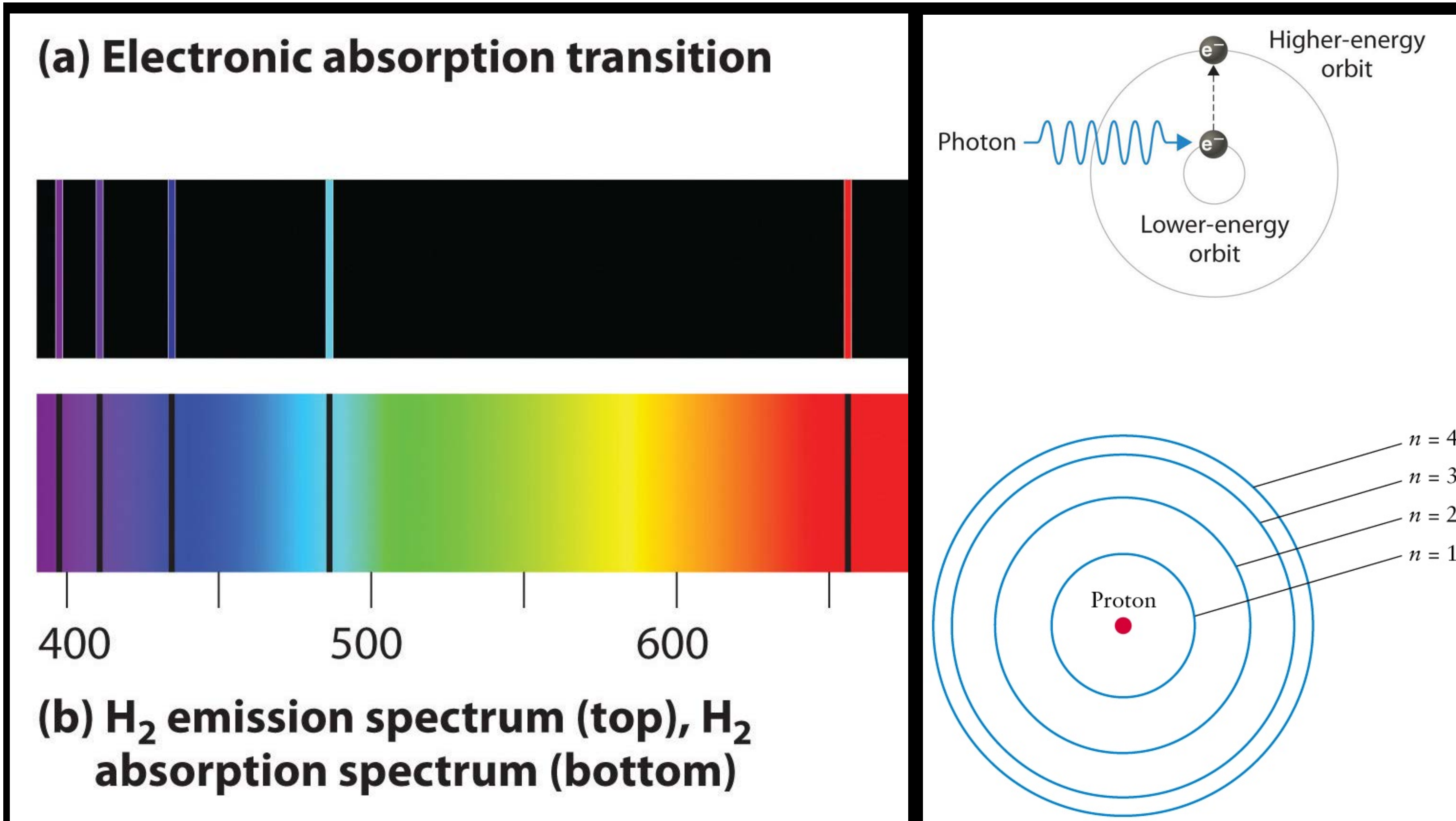
Periodic Table of Elements

Part 1 – Atoms – Introduction



Chemical Properties

Part 1 – **Atoms** – Hydrogen



Spectroscopy

Part 1 – **Atoms** – Hydrogen

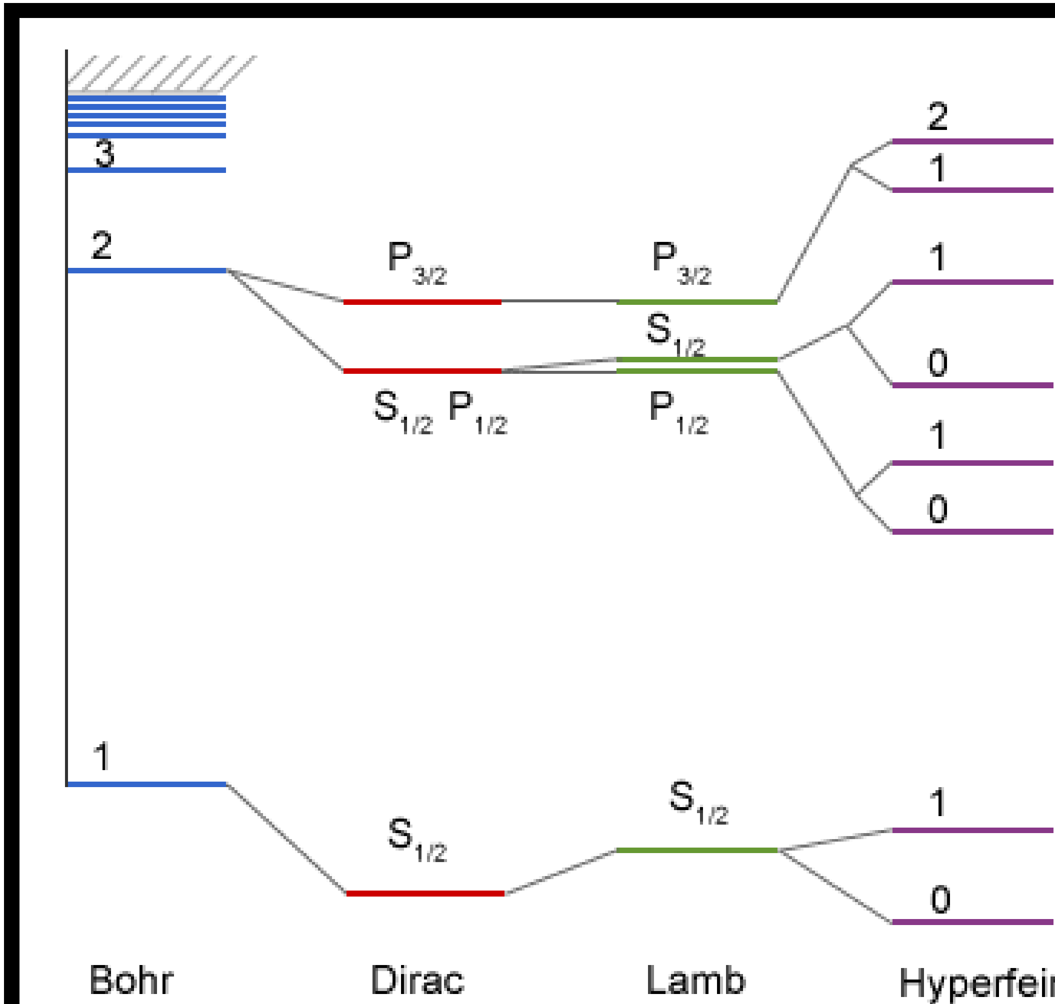
The **discrete energies** (“lines”) in the photon absorption and emission of hydrogen first posed a big puzzle, but subsequently provided detailed insight:

