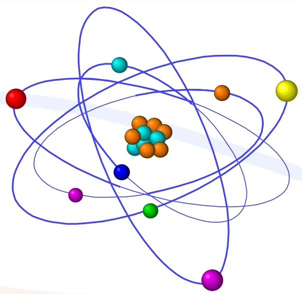
PHY401:
Nuclear And Particle Physics

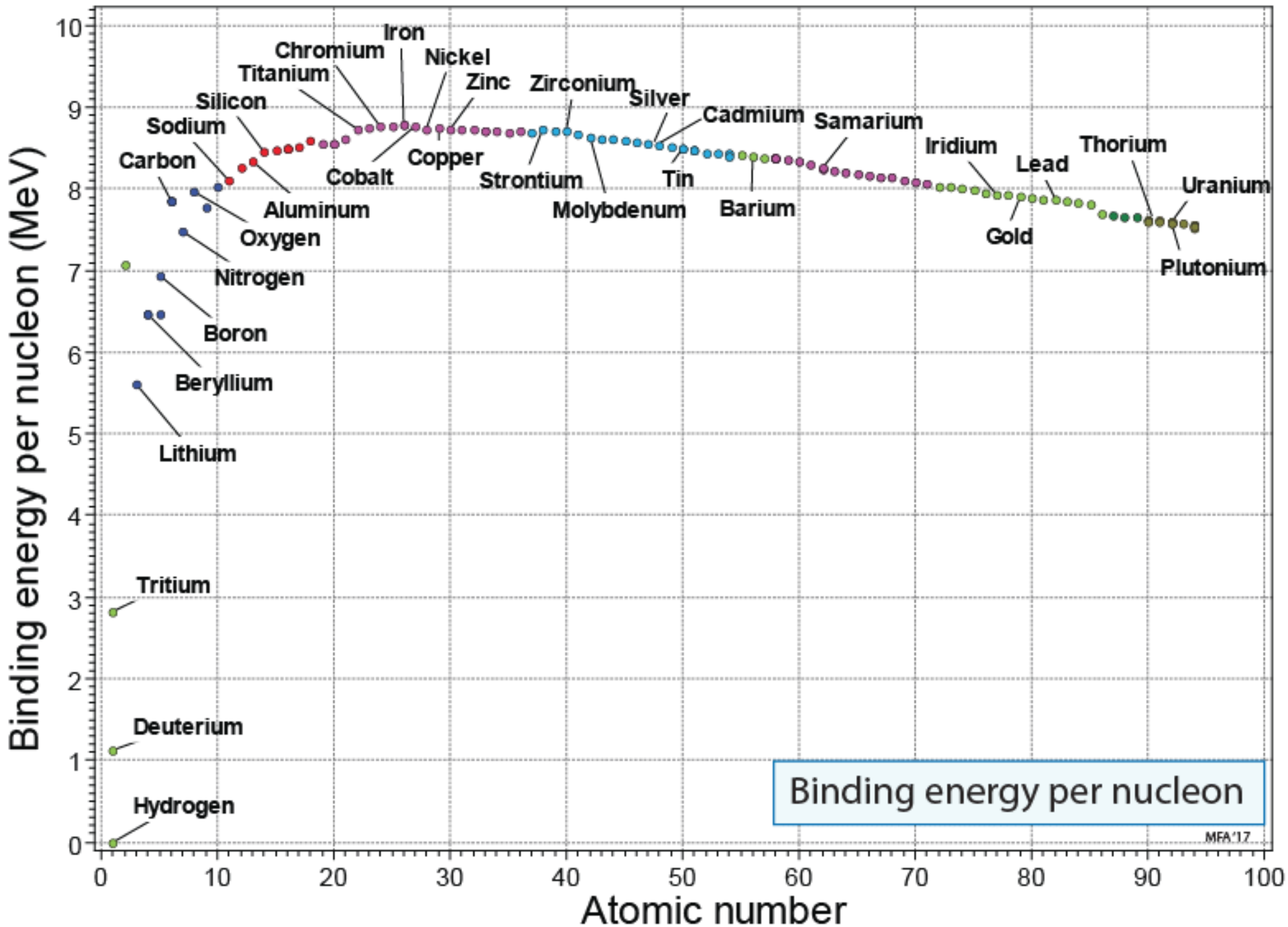


IISER

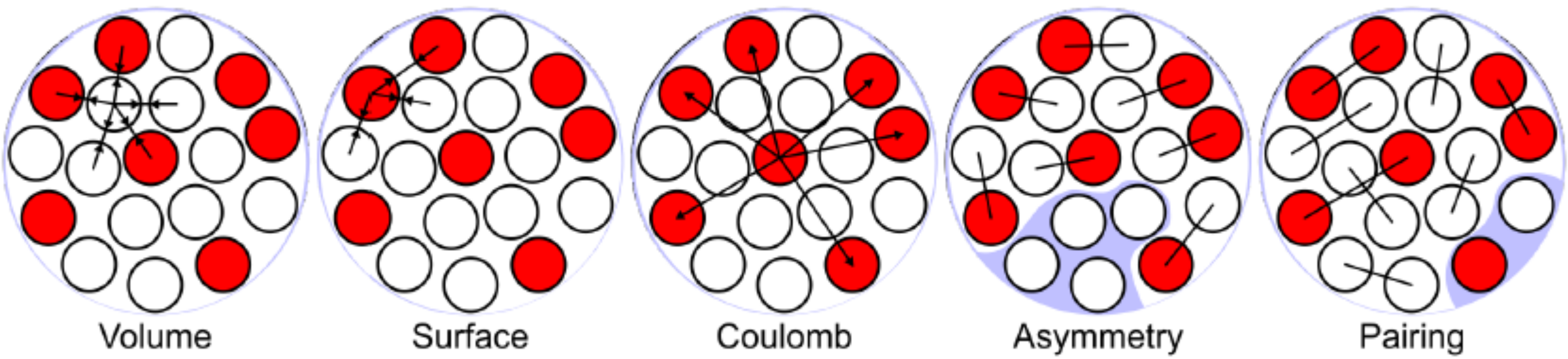
Satyajit Jena, 05-06/09/2024

A charged drop of incompressible liquid

For the nucleus we assume a liquid drop with a uniform positive charge.



A charged drop of incompressible liquid



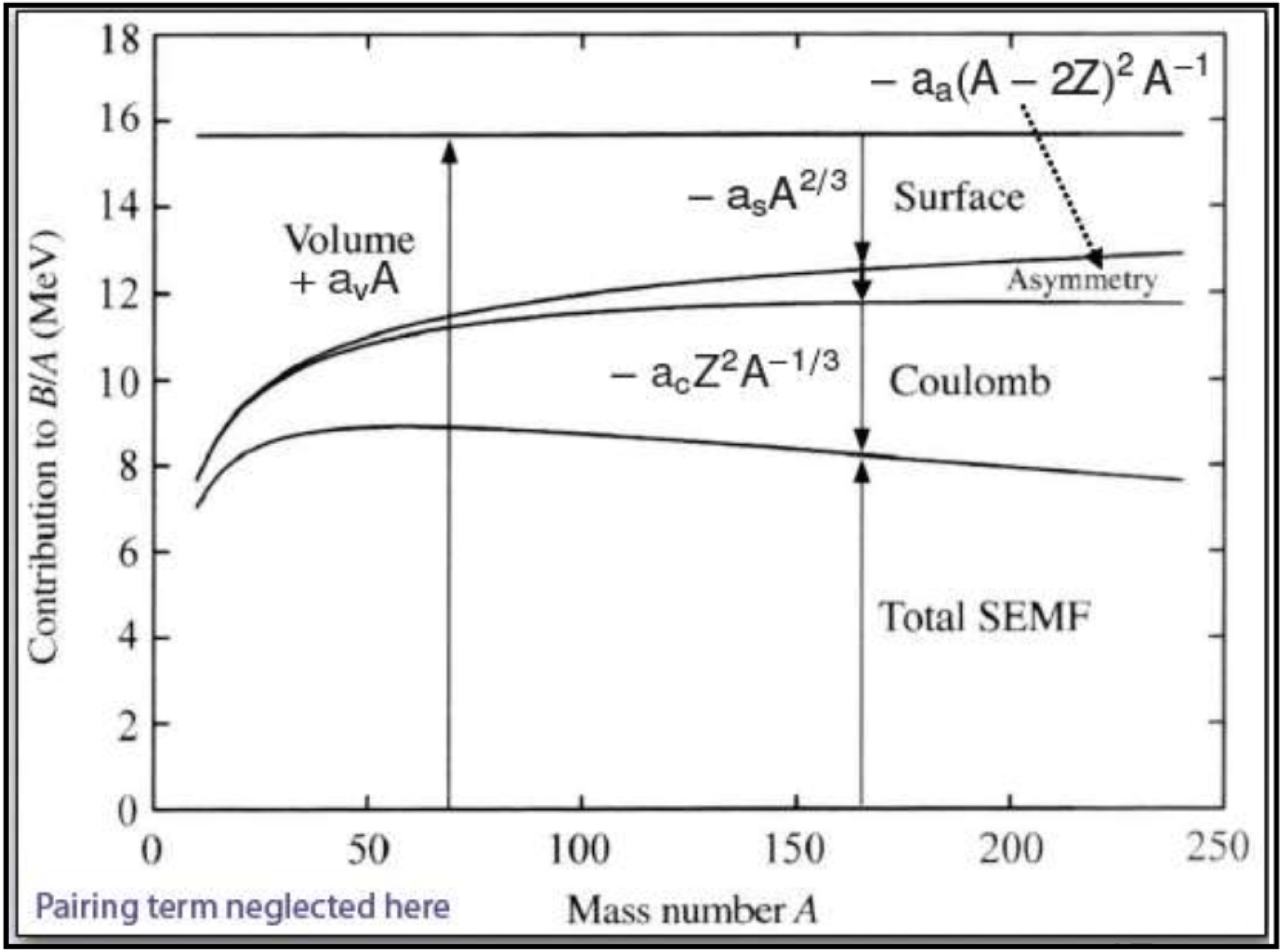
The Semi-Empirical Mass Formula

$$B(A,Z) = a_V \cdot A - a_S \cdot A^{2/3} - a_C \cdot \frac{Z\cdot(Z-1)}{A^{1/3}} - a_{asym} \cdot \frac{(A-2Z)^2}{A} + a_{pair} \cdot \frac{\delta}{A^{1/2}}$$

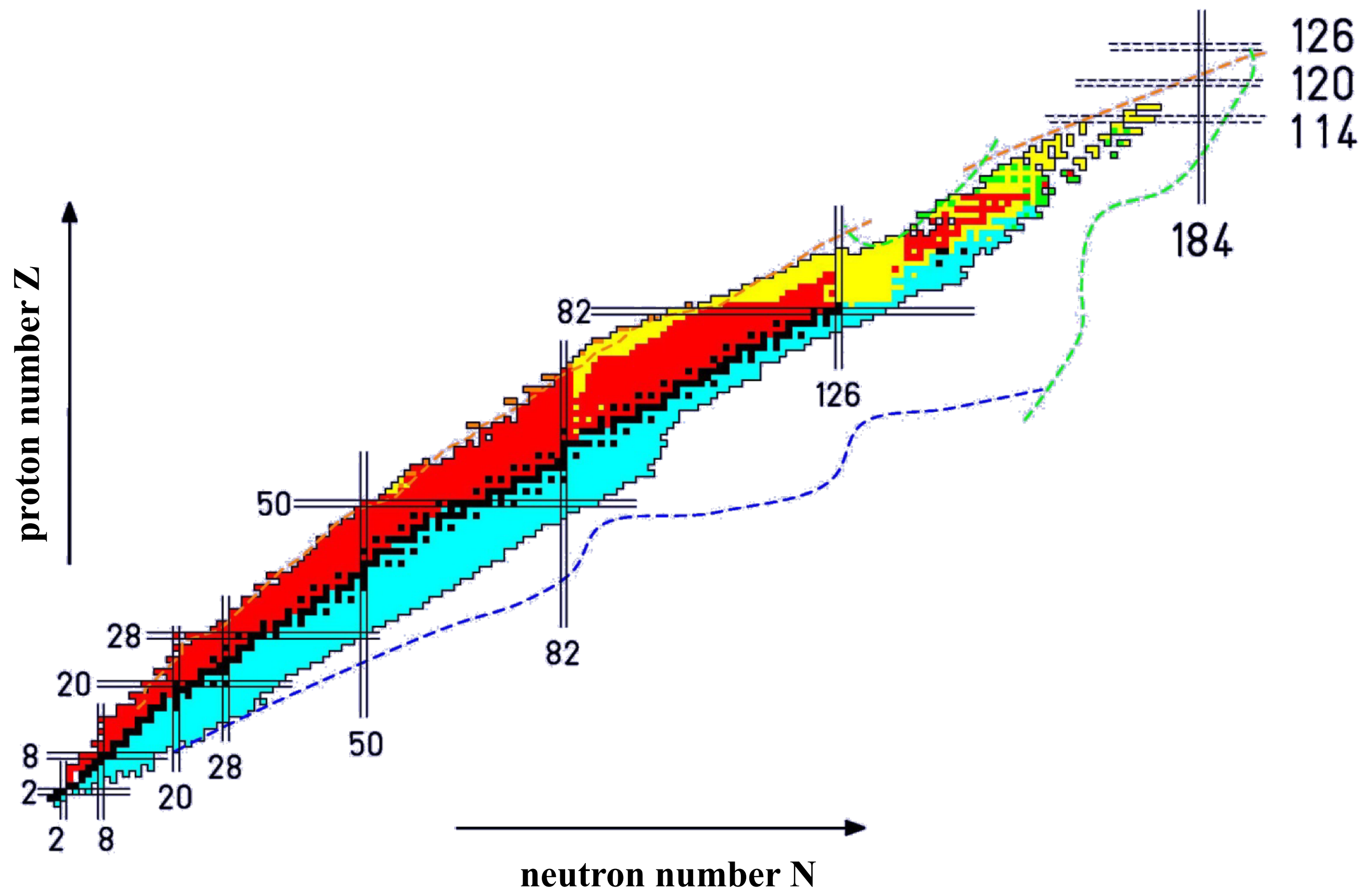
a_V	15.85 MeV
a_S	16.8 MeV
a_C	0.72 MeV
a_{asym}	23.21 MeV
a_{pair}	34 MeV

$$\delta = \begin{cases} +1 & for\ even - even\ nuclei \\ 0 & for\ odd - even\ nuclei \\ -1 & for\ odd - odd\ nuclei \end{cases}$$

