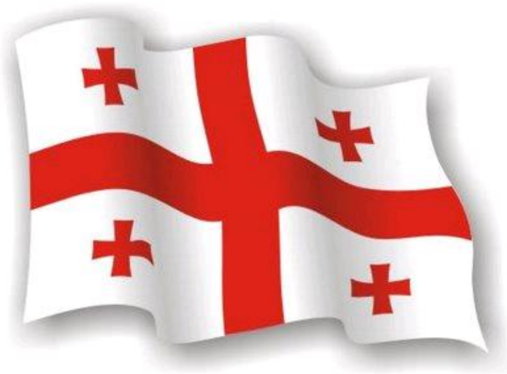
Mitglied der Helmholtz-Gemeinschaft

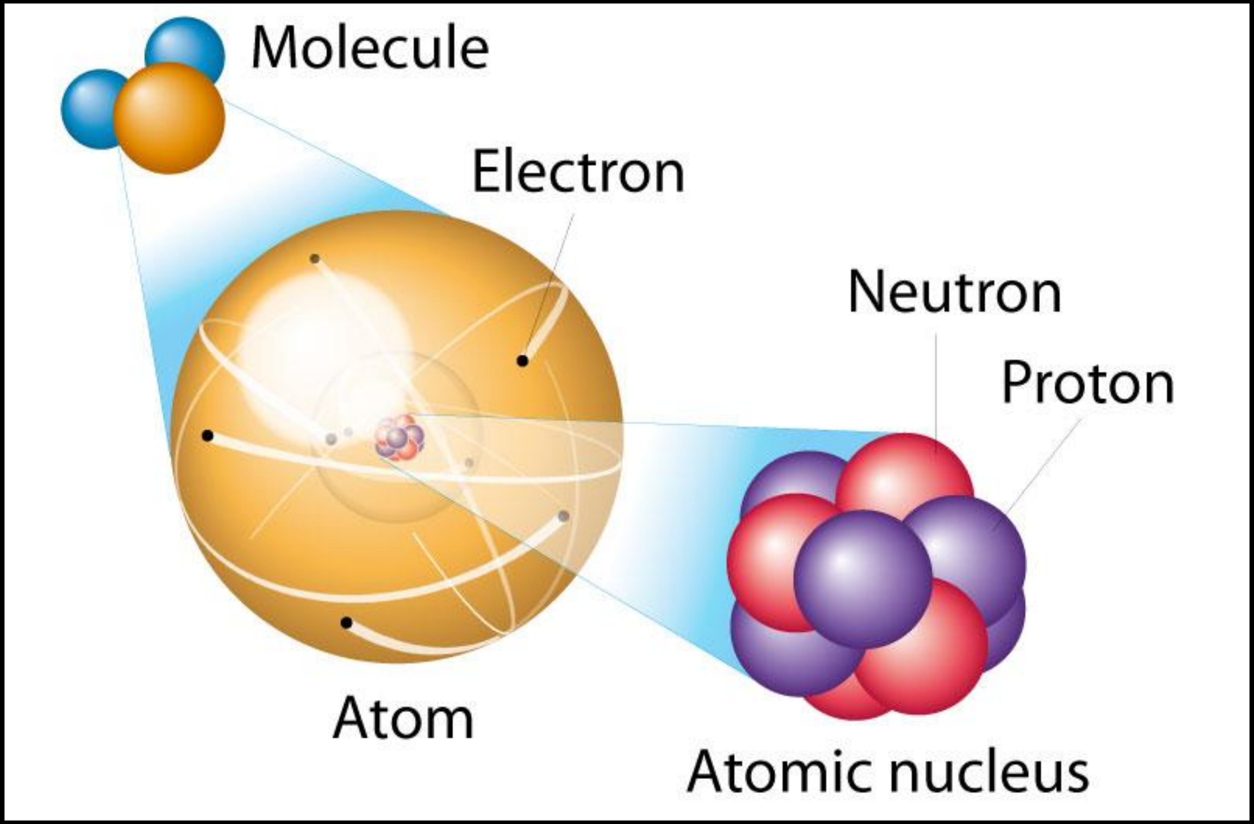


Georgian-German Science Bridge

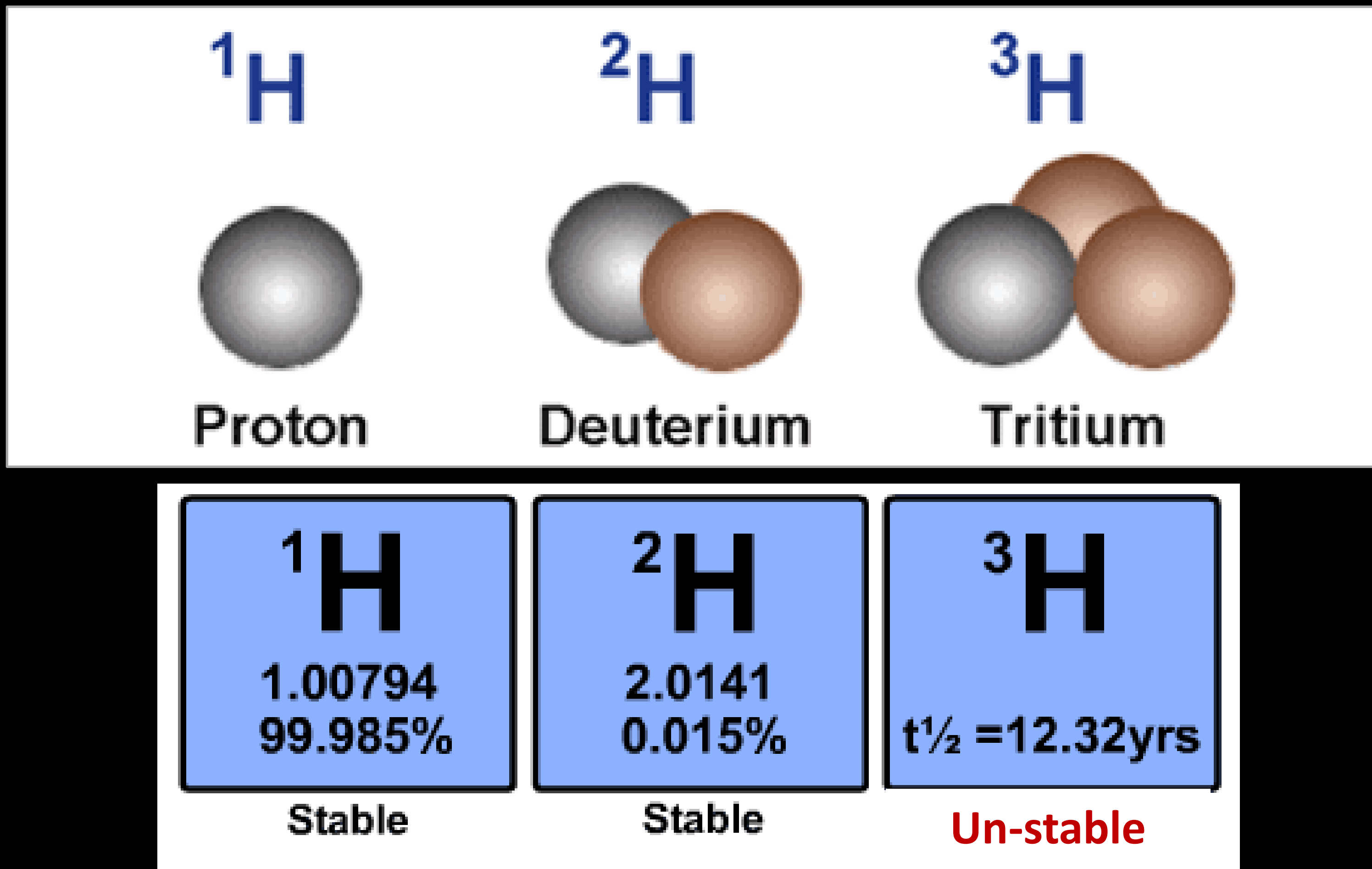
Structure of Matter (SoM): Lecture 2: Nuclei

October 15, 2013 | Hans Ströher (Forschungszentrum Jülich)

Previous Lecture: Atoms



(Atomic) Nuclei



Isotopes (different numbers of neutrons)

Lecture 2 – **Nuclei** – Introduction

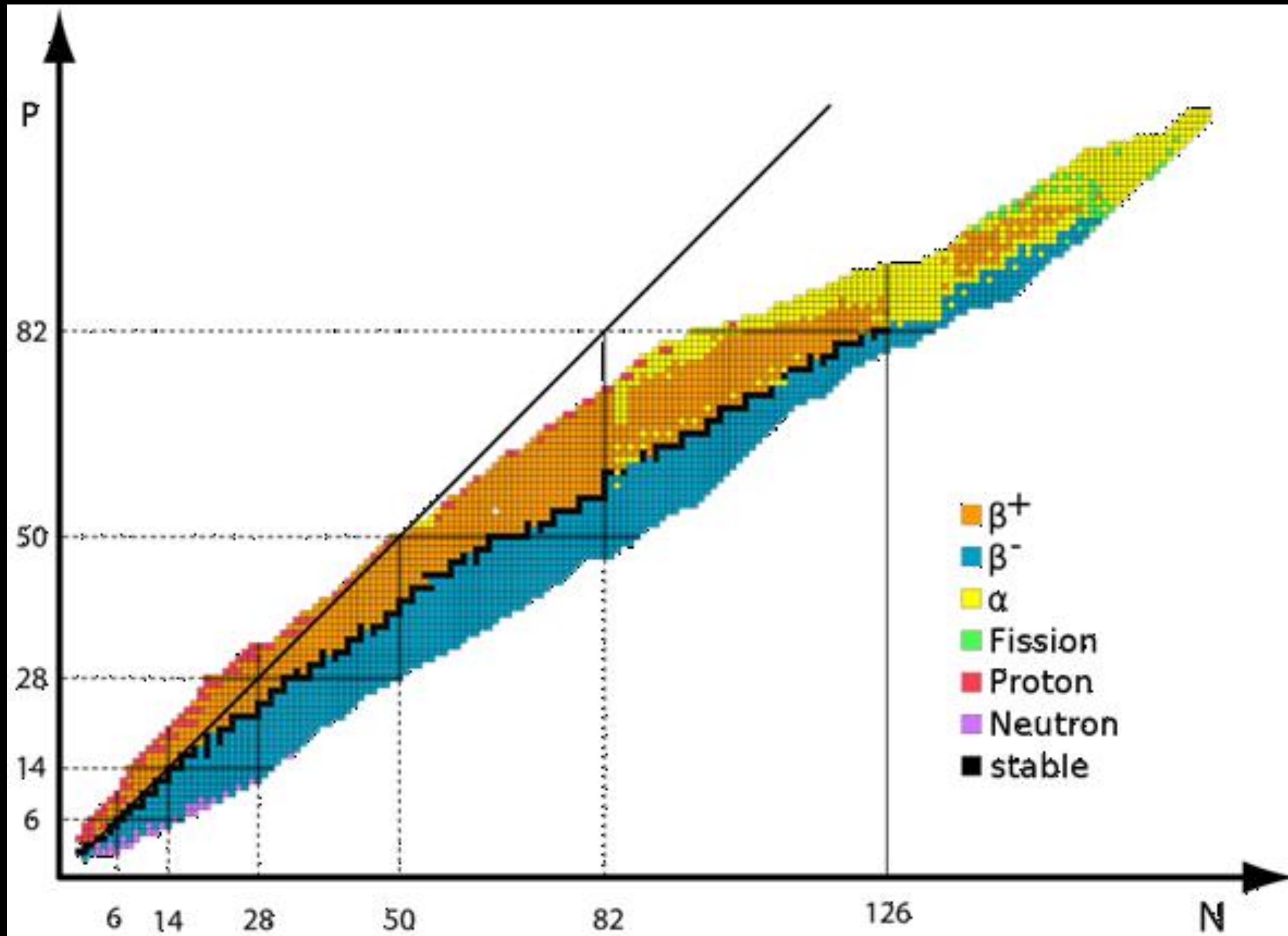
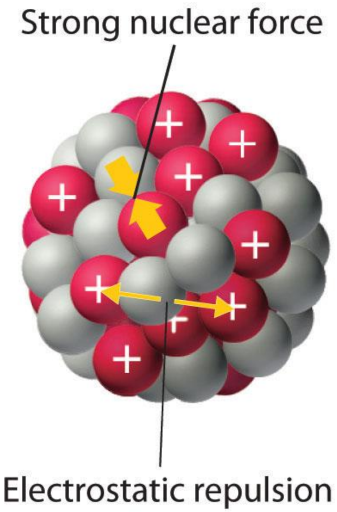


Table of Isotopes (Nuclides): Limits of Stability

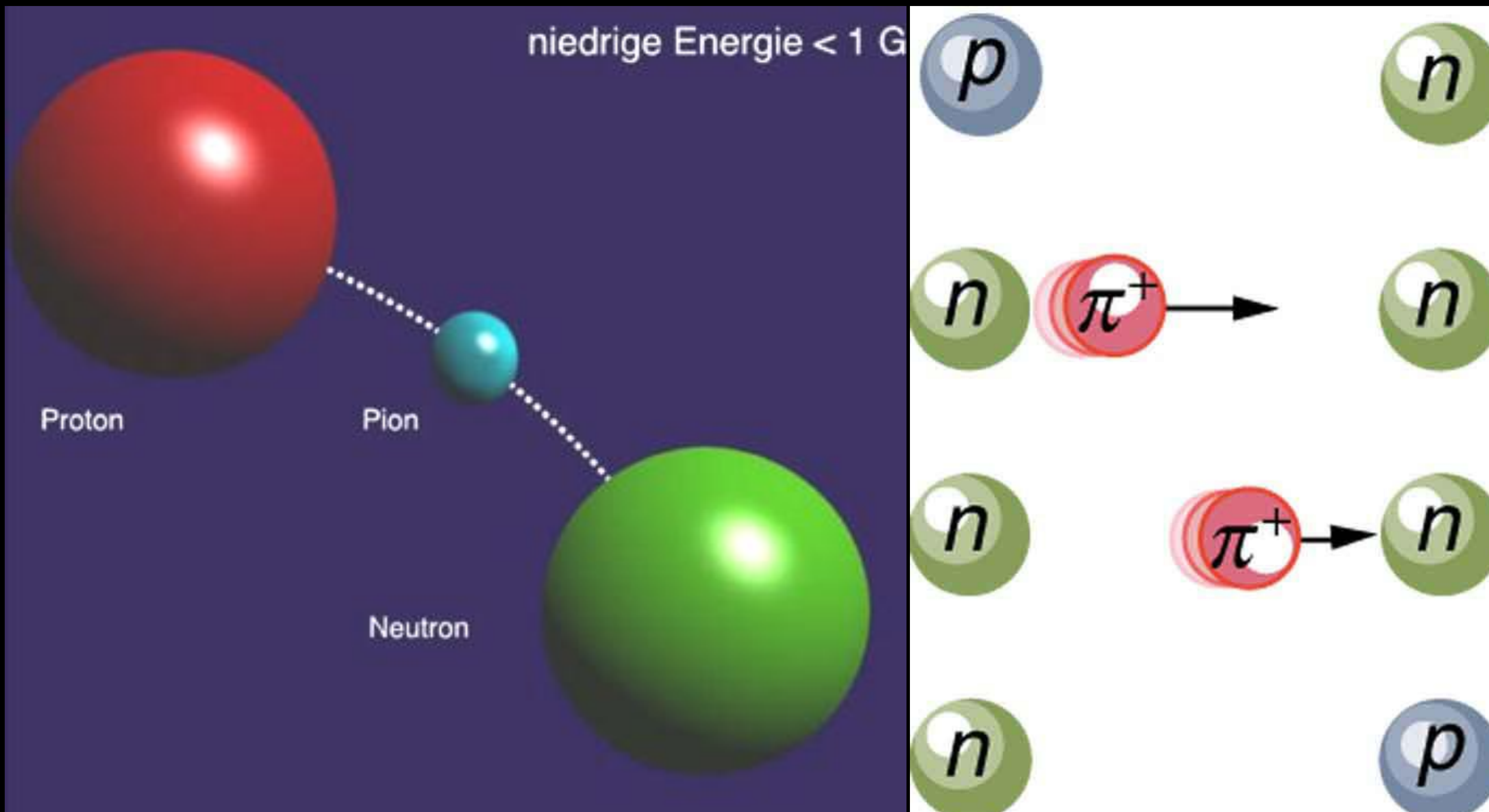
Lecture 2 – **Nuclei** – Stability

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 ?