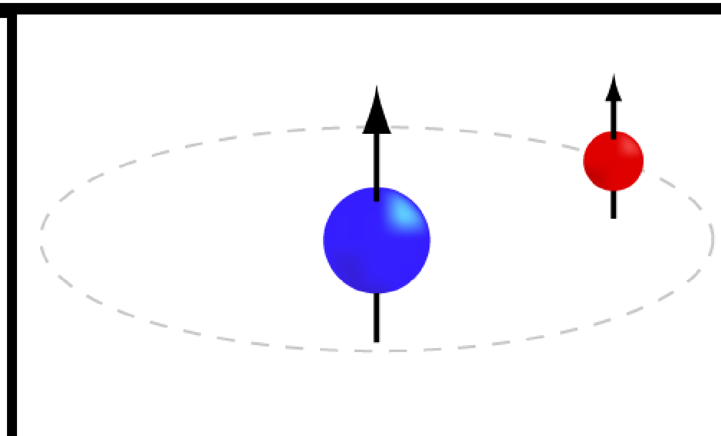
N. Bohr proposed that electrons could only have certain *classical* motions:

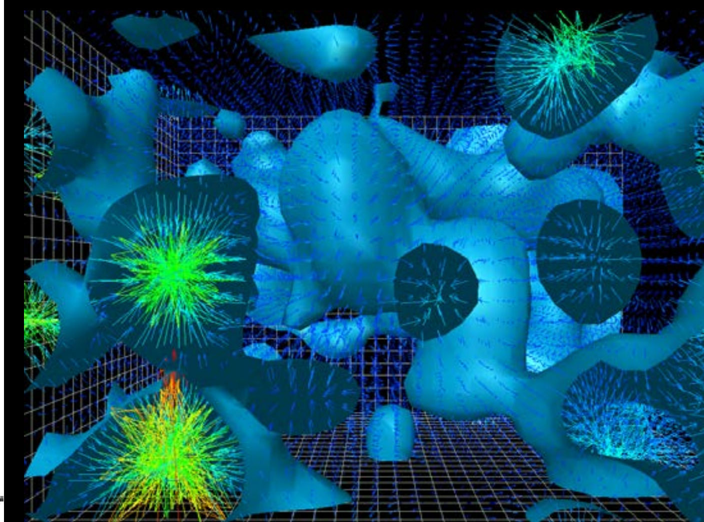
- The electrons can only orbit in certain discrete distances from the nucleus.
- These orbits are associated with definite energies and are also called **energy shells** or **energy levels**. In these orbits, the electron's acceleration does not result in radiation and corresponding energy loss as required by classical electromagnetics.

Actually the hydrogen energy levels are (much) **more complex** and interesting: “fine-structure” and “hyperfine-structure”, “Lamb-shift” …

Part 1 – **Atoms** – Hydrogen

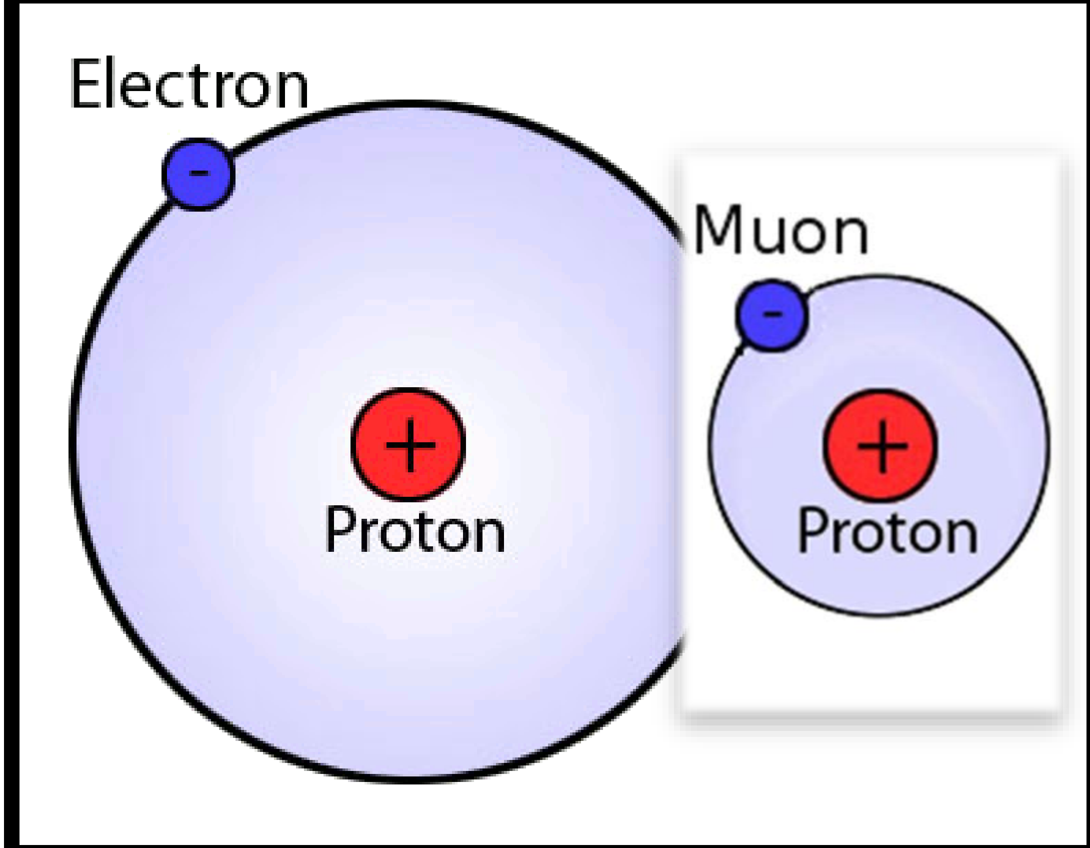


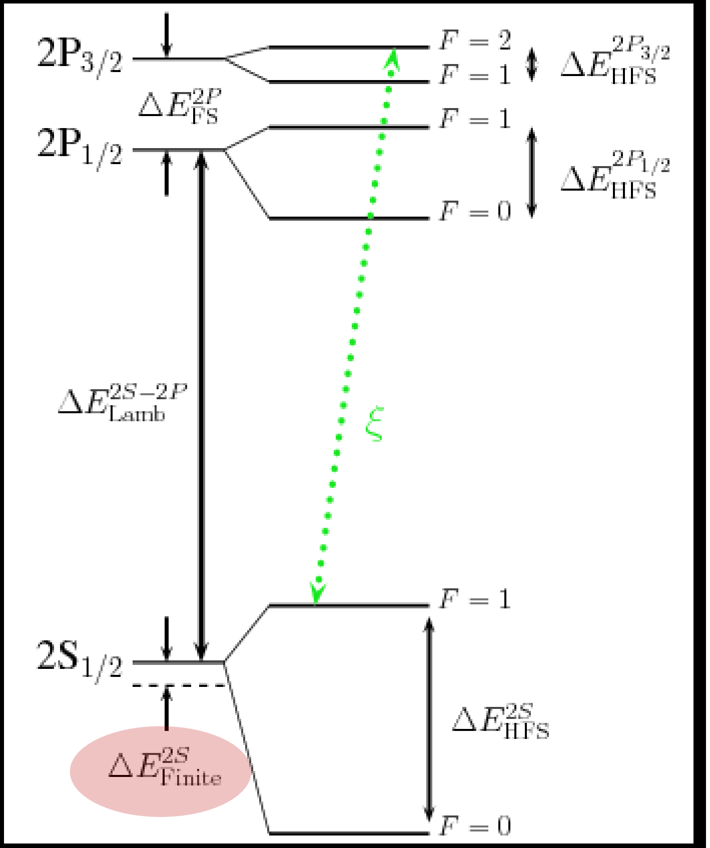




Spectroscopy

Part 1 – **Atoms** – Hydrogen





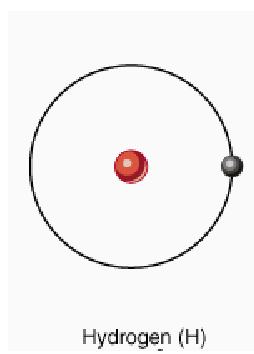
"… to understand hydrogen
is to understand all of physics."