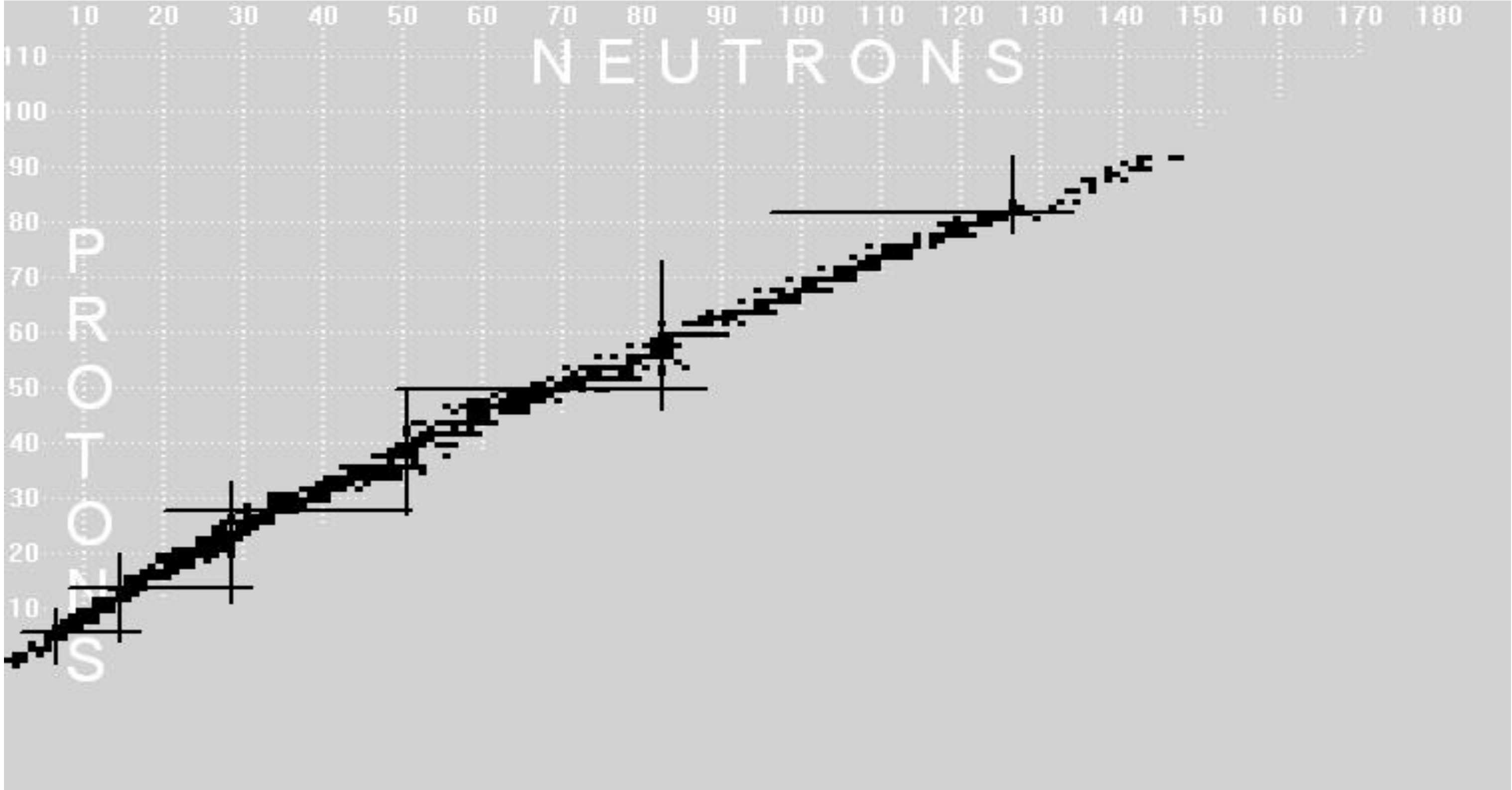
A charged drop of incompressible liquid



Liquid Drop Model: Line of Stability



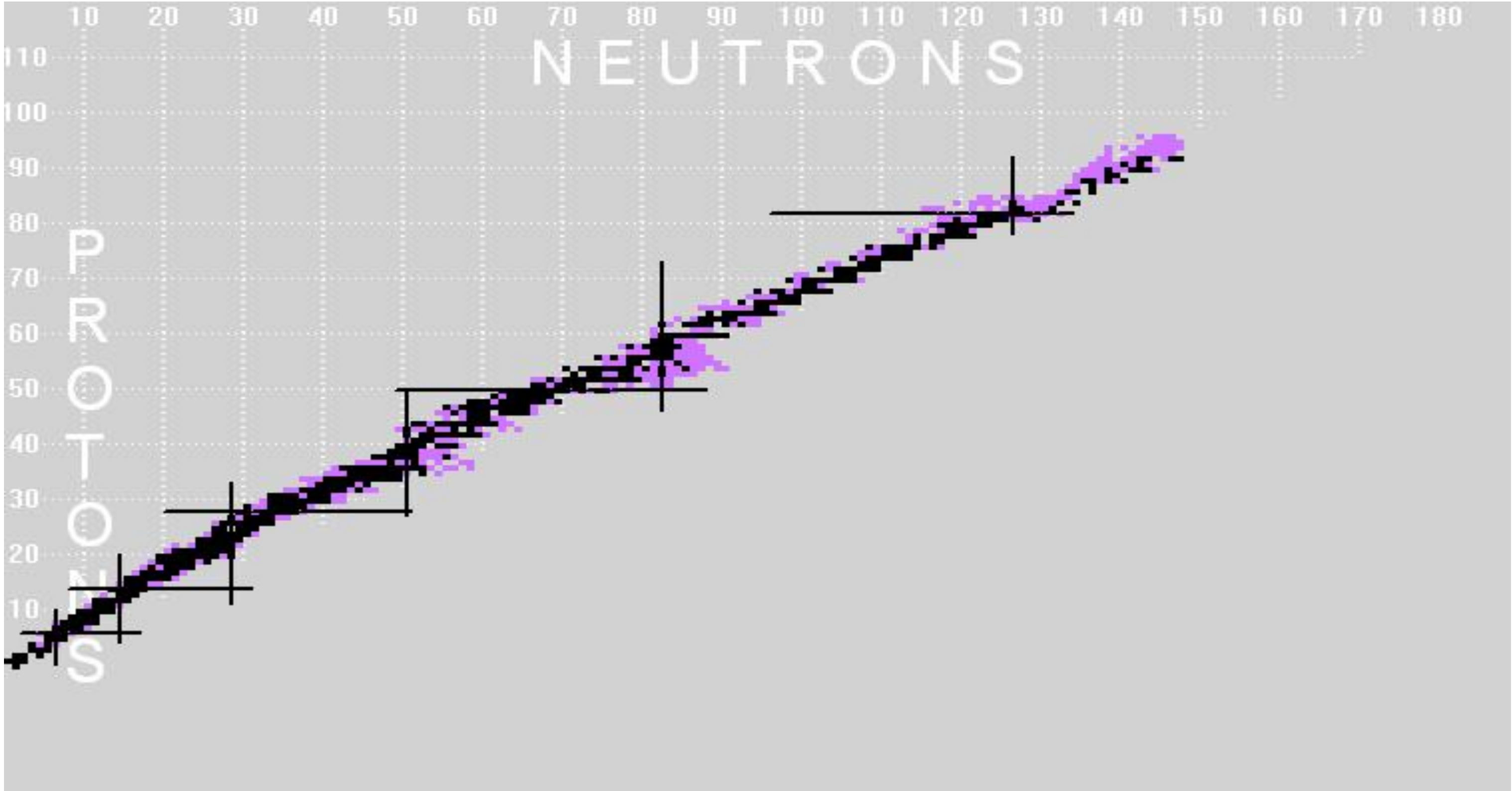
Nuclear Mass



Up to 1940!

Taken from **L. Geng**

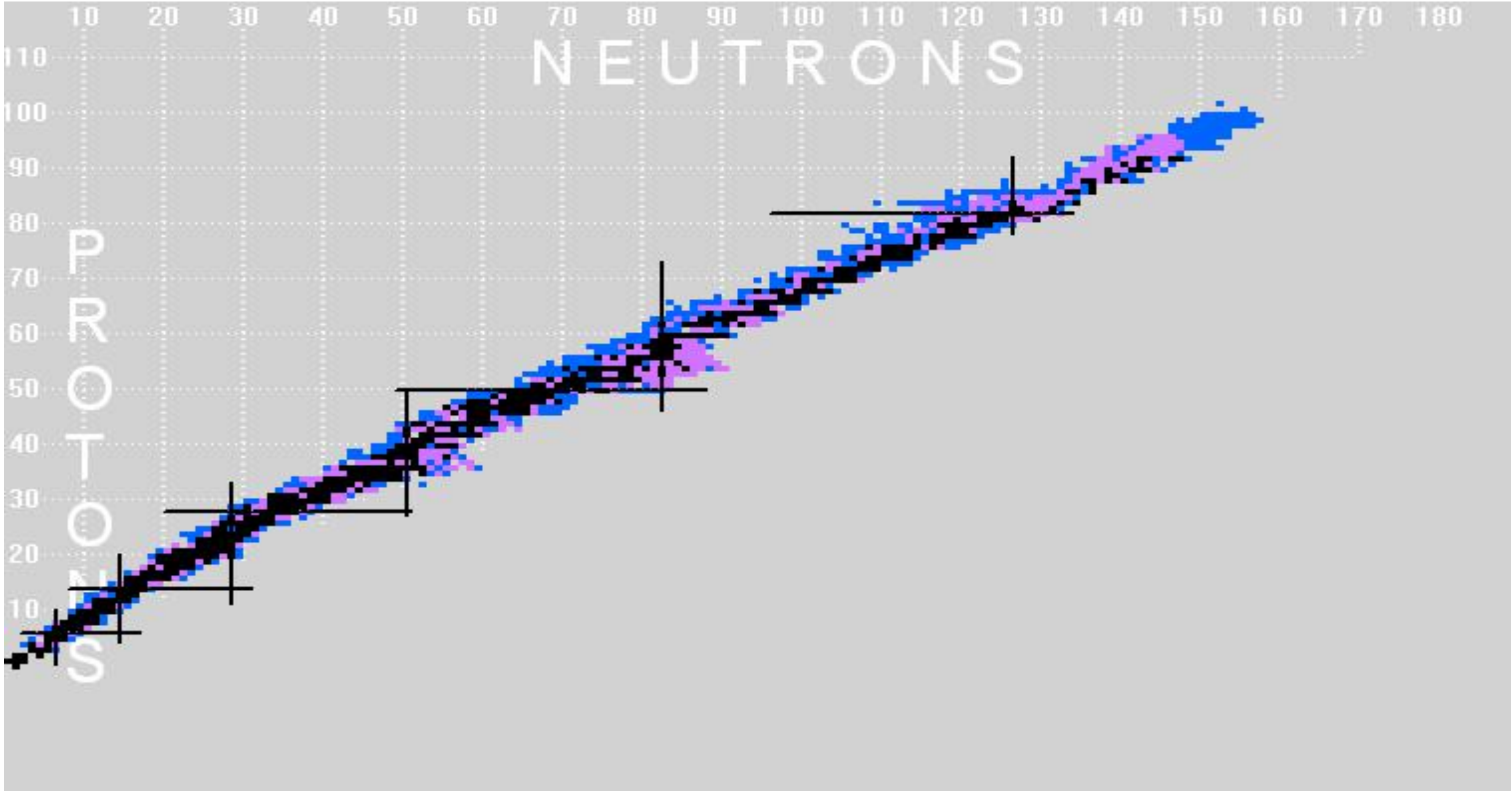
Nuclear Mass



Up to 1948!

Taken from **L. Geng**

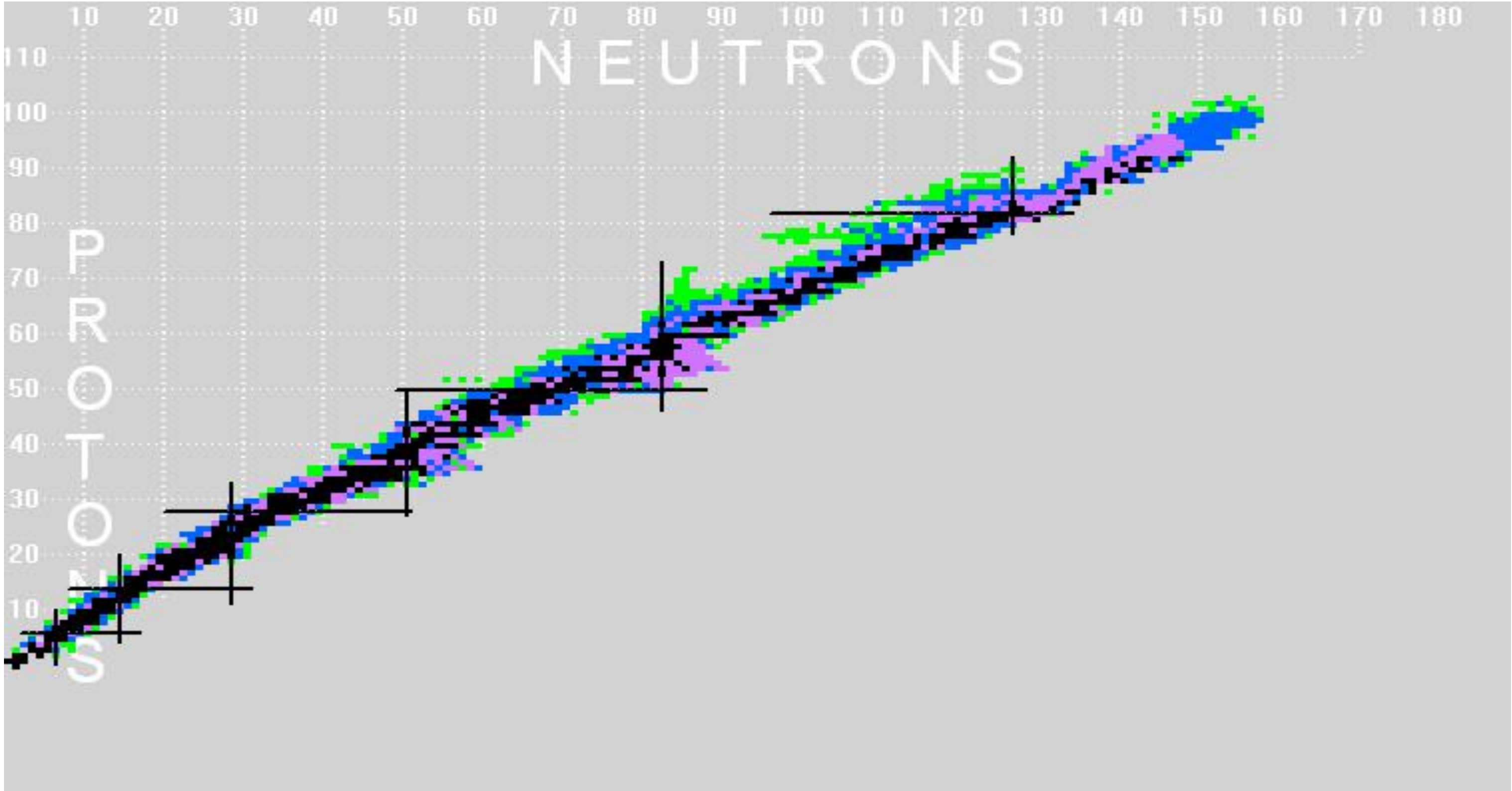
Nuclear Mass



Up to 1958!