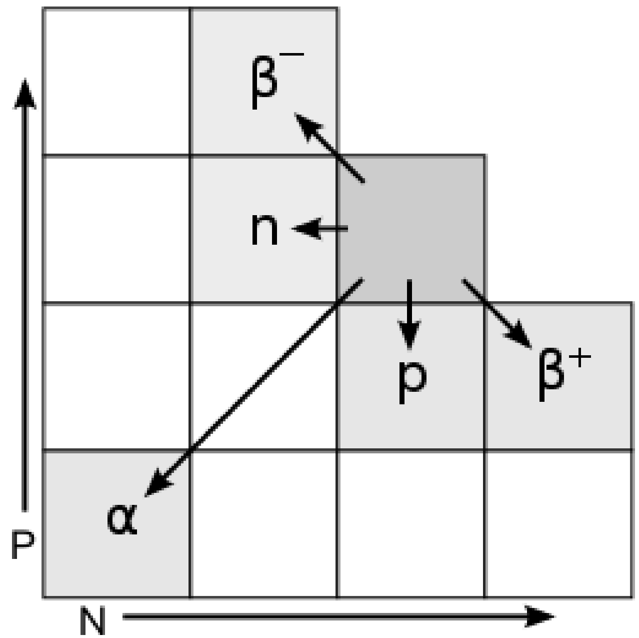


Nucleon-Nucleon Interaction

Lecture 2 – **Nuclei** – Stability

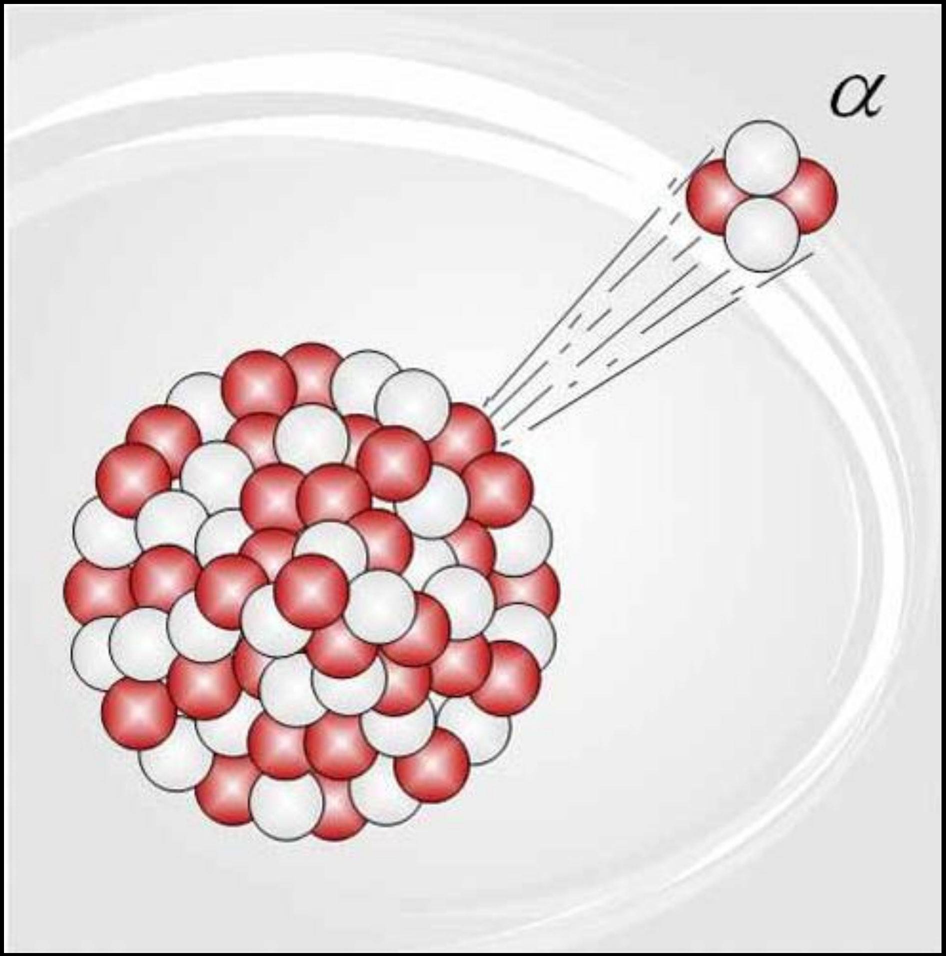
If the **number of protons and neutrons** in a nucleus is “not right”, it will be “unstable” and “decay” into a (more) stable configuration; this nuclear property is called “radioactivity”

The following possibilities exist for this transmutation:

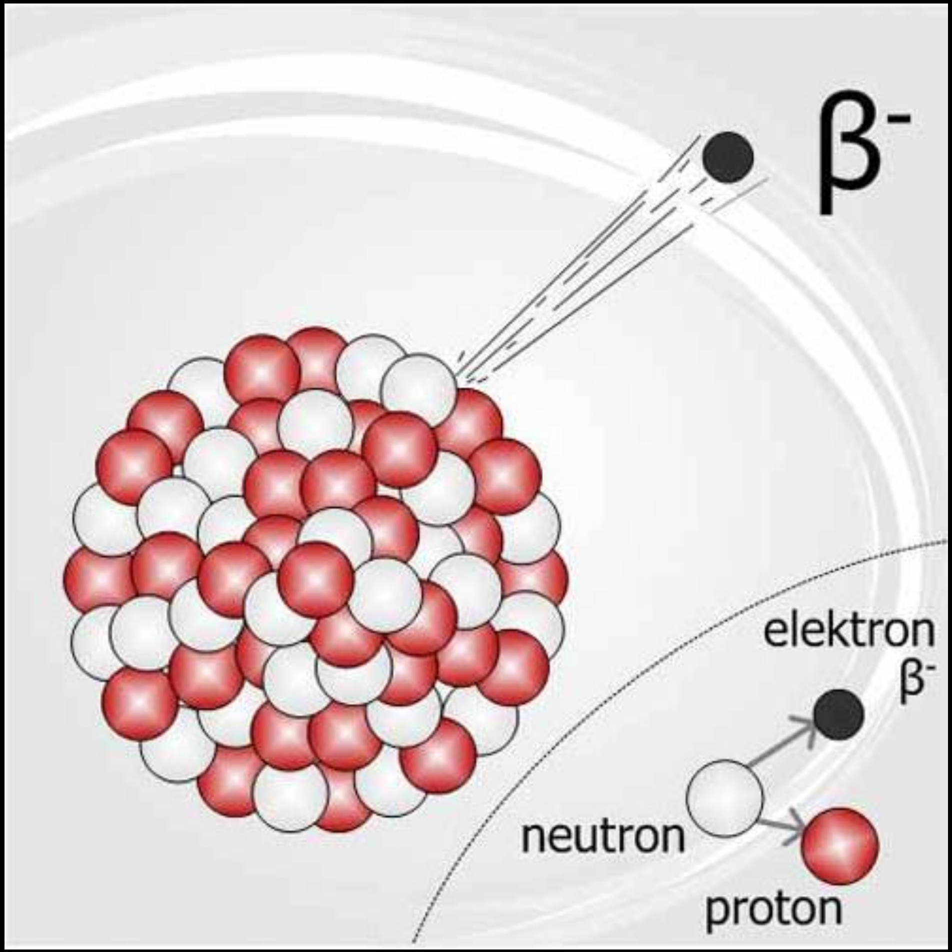


α-decay:	# p – 2, # n – 2
β^--decay:	# p + 1, # n – 1
β^+-decay:	# p – 1, # n +1
p-emission:	# p – 1
n-emission:	# n – 1

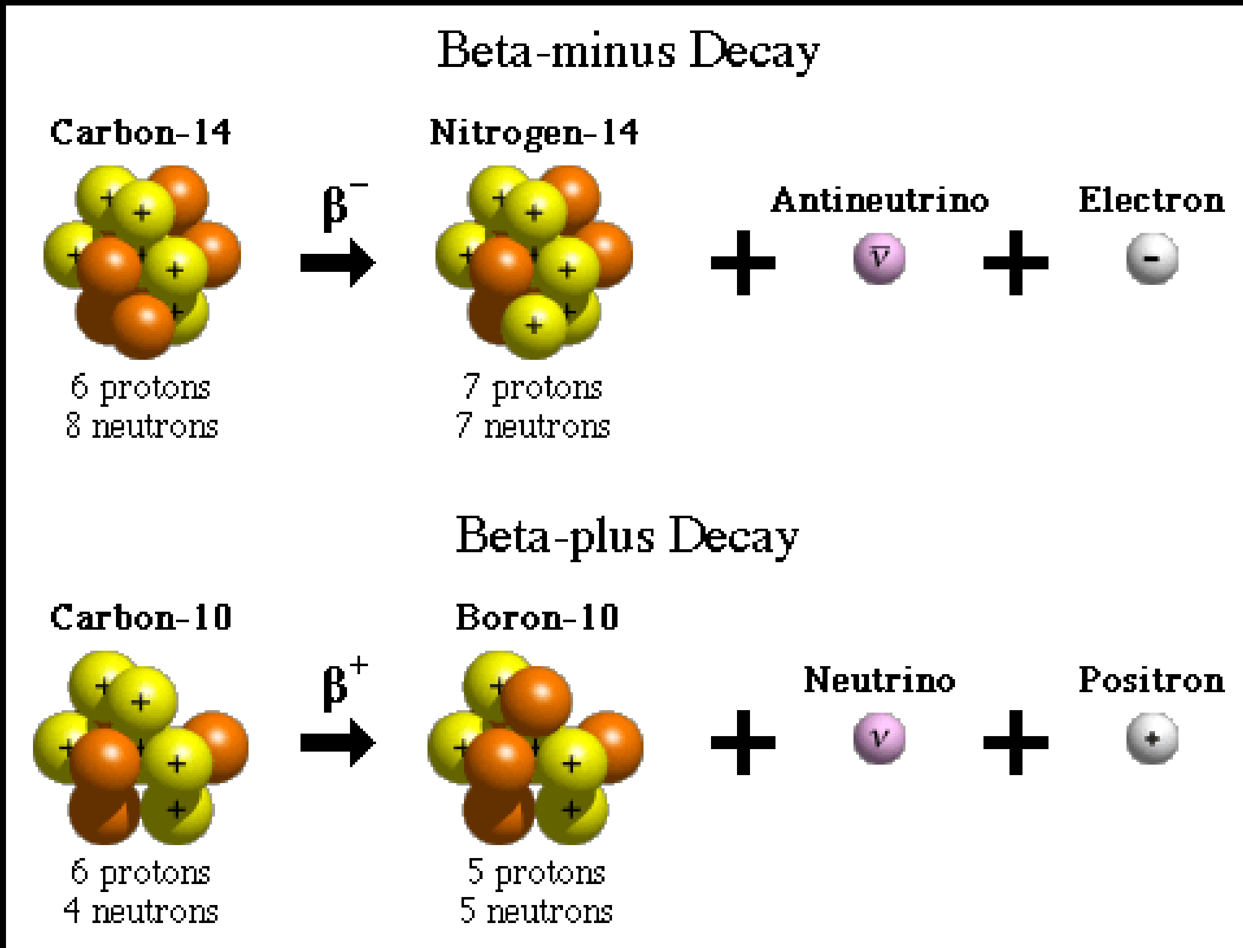
Plus: an excited nucleus (not in ground state) can emit **γ-rays**



α - Decay

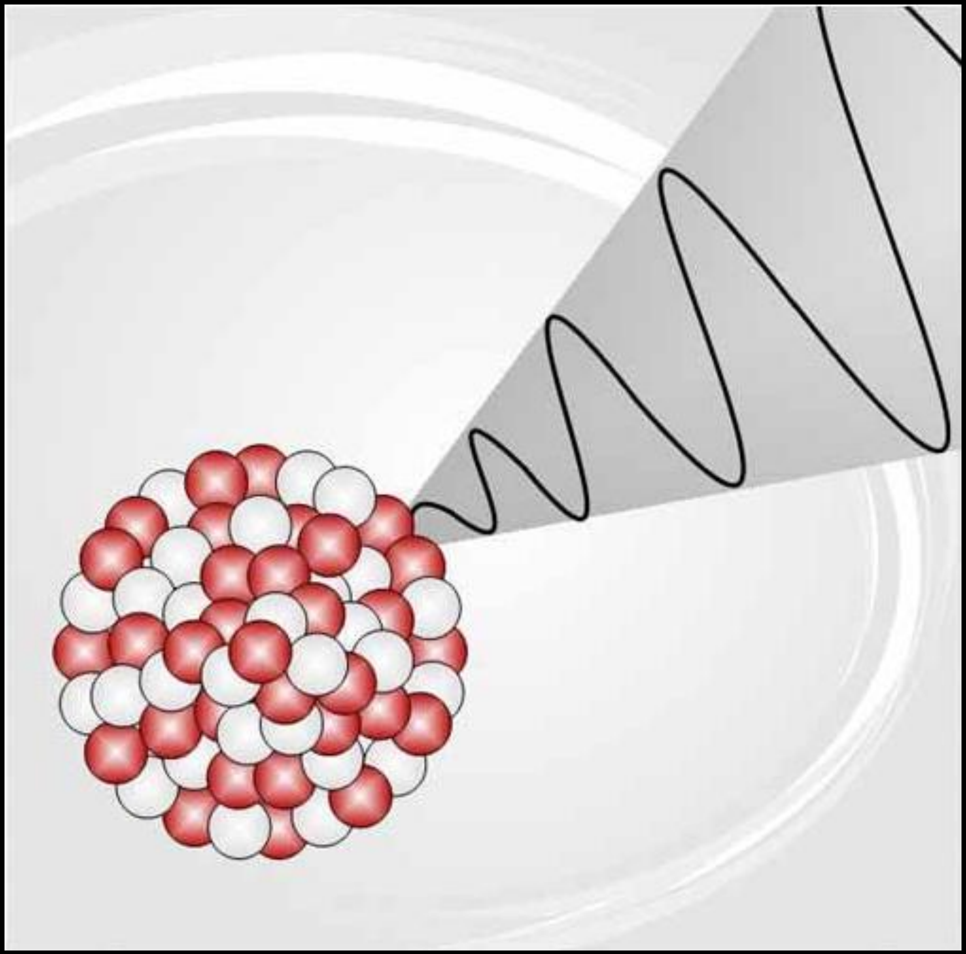


β- - Decay


Beta-minus Decay
Carbon-14
β−
Nitrogen-14
Antineutrino
Electron
6 protons
8 neutrons
7 protons
7 neutrons
Beta-plus Decay
Carbon-10
β+
Boron-10
Neutrino
Positron
6 protons
4 neutrons
5 protons
5 neutrons

β - Decay

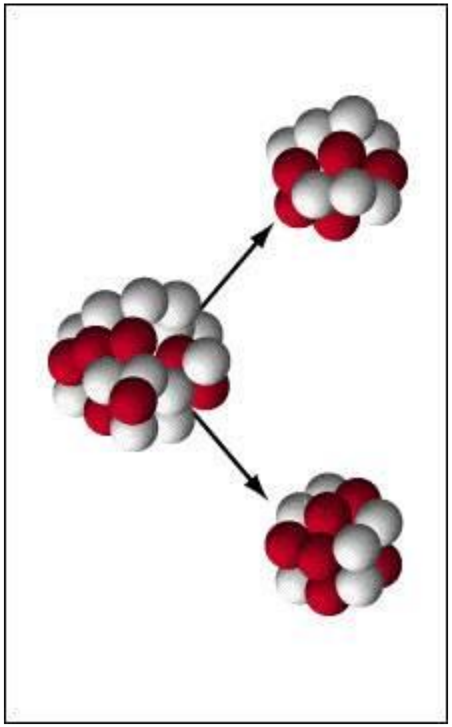
Lecture 2 – Nuclei – Stability



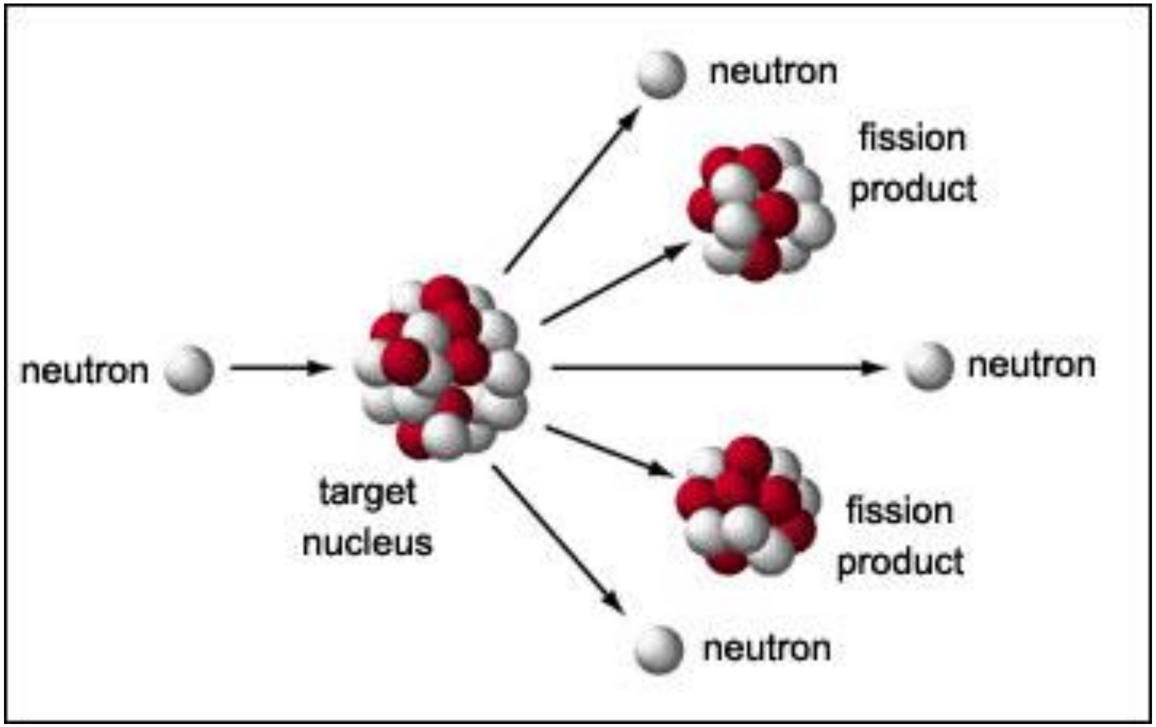
γ - Decay

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

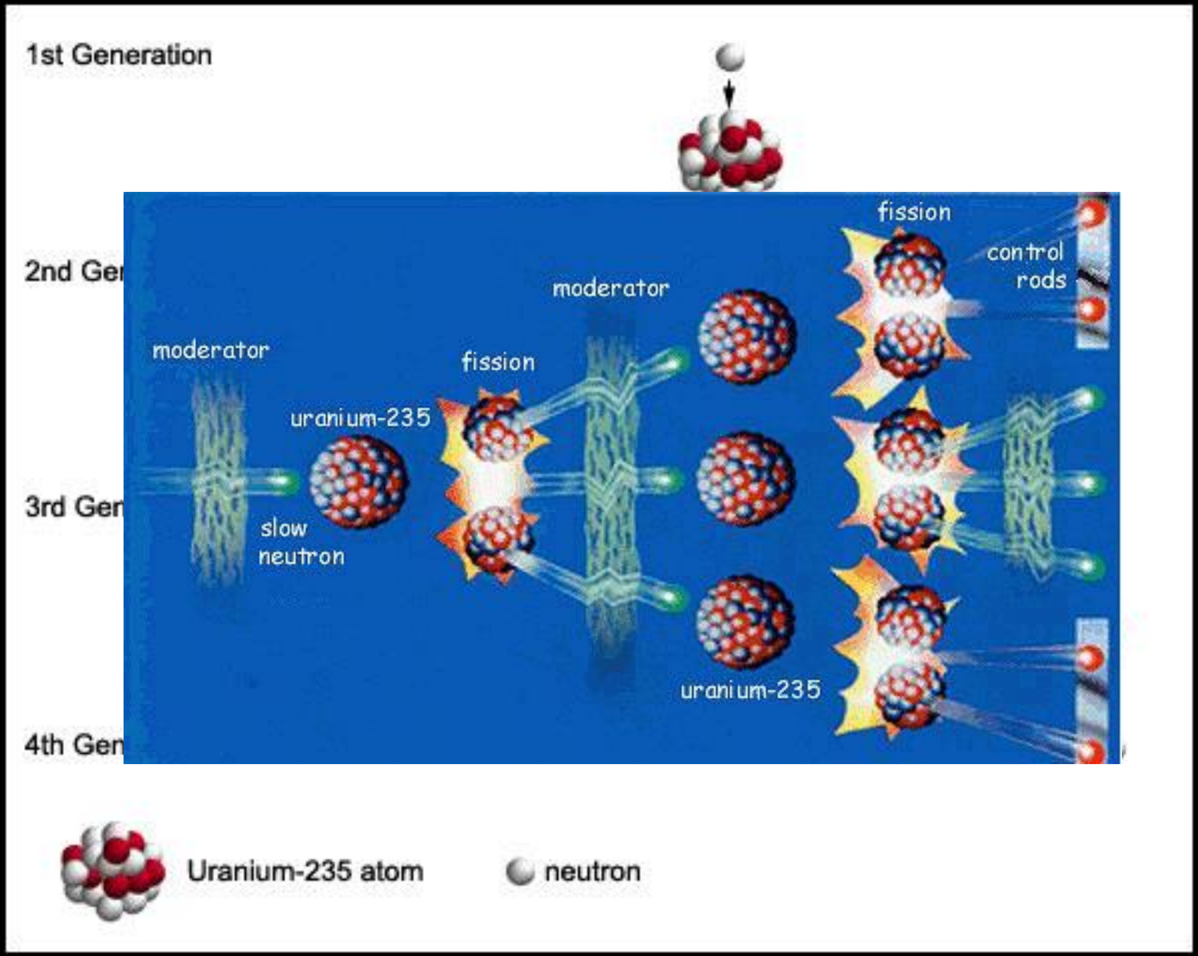
“spontaneously”



