Nuclear Physics

Phys 371

Fall 2020

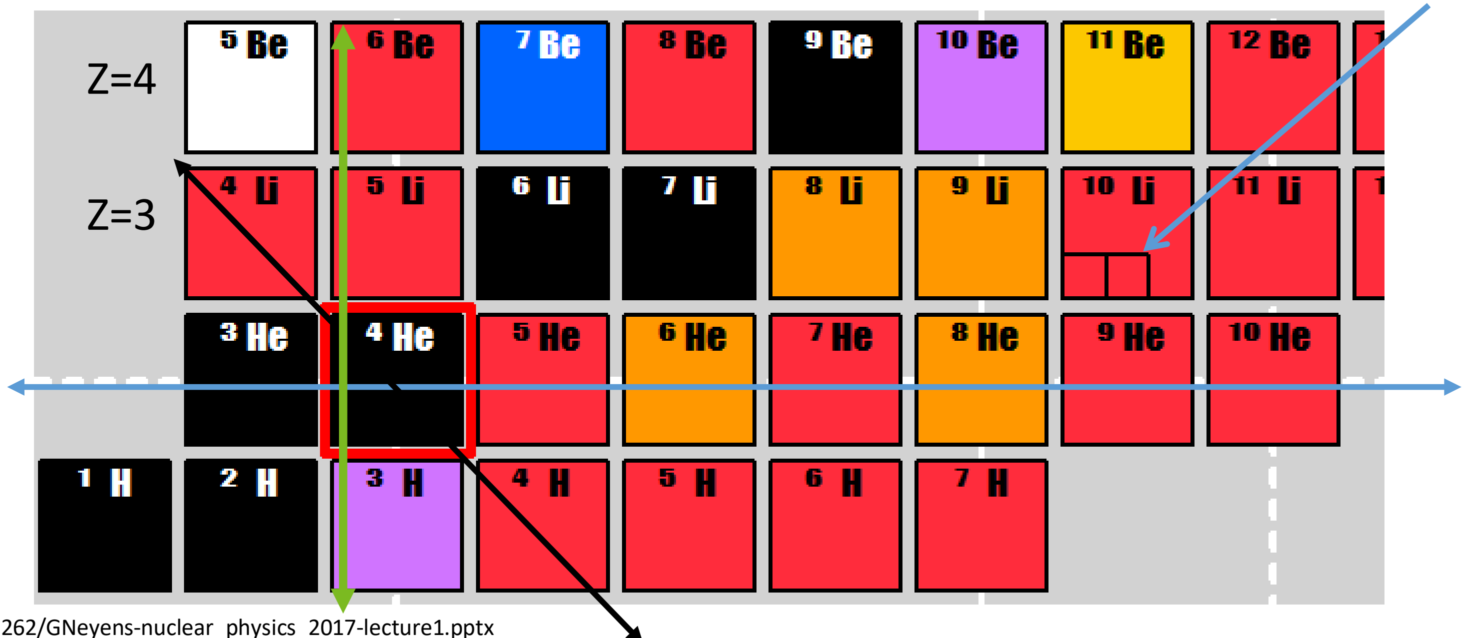
Terminology

- Nucleus/nuclide:

$${}^{A}_{Z}\mathbf{X}_{N}$$

- Z protons → element X
- N neutrons
- atomic number A = N+Z

- Nucleons: protons and neutrons inside the nucleus
- **Isotopes**: nuclides with the **same number of protons**, but not neutrons
- **Isotones**: nuclides with the **same number of neutrons**, but not protons
- **Isobars**: nuclides with the **same number of nucleons** (but different Z and N)



Isomers = long-lived excited nuclear states

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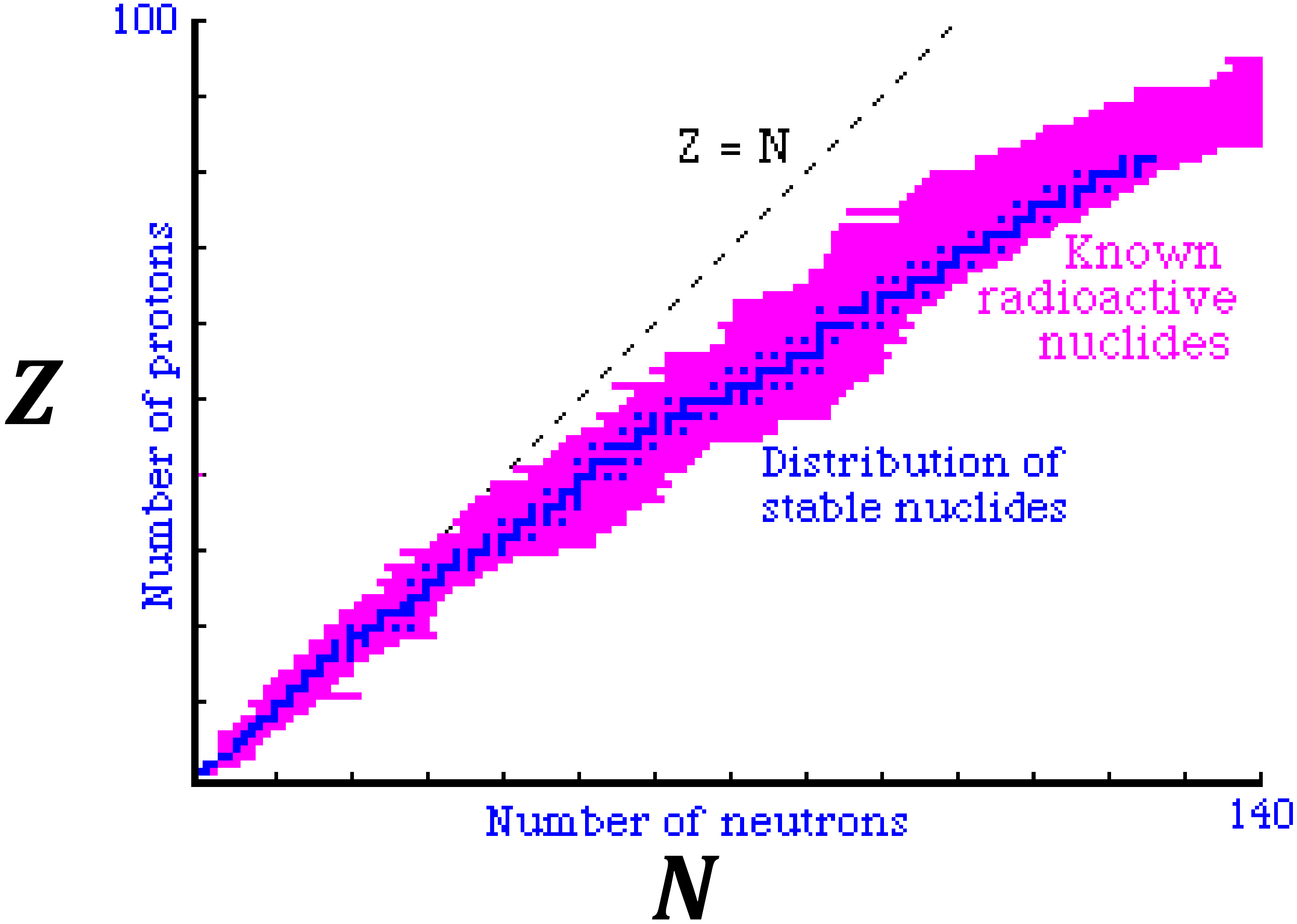
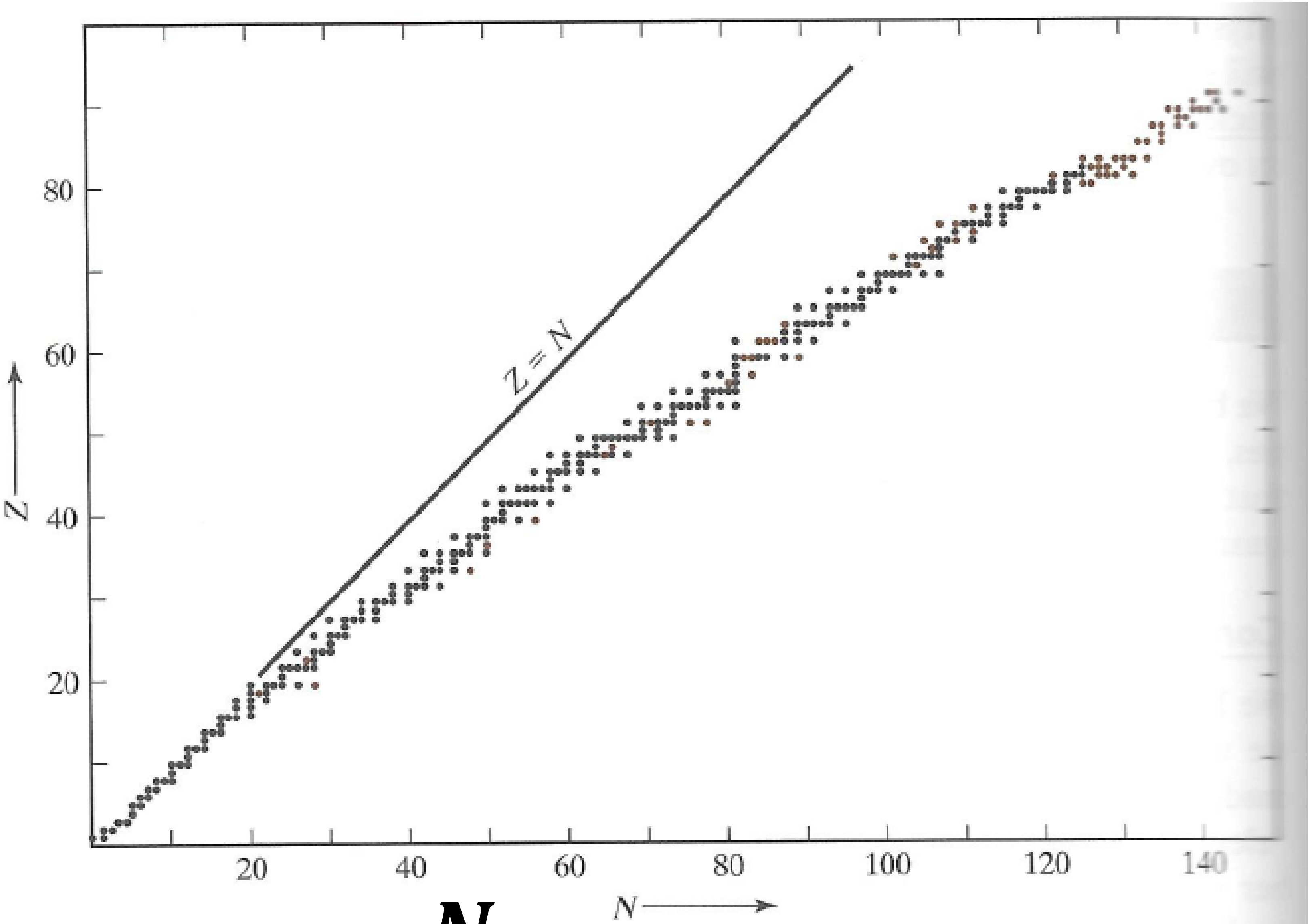