Taken from **L. Geng**

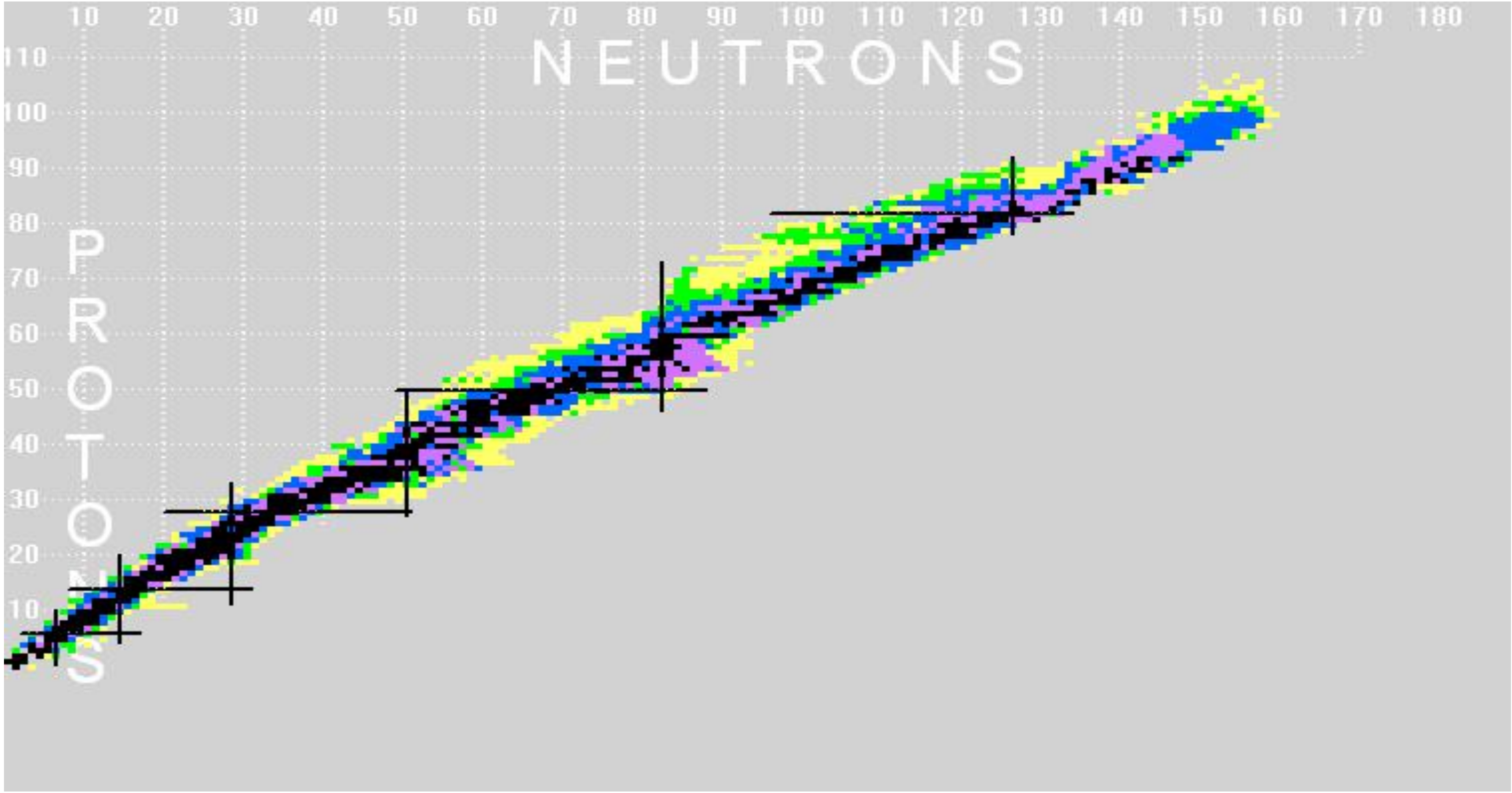
Nuclear Mass



Up to 1968!

Taken from **L. Geng**

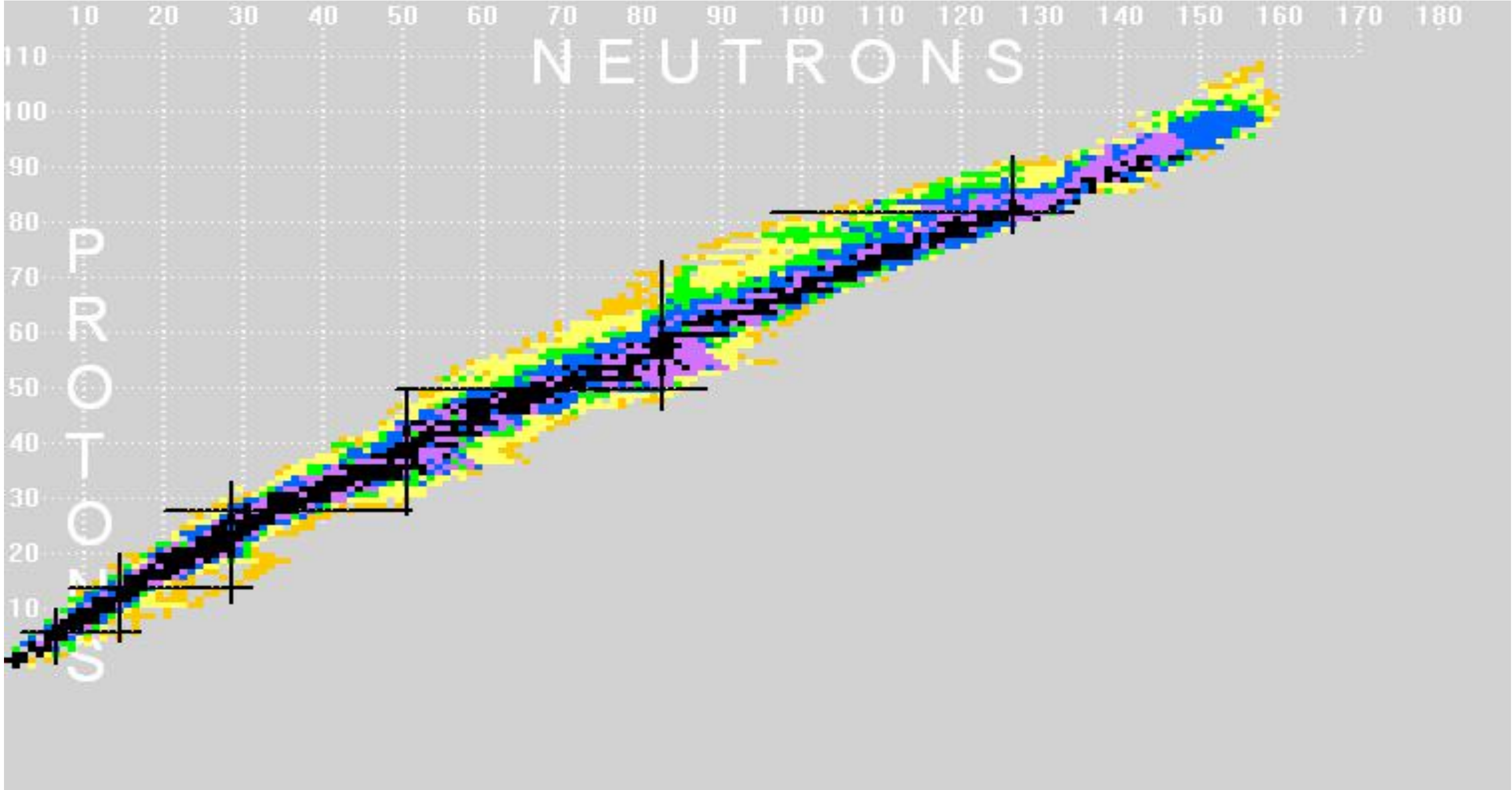
Nuclear Mass



Up to 1978!

Taken from **L. Geng**

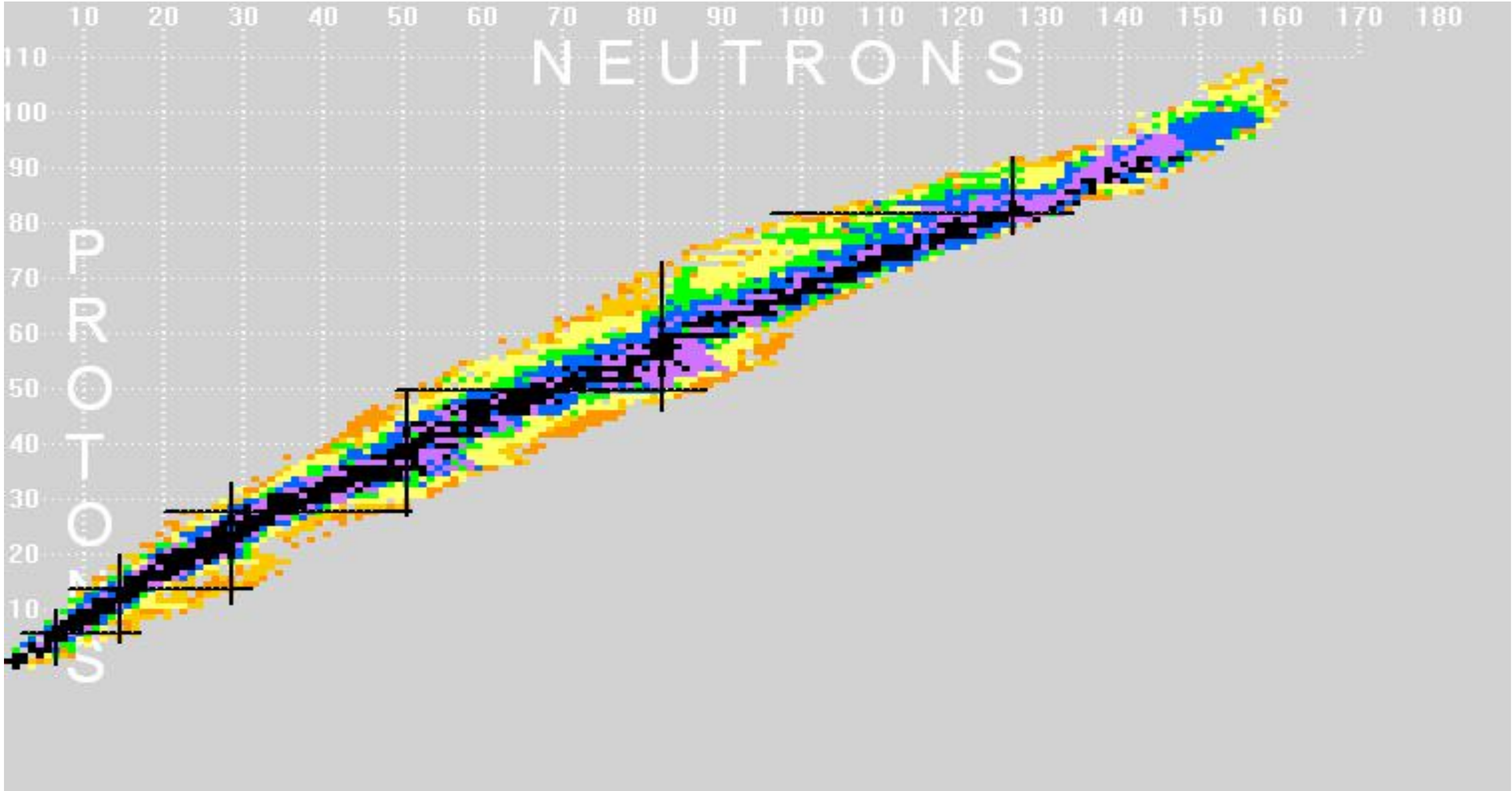
Nuclear Mass



Up to 1988!