“induced” (e.g., by a neutron)



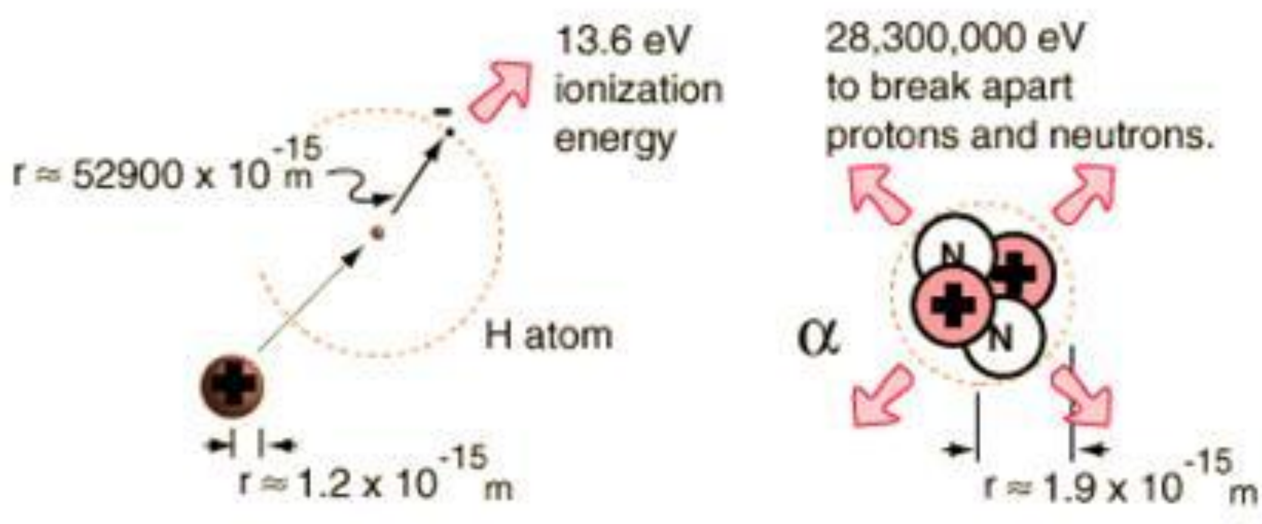
Lecture 2 – **Nuclei** – Stability



Chain Reaction (→ Reactor; Bomb)

In order to understand why one can **gain energy** in **nuclear fisson**, one has to look at the (binding) energy of the nucleons (protons and neutrons) in a nucleus:

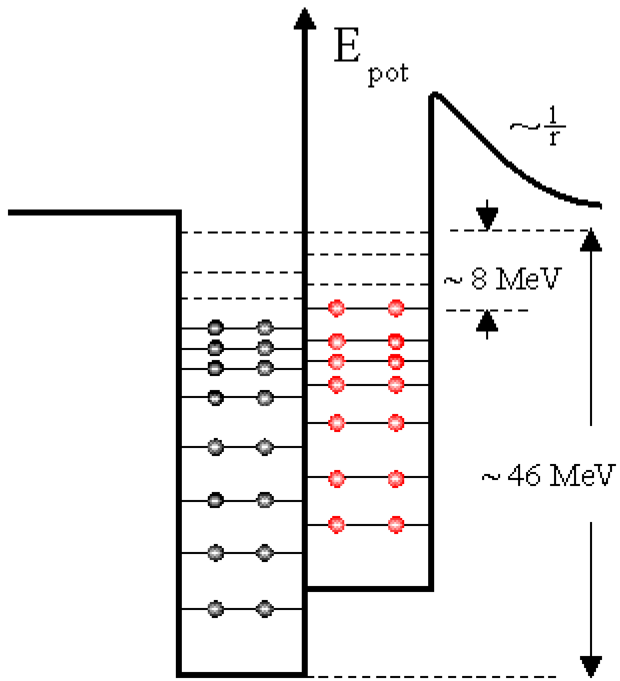
→ Start with a comparison of **nuclear binding** with atomic electron binding:



Binding energy is much larger!

Lecture 2 – Nuclei – Energy

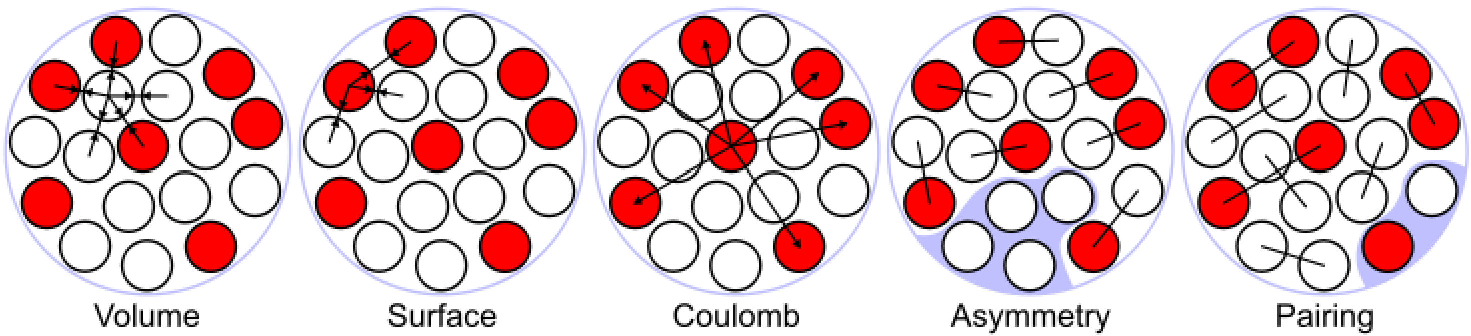
In nuclei the nucleons (protons, neutrons) also occupy certain energy states; since they are **fermions**, only two protons and two neutrons can be in one level:



The **binding energy** of the least bound nucleons is about 8 MeV.

Lecture 2 – Nuclei – Energy

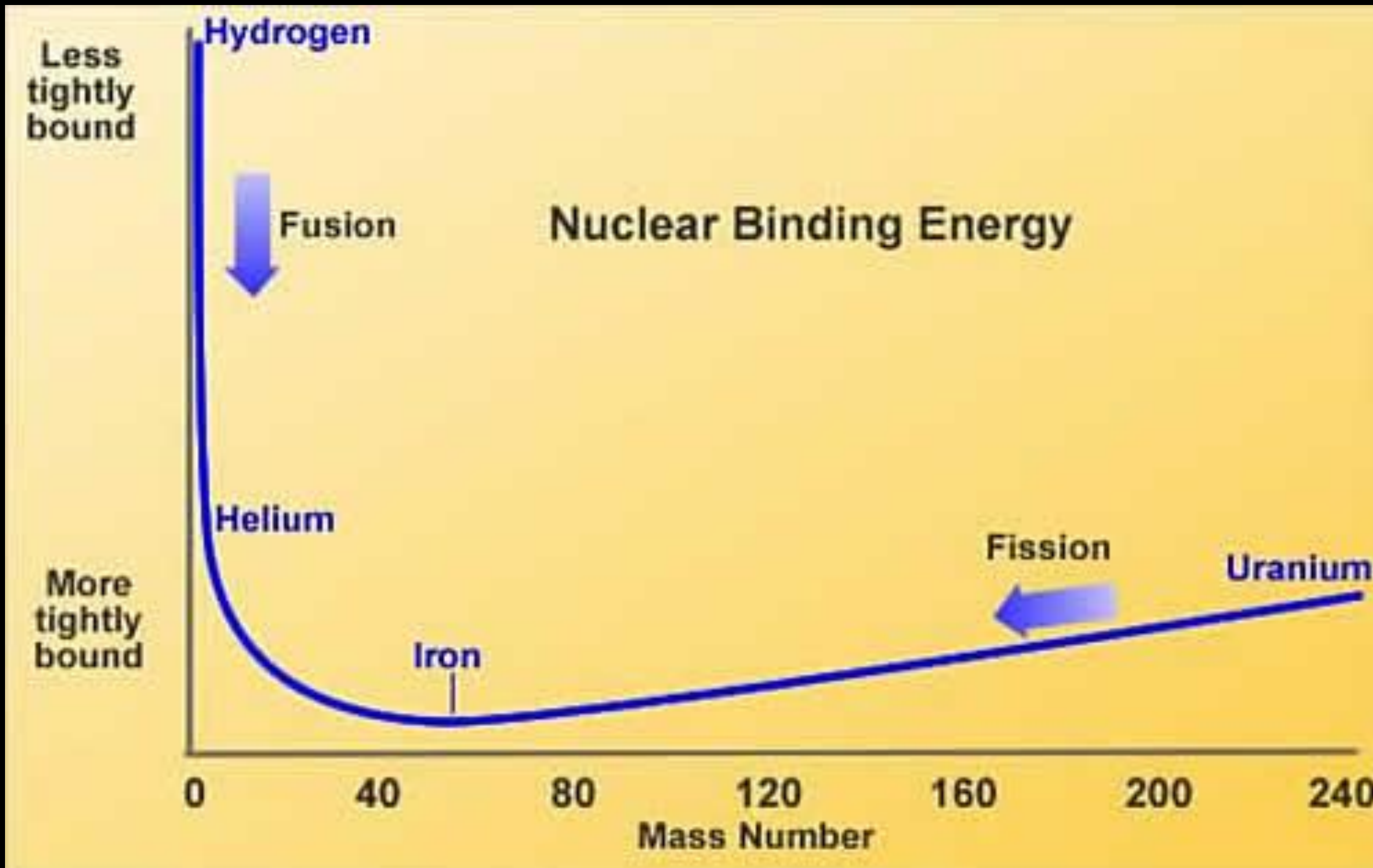
In order to obtain an estimate how the average binding energy of a nucleus comes about and how it changes with mass number A, the nucleus is considered a **liquid drop**; the energy then comprises:



$$E_{\text{Bindung}} = a_{\text{V}} \cdot A - a_{\text{O}} \cdot A^{\frac{2}{3}} - a_{\text{C}} \cdot Z \cdot (Z-1) \cdot A^{-\frac{1}{3}} - a_{\text{S}} \cdot \frac{(N-Z)^2}{4A} + \begin{cases} +a_{\text{P}} \cdot A^{-\frac{1}{2}} & \text{für gg-Kerne} \\ 0 & \text{für ug- und gu-Kerne} \\ -a_{\text{P}} \cdot A^{-\frac{1}{2}} & \text{für uu-Kerne} \end{cases}$$

The parameters are obtained by fitting the above expression to the experimental data.

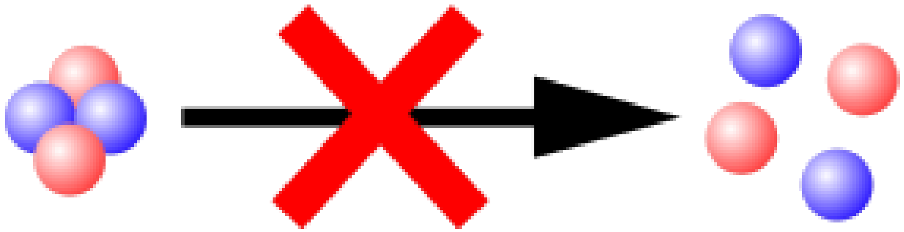
Lecture 2 – Nuclei – Energy



Binding Energy of Nuclei

Lecture 2 – Nuclei – Energy

Once a nucleus has been formed, it takes energy to take it apart:



Energy of the composite object + energy expended to split it up
= sum of the energies of the separate parts after the split

Mass of bound system
= sum of masses of its parts - (binding energy)/c^2

If the binding energy of the products is larger than one gains energy by splitting ("fission") or combing ("fusion") nuclei.

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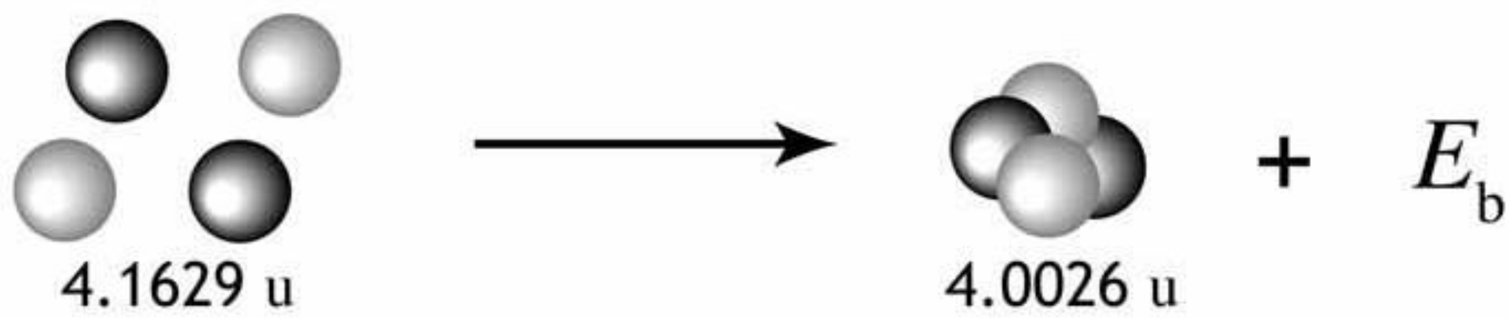
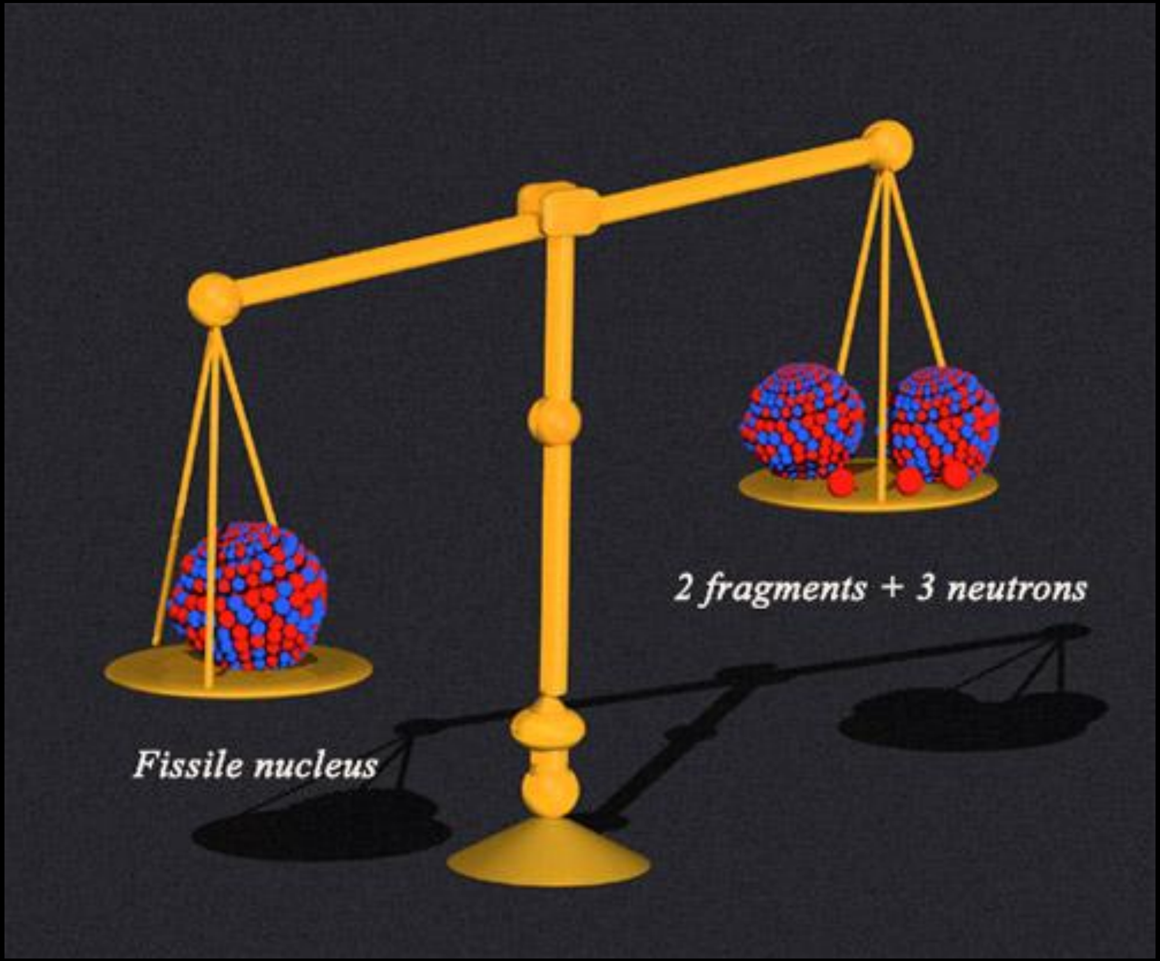
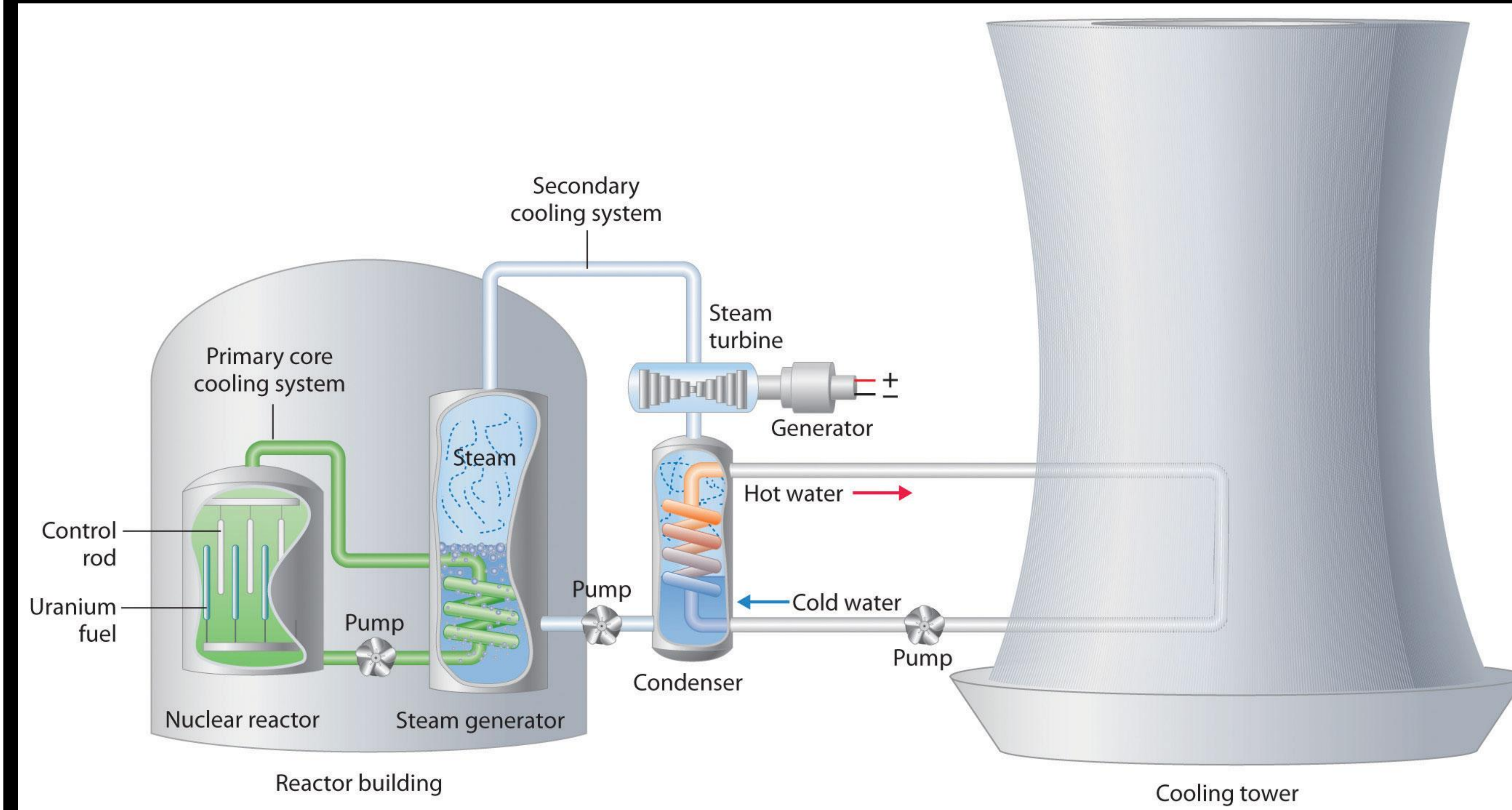