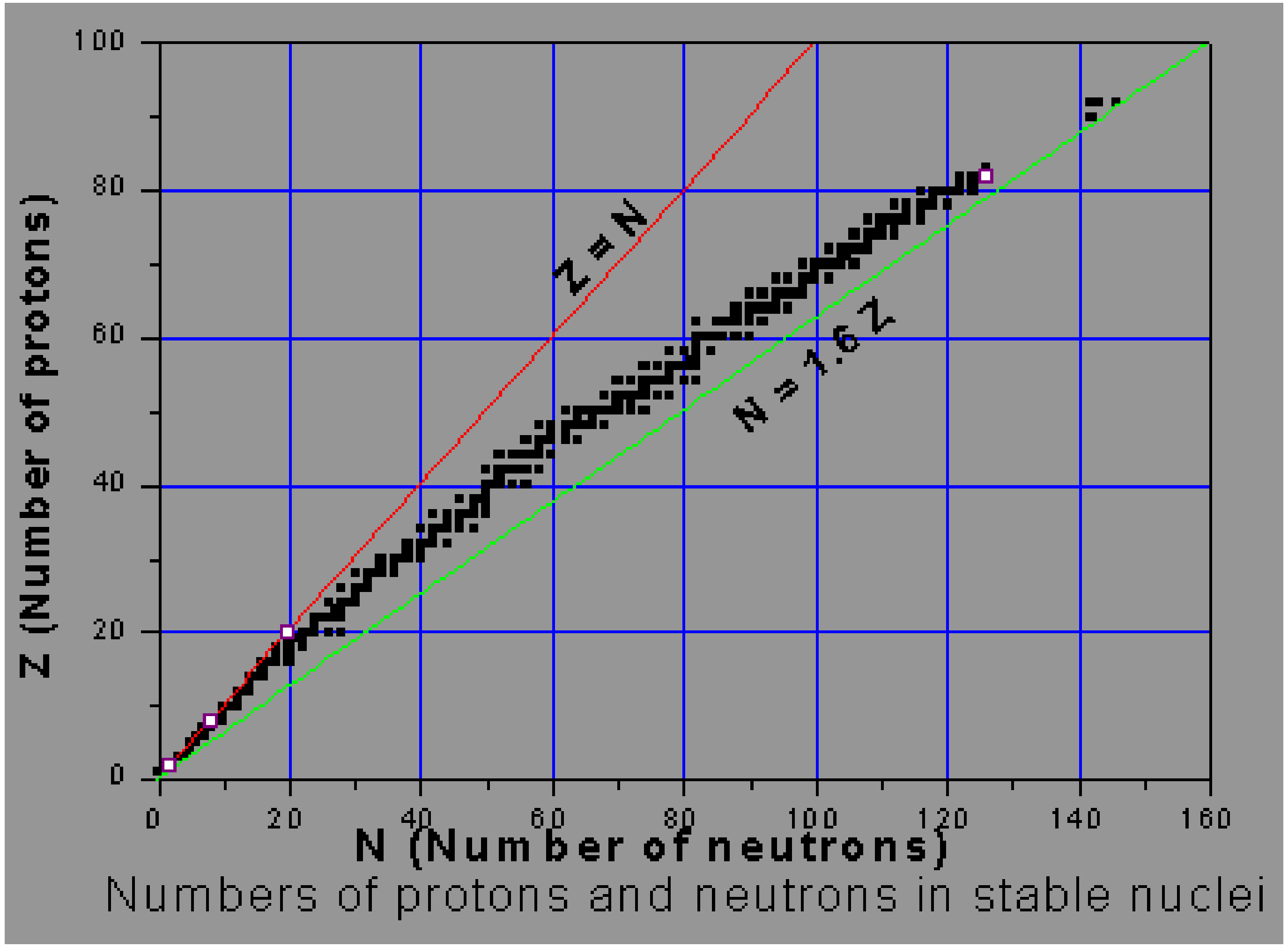
http://physics-database.group.shef.ac.uk/phy303/phy303-8.html

Z



N

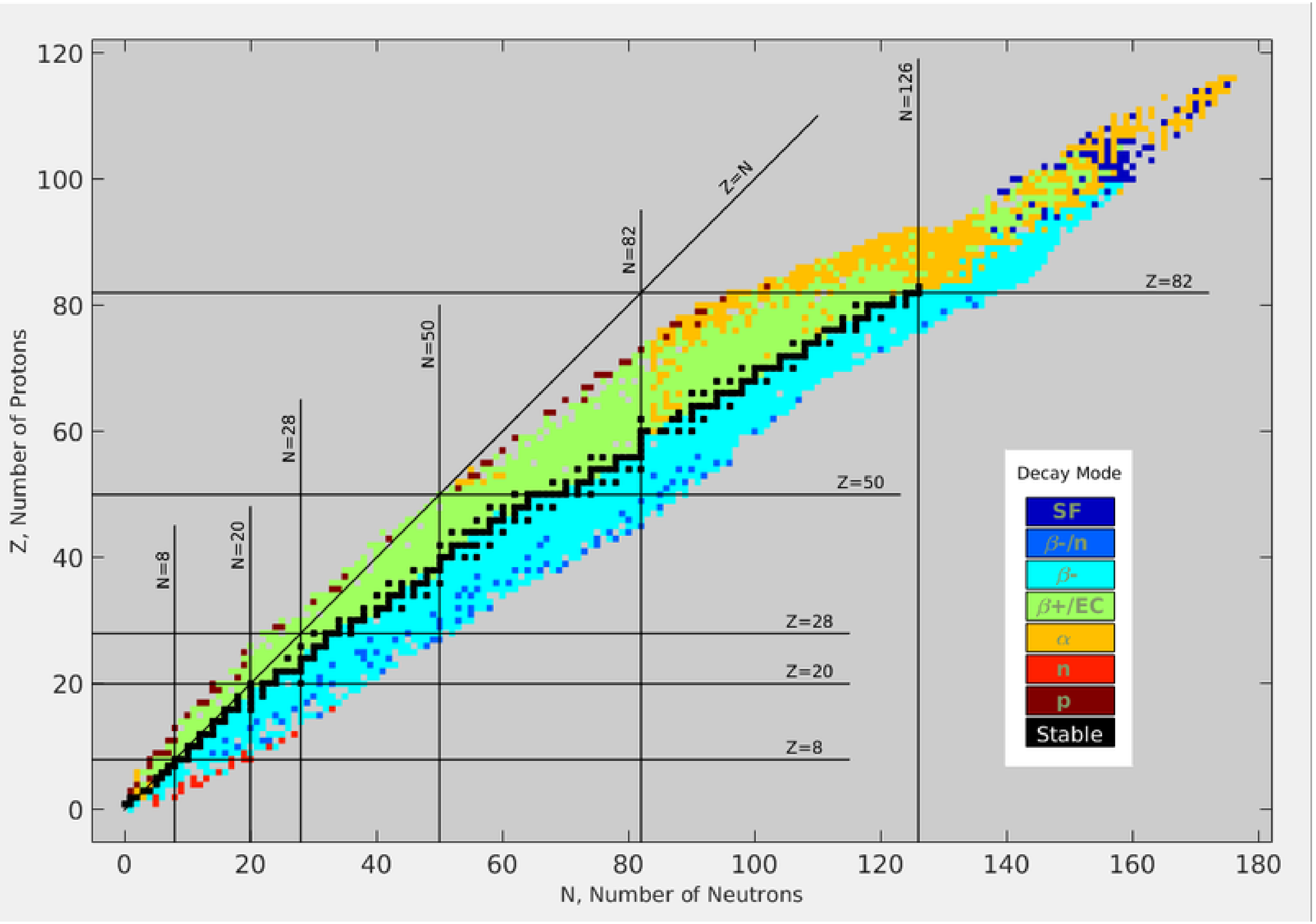
Z



Numbers of protons and neutrons in stable nuclei

N

Z



N

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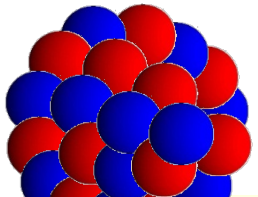
Forces acting in nuclei

- **Coulomb force** repels protons

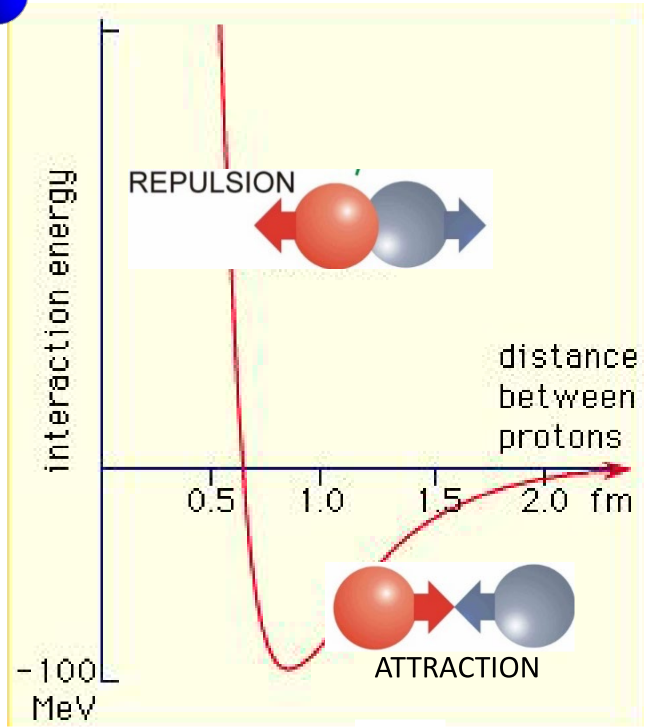


Protons charge = +
Neutron charge = 0

- **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**!)