Taken from **L. Geng**

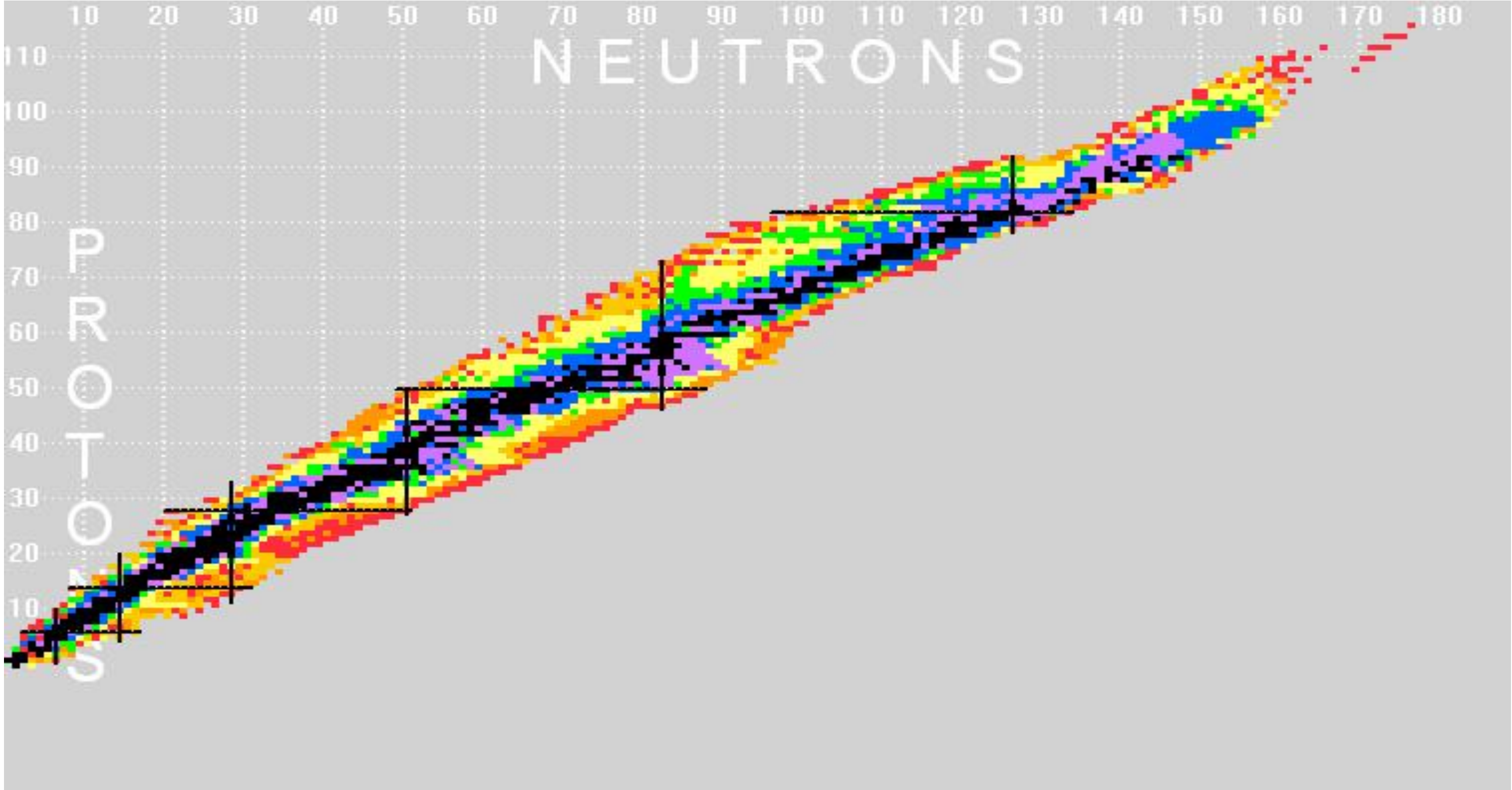
Nuclear Mass



Up to 1994!

Taken from **L. Geng**

Nuclear Mass



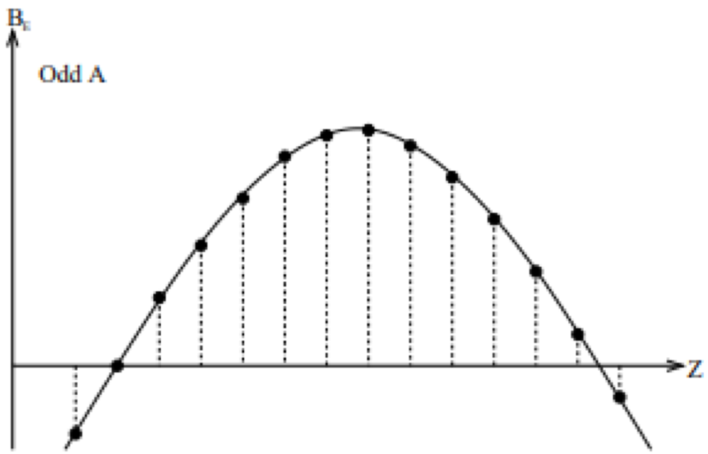
Up to 2004!

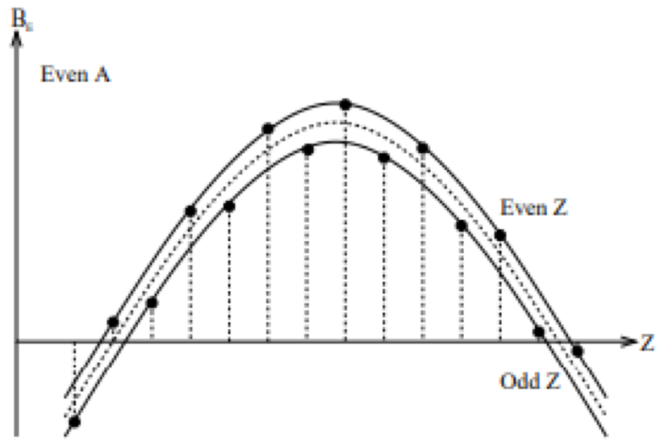
Taken from **L. Geng**

$$B = \{Zm_p + Nm_n - [m_A(^AX) - Zm_e]\}c^2$$

$$B_E = a_v A - a_s A^{2/3} - a_c \frac{Z(Z-1)}{A^{1/3}} - a_a \frac{(N-Z)^2}{A} + a_p \frac{1}{A^{1/2}}$$

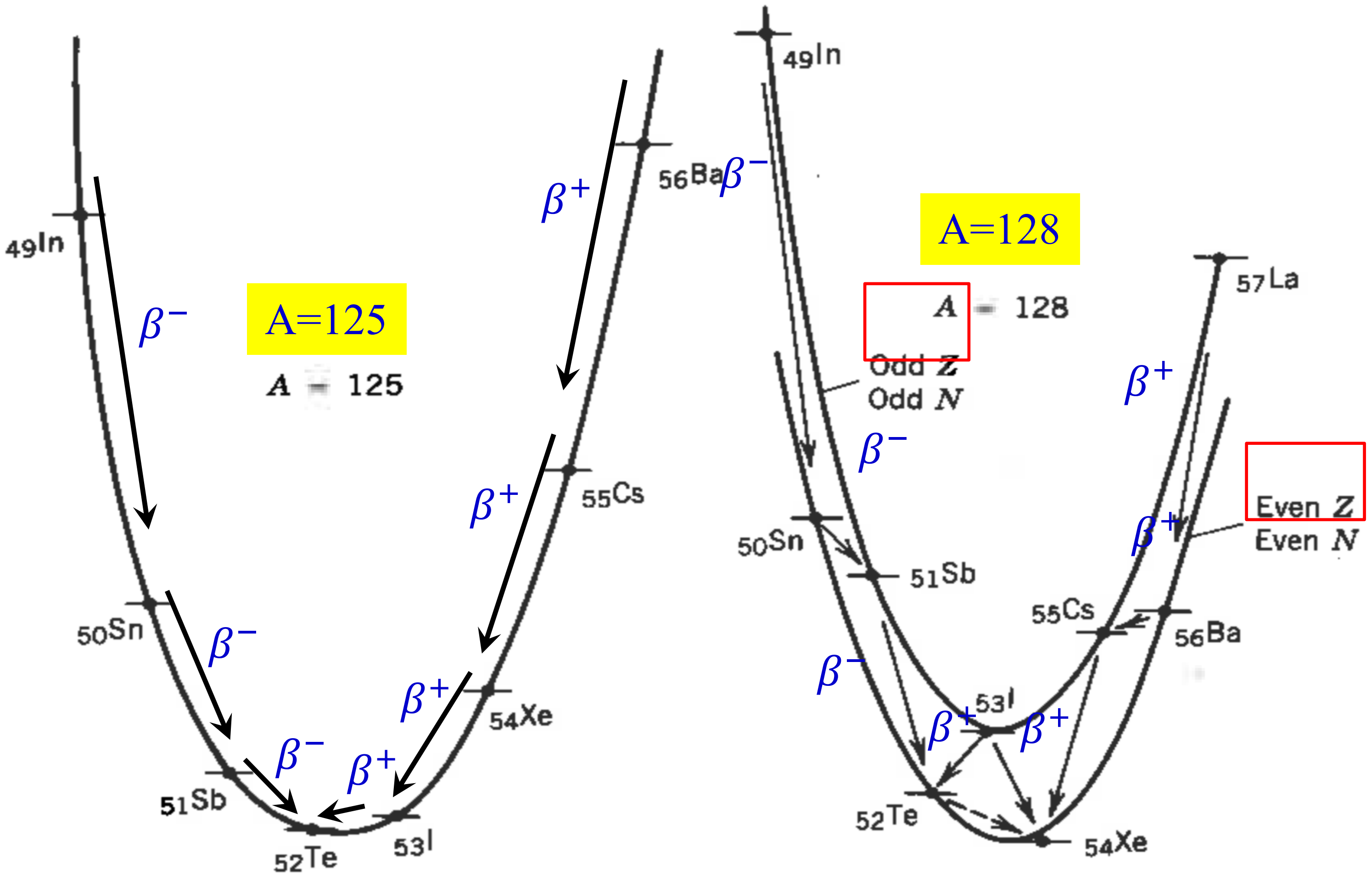
$$B_E = \left(a_v A - a_s A^{2/3} - a_a A + \frac{a_p}{A^{1/2}}\right) + \left(\frac{a_c}{A^{1/3}} + 4a_a\right) Z + \left(-\frac{a_c}{A^{1/3}} - \frac{4a_a}{A}\right) Z^2$$





Mass parabola

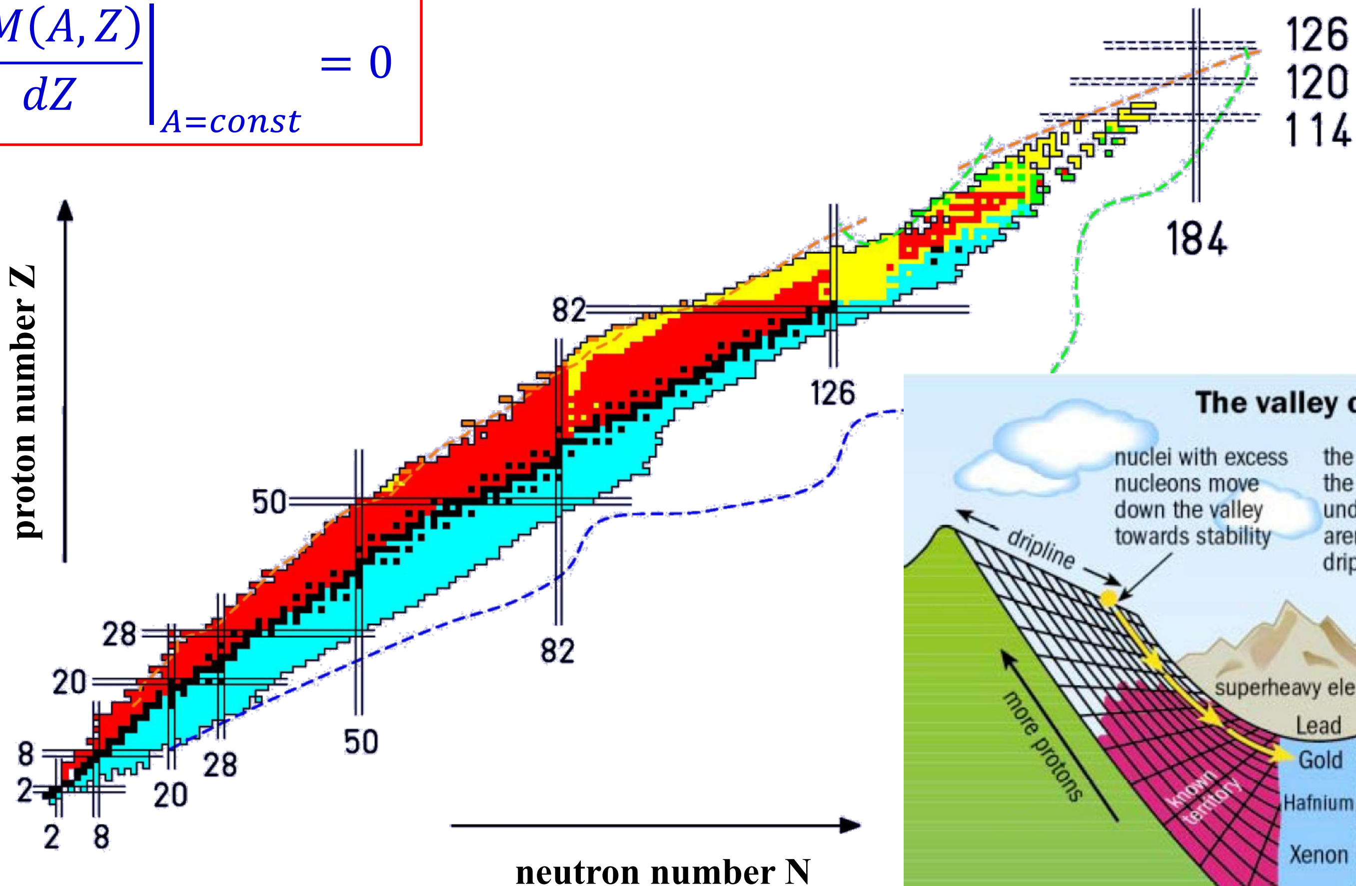
$$m_{\text{Nucleus}} = Zm_p + Nm_n - \frac{B_E}{c^2}$$