Example: 2p + 2n → ^{4}He

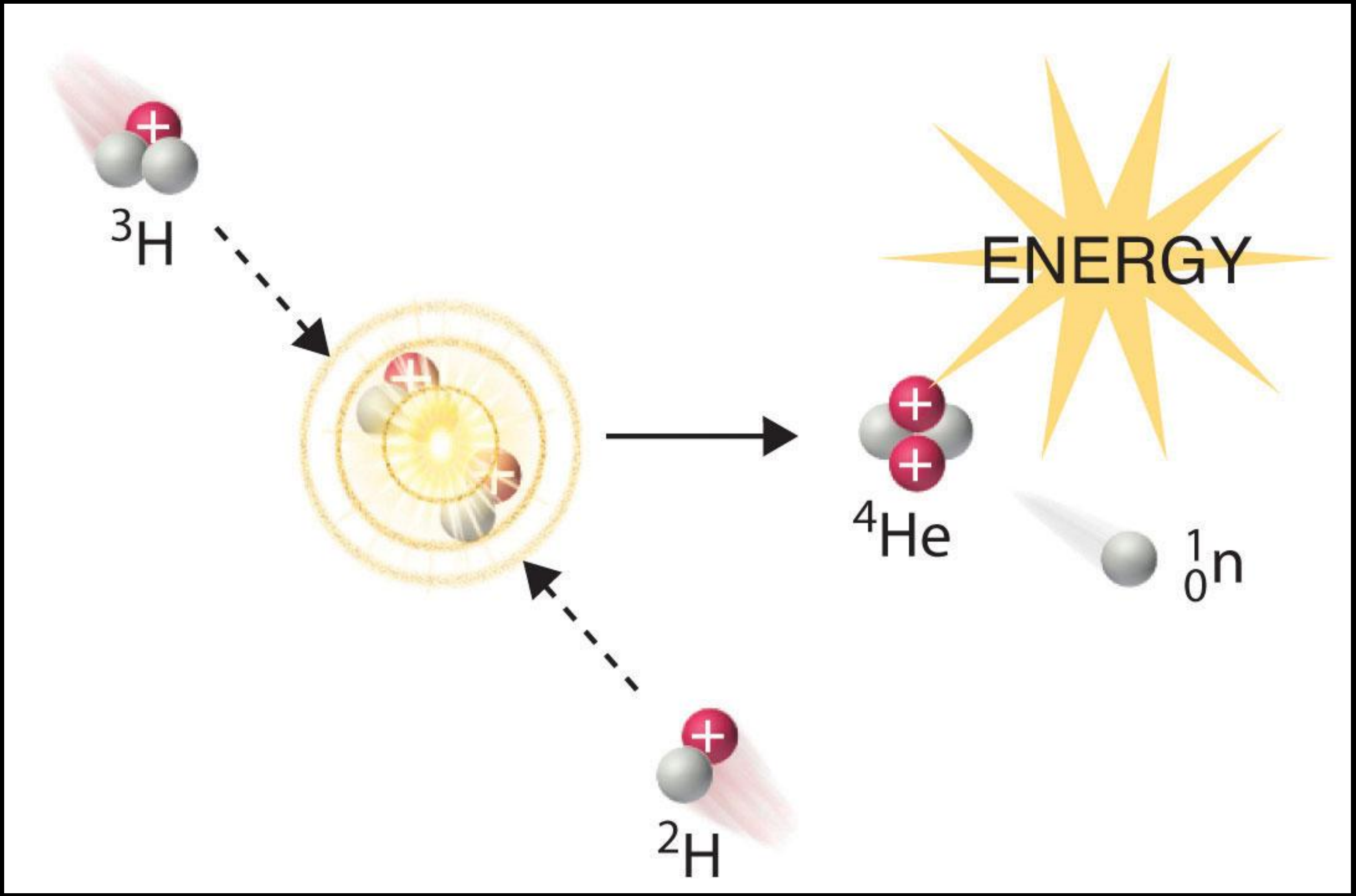


Energy Balance in Nuclear Fission

Lecture 2 – **Nuclei** – Energy

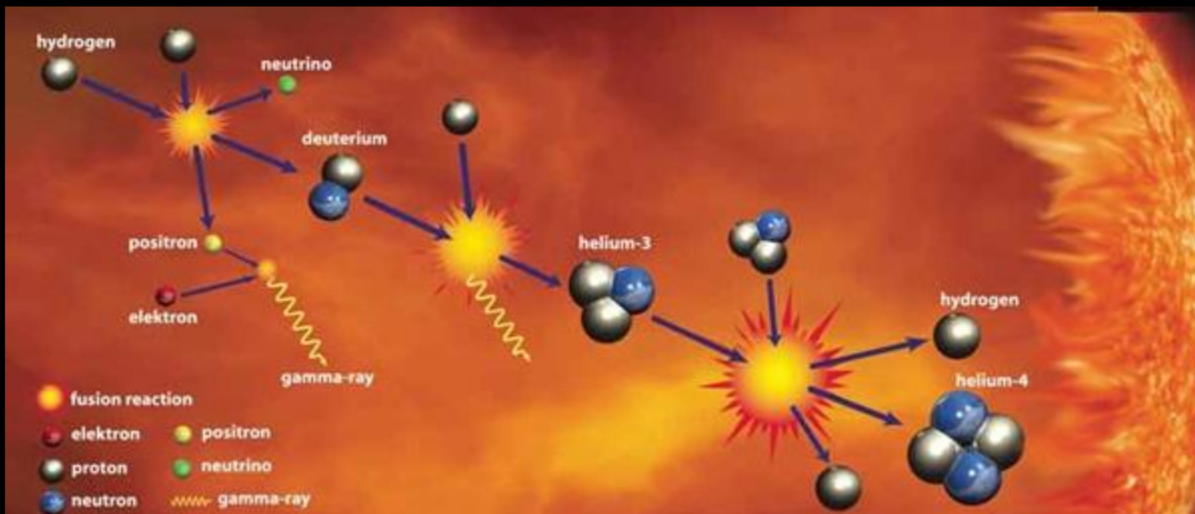


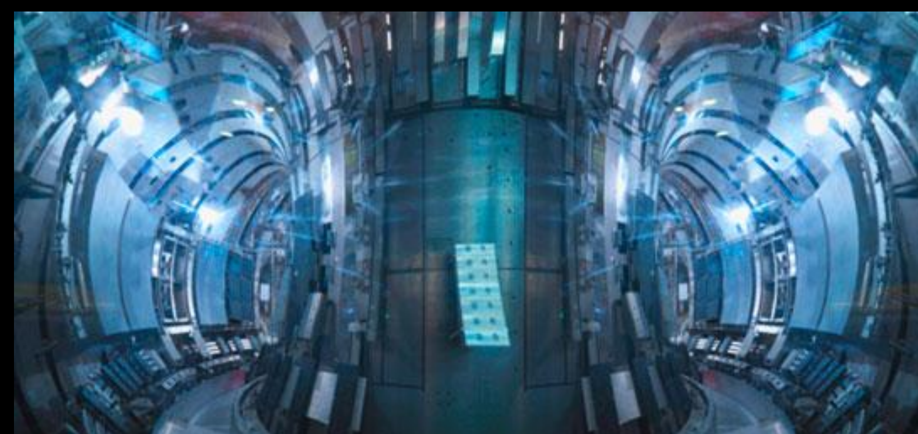
Nuclear Fission



Energy Balance in Nuclear Fusion

Lecture 2 – **Nuclei** – Energy





Nuclear Fusion

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ENERGY RELEASE

	CHEMICAL	FISSION	FUSION
REACTION	$C+O = CO_2$	$N+U^{235} =$ $Ba^{143}+Kr^{91}+2n$	$^{2}H + {}^{3}H = {}^{4}He+n$
FUEL	COAL	UO_2 (3% U-235 + 97% U-238)	Deuterium + Tritium
TEMPERATURE	700°K	1,000°K	100,000,000°K
ENERGY J/kg	3.3×10^{7}	2.1×10^{12}	3.4×10^{14}

Energy Production

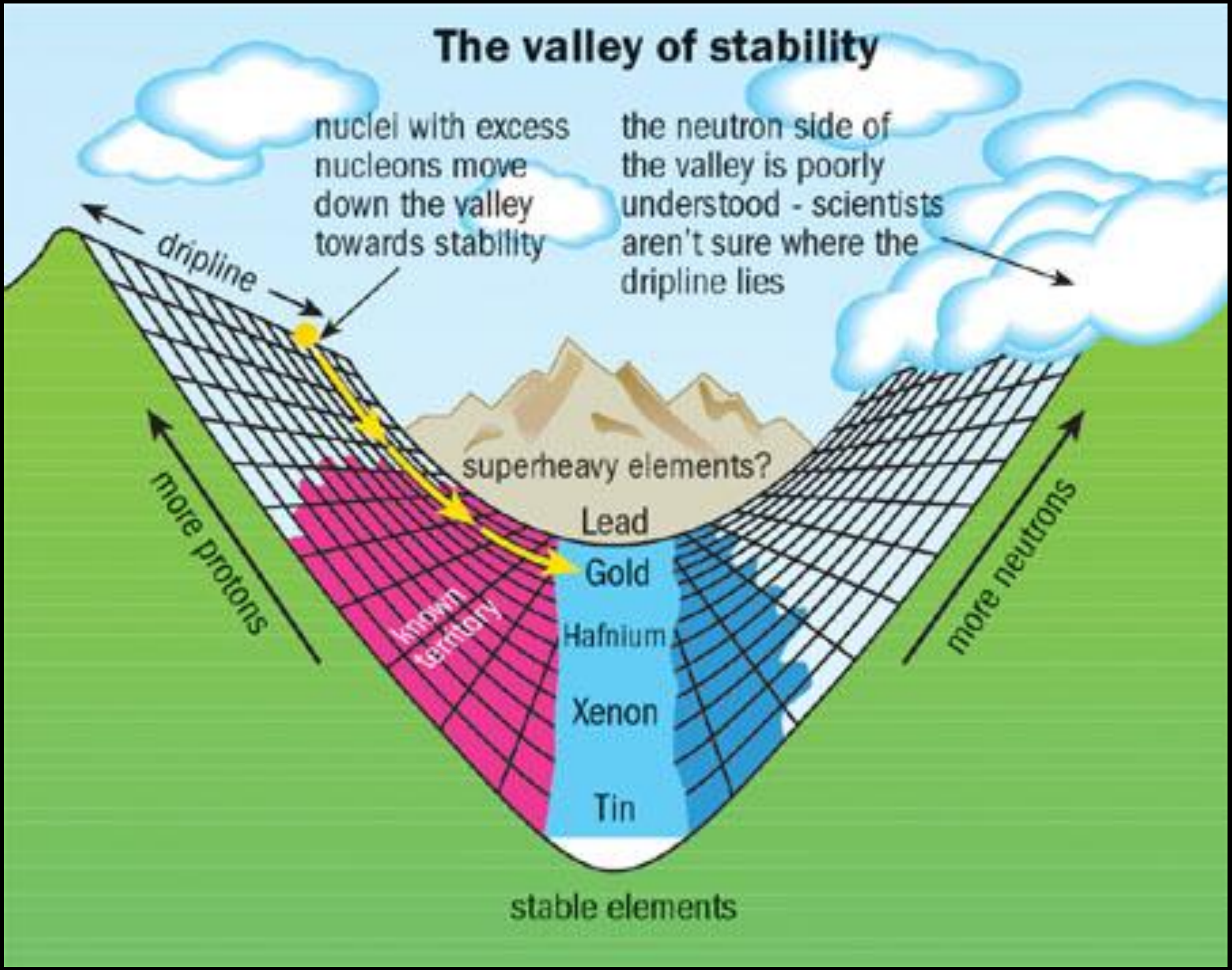
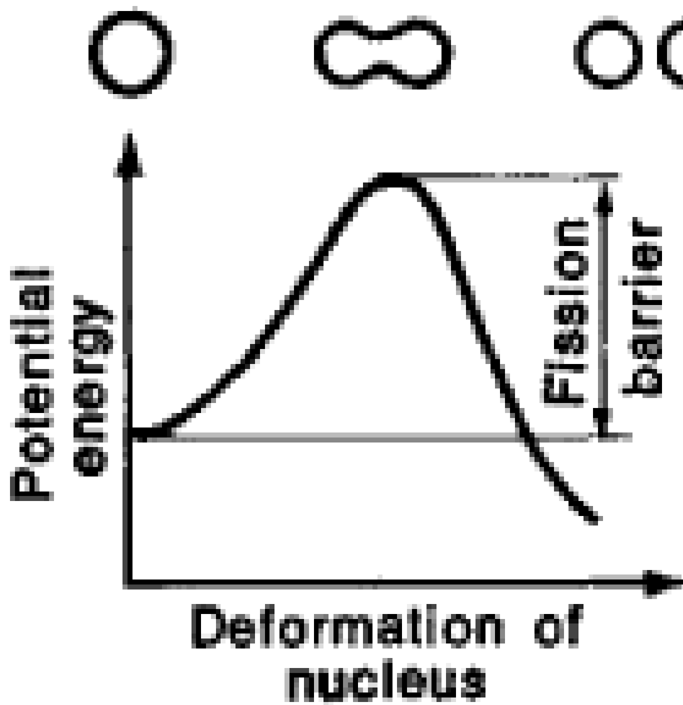