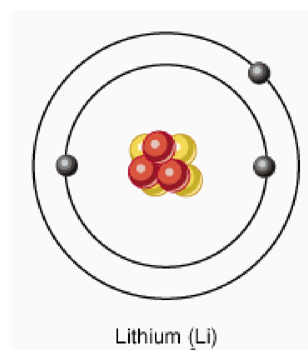
Part 1 – **Atoms** – Non-Hydrogen

Atoms with **more than one electron** … will be even more complex and complicated; the most simple cases are:

- atoms**,** which have lost all but one electron (“**hydrogen-like ions**”) e.g.:

- atoms, which have only one electron in the outermost electron shell (“**alkali atoms**”) e.g.;





Part 1 – Atoms – Summary

Atoms are the building blocks of matter; they are not fundamental but comprised of **electrons** (atomic shell) and a **nucleus** (with protons and neutrons);

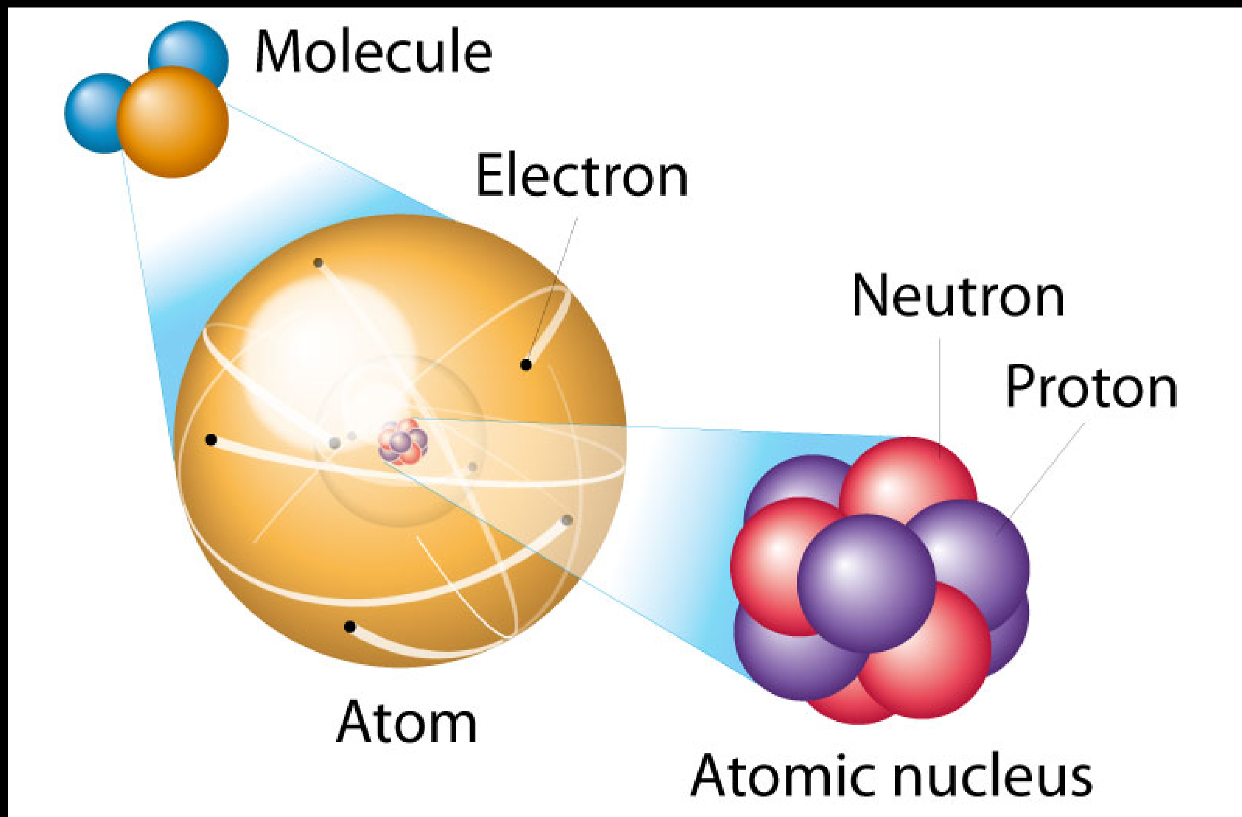
Much about the **structure of atoms** has been learned from the **light** (emitted or absorbed by them), and from the structure, deep insight has been obtained about the basic underlying physics;

The **number of protons** in the nucleus fixes the **chemical element**. The **atomic shell** (structure) largely determines the characteristics of the elements, e.g., their **chemical properties**;

With the help of the **Pauli (Exclusion) Principle**, the Table of Elements can be constructed.

→ **Why does the Table of Elements end ?**

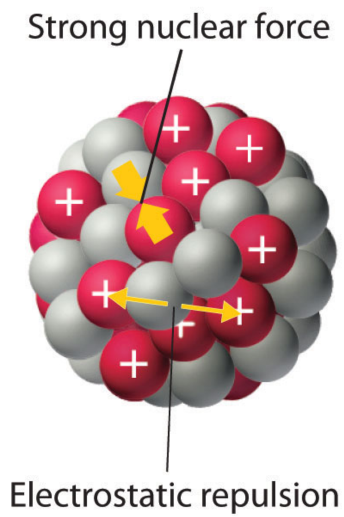
Part 1 – Nuclei – Introduction



Part 1 – Nuclei – Introduction

Nuclei with certain numbers of protons and neutrons, up to a maximum proton number, are “stable” (i.e. they do not change their identity over long periods of time).

The reason is that a **new force** (“nuclear force”, “nucleon-nucleon interaction”) counter-acts (over compensates) the electromagnetic repulsion between protons:



But: Two protons alone are NOT bound; in addition a neutron is needed

→ What nucleus is this ?