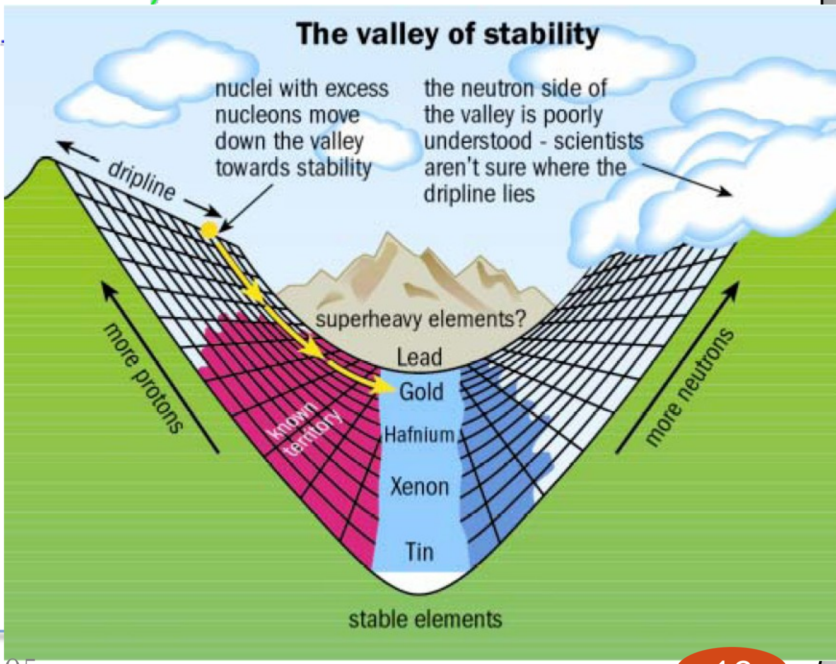


Liquid Drop Model: Line of Stability

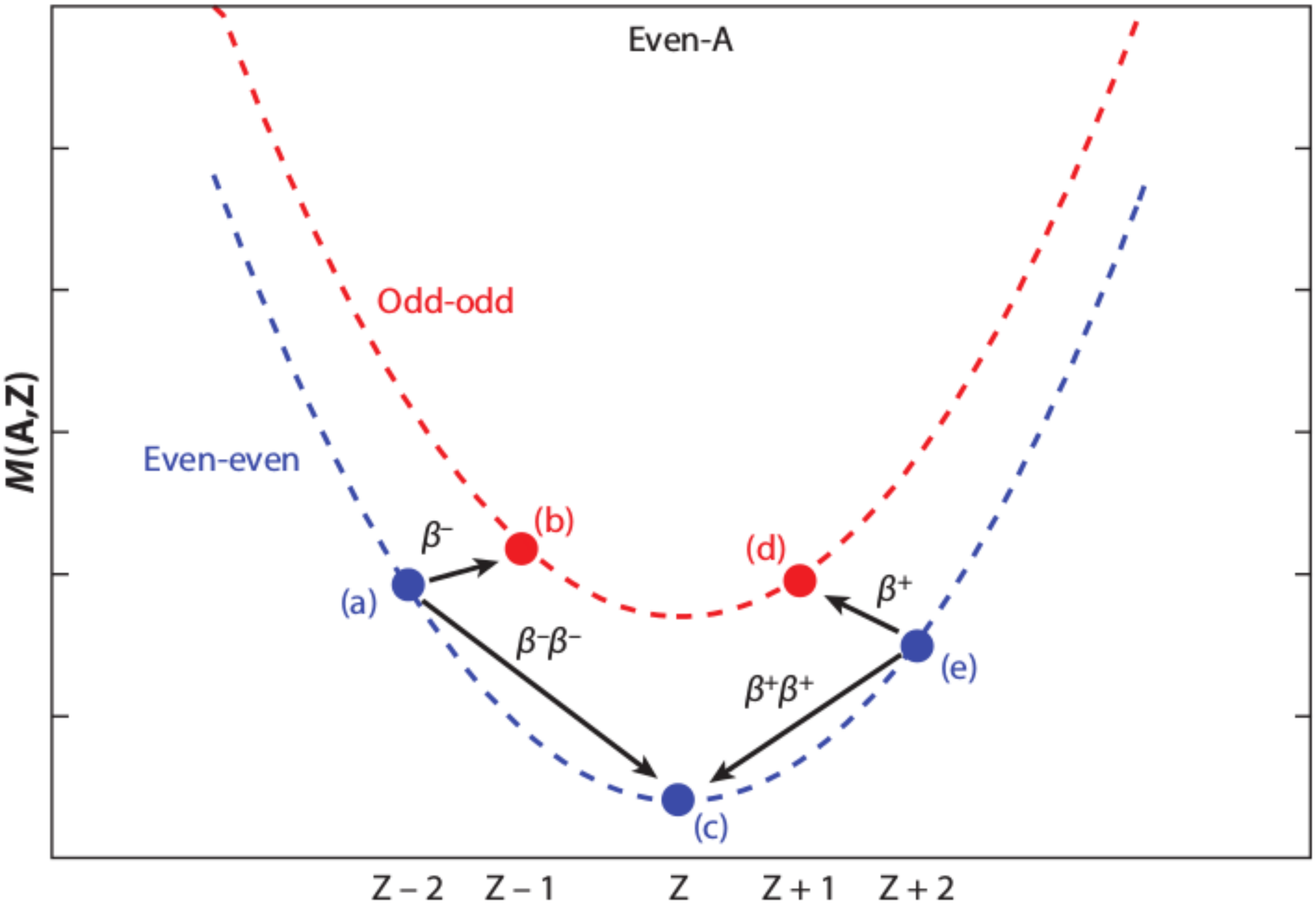
$$M(A,Z) = Z^2 \cdot \left[\frac{4 \cdot a_{asym}}{A} + \frac{a_C}{A^{\frac{1}{3}}}\right] + Z \cdot \left[M({}^1_1H) - M(n) - 4 \cdot a_{asym}\right] + A \cdot \left[M(n) - a_V + \frac{a_S}{A^{\frac{1}{3}}} + a_A\right] + \delta(A,Z)$$

$$\boxed{\left.\frac{dM(A,Z)}{dZ}\right|_{A=const} = 0}$$





Stable and radioactive nuclei



Isotopes

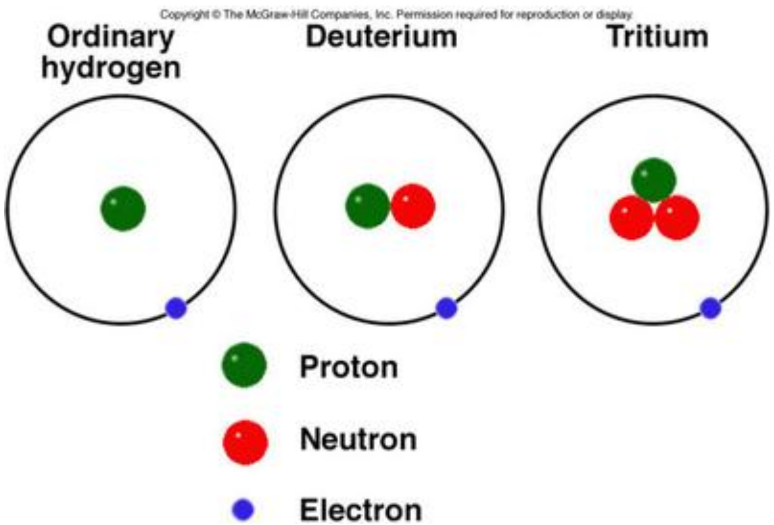
- All atoms of a given element have the same number of protons in their nuclei, but not necessarily the same number of neutrons.
- Isotopes of an element have atoms with the same **atomic number** but different **atomic masses**.
  - Their number of neutrons varies.
- All elements have isotopes.

•About 1 in every 7000 hydrogen atoms is a deuterium atom.

•Only about 2 kg of tritium of natural origin is present of the Earth, nearly all in the oceans.

•Tritium decays to a helium isotope.

•Nuclear reactions in the atmosphere caused by cosmic rays from space continually replenish the Earth's tritium.



Isotopes

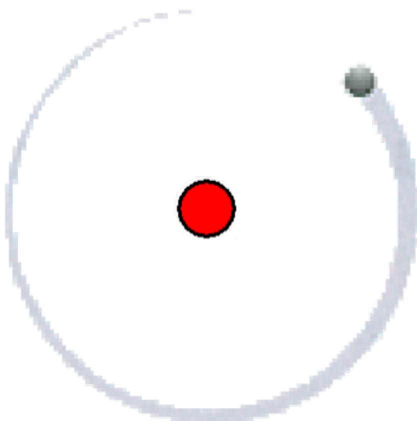
Isotopes are atoms that have identical atomic numbers but different mass numbers as the result of differing numbers of neutrons.

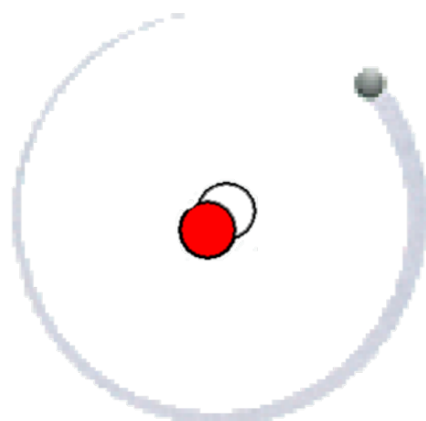
carbon-12	carbon-13
$^{12}_{6}C$	$^{13}_{6}C$

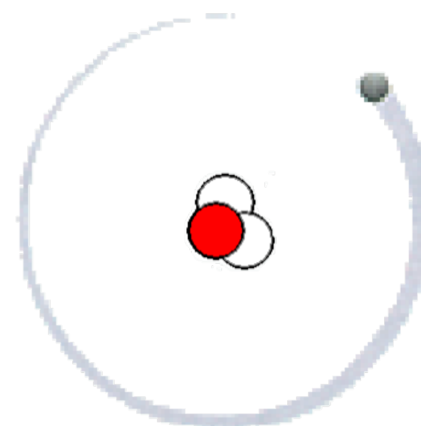
For each carbon isotope, there are how many…

electrons? **protons?** **neutrons?**

Hydrogen isotopes







ordinary hydrogen

(light hydrogen)

1 p, 0 n, 1 e

heavy hydrogen

deuterium

1 p, 1 n, 1 e

superheavy hydrogen

tritium

1 p, 2 n, 1 e

TYPES OF NUCLEIDE

1. Isotope

Isotope is one of two or more species of an element atom having the same atomic number, but differ in mass number. The examples of isotopes are carbon isotopes, namely

$${}^{12}_{6}C \text{ and } {}^{13}_{6}C$$

2. Isobar

Isobar is an atom which comes from different element but has the same mass number. The examples of the isobar are

$${}^{14}_{6}C \text{ and } {}^{14}_{7}N$$

3. Isotone

Isotone is an atom which comes from different element but has same the number of neutrons. The examples of the isotone are

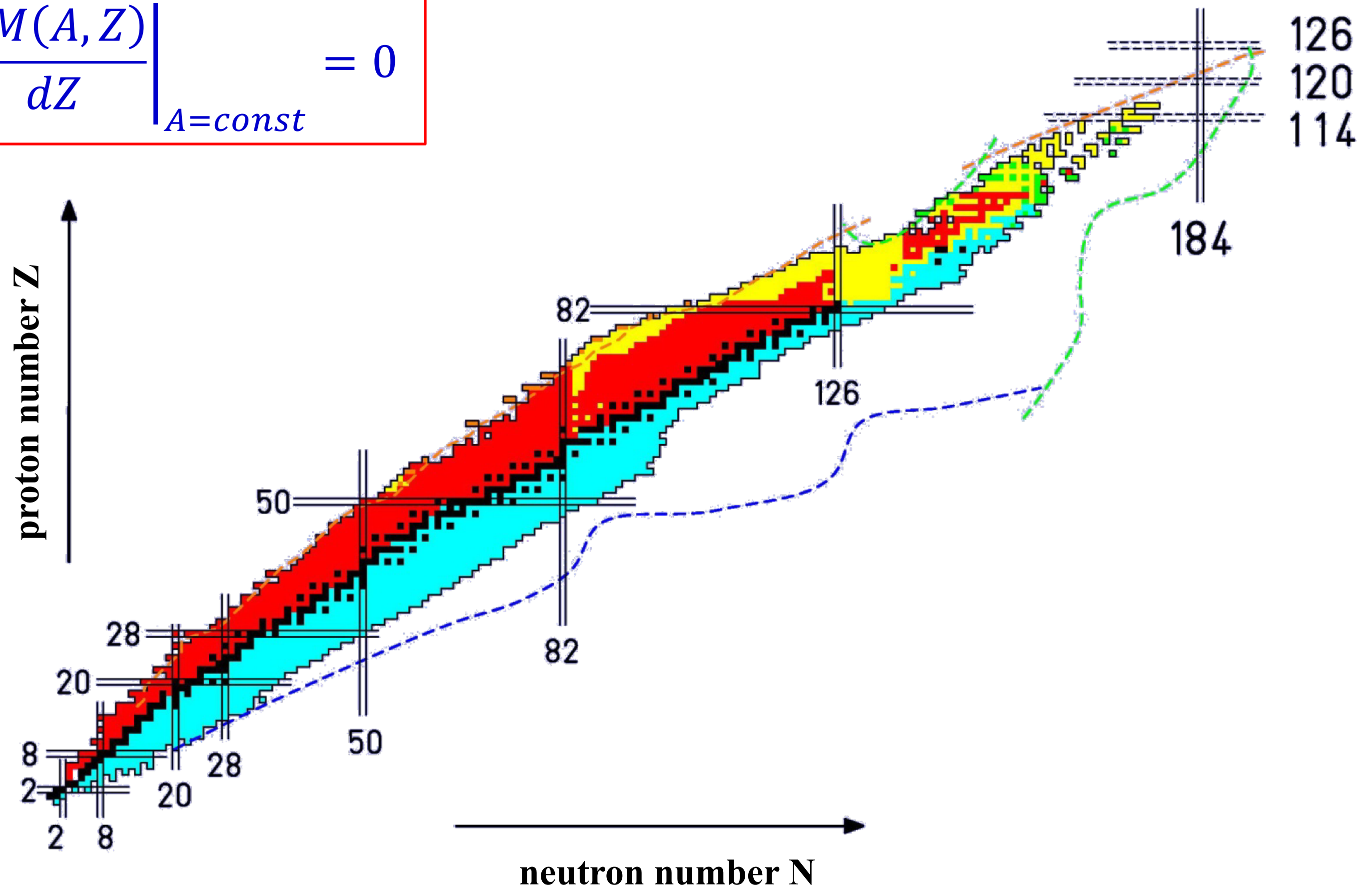
$${}^{32}_{16}S \text{ and } {}^{31}_{15}P$$