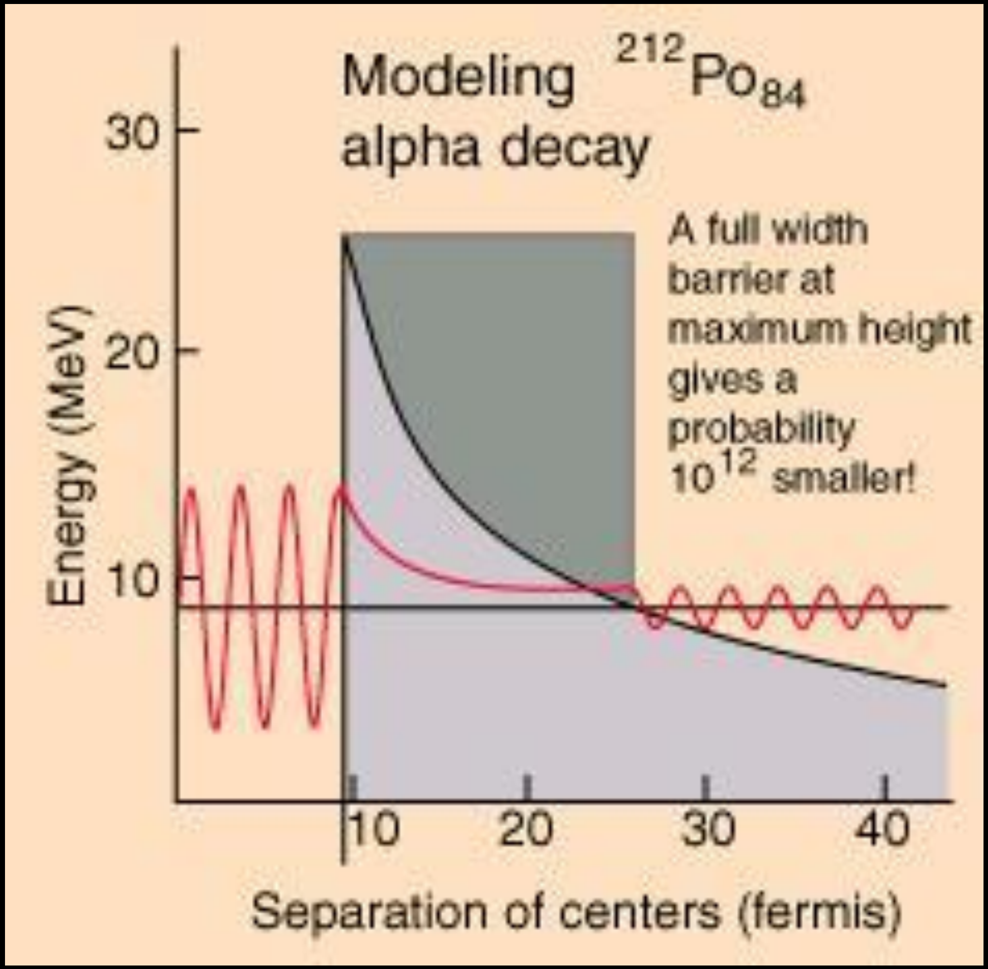
Table of Isotopes (Nuclides) in 3D

Lecture 2 – Nuclei – Energy/Stability

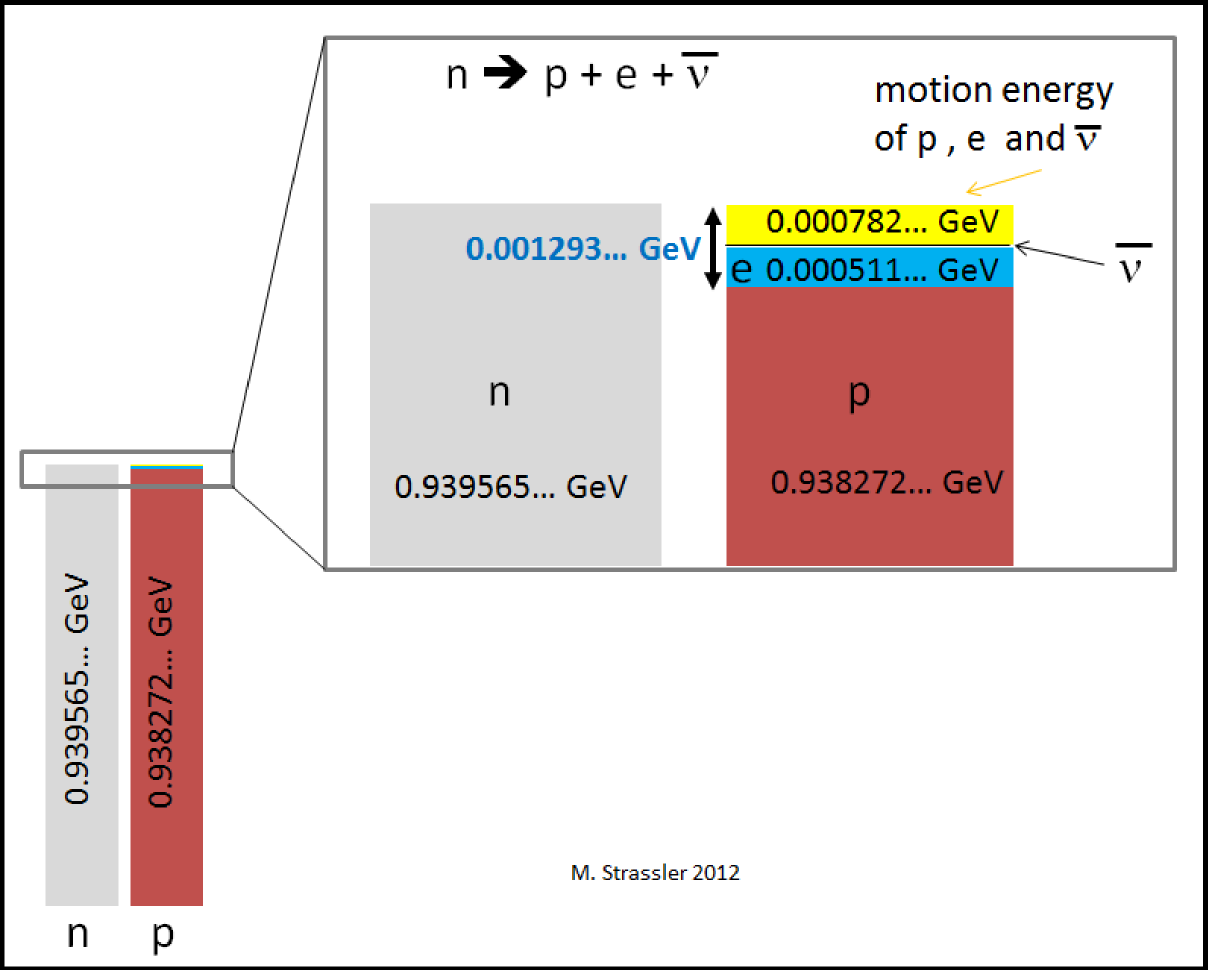
If it is energetically favorable to fission or to fuse, why does this not happen all the time?



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



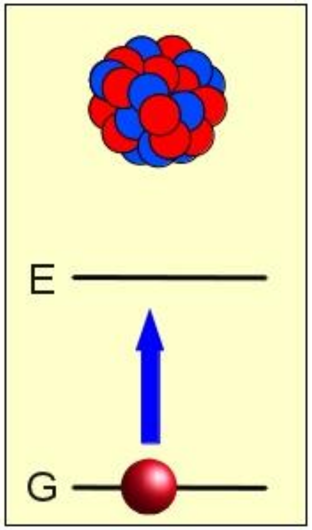
Quantum Mechanical „Tunneling“



Mass of Neutron and Proton

Lecture 2 – Nuclei – Excitation

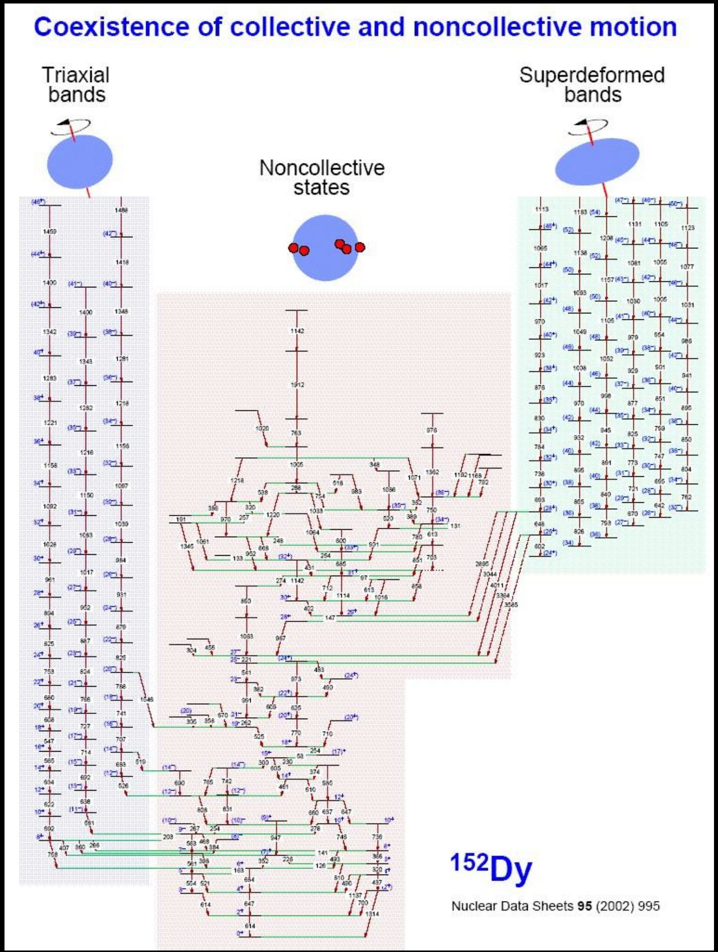
Ground-state nuclei can absorb energy and become “**excited**”



There are **many possibilities**:

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

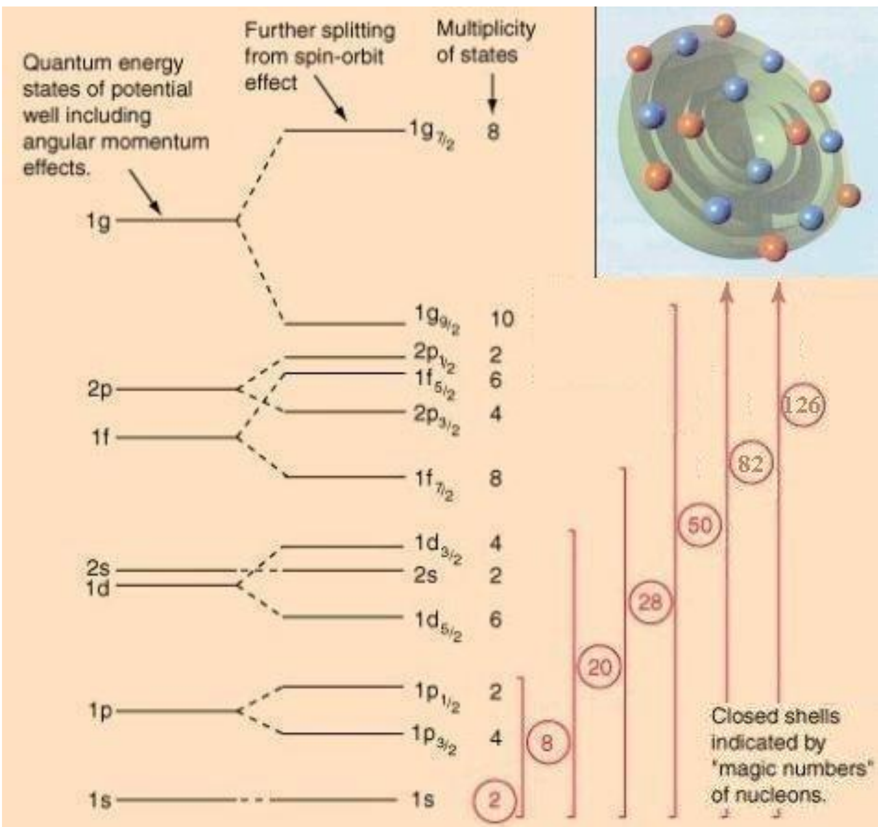
De-excitation (“decay”) frequently happens by **light** (→ photons, γ-rays) and also by **particle emission**

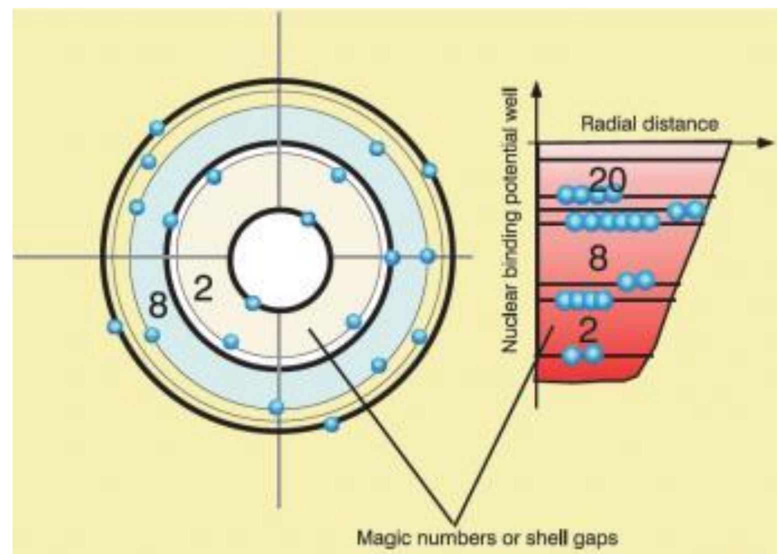


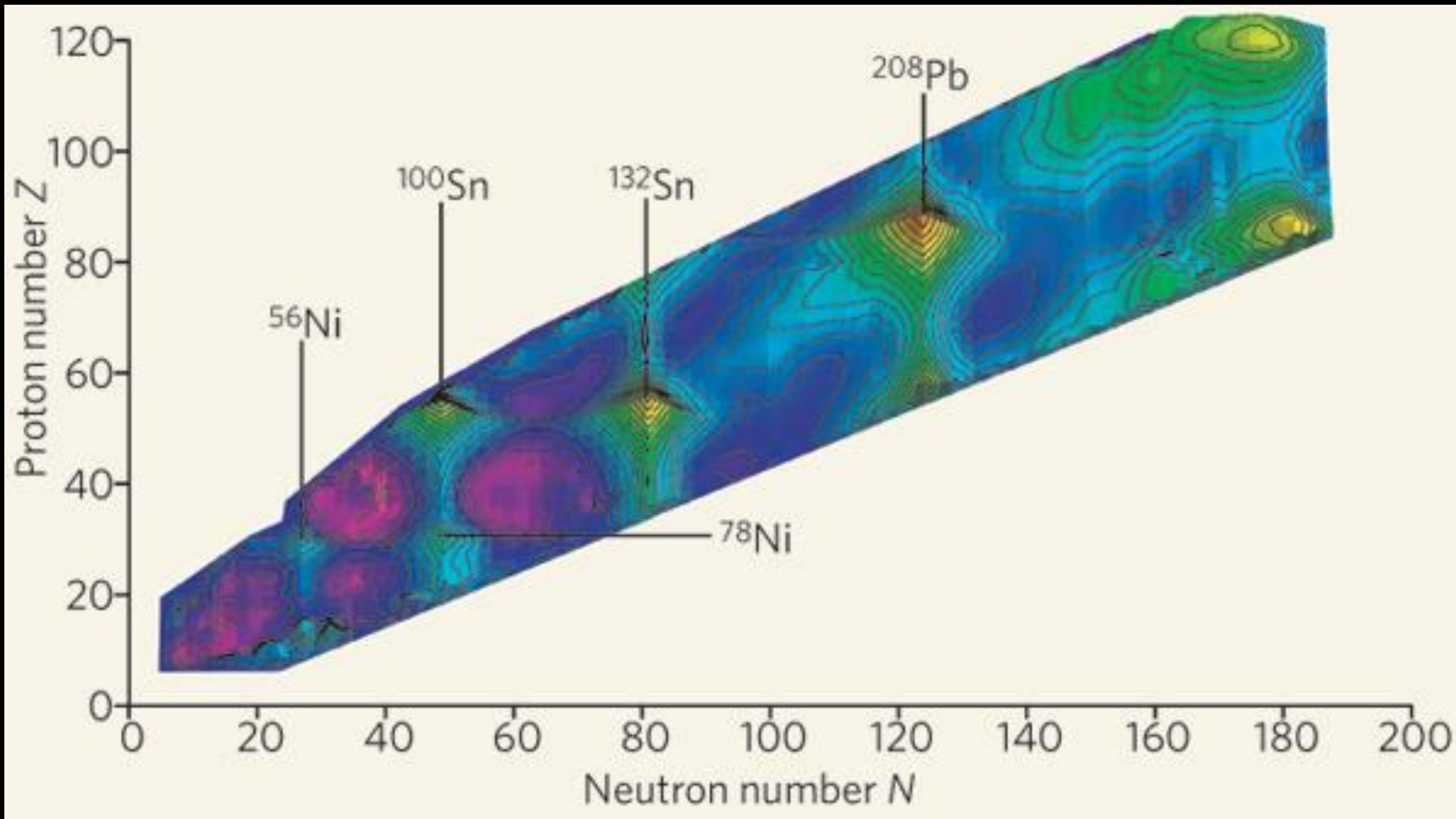
Excited States of a Nucleus

Lecture 2 – Nuclei – QM Model

Besides the “bulk models” (Fermi-gas, liquid drop model), there are also **quantum mechanical models** which describe the nucleus as a system of independent (i.e. not directly interacting nucleon system) in a mean nuclear potential (nuclear “shell model”):



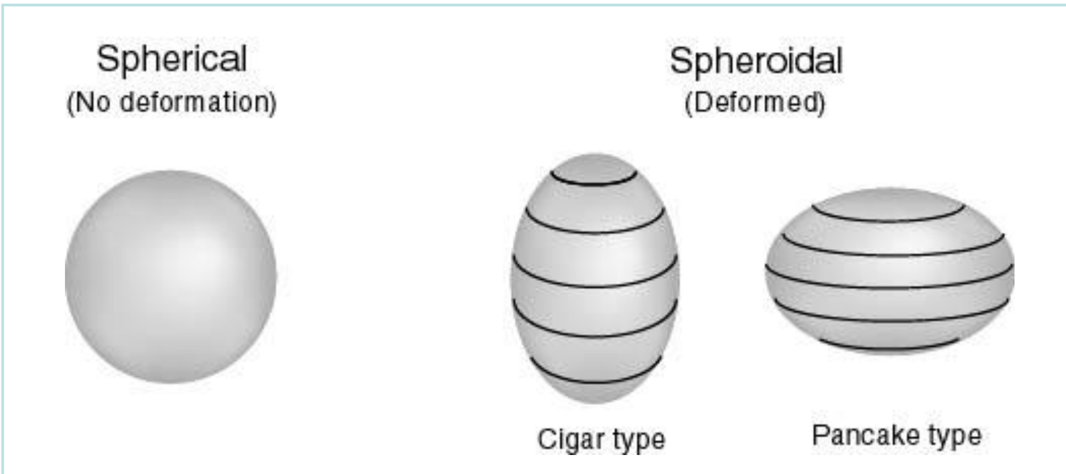




Magic Numbers in Nuclei (as seen in BE)