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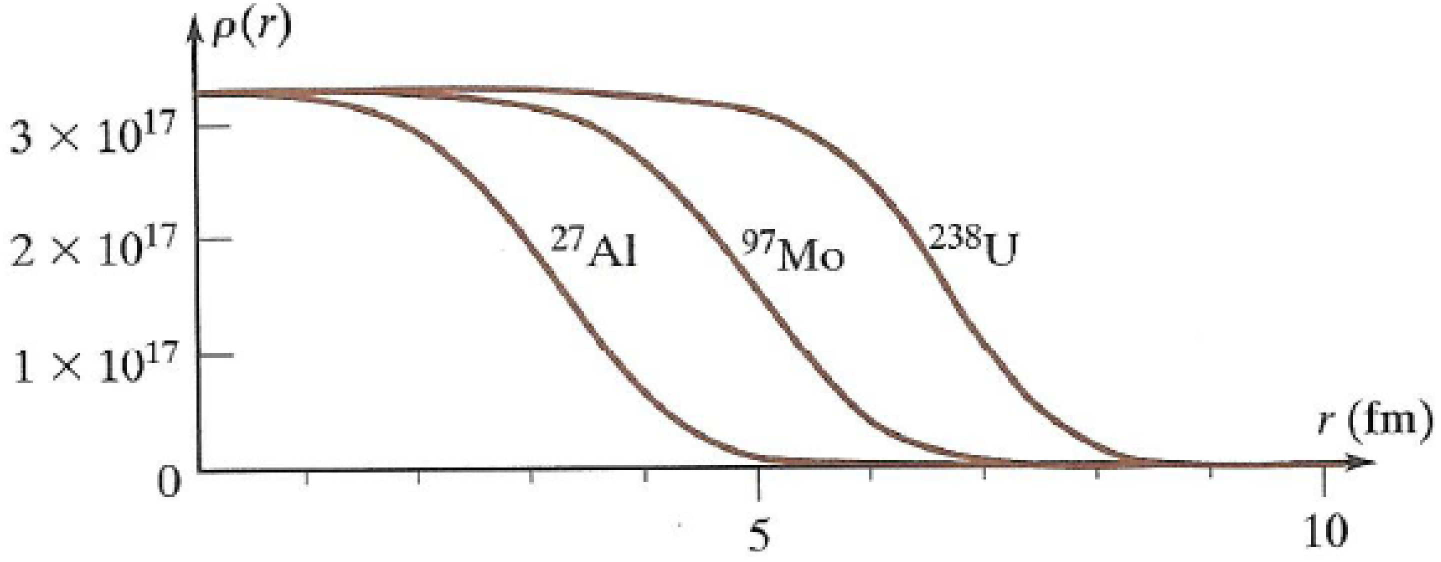
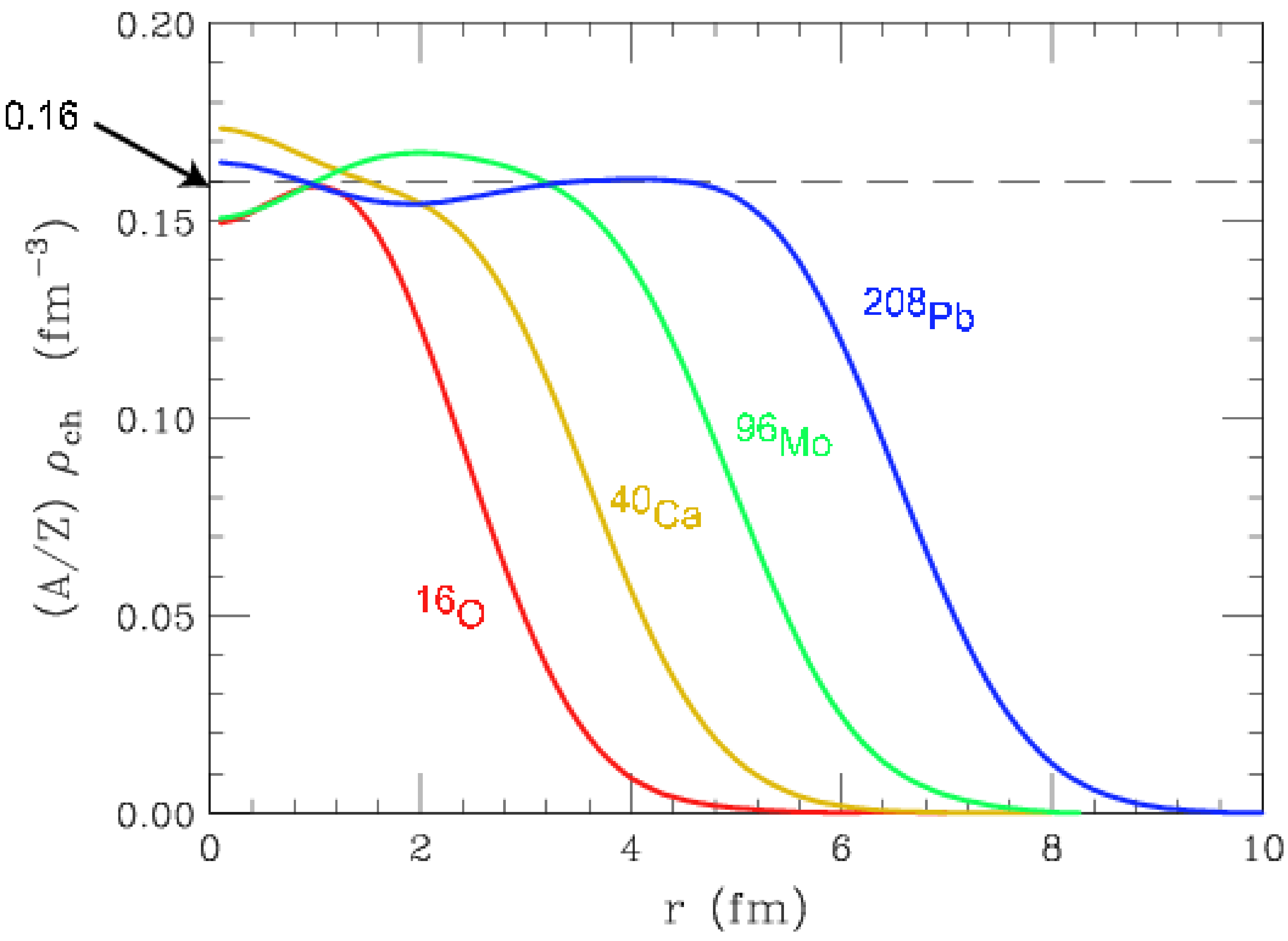
Nuclear Density vs. Distance from Center

FIGURE 16.2

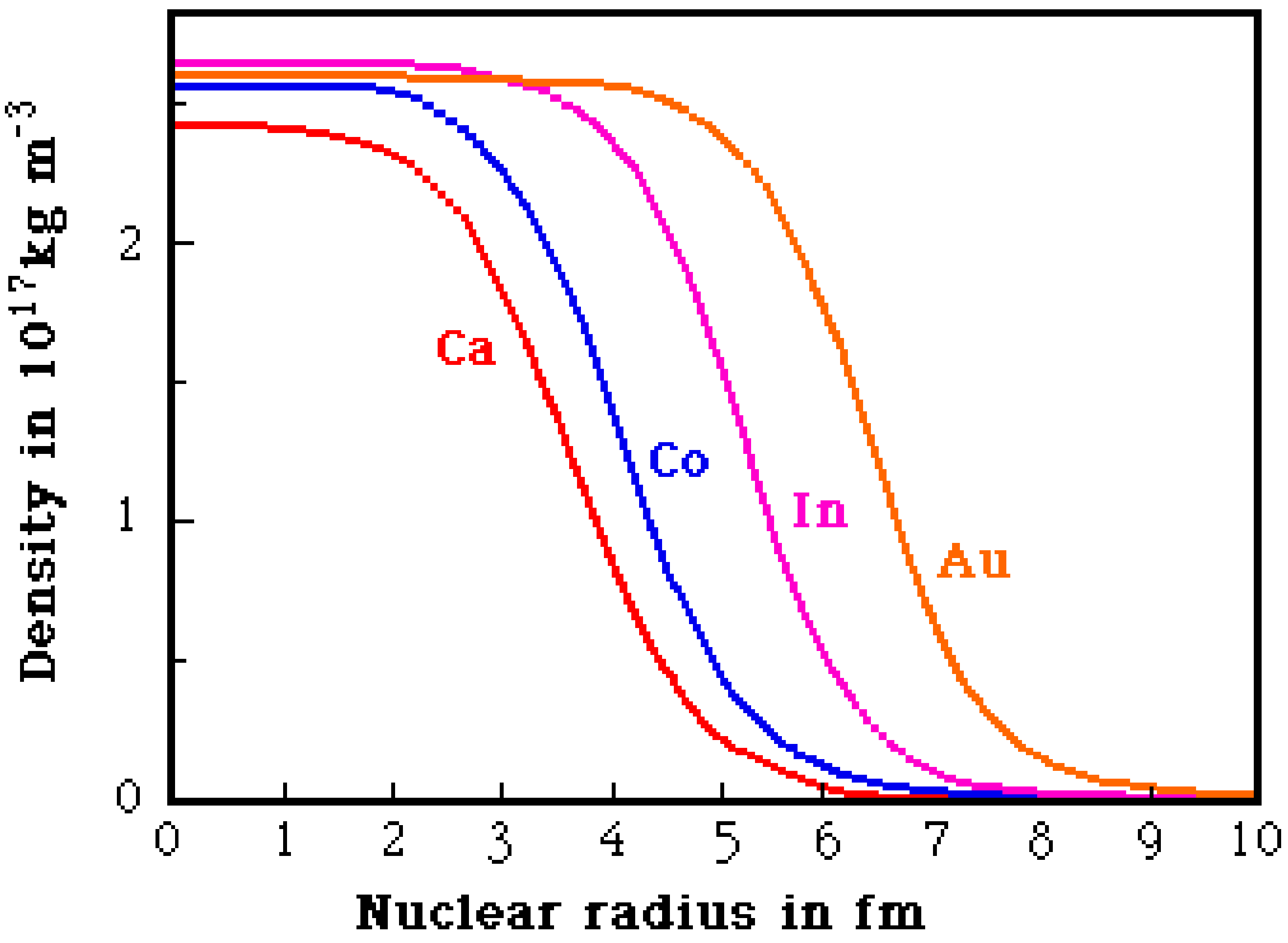
The density, in $\mathrm{kg/m^3}$, as a function of r in the nuclei of aluminum, molybdenum, and uranium. These graphs can be accurately fitted by an analytic expression called the Fermi function. (See Problems 16.15 and 16.63 to 16.65.)