4.ISOMERS – two nuclei of the same species but different energy states, of which at least one is metastable

A charged drop of incompressible liquid

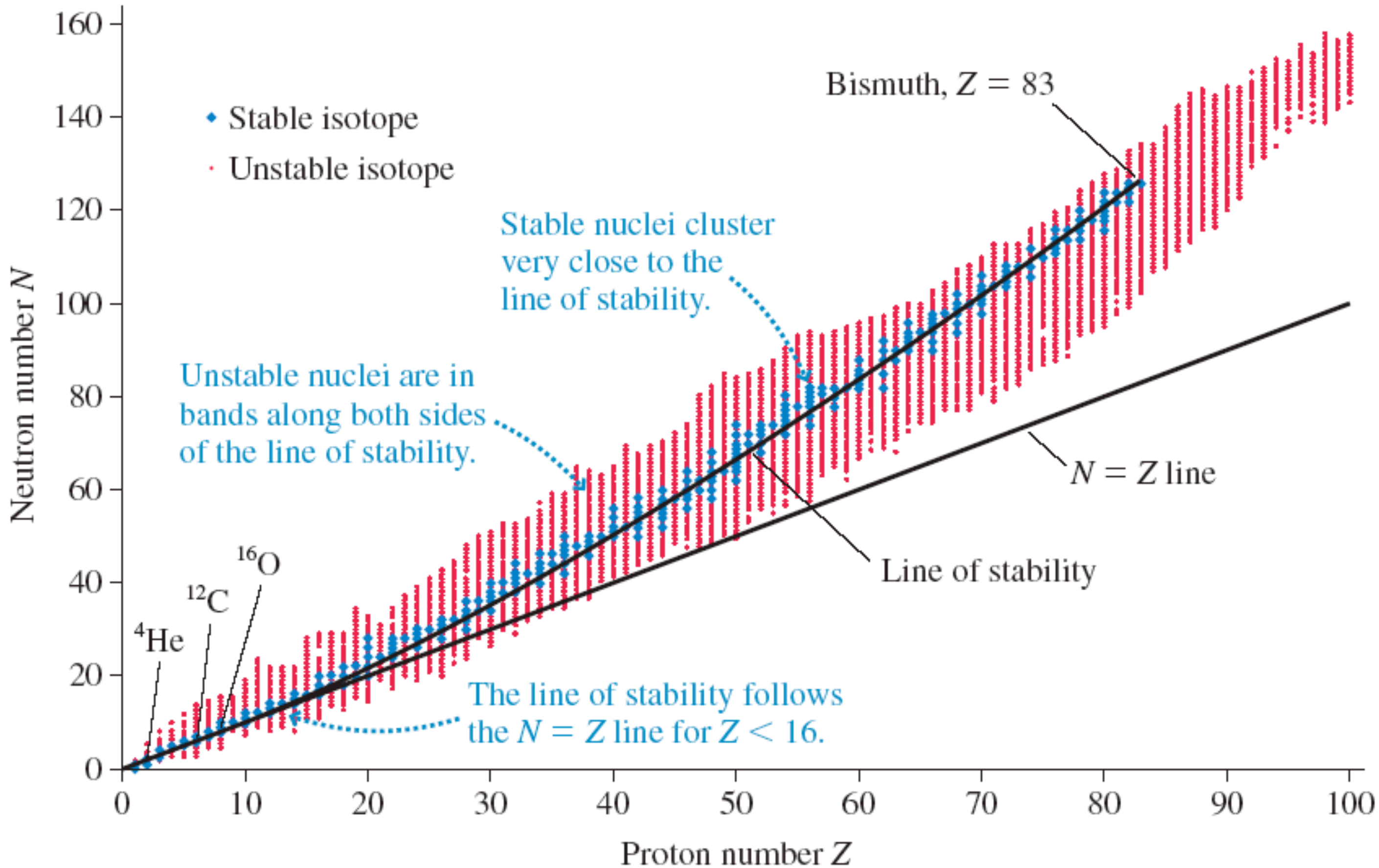
$$M(A,Z) = Z^2 \cdot \left[\frac{4 \cdot a_{asym}}{A} + \frac{a_C}{A^{\frac{1}{3}}}\right] + Z \cdot \left[M(\,^1H) - M(n) - 4 \cdot a_{asym}\right] + A \cdot \left[M(n) - a_V + \frac{a_S}{A^{\frac{1}{3}}} + a_A\right] + \delta(A,Z)$$

$$\boxed{\left.\frac{dM(A,Z)}{dZ}\right|_{A=const} = 0}$$



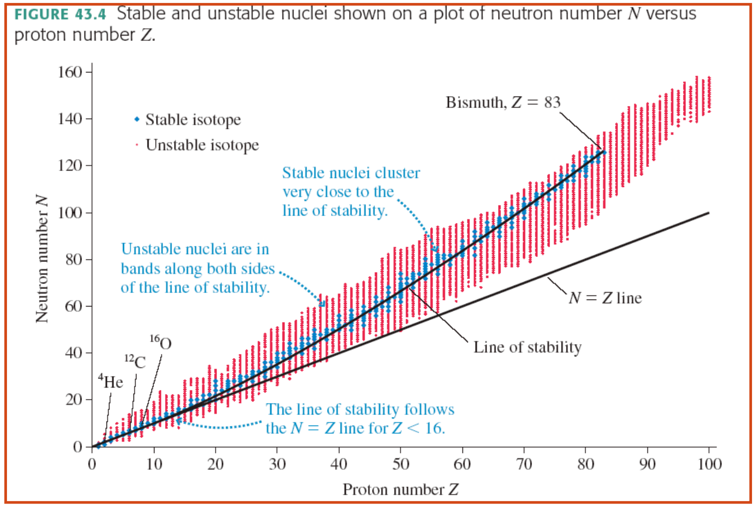
Nuclear Stability: The chart of Nuclides

FIGURE 43.4 Stable and unstable nuclei shown on a plot of neutron number N versus proton number Z.



As the number of protons increase, the number of neutrons must increase even more for stability All elements with >83 protons are unstable

Nuclear Stability: The chart of Nuclides



Isotopes

Atoms having the same number of protons (Z) but different number of neutrons (N) are isotopes.

Isobars

Atoms having the same mass number (A) are isobars.

Isotones

Atoms having the same number of neutrons (N) but a different number of protons (Z) are isotones.

Isomers

Atoms of the same element (same Z and N) but which are in different excited states are isomers.

- As the number of protons, ***Z***, increases the neutron to proton ratio required for **nuclear stability** also increases.
- Nuclides with **Z > 83** (Bismuth) are unstable.
- **Light nuclides** are stable when the neutron to proton ratio is close to one.
- **Even numbers** of protons and neutrons seem to favor nuclear stability.
- Certain specific numbers of protons or neutrons produce highly stable nuclides. The **magic numbers** are **2, 8, 20, 28, 50, 82,** and **126**.

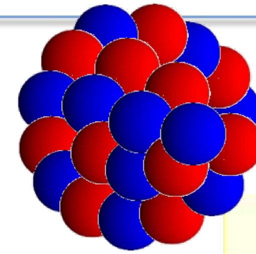
Isotopic abundance

- Everywhere on Earth, elements are composed from same isotopes in fixed relative proportions.
- These proportions are called **isotopic abundance** of an element.

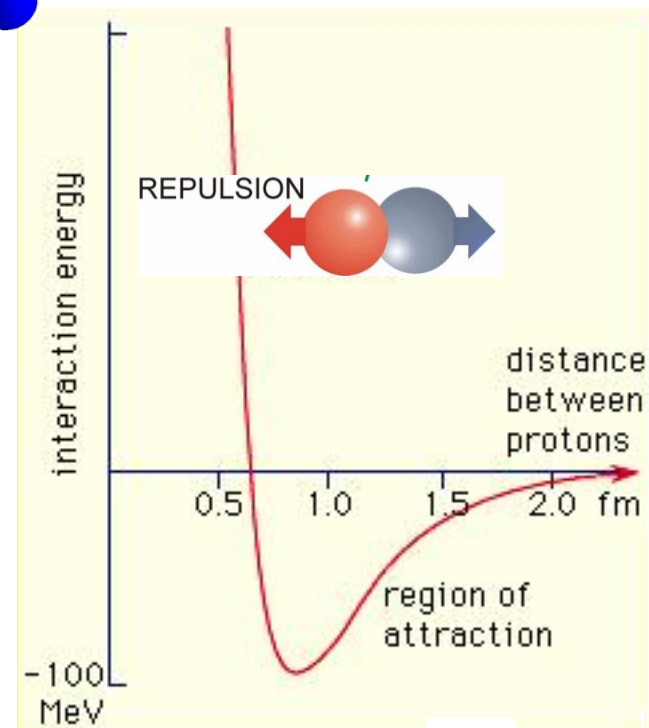
Element	Isotopes and their relative proportions
Hydrogen	^{1}H – 99.985% ^{2}H – 0.015%
Boron	^{10}B – 19.8% ^{11}B – 80.2%
Aluminium	^{27}Al – 100%
Iron	^{54}Fe – 5.8% ^{56}Fe – 91.72% ^{57}Fe – 2.2% ^{58}Fe – 0.28%
Uranium	^{234}U – 0.0054% ^{235}U – 0.72% ^{238}U – 99.2746%

Forces acting in nuclei

- **Coulomb Force** Reppels Protons



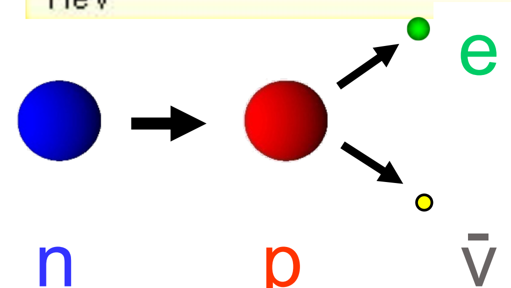
Protons charge = +
Neutron charge = 0



- **Strong interaction** ("nuclear force") causes **binding** between nucleons (=attractive).

It is stronger for proton-neutron (pn) systems than pp- or nn-systems

- Neutrons alone form no bound states (exception: neutron stars (gravitation!)

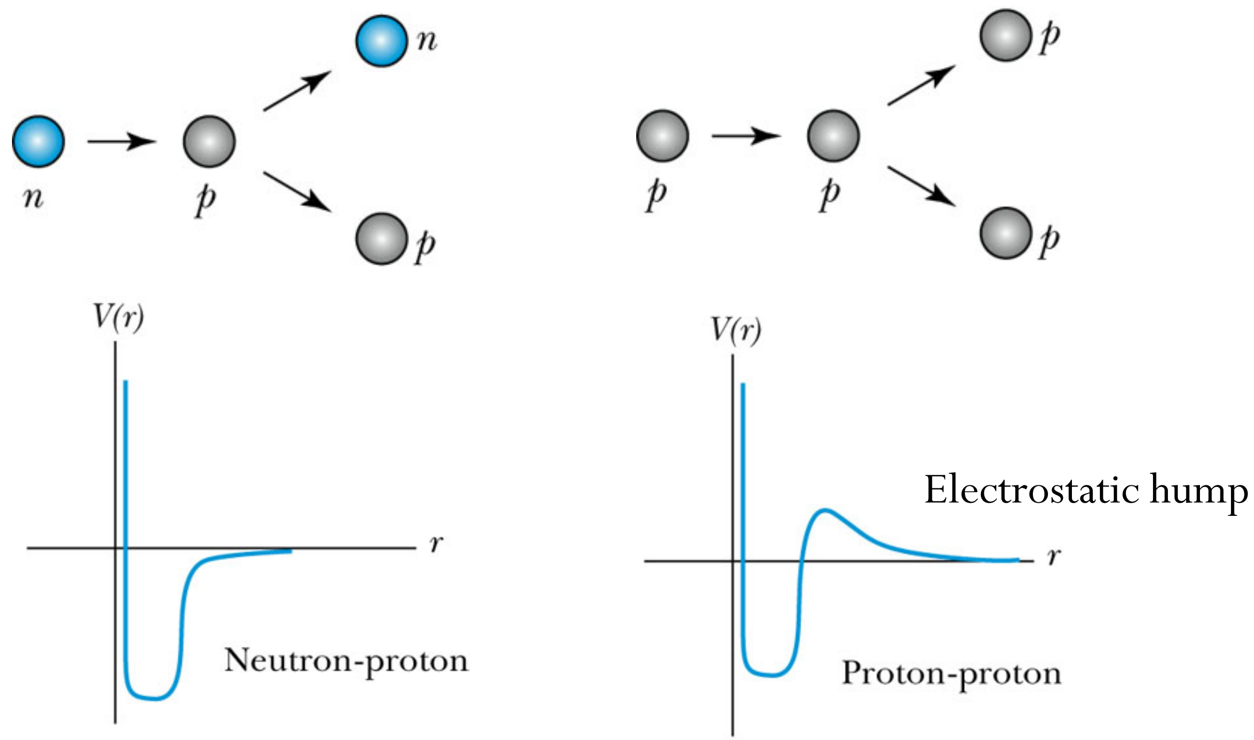


- **Weak interaction** causes β-decay

Nuclear Force

- Neutron + proton (*np*) and proton + proton (*pp*) elastic collisions.