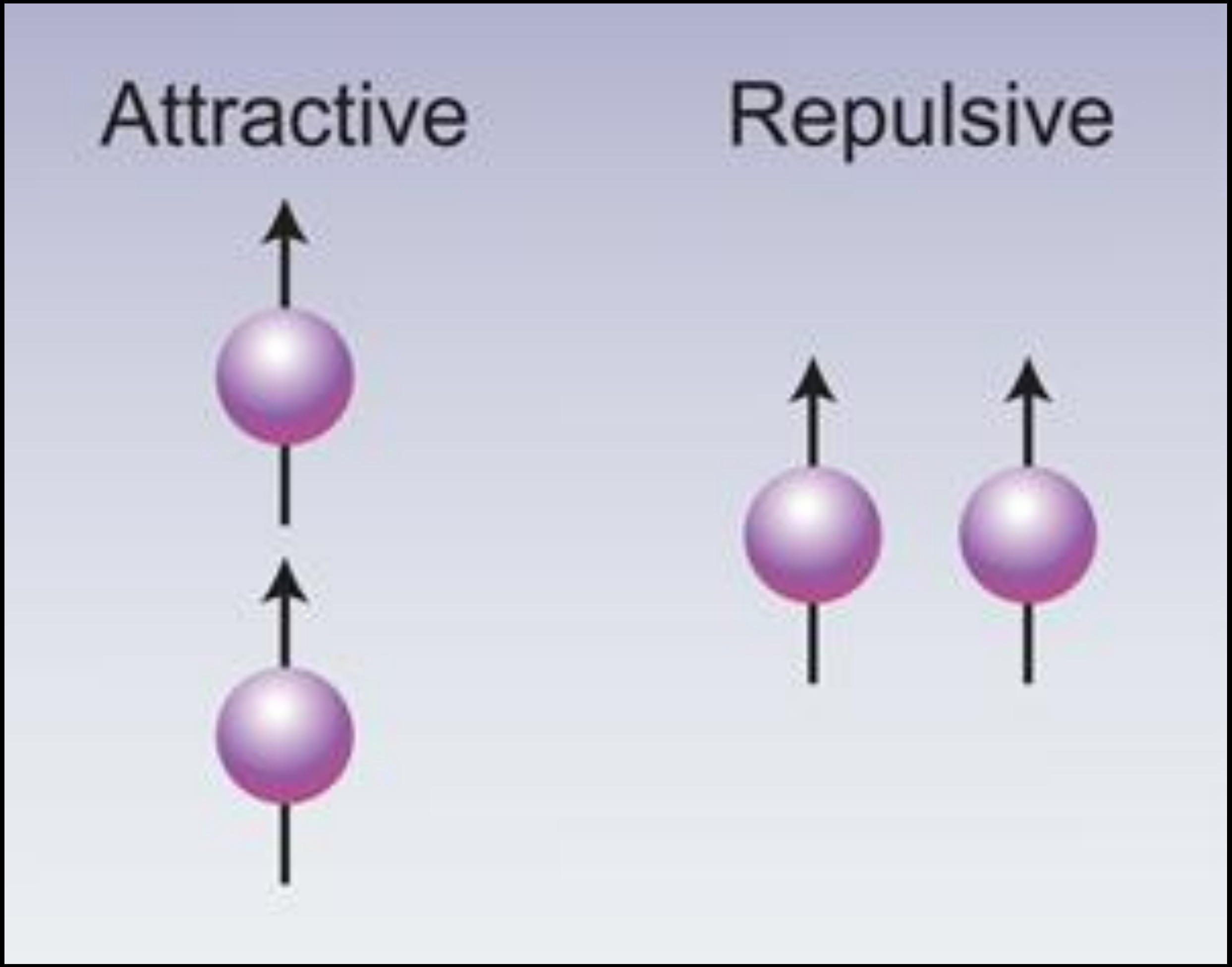
Lecture 2 – Nuclei – Deformation

Nuclei in their ground state can either be **spherical** or **deformed**; the following (static) **nuclear shapes** have been observed:

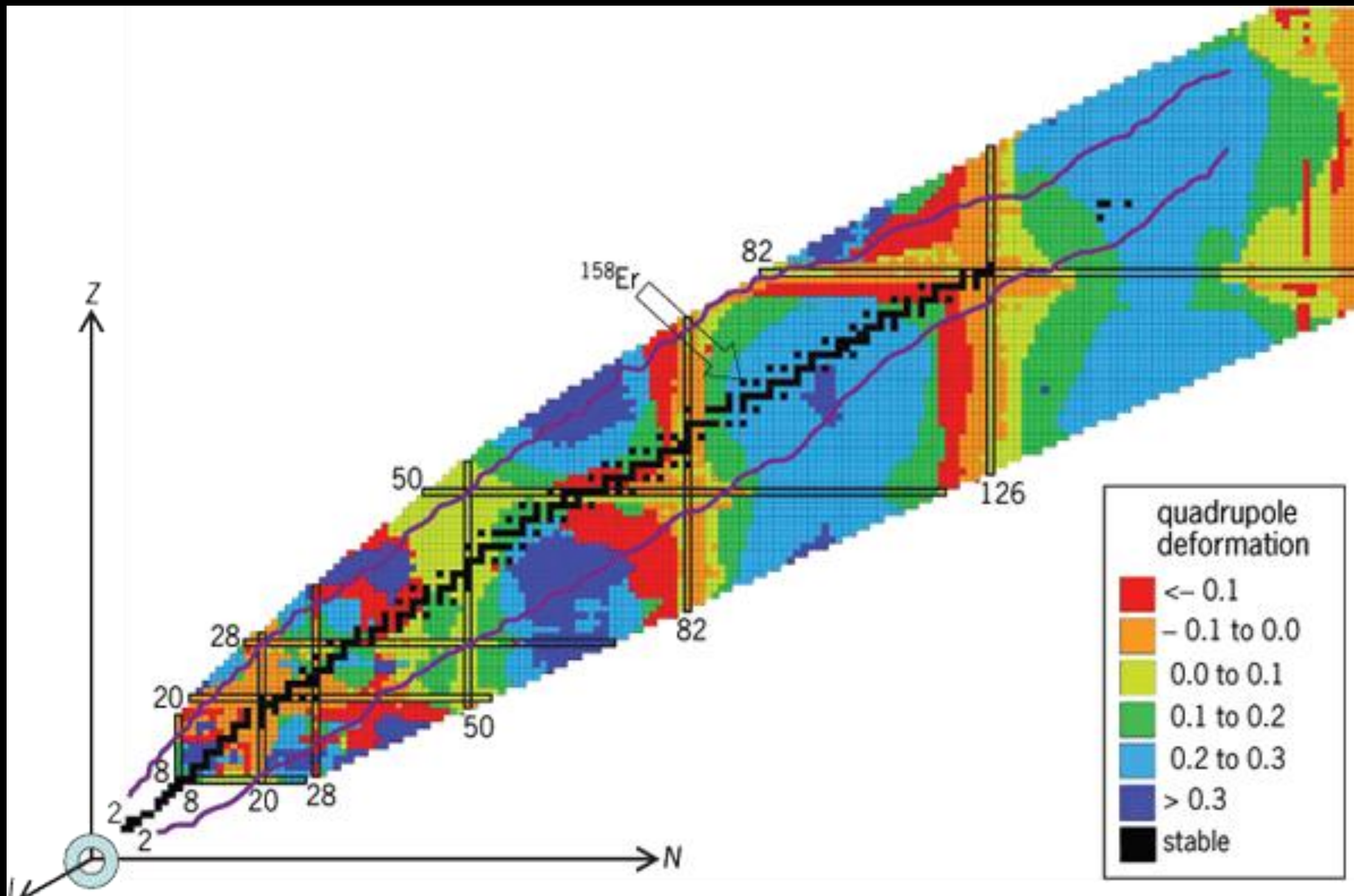


The reason why this is so (i.e. why the **minimum energy** is not reached for a sphere) is complicated due to the complexity of the **nuclear forces** (which themselves are the result of the **strong force** between quarks (see below)).

Lecture 2 – Nuclei – Deformation



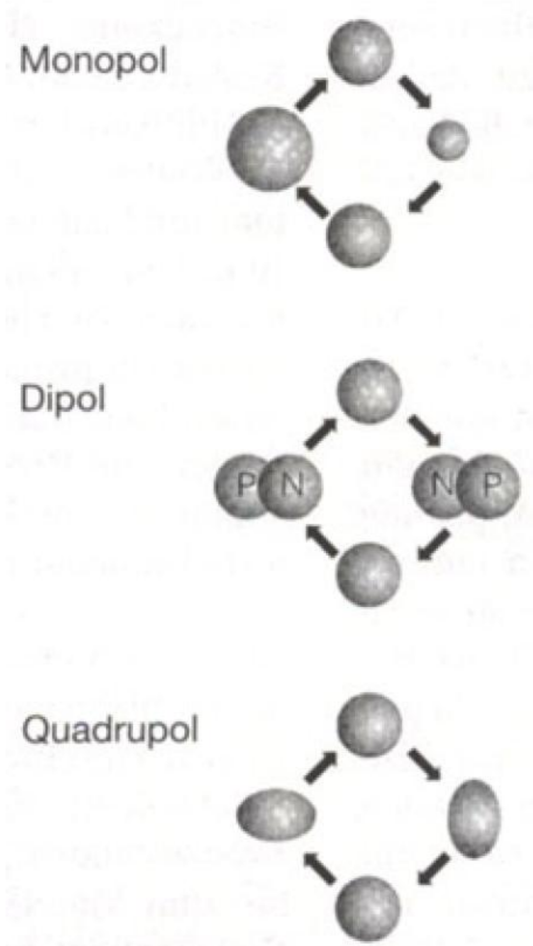
Example Deuteron



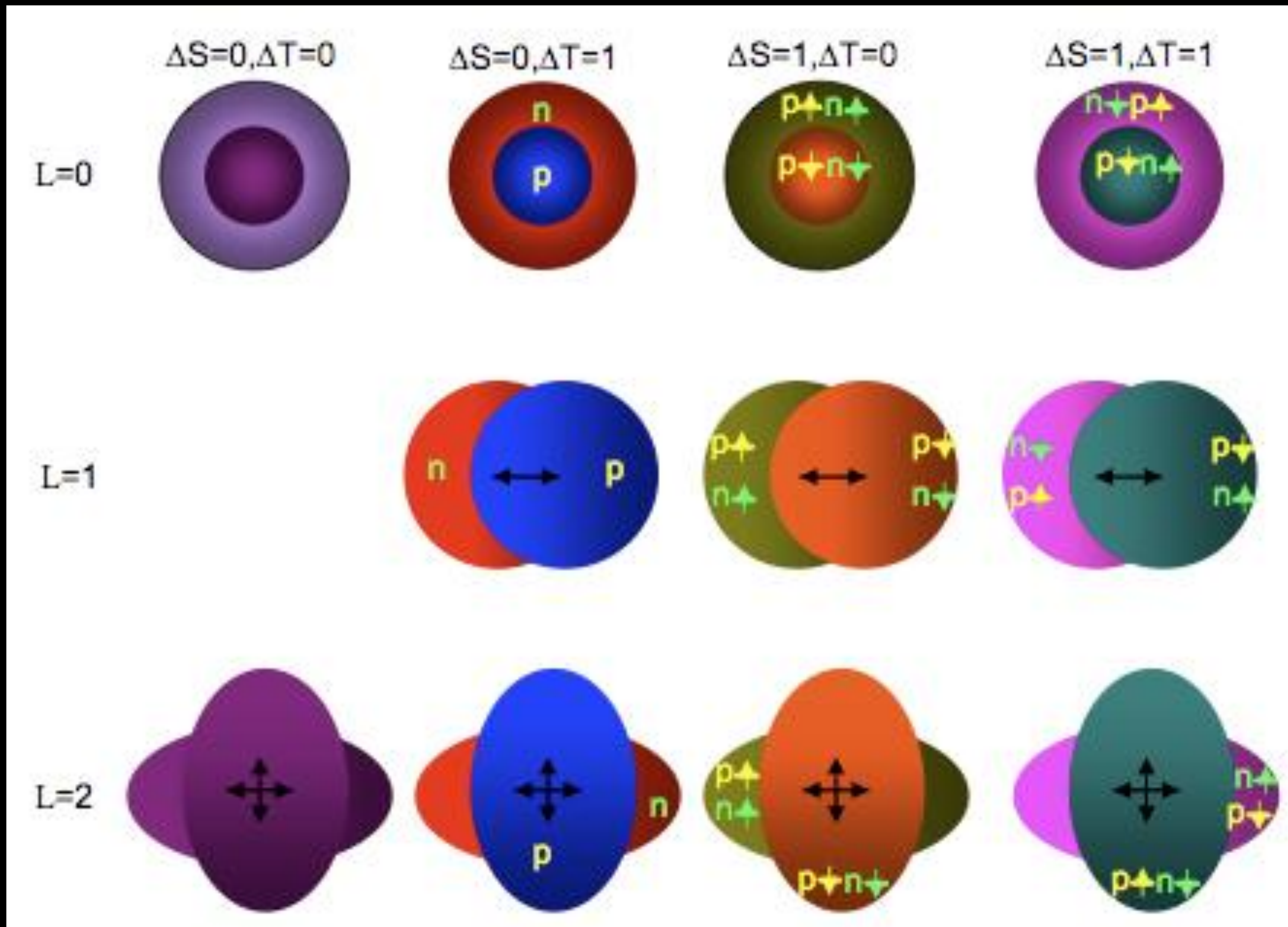
Spheroidal („Quadrupole“) Deformation

Lecture 2 – **Nuclei** – Excitation

Nucleons in a nucleus can **oscillate coherently** in different ways
→ “giant resonances”