Part 1 – Nuclei – Introduction

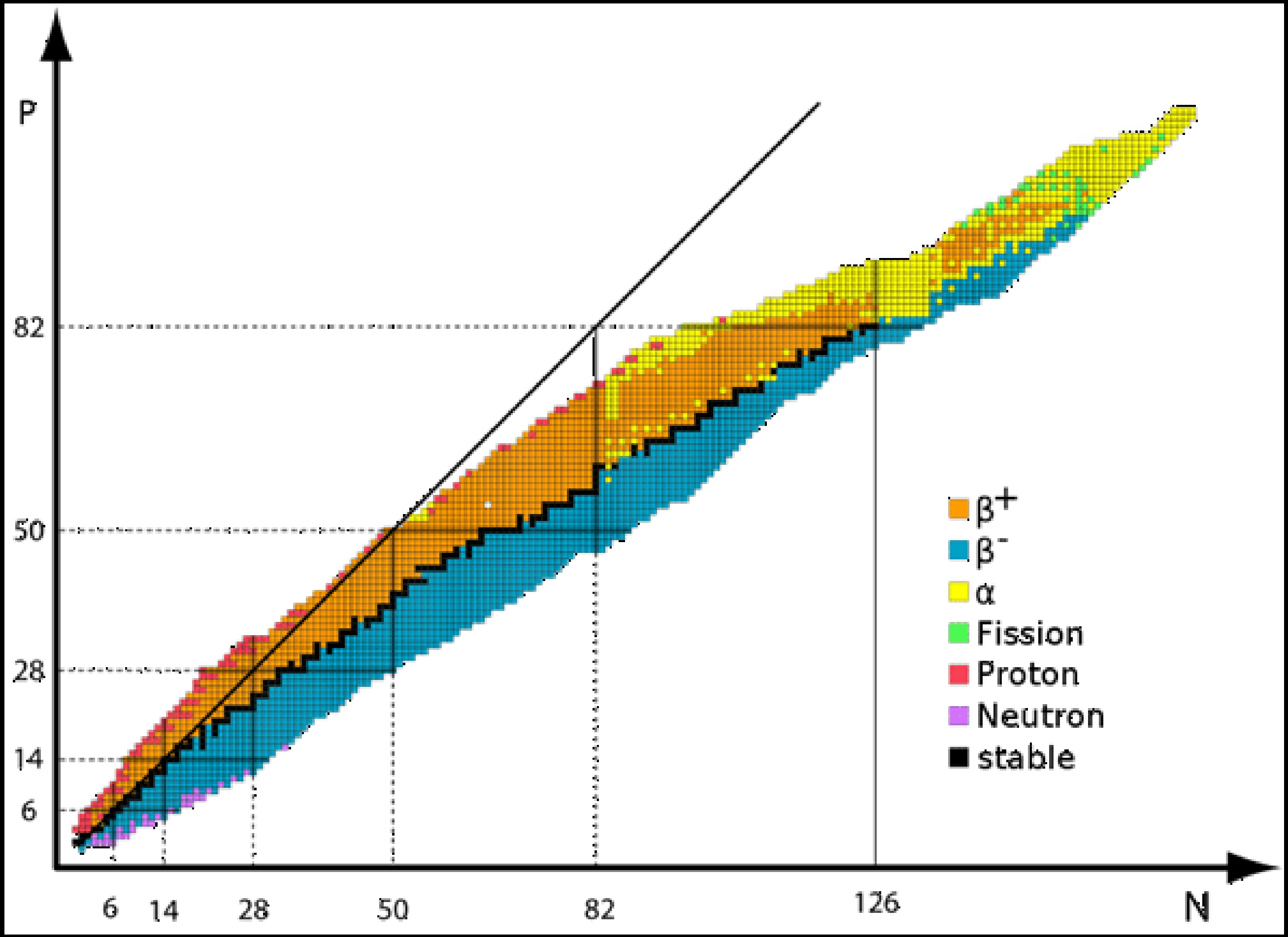
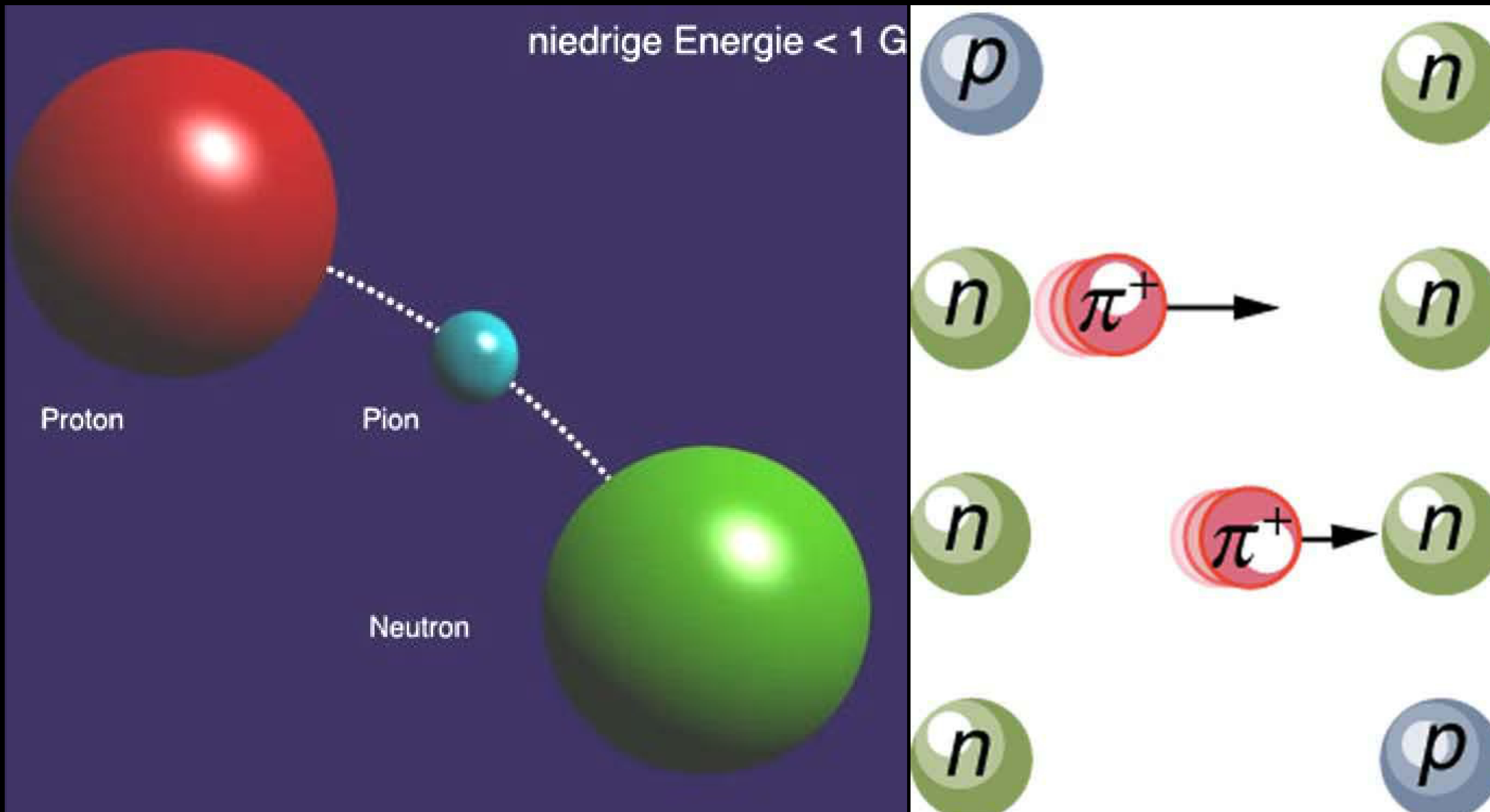


Table of Isotopes (Nuclides): Limits of Stability

Part 1 – Nuclei – Introduction

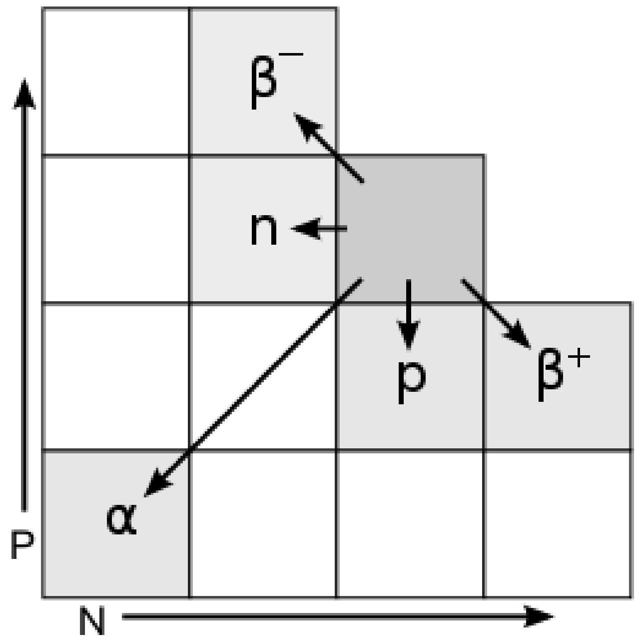


Nucleon-Nucleon Interaction

Part 1 – Nuclei – In(-stability)