Very high density in the nucleolus, all nuclei are constantly moving about and scatter of reach other

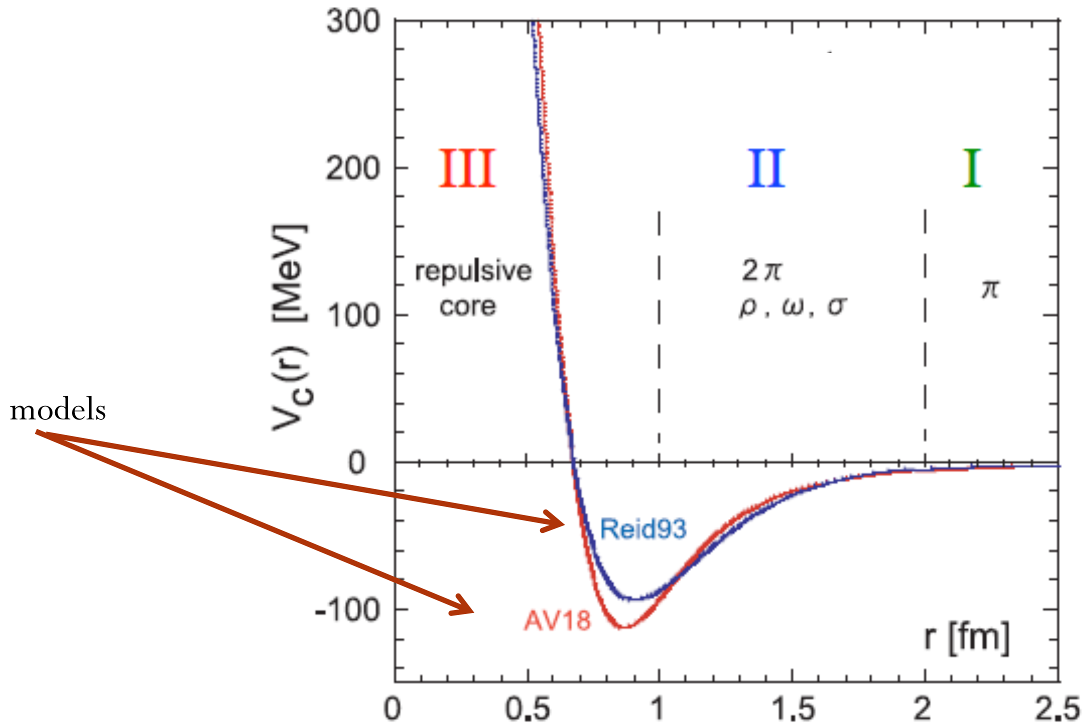


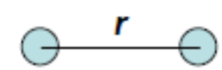
The nuclear potential energy function for two particles, similar for many particles

Properties of nuclear interaction

- Has a very short range (fm = 10^{-15} m)
- Consists mostly of attractive central potential
- Is charge symmetric
- Is nearly charge independent (similar p and n)
- Becomes repulsive at short distances

Nucleon-nucleon interaction





I Long range part

one pion exchange potential

II Medium range part

σ, ρ, ω exchange

2π exchange

III Short range part

repulsive core (RC)

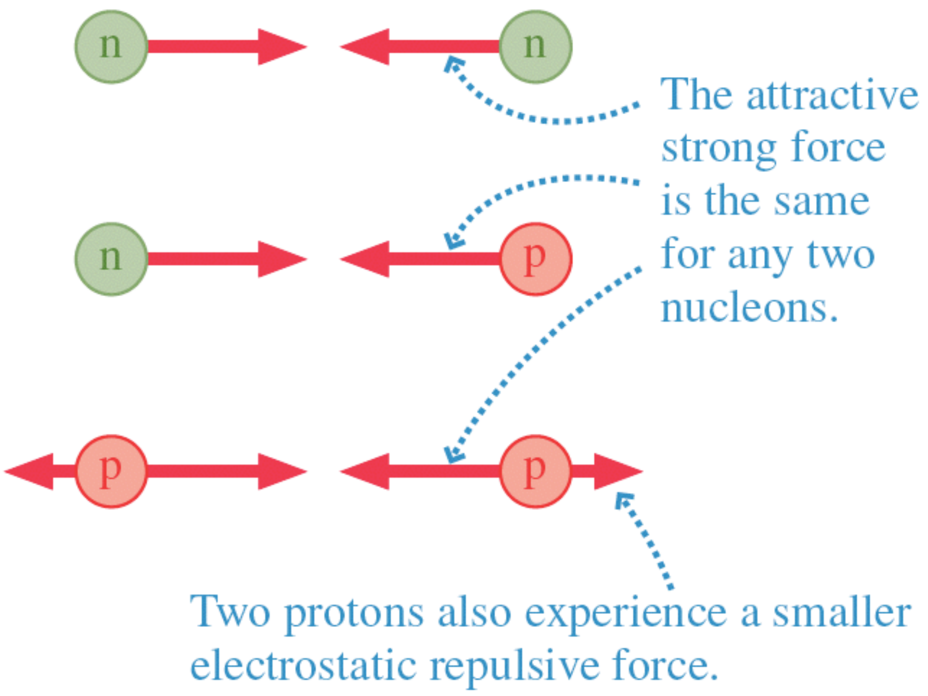
quark ?

The Strong Force

The strong force has four important properties:

1. It is an *attractive* force between any two nucleons.
2. It does not act on electrons.
3. It is a *short-range* force, acting only over nuclear distances.
4. Over the range where it acts, it is *stronger* than the electrostatic force that tries to push two protons apart.

FIGURE 43.7 The strong force is the same between any two nucleons.



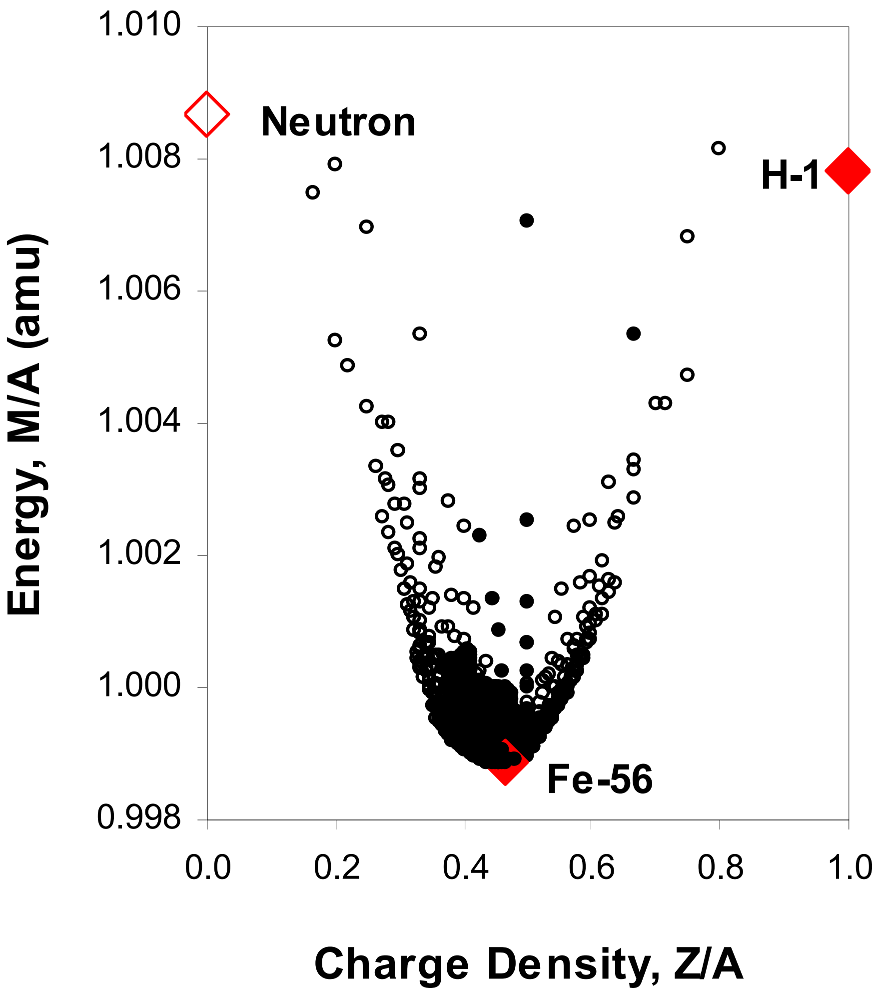
Thermodynamics

When the energies of all 2850 isotopes are plotted vs. their charge density, the nuclides form a parabola.

The free neutron has the highest M/A & is unstable. It decays to form a proton, ^{1}H, in 10.6 minutes.

As the radioactive elements decay, they go from higher M/A values to lower M/A values thus becoming more thermodynamically stable.

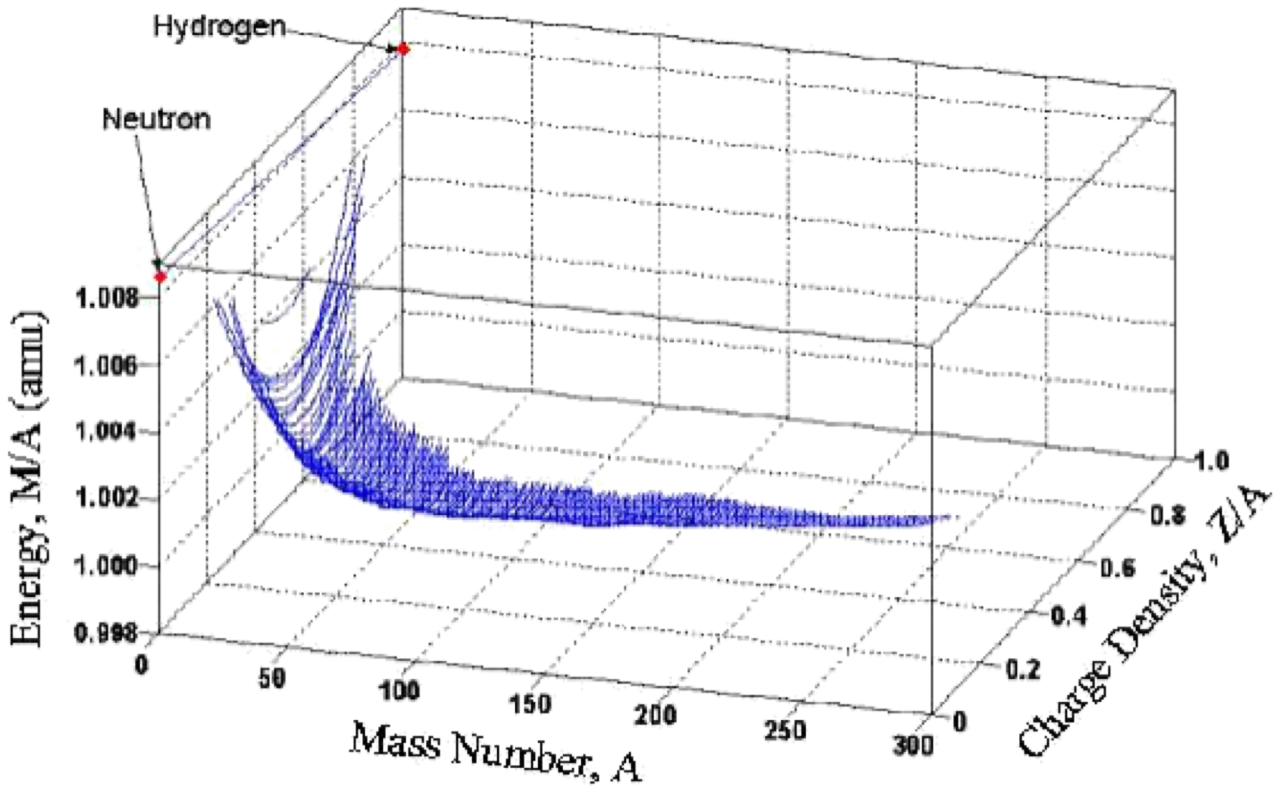
The ^{56}Fe atom has the lowest value of M/A. So all elements on the periodic table beyond ^{56}Fe, must have been formed by a Super Nova.



The open symbols are radioactive nuclides; the filled symbols are stable and long lived.

Thermodynamics

Taken from Internet

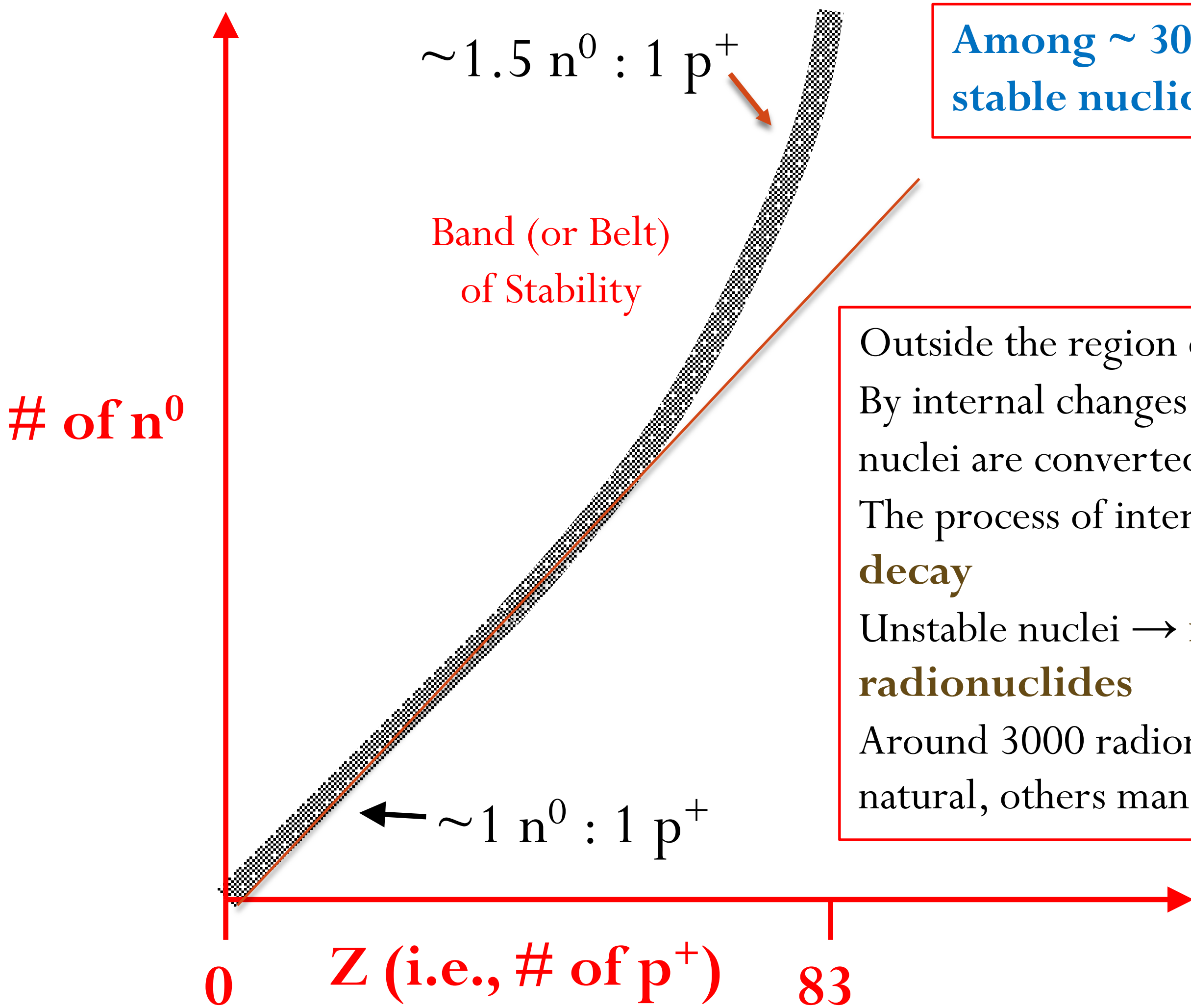


The "Cradle of the Nuclides" results when the chart of the nuclides and the parabolas are combined into one 3-D graph. It shows the ground states of all stable and radioactive nuclides.