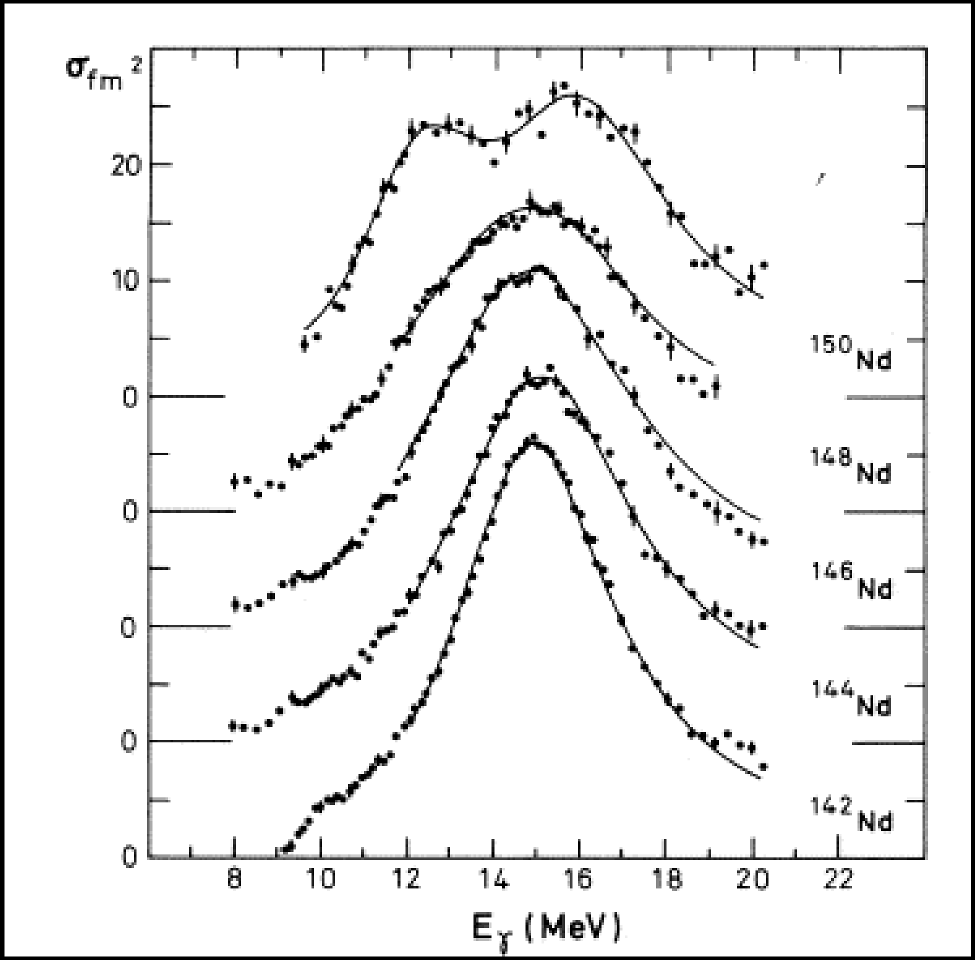


Lecture 2 – Nuclei – Excitation



Nuclear Giant Resonances

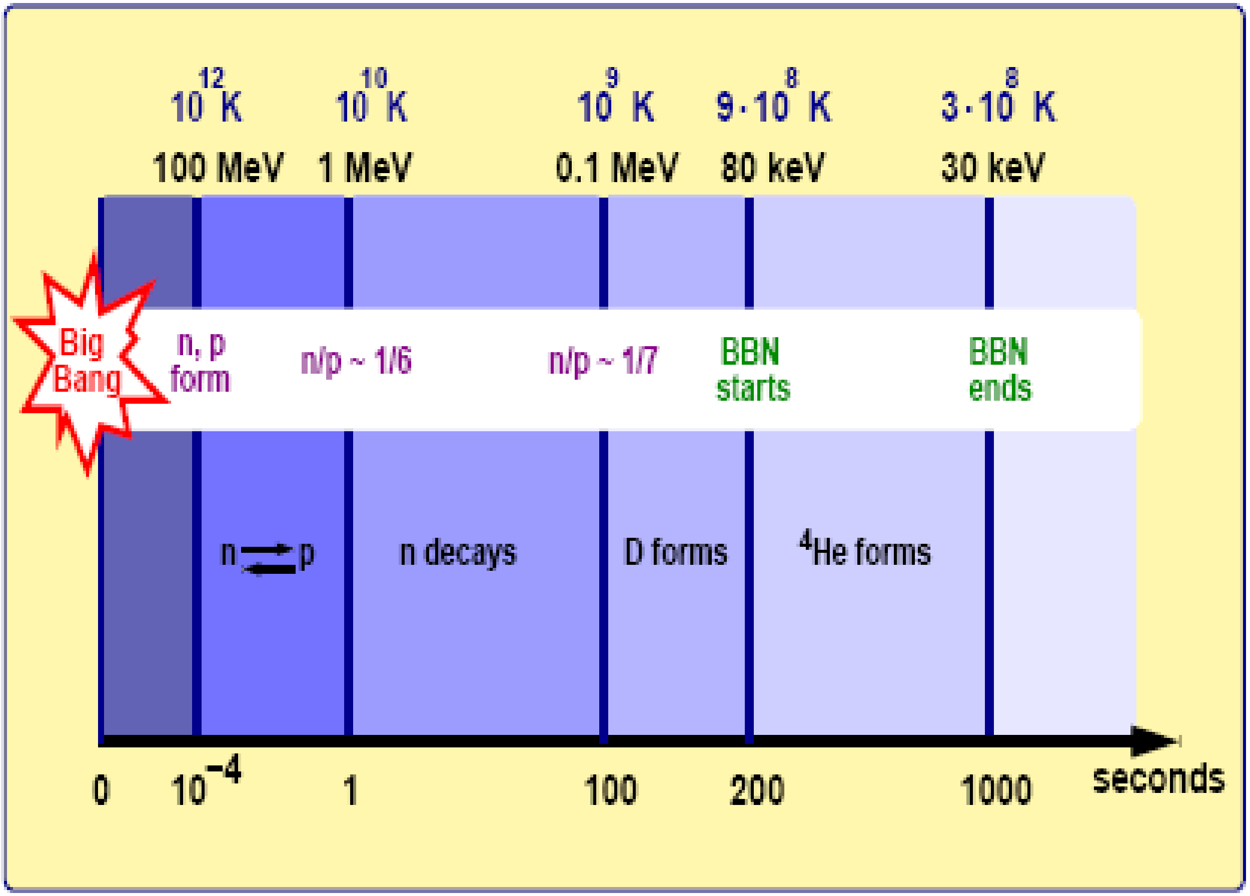
Lecture 2 – **Nuclei** – Excitation

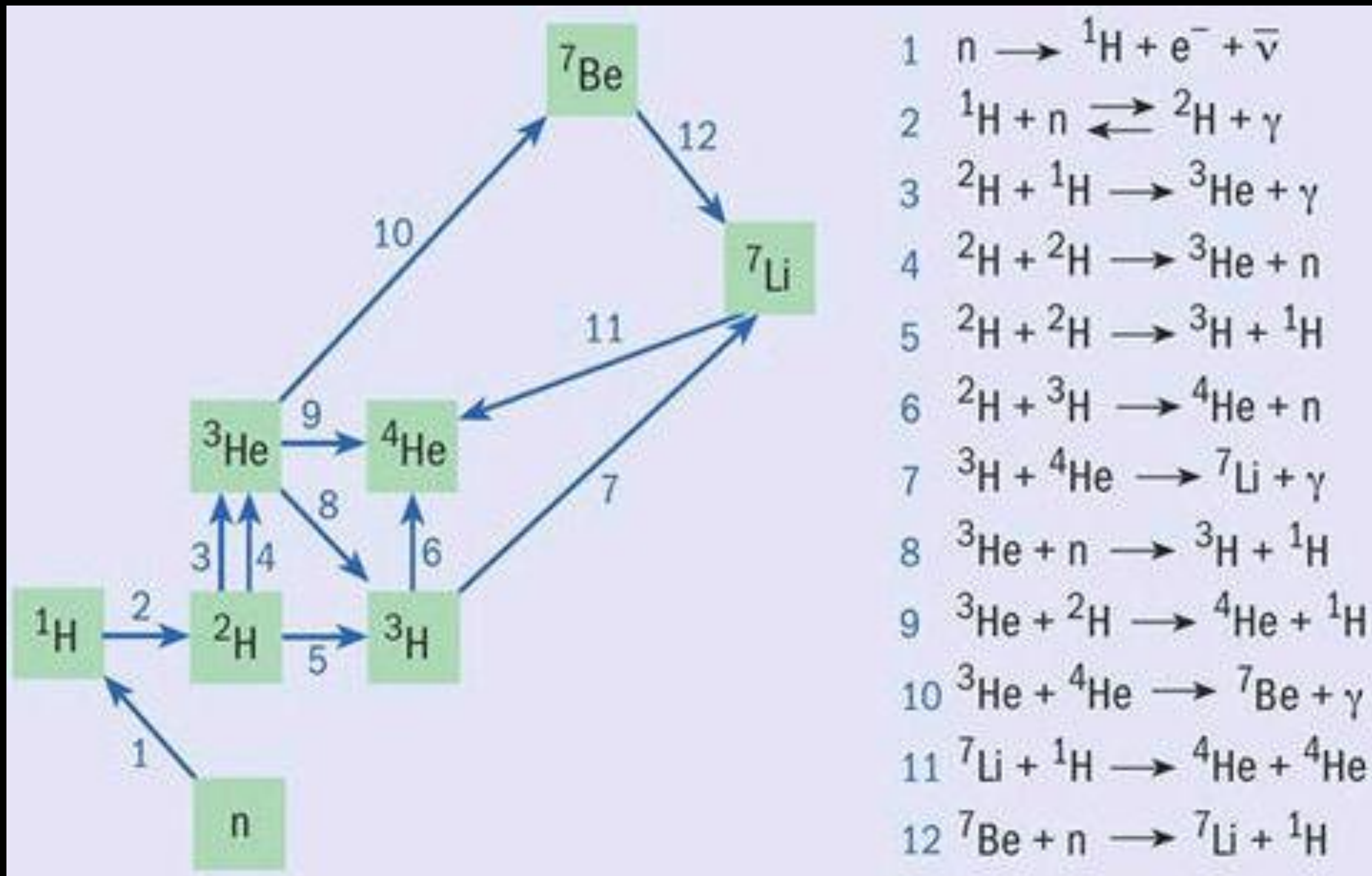


Giant Dipole Resonances

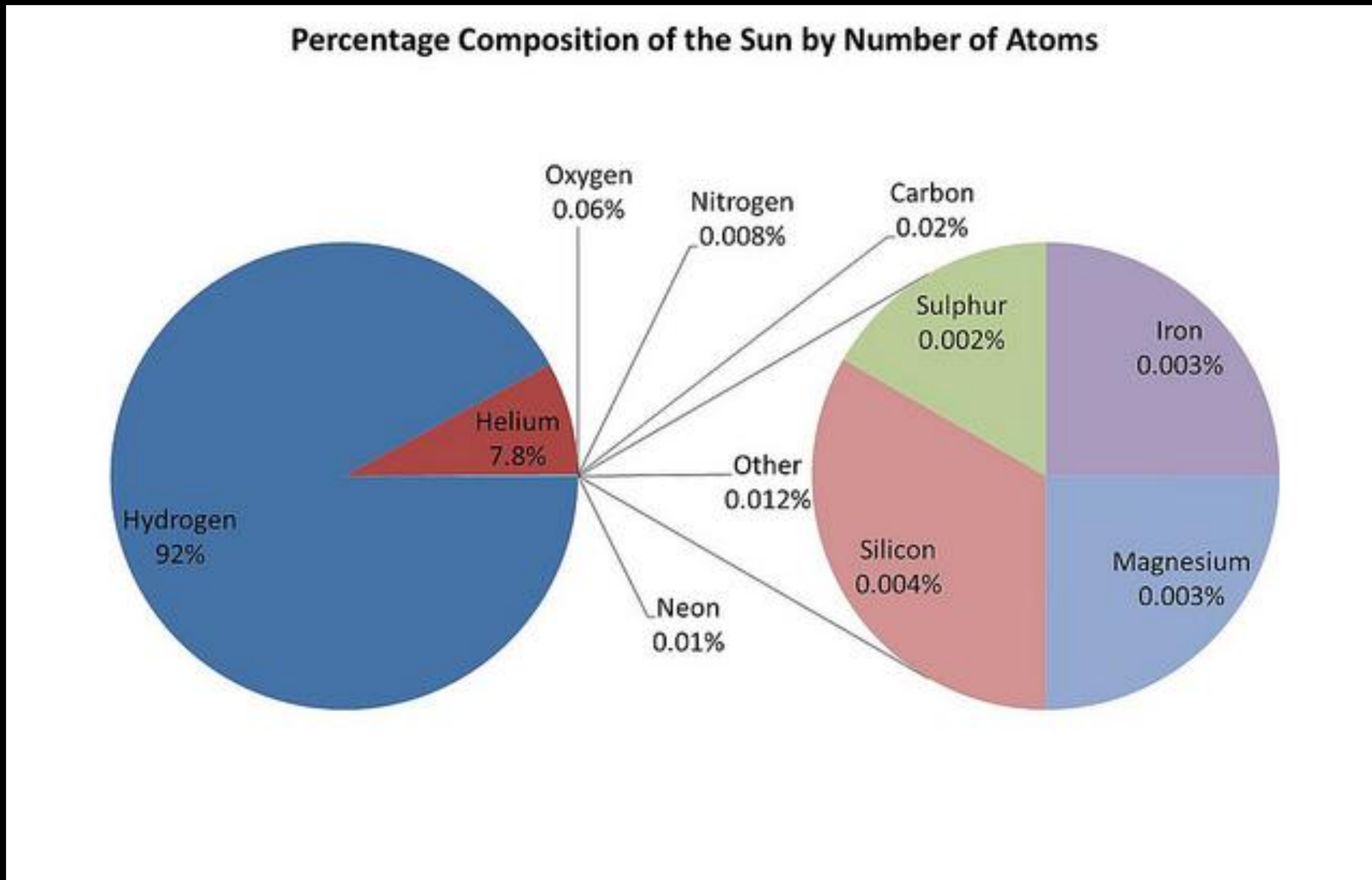
Lecture 2 – **Nuclei** – Nucleosynthesis

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:



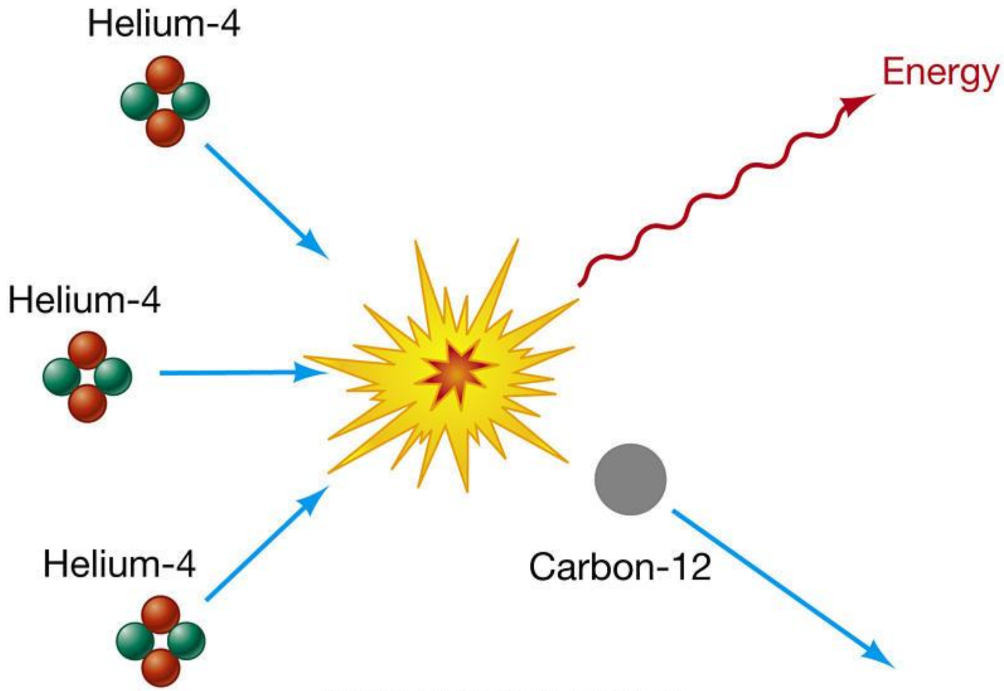


Big Bang Nucleosynthesis (BBN)



Big Bang Nucleosynthesis (BBN)

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:



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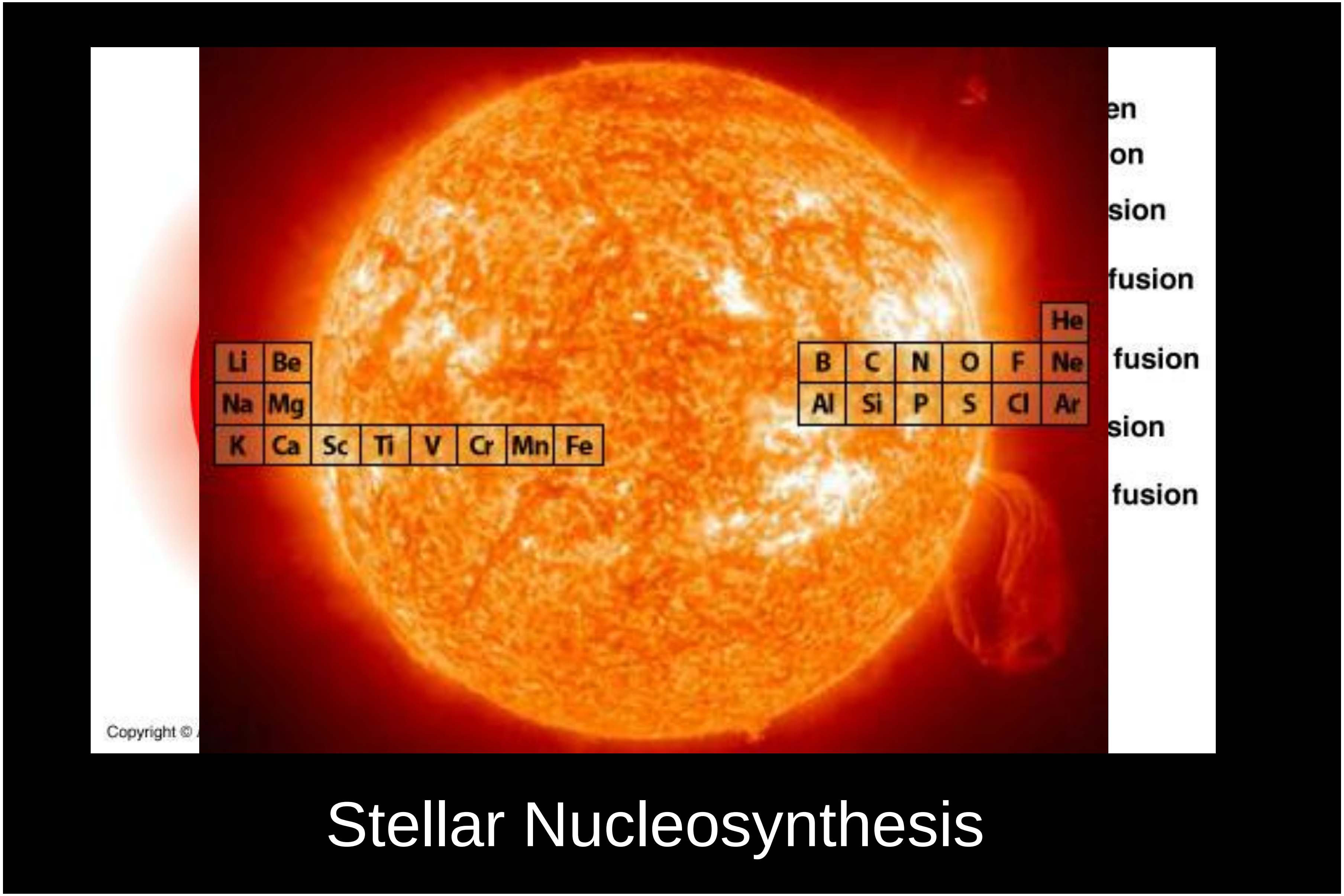
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He
Li Be
Na Mg
K Ca Sc Ti V Cr Mn Fe
B C N O F Ne
Al Si P S Cl Ar
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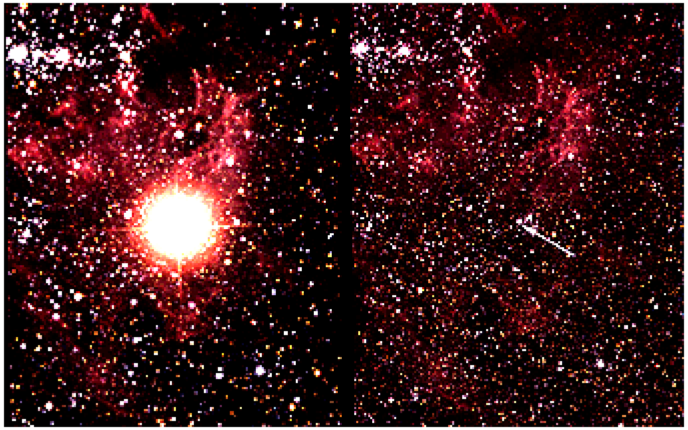
Stellar Nucleosynthesis

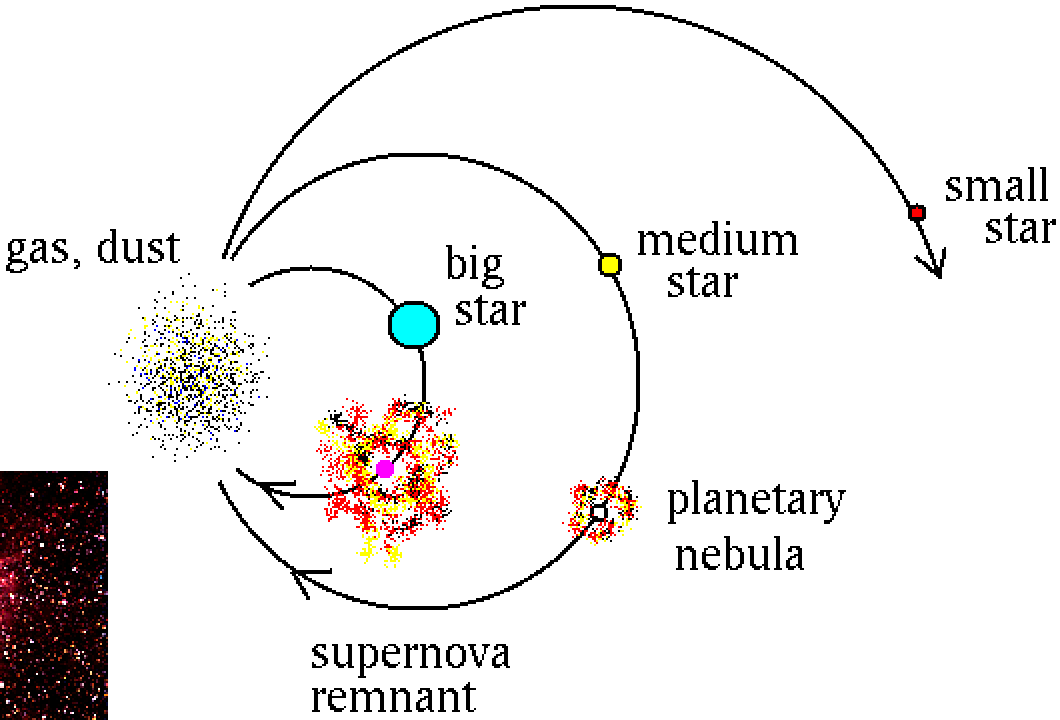
Lecture 2 – **Nuclei** – Nucleosynthesis