Nuclear Density vs. Distance from Center



Nuclear Density vs. Distance from Center



Energy Levels of Isobars

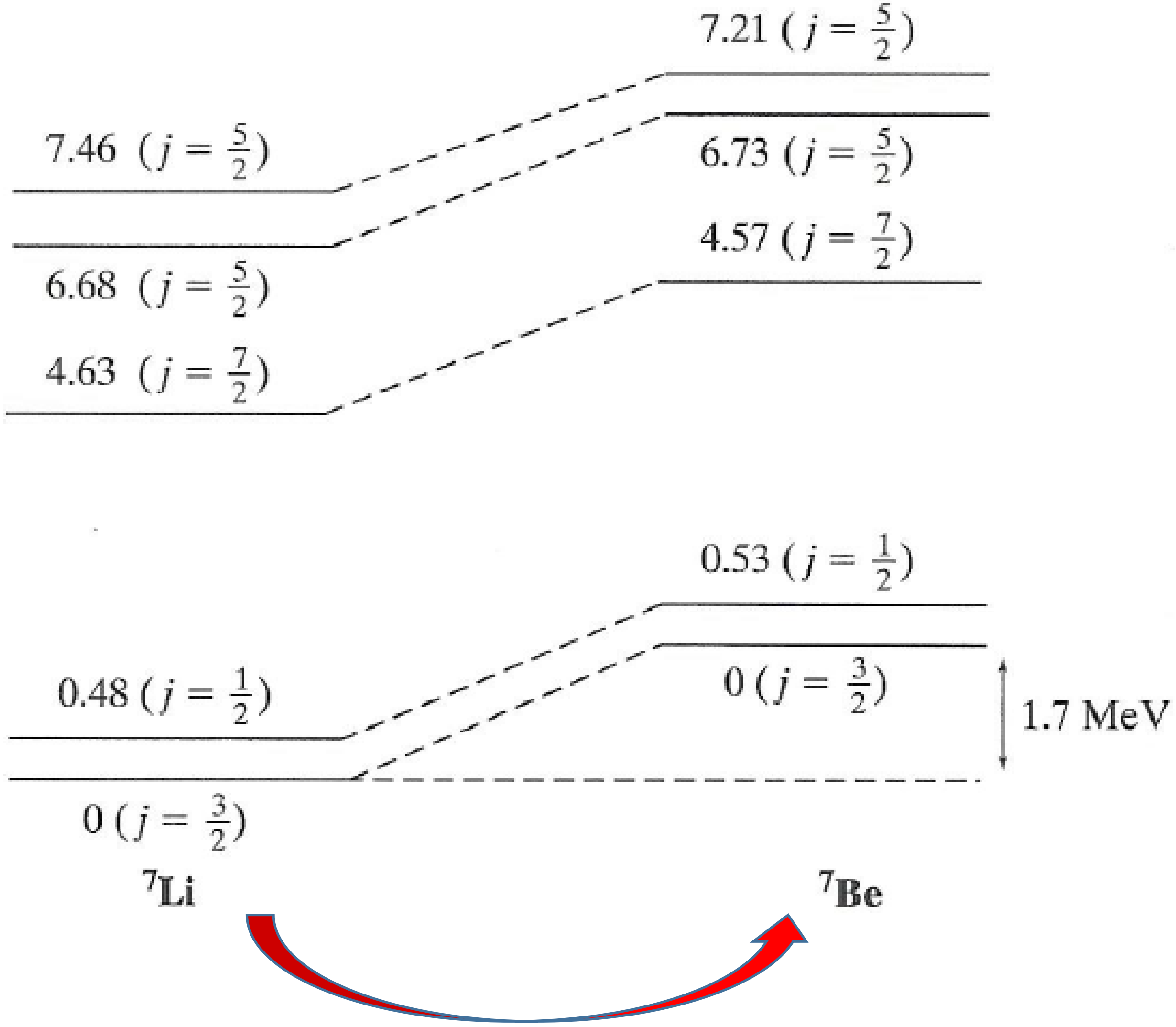


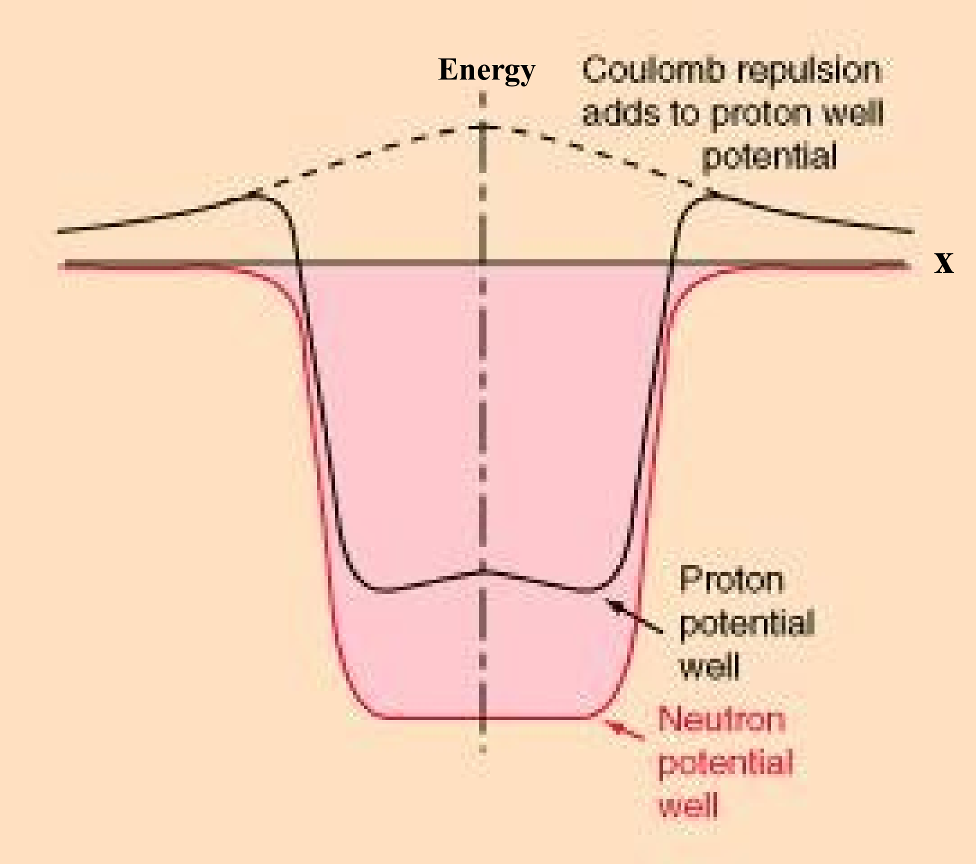
FIGURE 16.4

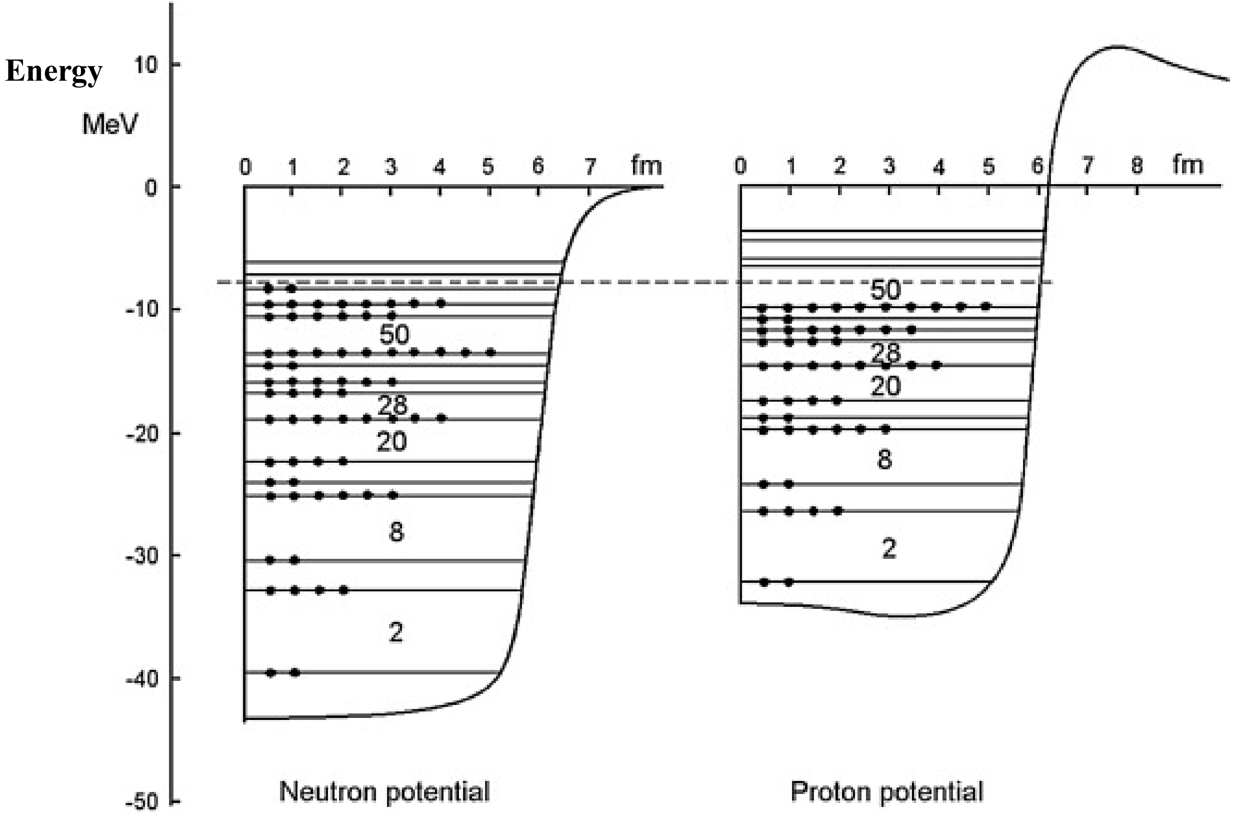
Energy levels of the isobars $^7_3\mathrm{Li}_4$ and $^7_4\mathrm{Be}_3$. The numbers labeling each level are its excitation energy in MeV and its angular-momentum quantum number j. Corresponding levels are connected by a dashed line; they have angular momenta that are exactly equal and excitation energies that are very nearly so. This close agreement is evidence for the charge independence of nuclear forces.