The stable and long-lived nuclides are located in the valley. The radioactive nuclides or those easily destroyed by fusion or fission occupy higher positions in the cradle.

Nuclear Stability: The chart of Nuclides

Nucleons are held together by the strong force.



Among ~ 3000 nuclides there are 237 stable nuclides

Outside the region of stability, the nuclei are unstable

By internal changes and particle emissions unstable nuclei are converted to stable nuclei

The process of internal changes → **radioactive decay**

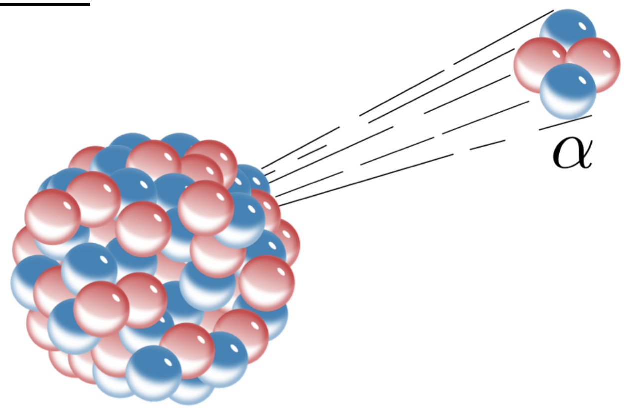
Unstable nuclei → **radioactive nuclides** or **radionuclides**

Around 3000 radionuclides are known (~ 100 natural, others man-made)

At Z > 83, none are stable (i.e., all are radioactive).

Nuclear Stability

The higher the BE between nucleons, the more E/work needed to split it up, the more <u>stable</u> the nucleus – the less likely to decay (fall apart)



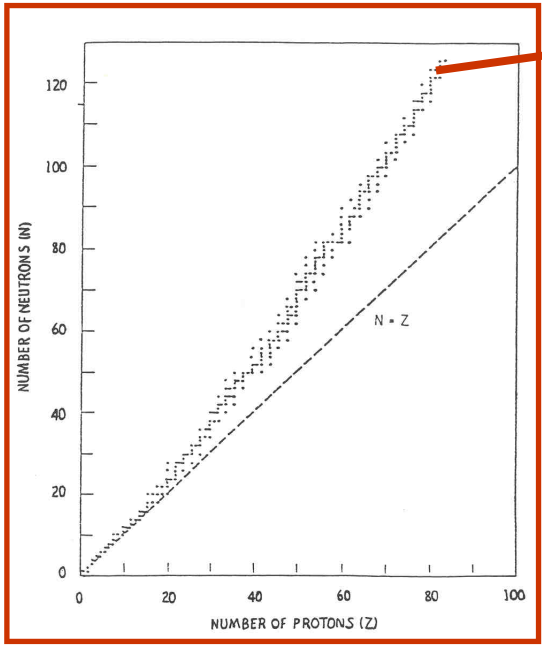
More massive nuclei require extra neutrons to overcome the Coulomb repulsion of the protons in order to be stable.

- The nuclear force is an extremely short-range force
- It acts over a maximum distance of about two proton diameters
- The nuclear force is responsible for the binding energy that holds the nucleus together

Attractive nuclear forces are limited in range and primarily operate between nearest neighbors ("saturation"), so there is a nuclear size beyond which neutrons are unable to overcome the proton-proton repulsion.

Nuclear Stability

- A stable or non-radioactive nuclide is one whose atoms do not decay
- If one plots the stable nuclei, an interesting pattern emerges (shown in next slide)
- The graph in the next slide shows a plot of neutron number N vs atomic number Z for the stable nuclei



N > Z

Protons in the nucleus are positively charged and thus tend to repel each other. Were it not for the poorly understood nuclear force, the nucleus would fly apart due to this electrical repulsion. The nuclear force keeps the nucleus together.

Nuclear Stability

- For the heaviest stable nuclei, N is about 1.5 times Z
- The presence of the extra neutrons overcomes the positively charged protons' tendency to repel each other and disrupt the nucleus
- The nucleus is held together by a poorly understood force, the Nuclear Force
- Nuclei which do not fall on the line of stability tend to be unstable or "radioactive": they are called "radionuclides"
- A few radionuclides do fall on the line of stability but their rate of decay is so slow that for all practical purposes they are stable
- Radionuclides undergo a process called radioactive transformation or disintegration
- In this process, the nucleus emits particles to adjust its neutron (N) to proton (Z) ratio
- This change in the N to Z ratio tends to move the radionuclide toward the line of stability

Nuclear Stability

Kinetic Stability

- One refers to whether a nuclide *will undergo spontaneous nuclear decay*.
  - Does the nuclide decay (unstable, radioactive) or not (stable)?
  - The "valley of stability"

Ex. ^{206}Pb is a stable nuclide. ^{238}U is radioactive

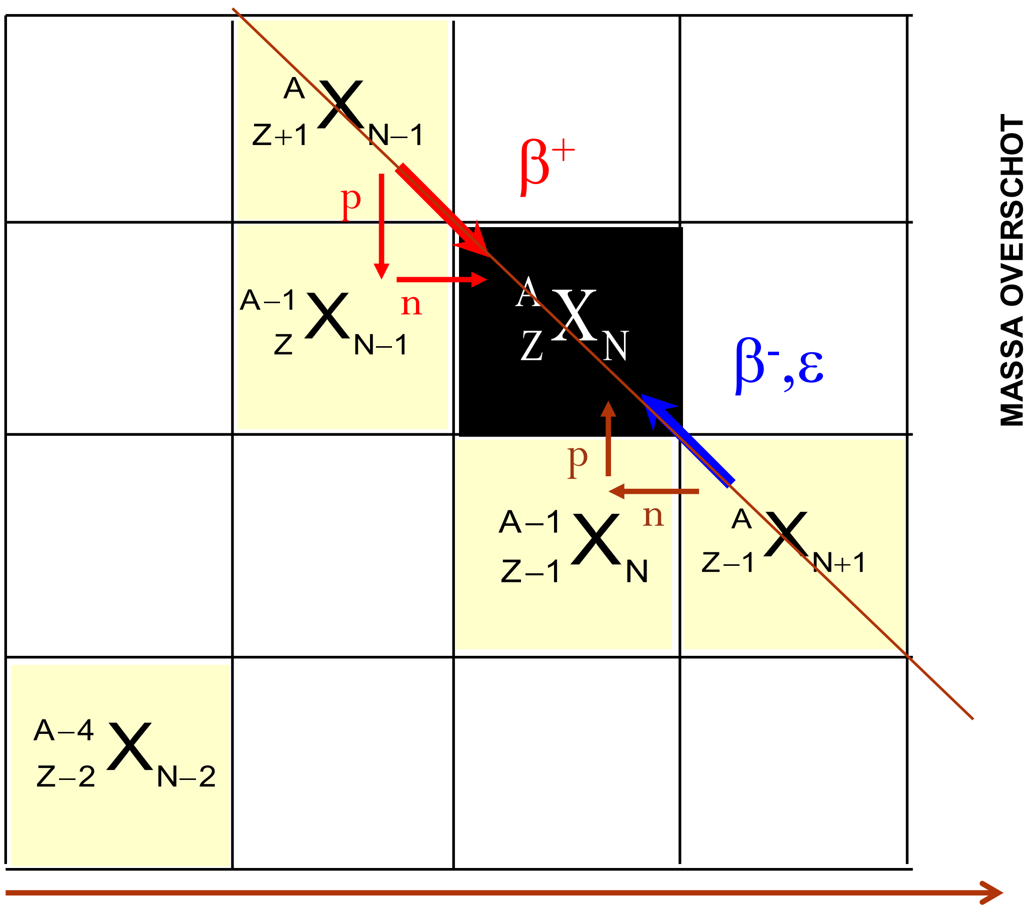
Thermo-dynamic Stability

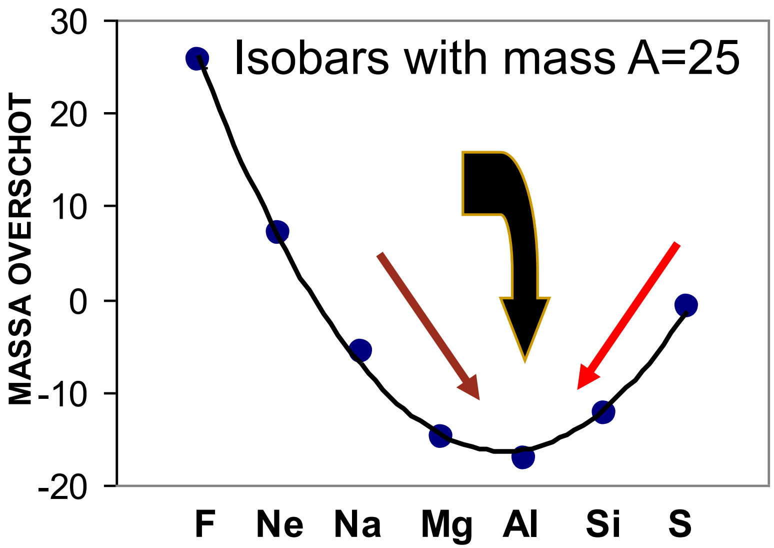
- One refers to how stable one nuclide is *compared to another*, in terms of "overall configuration of nucleons"
  - Applies to all nuclides, radioactive or not
  - Assessed by **Binding energy per nucleon**

Ex. ^{56}Fe is more stable than ^{206}Pb or ^{2}H

Nuclear Decay

- In nature → systems aim at a minimal energy
- NUCLEAR MASS = SUM OF NUCLEON MASSES – (binding)**energy !**
- **Along isobaric chain → decay towards isobar lowest mass (= energy)** $E=mc^2$



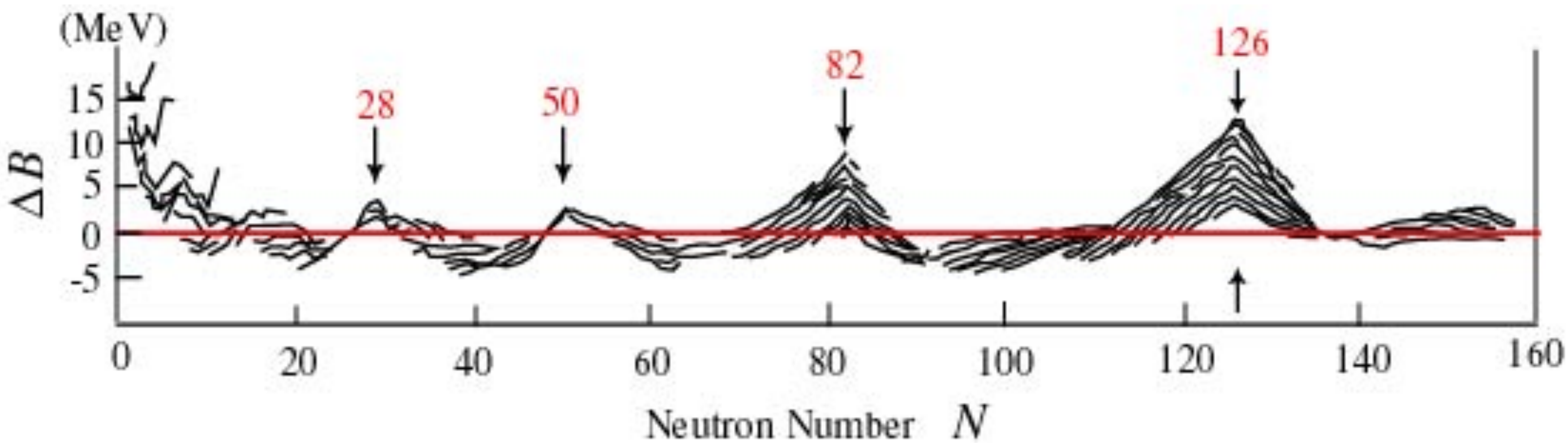


Al is most stable A=25 isotope

Isobars = same A
but not exactly same mass

Deviation from Experimental Results

ΔB = Binding energy (experiment) – Weizsaecker-Bethe mass formula



$^{4}_{2}\mathrm{He}_{2}$ (Helium)

$^{16}_{8}\mathrm{O}_{8}$ (Oxygen)

$^{40}_{20}\mathrm{Ca}_{20}$ (Calcium)

$^{208}_{82}\mathrm{Pb}_{126}$ (Lead)

- proton: 2, 8, 20, 28, 50, 82, 114
- neutron: 2, 8, 20, 28, 50, 82, 126, 184

Deviation from Liquid Drop Model