If the **number of protons and neutrons** in a nucleus is "not right", it will be "unstable" and "decay" into a (more) stable configuration; this nuclear property is called "radioactivity"

The following possibilities exist for this transmutation:



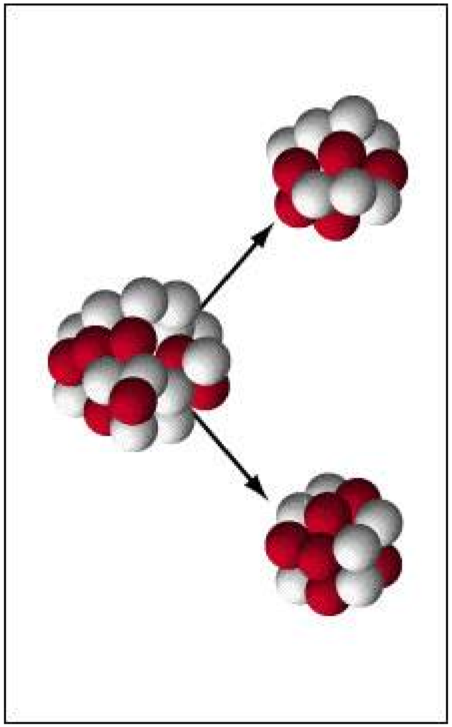
α-decay:	# p – 2, # n – 2
β^--decay:	# p + 1, # n – 1
β^+-decay:	# p – 1, # n +1
p-emission:	# p – 1
n-emission:	# n – 1

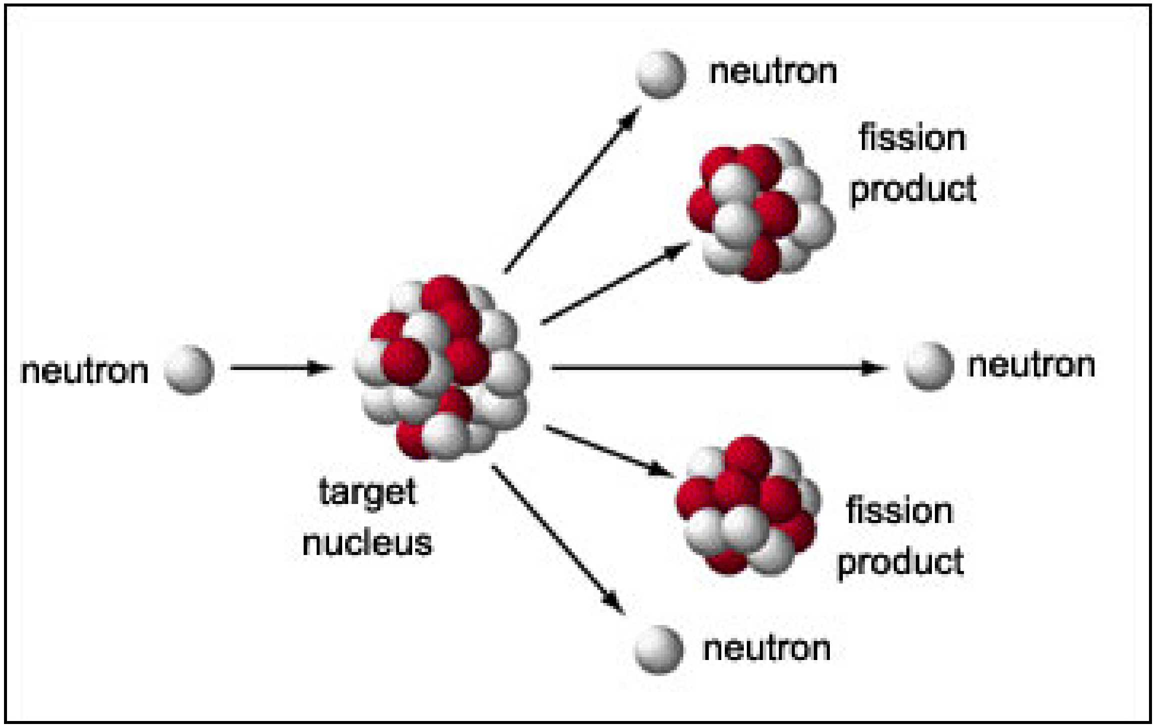
Plus: an excited nucleus (not in ground state) can emit **γ-rays**

Part 1 – Nuclei – In(-stability)

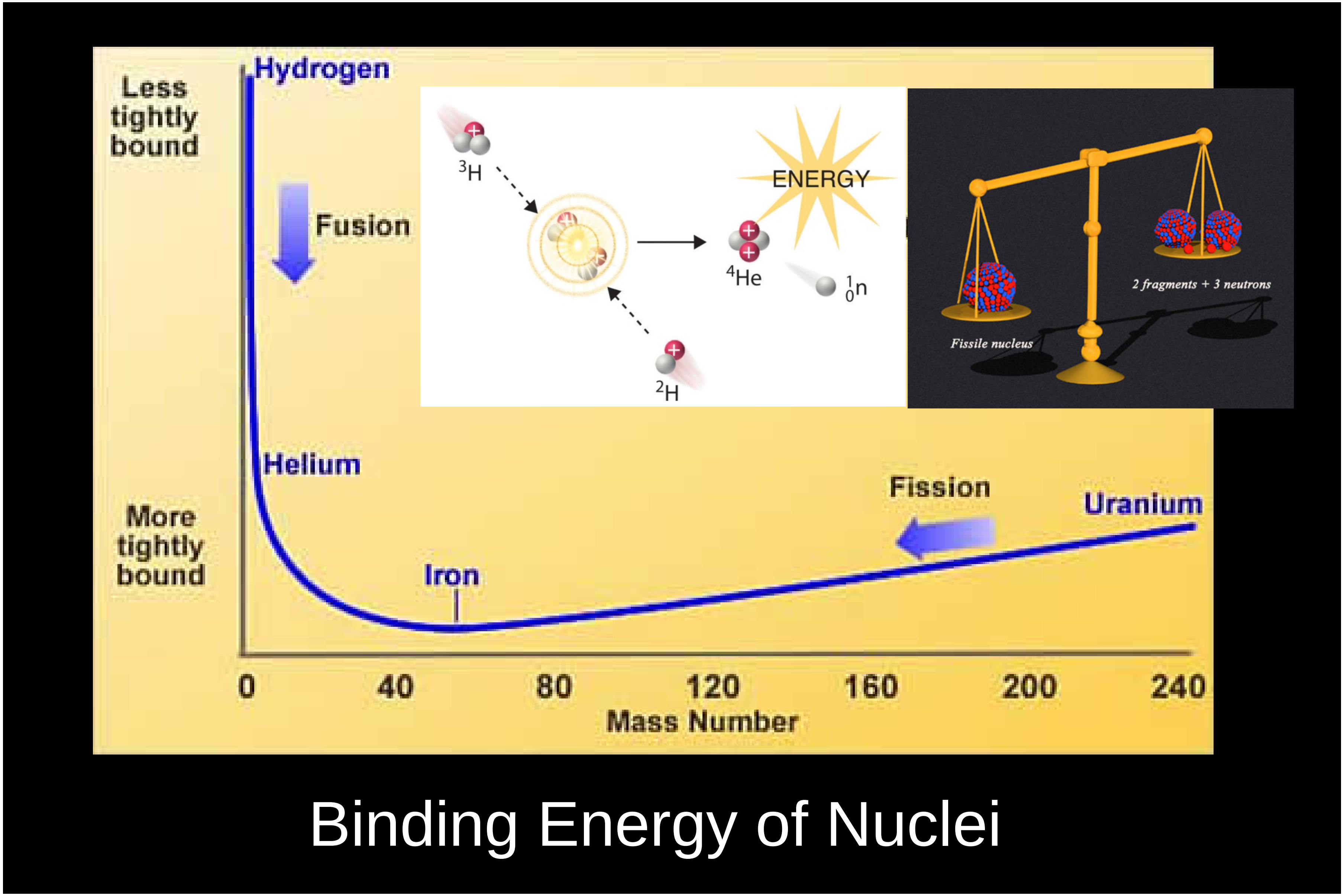
If the **number of protons** in a nucleus becomes **too large**, the electro-static repulsion between protons cannot be compensated, and the nucleus “fissions”:

“spontaneously” “induced” (e.g., by a neutron)



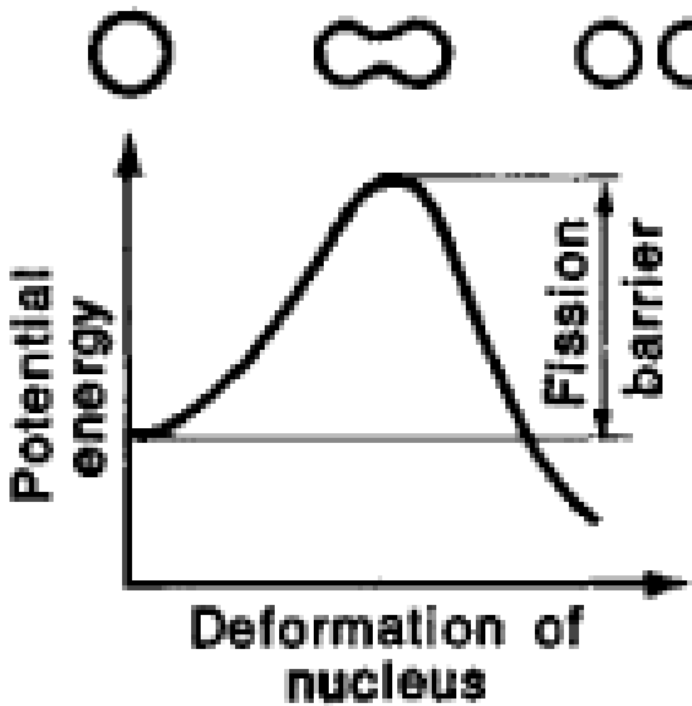


Part 1 – **Nuclei** – Energy



Part 1 – Nuclei – Energy/Stability

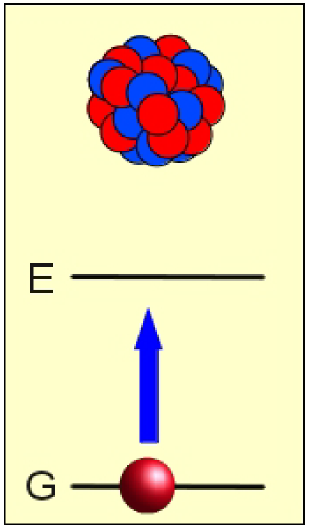
If it is energetically favorable to fission or to fuse, why does this not happen all the time?



→ A “**barrier**” is prohibiting or preventing this; but: the barrier can also be “tunneled” (a quantum mechanical effect).

Part 1 – Nuclei – Excitation

Ground-state nuclei can absorb energy and become "**excited**"



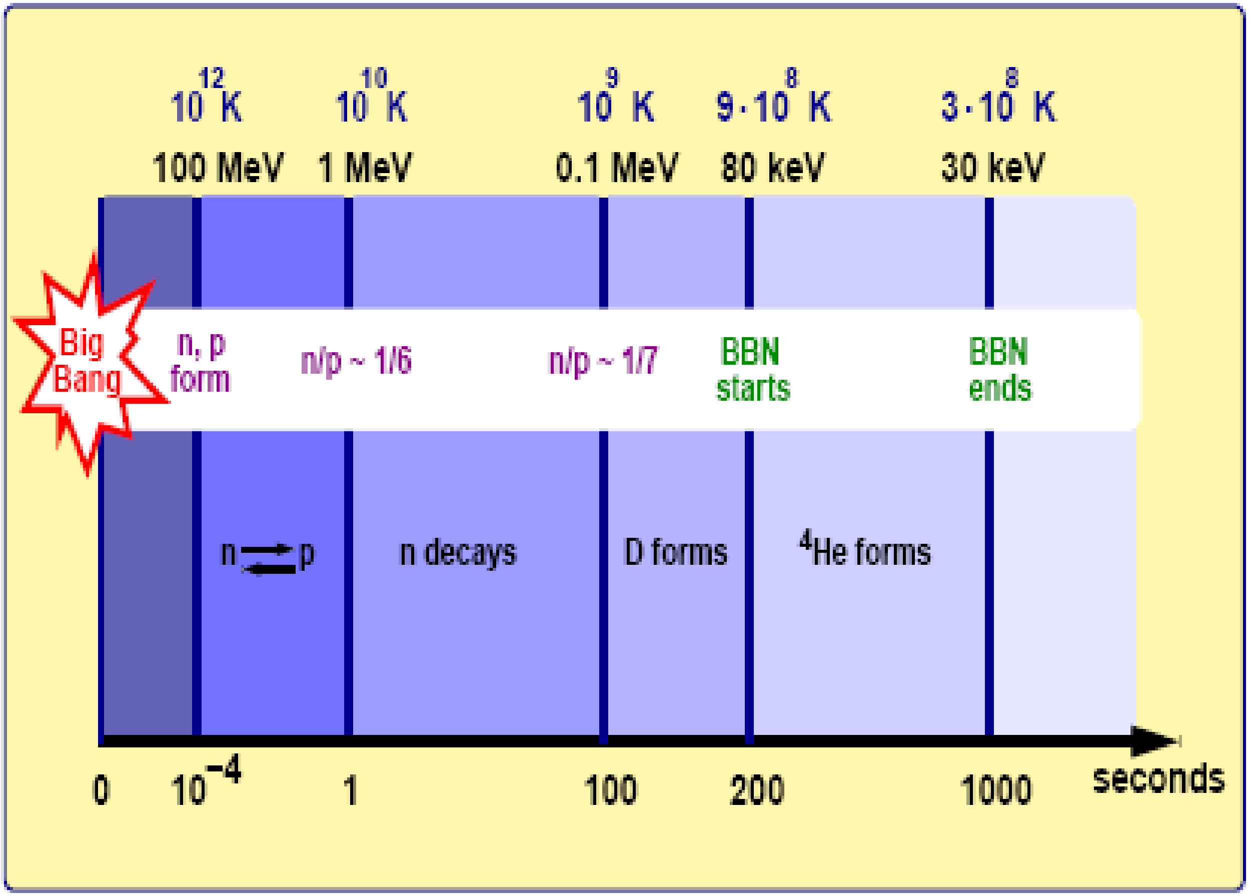
There are **many possibilities**:

(i) single nucleon (neutron, proton) excitations
(ii) collective excitations (rotation, surface vibration, oscillation)