Adding one proton and removing one neutron

Total IPA Nuclear Potential for Protons and Neutrons

Energy Levels of Protons and Neutrons





Finite-Square-Well-Like Energy States in Nuclei
and the Pauli Exclusion Principle

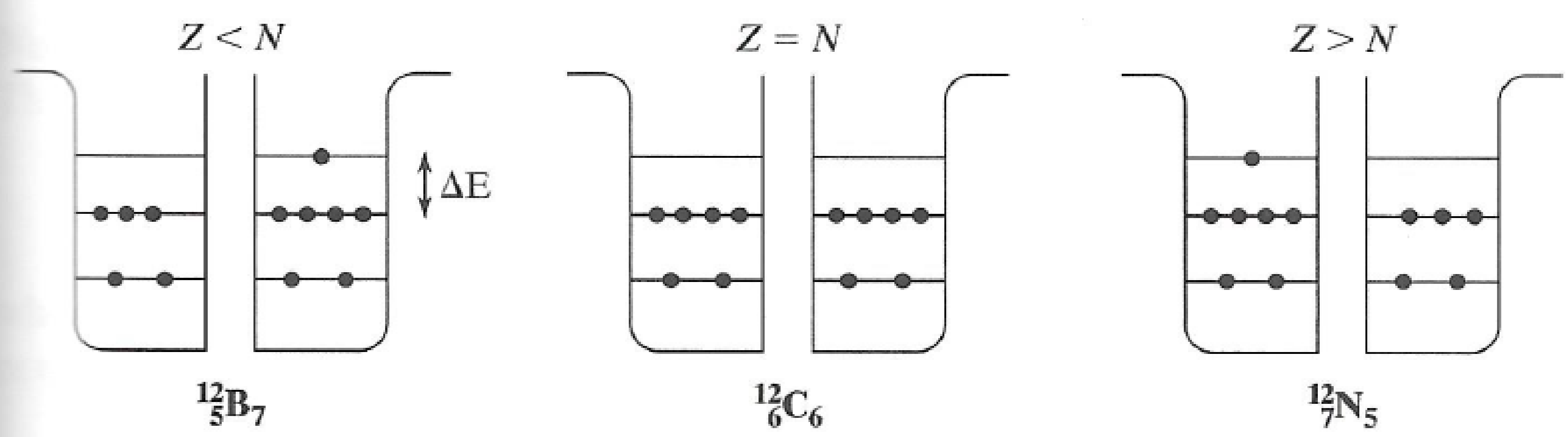
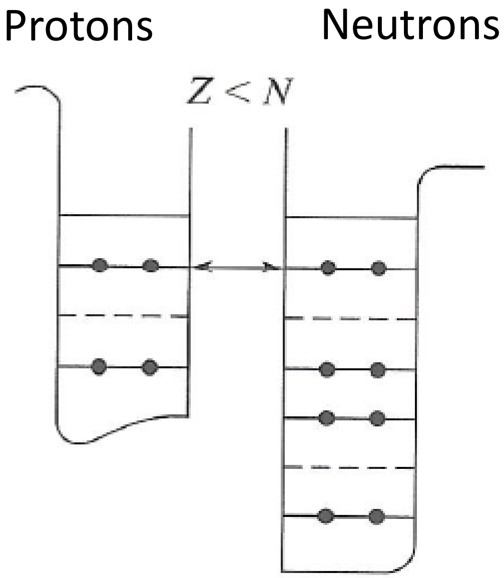


FIGURE 16.11

The ground states of the three isobars ^{12}B, ^{12}C, and ^{12}N. Because of the Pauli principle, the two nuclei with $Z \neq N$ have higher energy by the amount shown as ΔE.

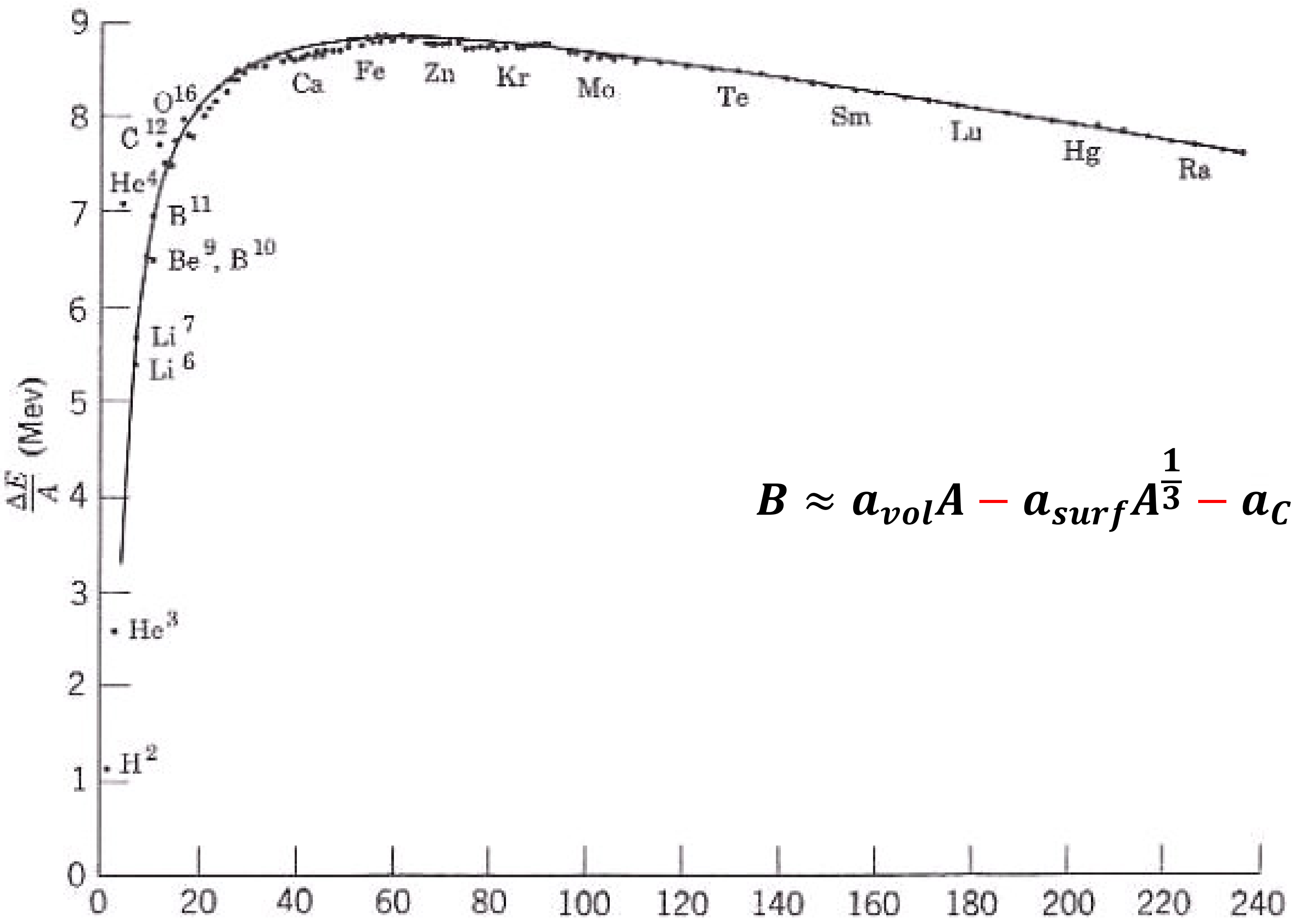
The "Symmetry Effect" favors $Z = N$ in light nuclei

Coulomb repulsion of protons favors $Z < N$ in heavy nuclei



Binding Energy per Nucleon (B/A) vs. the number of Nucleons A

B/A

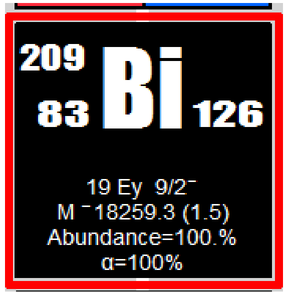


$$B \approx a_{vol}A - a_{surf}A^{\frac{1}{3}} - a_{Coul}\frac{Z^2}{A^{1/3}} + \cdots$$

A

Lifetime

- Some nuclei are stable (i.e. their lifetimes are comparable to that of a proton and we have not seen their decay)
  - E.g. until recently 209Bi was thought to be stable
- Others are unstable – they transform into more stable nuclei
- Decay is a statistical process: exponentially
  - **Half-life = time after which half of the initial nuclei have decayed**