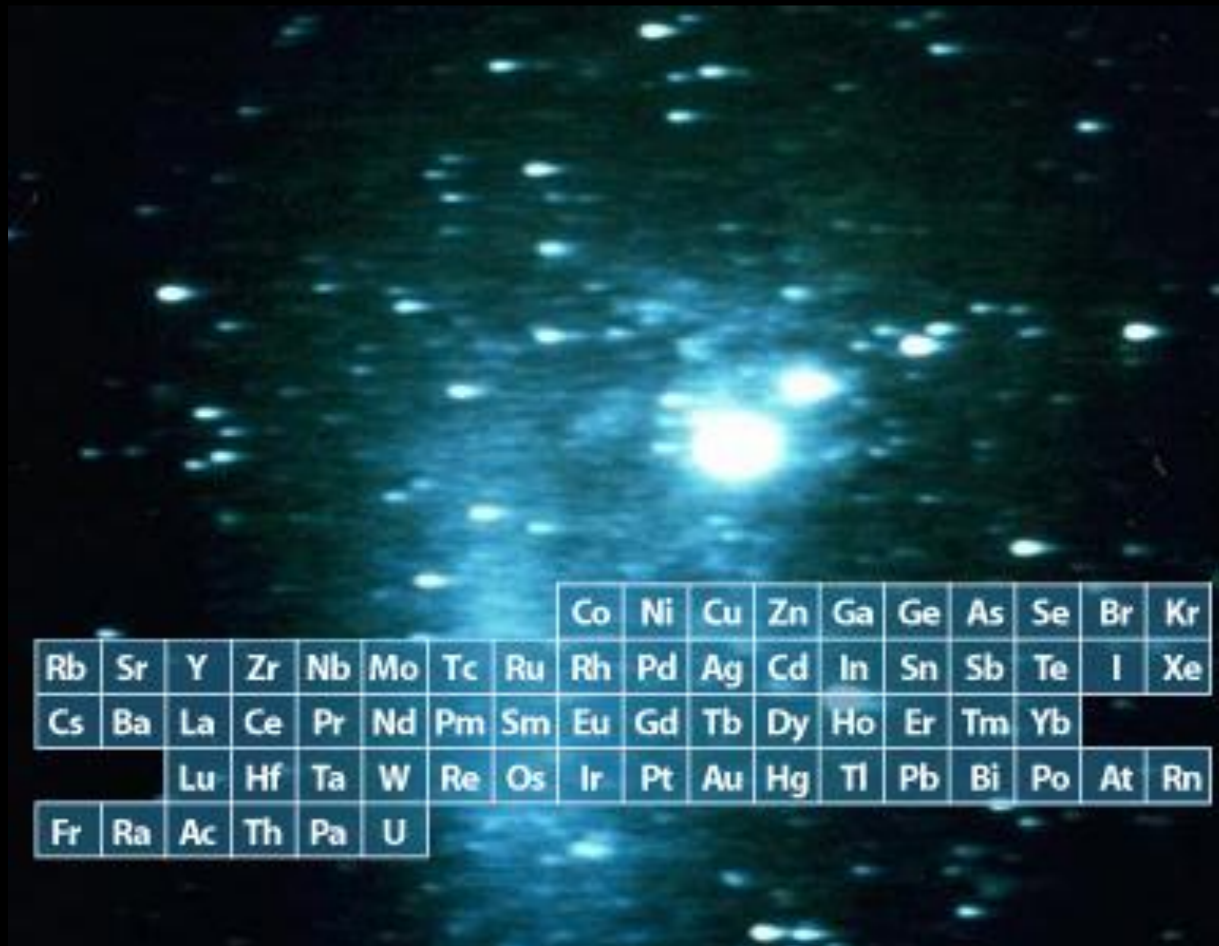
Stellar nucleosynthesis in stars by thermonuclear fusion stops around iron; heavier elements are produced in **explosive nucleosynthesis** in supernovae:

Example: SN1987A

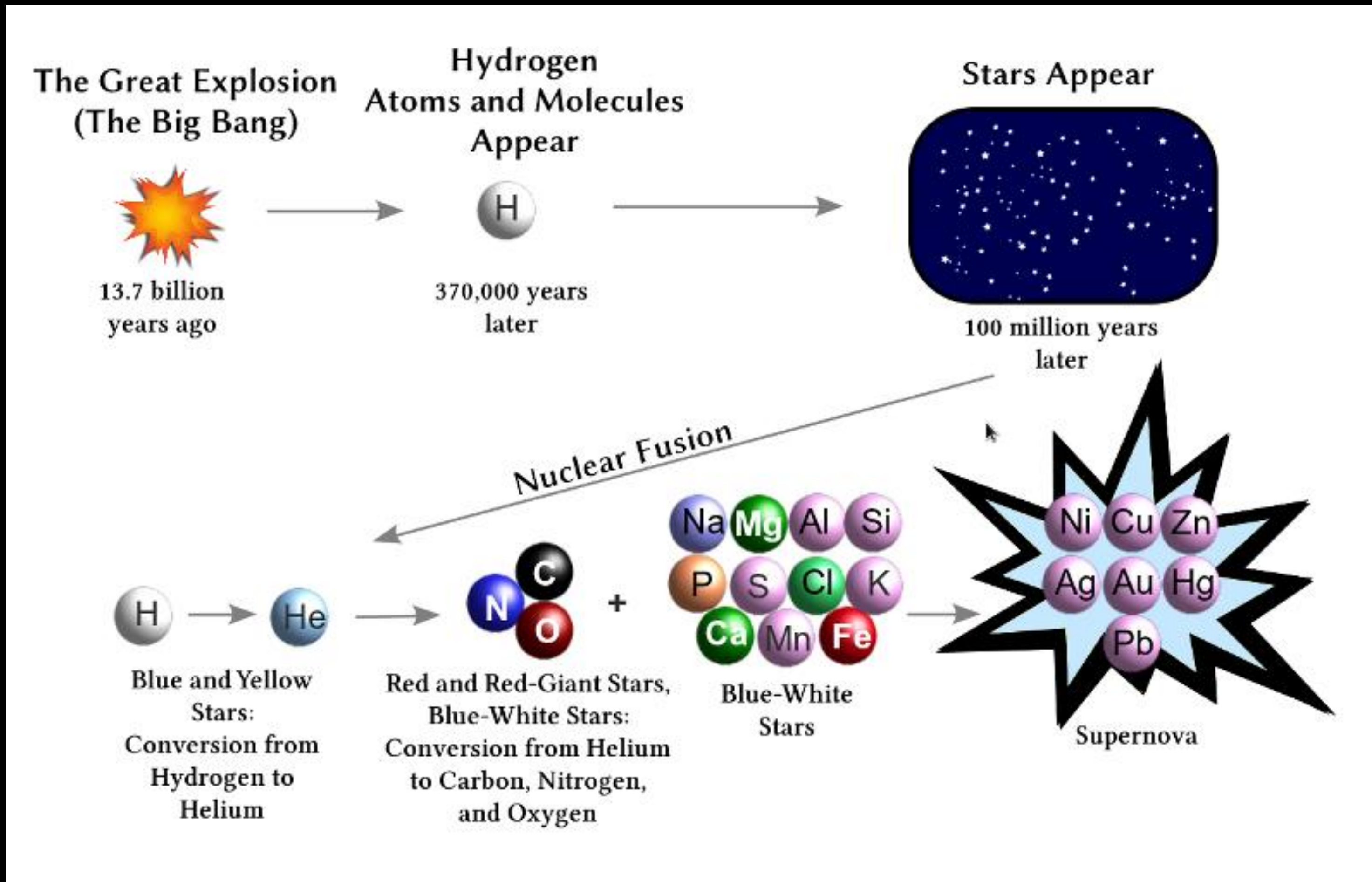
after before







Explosive Nucleosynthesis



Summary Nucleosynthesis

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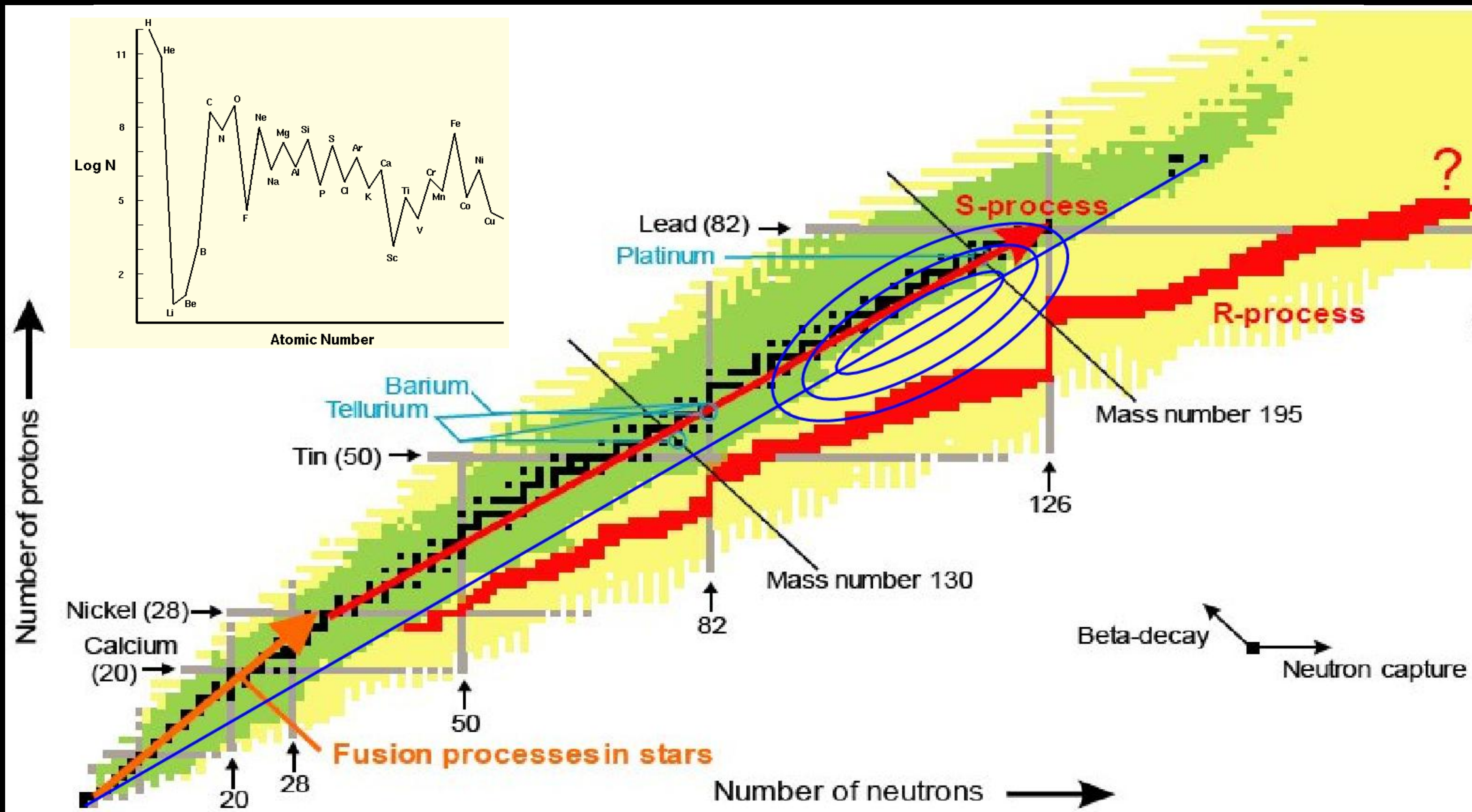
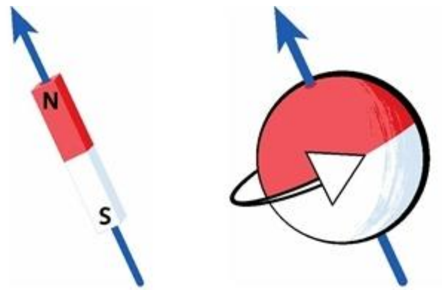


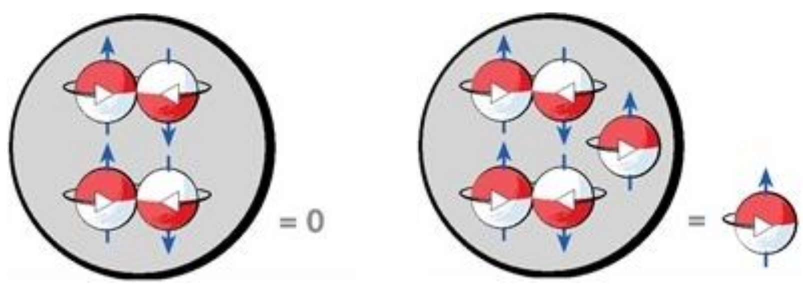
Summary Nucleosynthesis

Lecture 2 – Nuclei – Properties

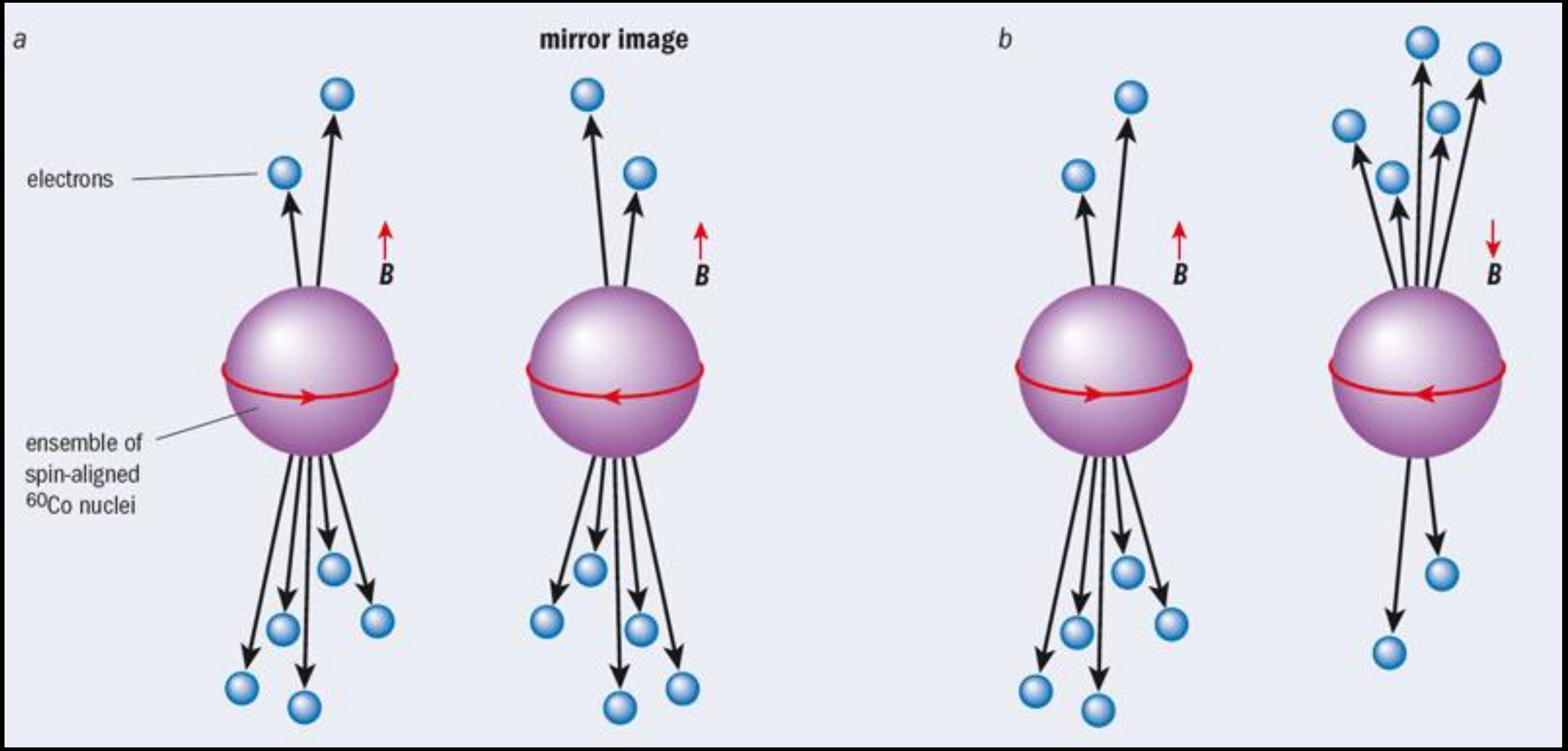
The nuclear constituents, protons and neutrons, have the quantum-mechanical property of "**spin**" (often illustrated as an internal rotation, like a spinning top); affiliated with it is a **magnetic moment**:



Nuclei with an **even number of protons and neutrons** do not have a net **nuclear spin**; they are magnetically neutral; nuclei with an **uneven number of protons or neutrons** have a net spin / magnetic moment:

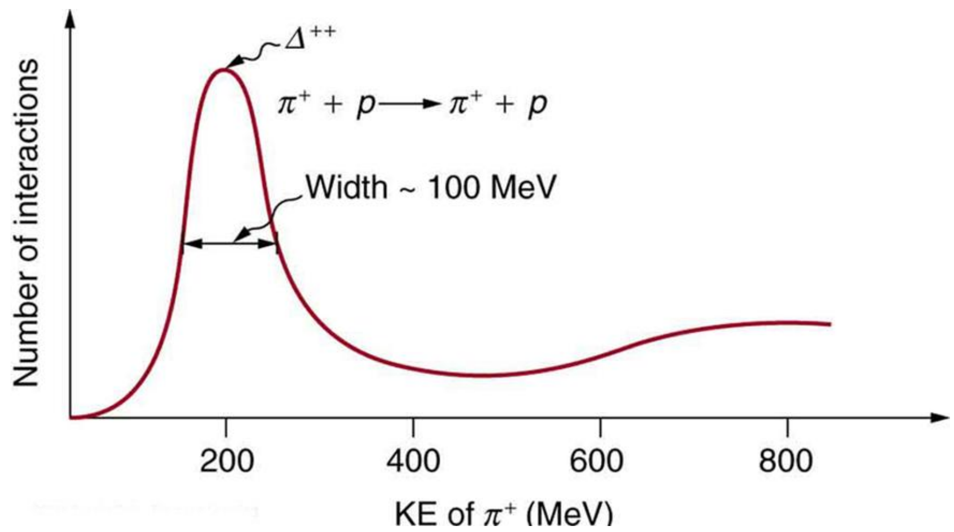


(→ this will become important for MRI)



Example: Parity Violation in ^{60}Co

The simplest nucleus, the **proton** (also the **neutron**), can be **excited** by different meachnisms (e.g. absorption of a photon or a particle) into the so-called **Δ-** and other (more massive/more energetic) **resonances**:



This is a very strong indication that the "**nucleon**" (proton, neutron) is **not** an **elementary** particle, but has internal structure!

Lecture 2 – Nuclei – Summary

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

The **diameter of the nucleus** is in the range of 1.75 fm (1.75×10^{-15} m) for hydrogen (i.e. a single proton) to about 15 fm for the heaviest atoms, such as uranium. These dimensions are much smaller than the diameter of the atom itself (nucleus + electron cloud), by a factor of about 23,000 (uranium) to about 145,000 (hydrogen).

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 can be excited in many different ways; they decay via α, β and γ-decay (called "**radioactivity**") and by nuclear fission.

→ **What is the internal structure of the nucleon?** → Next lecture!

გმადლობთ

Lecture 2 – **Nuclei** – Properties