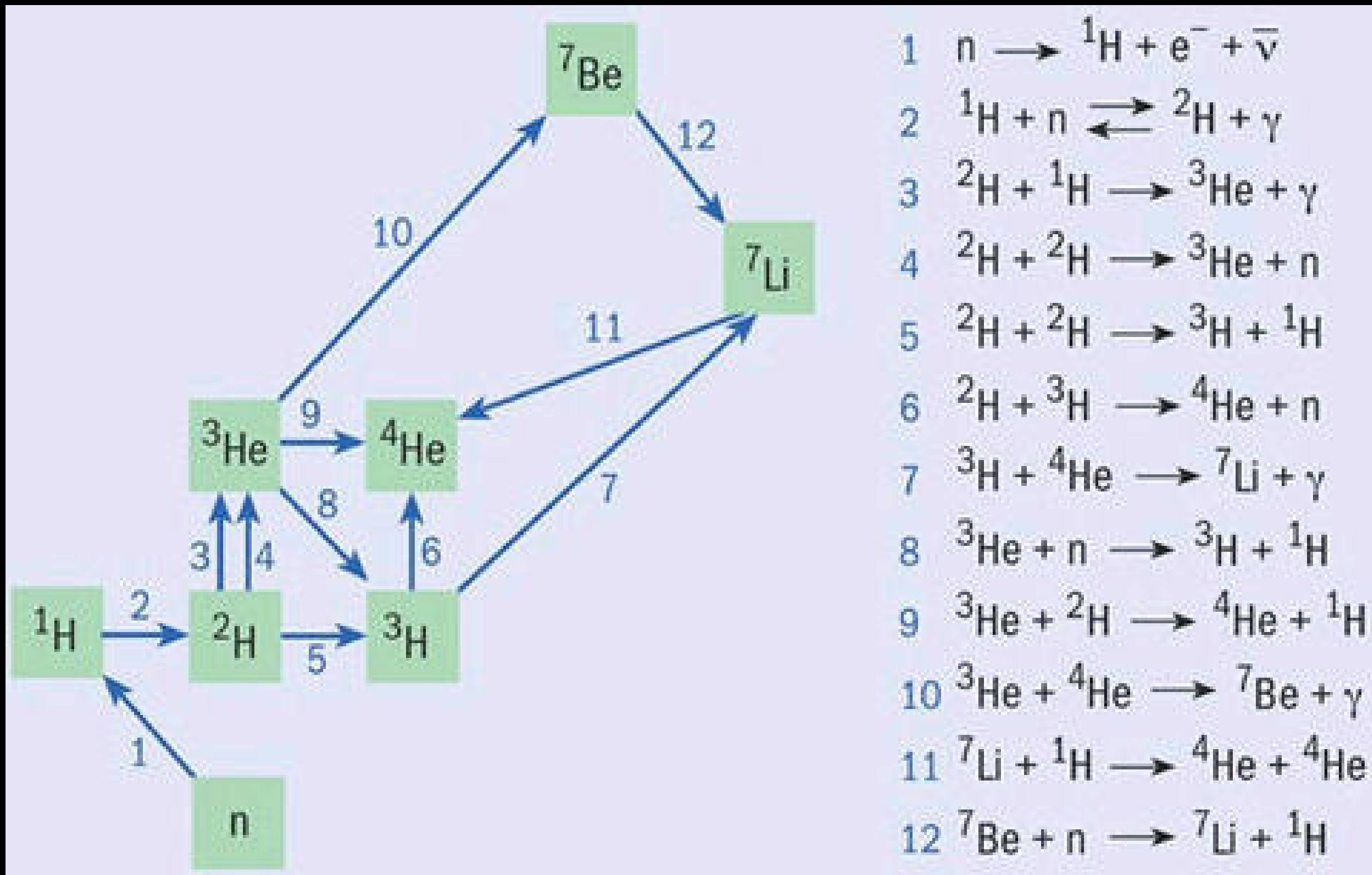
De-excitation ("decay") frequently happens by **light** (→ photons, γ-rays) and also by **particle emission**

Part 1 – Nuclei – Synthesis

Big Bang nucleosynthesis (BBN) began a few minutes after the Big Bang, when the universe had cooled sufficiently to allow **deuterium** nuclei to survive disruption by high-energy photons:



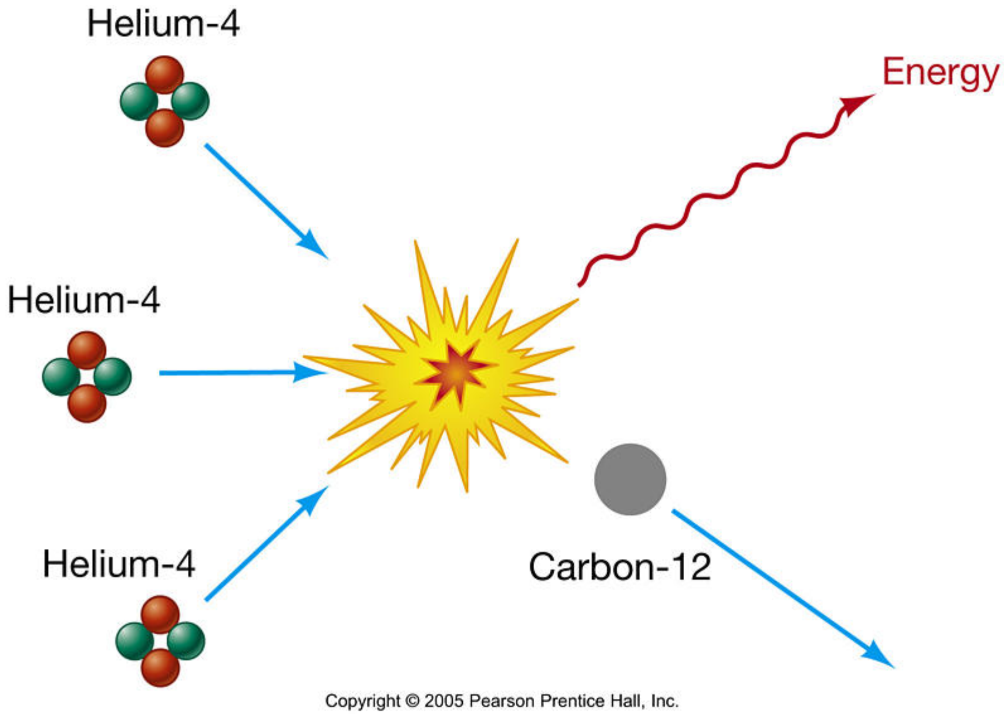
Part 1 – Nuclei – Synthesis



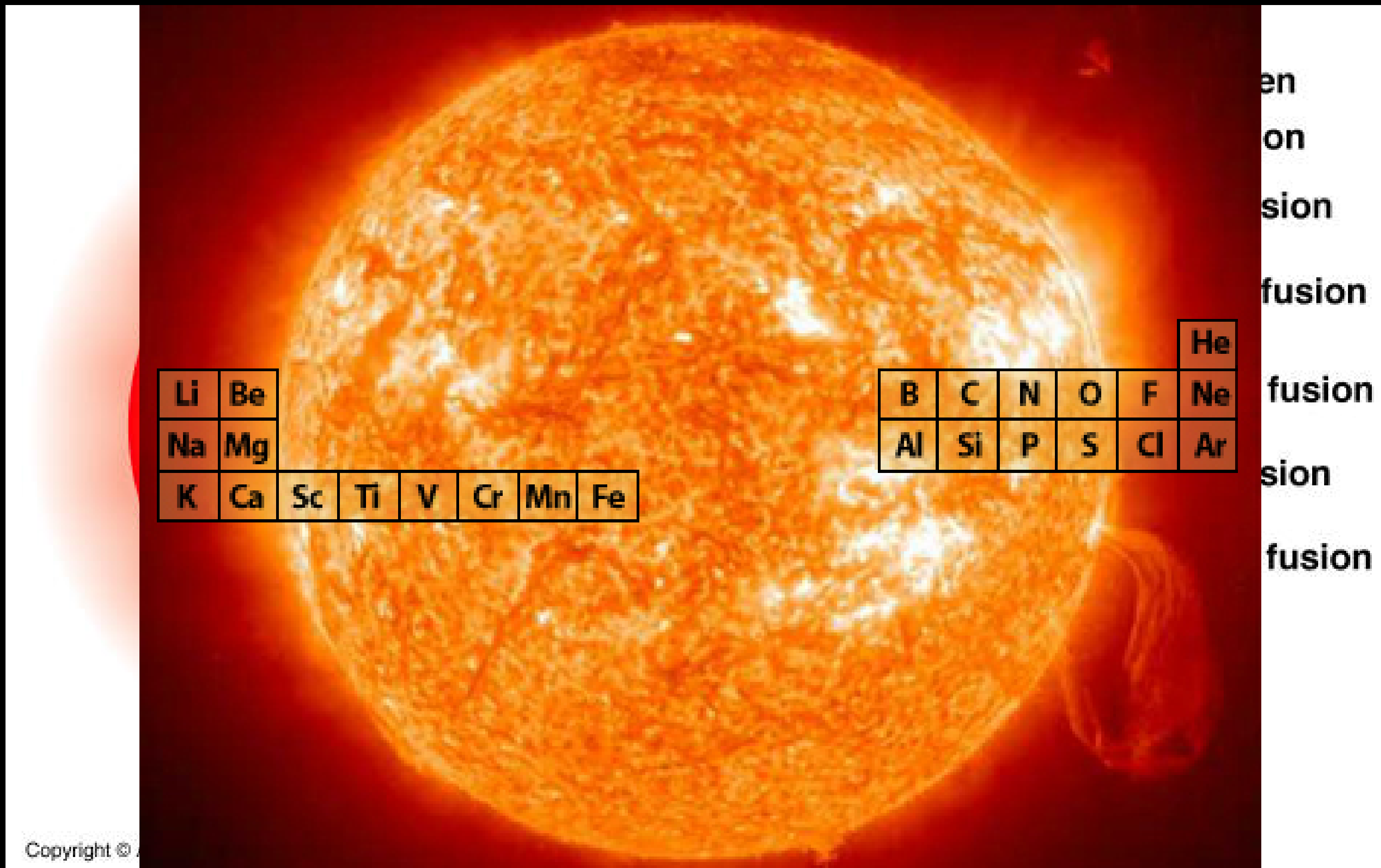
Big Bang Nucleosynthesis (BBN)

Part 1 – Nuclei – Synthesis

In BBN, no elements heavier than beryllium (or possibly boron) could be formed. **Stellar nucleosynthesis** in stars is responsible for the galactic abundances of elements from carbon to iron by thermonuclear fusion. Of particular importance is carbon, because its formation from He is a bottleneck in the entire process. Carbon is produced by the **triple-alpha process** in all stars:

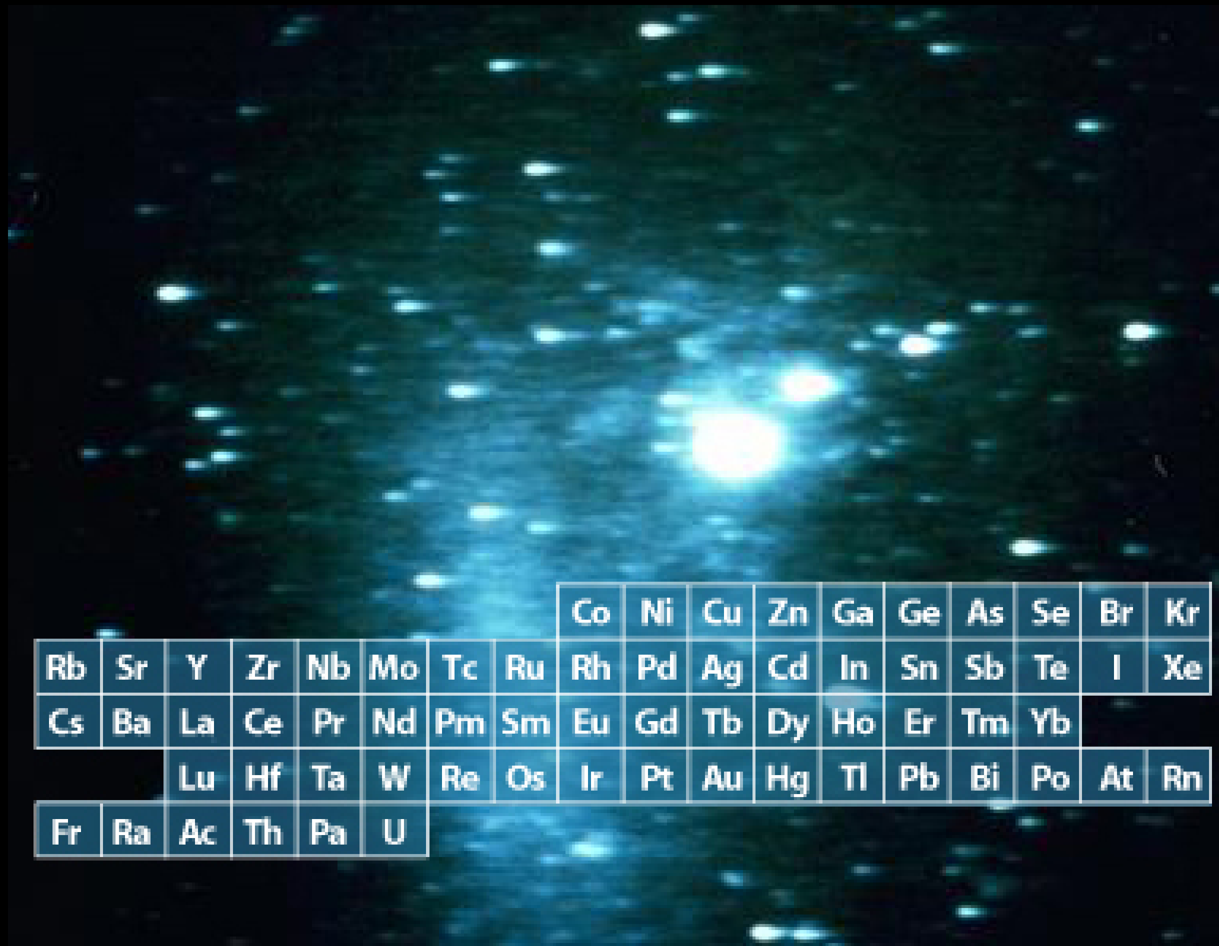


Part 1 – Nuclei – Synthesis



Stellar Nucleosynthesis

Part 1 – **Nuclei** – Synthesis



Explosive Nucleosynthesis

Part 1 – Nuclei – Summary

Atomic Nuclei: the nucleus is the very dense region consisting of protons and neutrons at the center of an atom.

Nuclei are bound together by the **nuclear force**, which is attractive at the distance of typical nucleon separation, and this overwhelms the repulsion between protons due to the electromagnetic force, thus allowing nuclei to exist.

Nuclei have been **produced** in the Big Bang, and are continuously being produced in stars (e.g. sun) and supernovae.

Some nuclei are stable ((very) long lifetime); others are un-stable ("**radioactive**") and decay via α, β and γ- decay or by nuclear fission. The decay can be spontaneous or induced be "excitation"; i.e. by bringing energy into the system.

Nuclei are comprised of **nucleons** (protons, neutrons):
→ **What is the internal structure of the nucleon?** → Next lecture!

გმადლობთ