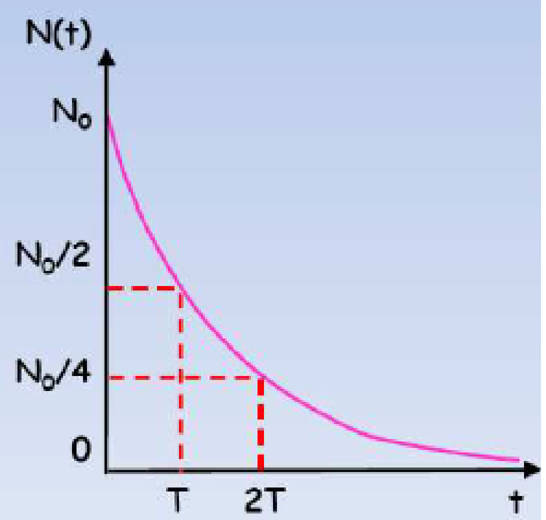


$^{209}_{83}\mathrm{Bi}_{126}$

19 Ey 9/2⁻
M ⁻18259.3 (1.5)
Abundance=100.%
α=100%

Exponential decay

$$\frac{dN}{dt} = -\lambda N(t)$$



Half-life T= $T_{1/2}$

Examples of half-lives:
11Li: 9 ms
13Be: 0.5 ns
77Ge: 11h
173Lu: 74 μs
208Pb: stable

After 6 half-lives: only about 1.5% remains

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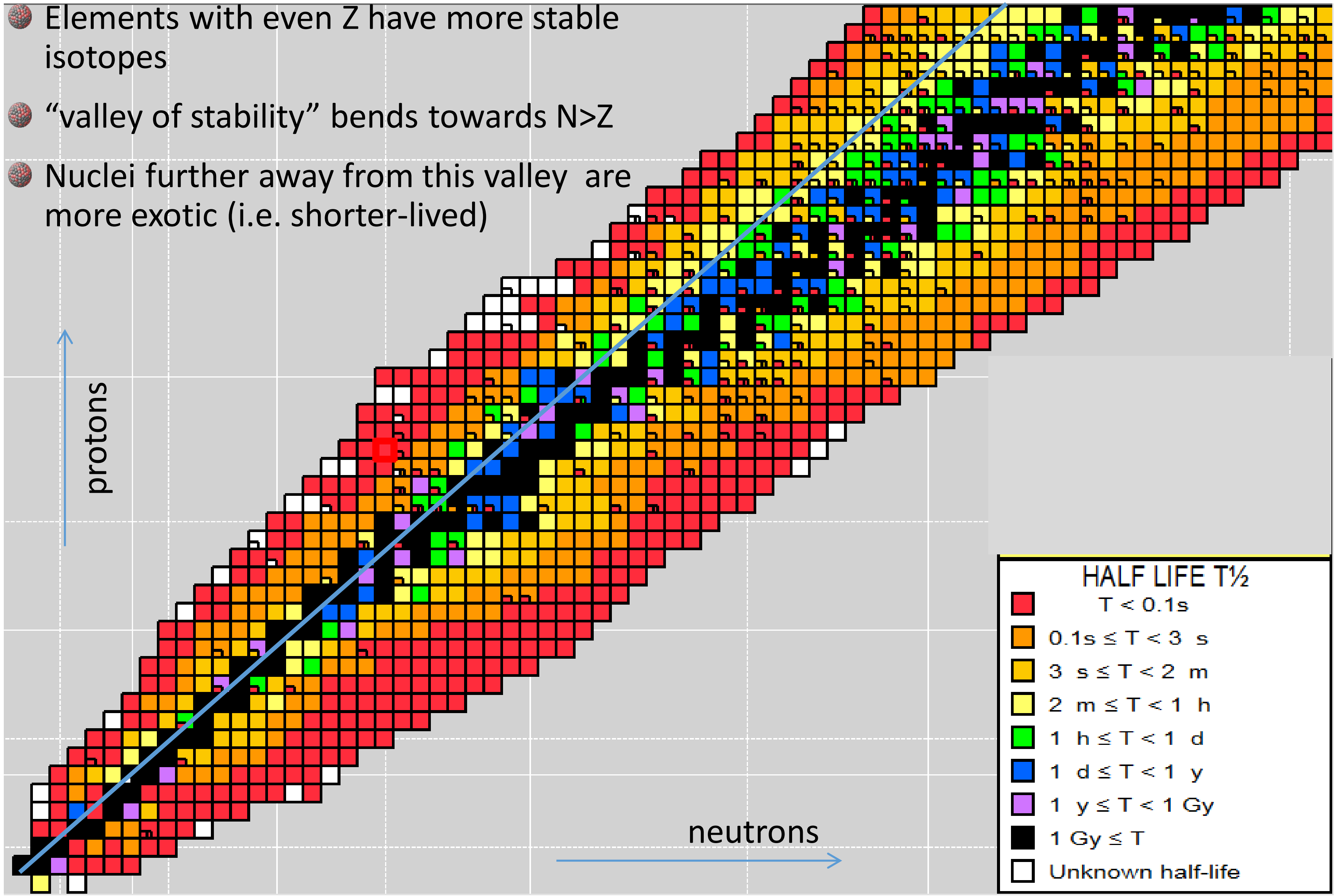
Lifetime

- Elements with even Z have more stable isotopes
- “valley of stability” bends towards N>Z
- Nuclei further away from this valley are more exotic (i.e. shorter-lived)



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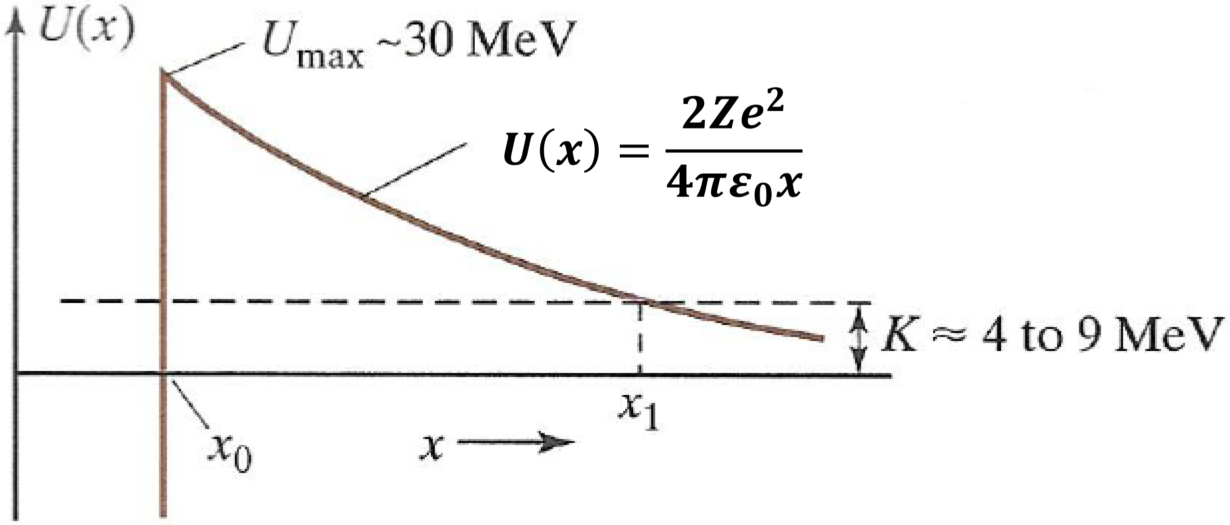
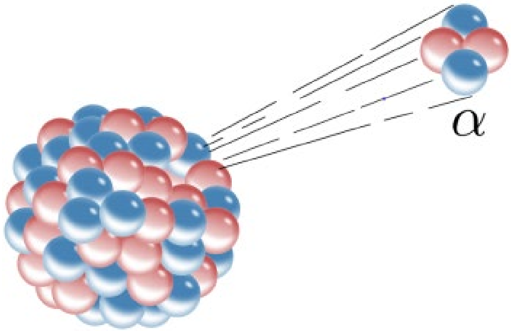
Alpha Decay of Heavy Nucleus

Potential experienced by the α-particle



$$U(x) = \frac{2Ze^2}{4\pi\varepsilon_0 x}$$



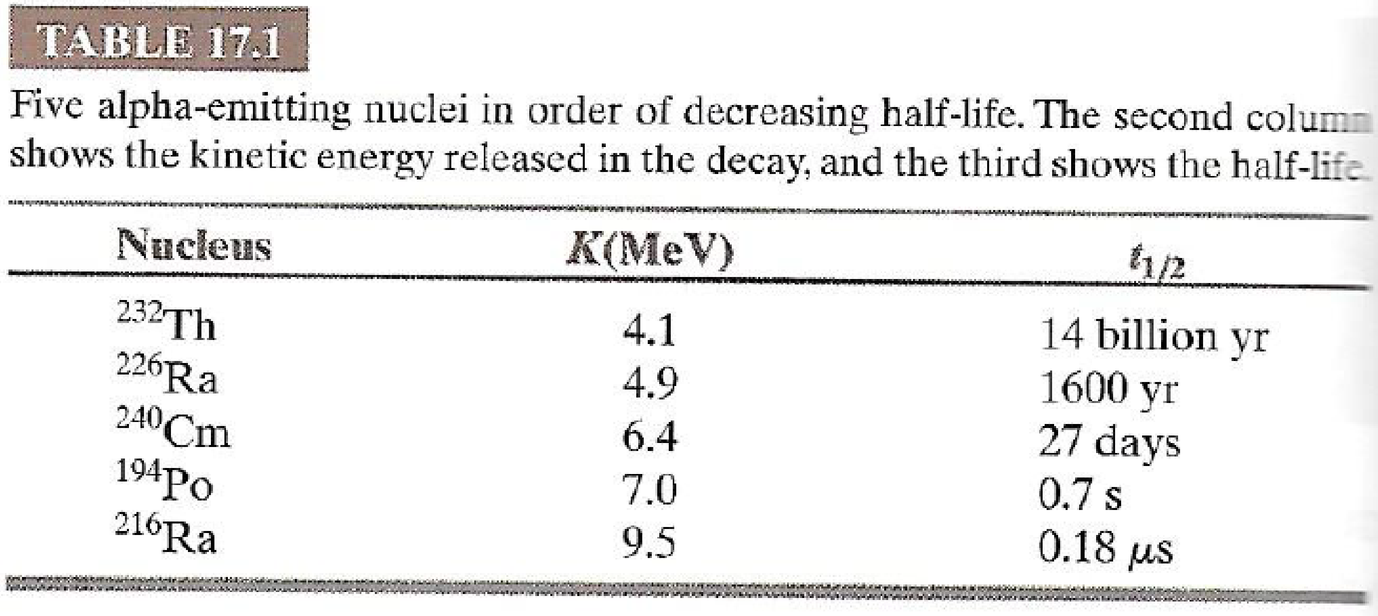
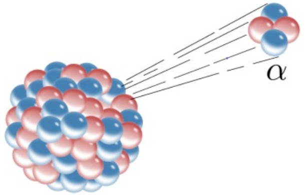


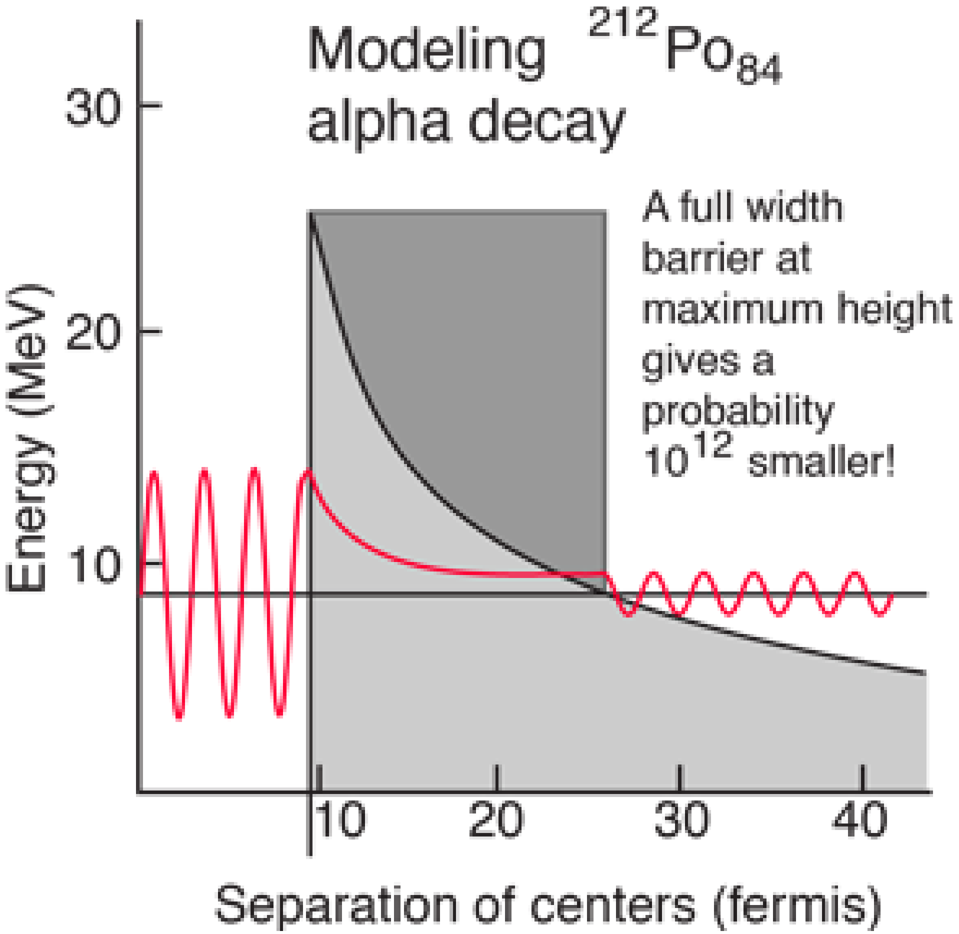
TABLE 17.1

Five alpha-emitting nuclei in order of decreasing half-life. The second column shows the kinetic energy released in the decay, and the third shows the half-life.

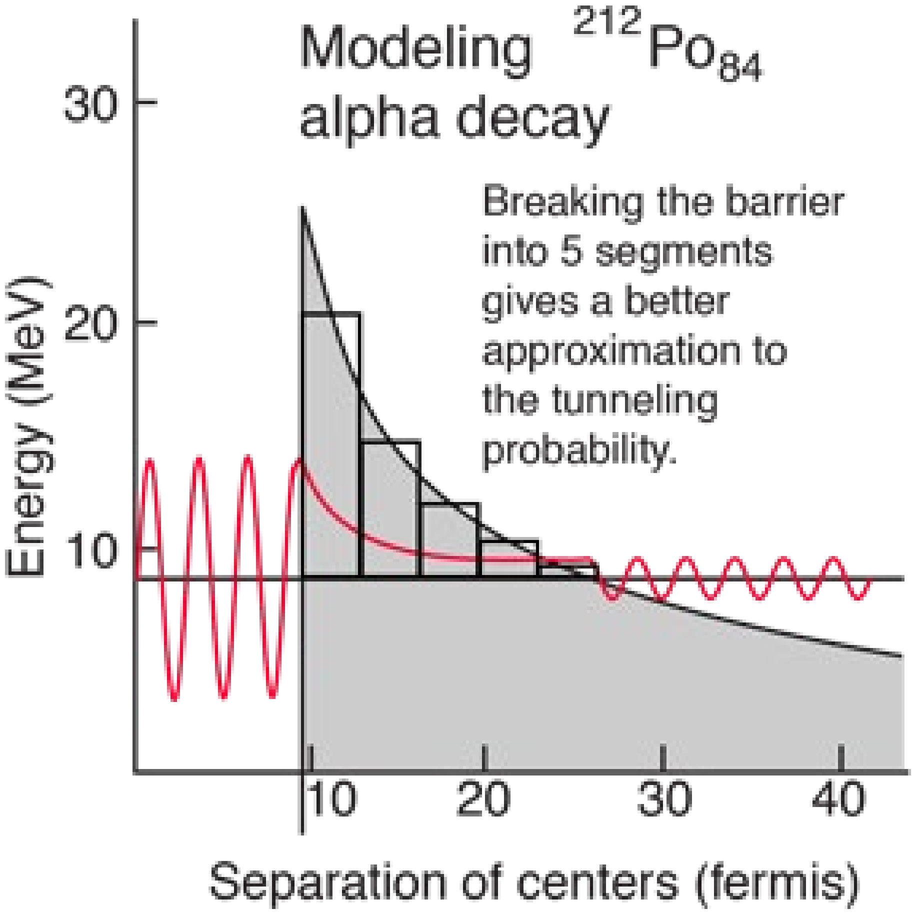
Nucleus	K(MeV)	$t_{1/2}$
^{232}Th	4.1	14 billion yr
^{226}Ra	4.9	1600 yr
^{240}Cm	6.4	27 days
^{194}Po	7.0	0.7 s
^{216}Ra	9.5	0.18 μs



Alpha Decay of Heavy Nucleus



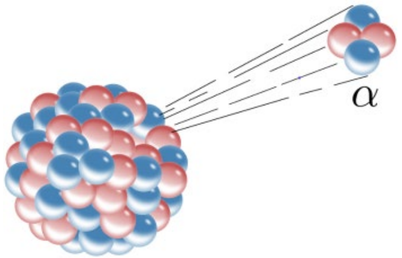
A full width barrier at maximum height gives a probability 10^{12} smaller!



Breaking the barrier into 5 segments gives a better approximation to the tunneling probability.

Square barrier tunneling prob. $\boldsymbol{T \approx e^{-2\alpha a}}$ $\alpha = \sqrt{2m(V_0 - E)}/\hbar$

http://hyperphysics.phy-astr.gsu.edu/hbase/Nuclear/alptun2.html



Half Life of Po Alpha Decay vs $1/\sqrt{K}$

K = Kinetic energy of α-particle

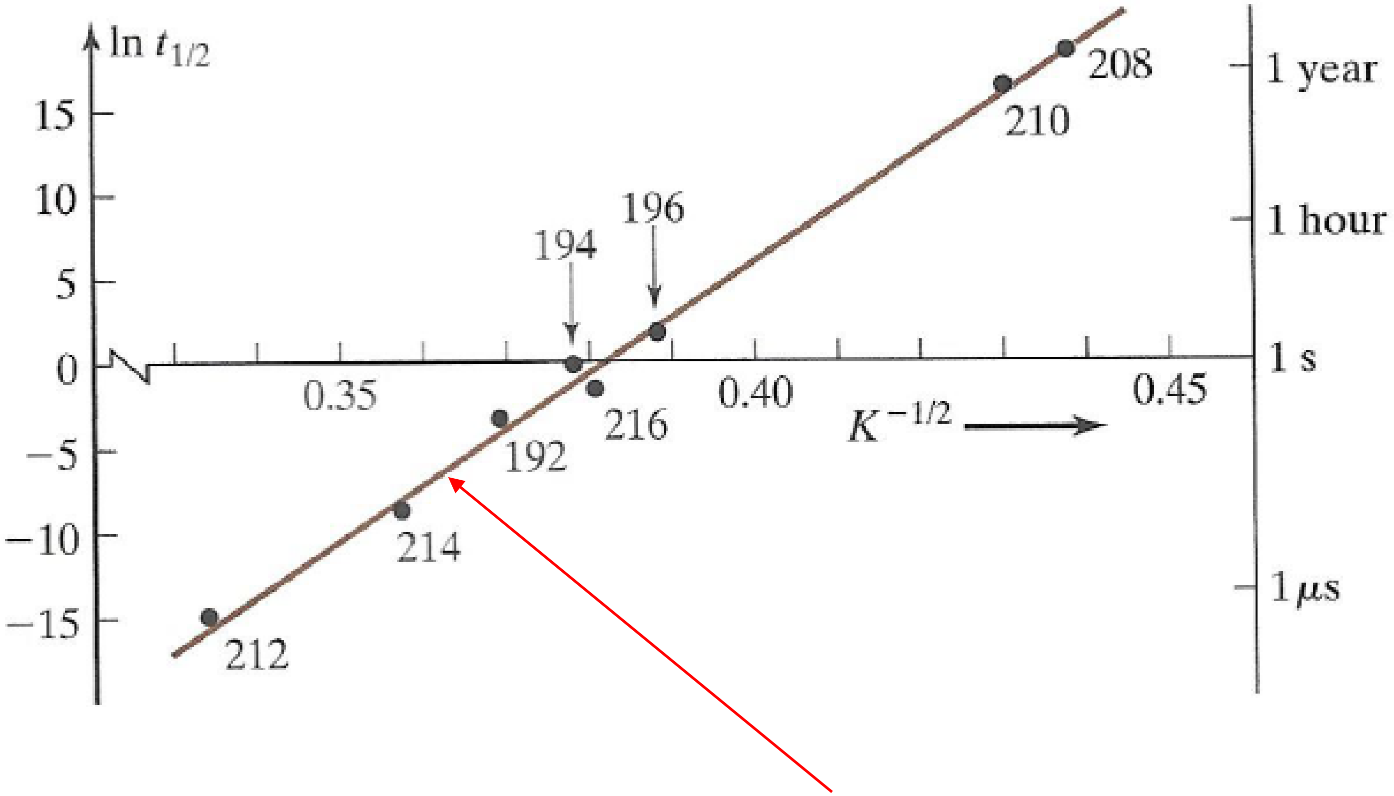


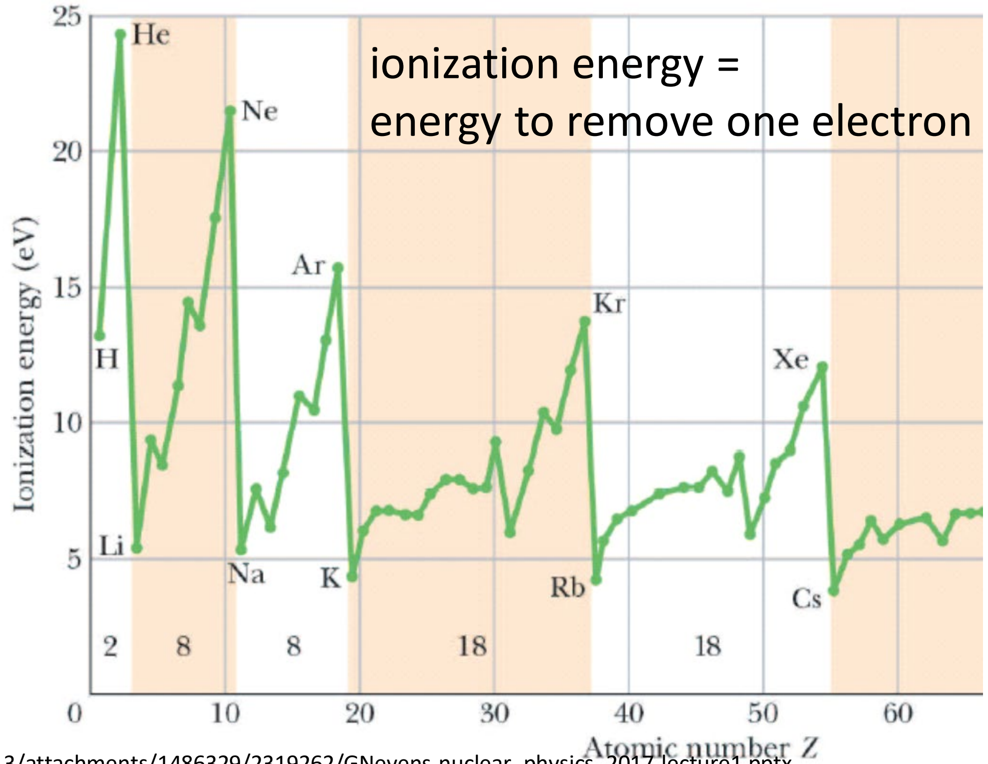
FIGURE 17.22

Plot of $\ln t_{1/2}$ against $K^{-1/2}$ for eight alpha-emitting isotopes of polonium. (Half-lives, $t_{1/2}$, in seconds and energy release, K, in MeV.) The number beside each point is the mass number A of the isotope. The line is the least-squares fit to the data, and the axis on the right shows $t_{1/2}$ itself.

$$lnt_{1/2} = \frac{aZ}{\sqrt{K}} - b\sqrt{Z\,R} + \mathrm{c}$$

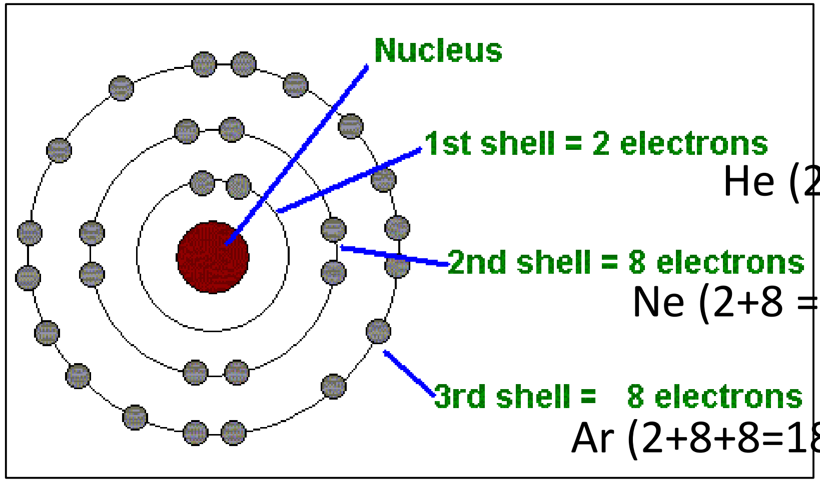
Nuclear shell model

- Created in analogy to the atomic shell model (electrons orbiting a nucleus in particular quantum orbits induced by the nuclear field)
  - When electrons ‘fill’ a quantum orbit ➔ element is more stable (higher ionization energy)
  - Explains why noble gasses are more ‘stable’ (less reactive) than other elements
- Also in chart of nuclei: some nuclei are more stable than their neighbours
  - filled shell of neutrons or protons results in greater stability
  - neutron and proton numbers corresponding to a closed shell are called ‘magic‘



ionization energy =
energy to remove one electron

Atomic shell model



He (2)

Ne (2+8 =10)

Ar (2+8+8=18)

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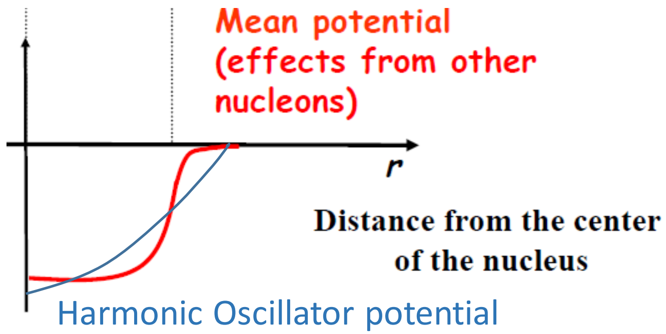
Nuclear shell model

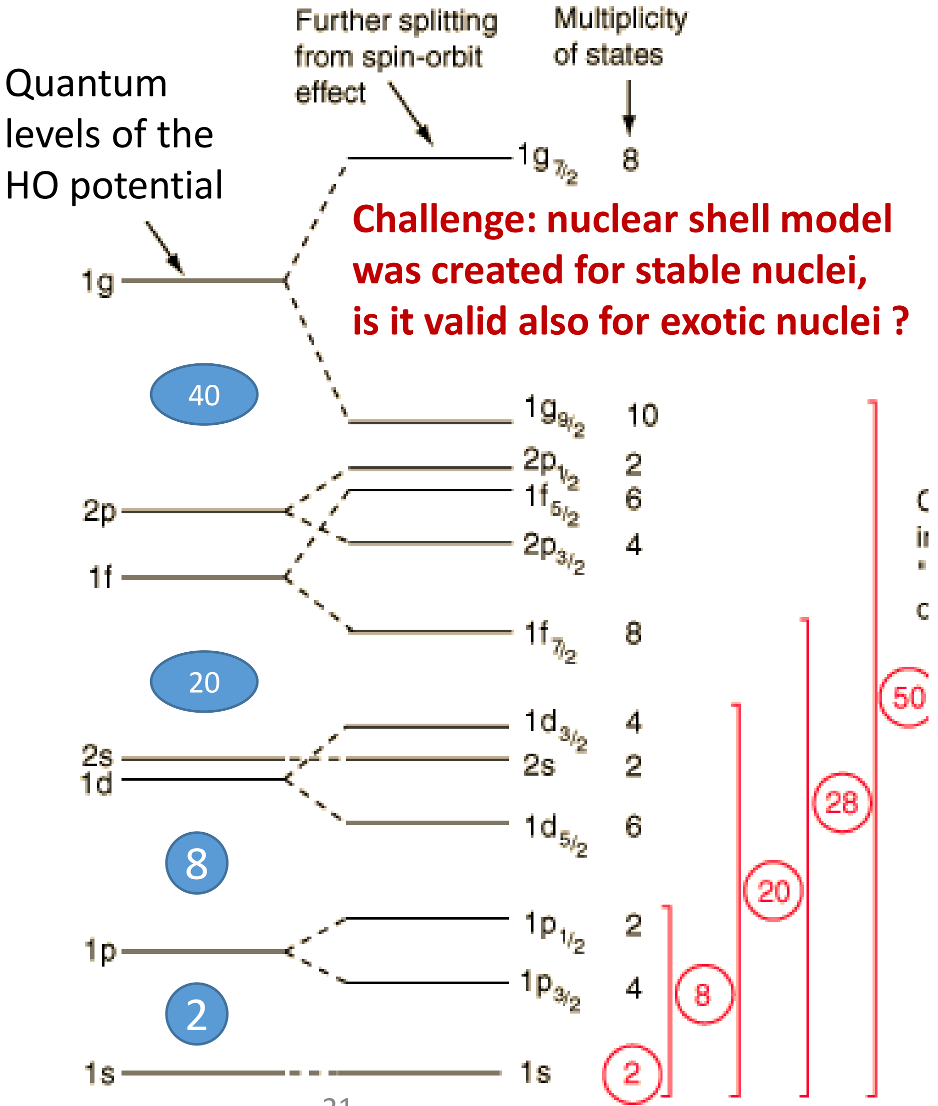


Differences to atomic shell model:

1. The field generating the potential
   - ➢ No central potential but a self-created one → needs to be modelled !
   - ➢ Two kinds of nucleons
   - ➢ Strong spin-orbit coupling changes magic numbers: 8,20,28,50, 82, 126, …

2. The interaction between the particles
   - ➢ Nucleon-nucleon interaction
   - ➢ strong interaction in nuclear medium → needs to be modelled !

Quantum orbits in the independent particle shell model



Challenge: nuclear shell model was created for stable nuclei, is it valid also for exotic nuclei ?

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