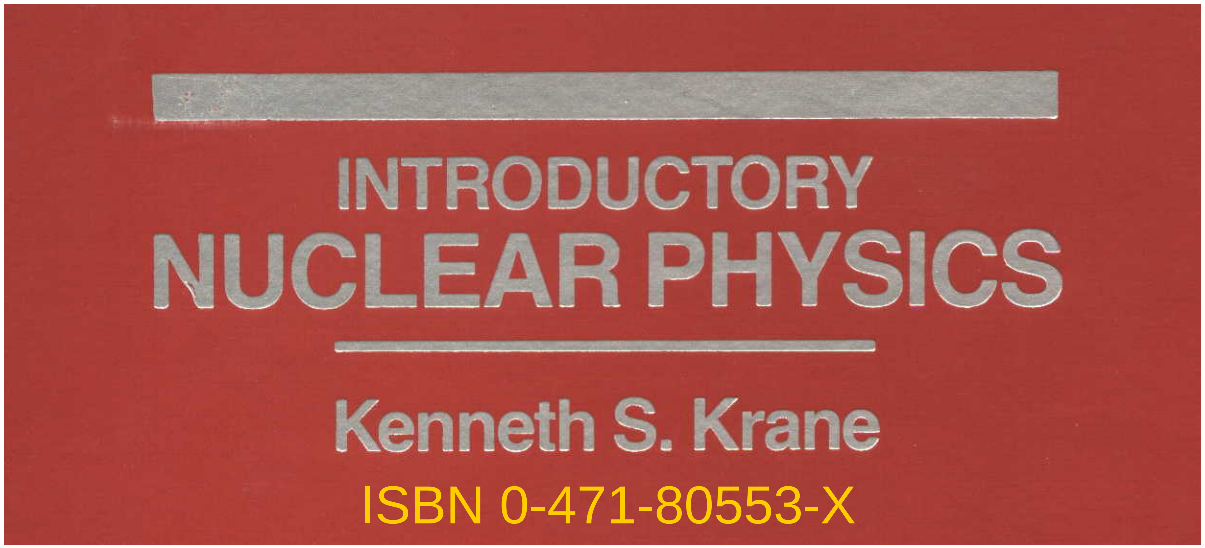
2NPP PHY2067 NUCLEAR AND PARTICLE PHYSICS
Prof. W.N. Catford

This course is based most closely on the book:



ISBN 0-471-80553-X

These are NOT lecture notes, as such. you will NEED to make your own notes, so that they make sense when you go to read them through, later !!

All OHP material will be copied and circulated to the class at lectures.
There will be problems classes (with solutions) during the semester.

But they DO have everything included.

There will be one 1.5 hour examination for PHY2067
during the normal examination period at the end of semester.
You will need to answer 2 questions chosen from 3.
This counts 70% of the marks for PHY2067, with 30% coming from labs.

2NPP NUCLEAR & PARTICLE PHYSICS PHY2017
Prof. W.N. Catford
SYLLABUS

KNPn.n refers to Krane's *Introductory Nuclear Physics*, ISBN 0-471-80553-X,
MPn.n refers to Krane's *Modern Physics*, ISBN 0-471-82872-6,

1. Basic Properties of Nuclei *(2 lectures)*	
Nucleus, nucleons, isotopes, isotones, isobars	KNP1.2,MP12.1
Atomic number Z, neutron and mass numbers N,A	KNP1.2,MP12.1
Chart of the nuclides (Segrè chart)	KNP1.3,MP12.5
Isotope separation, nuclear size, nuclear forces	KNP1.4,KNP3.1
Curve of the nuclear binding energies	KNP3.3,MP12.3
Semi-empirical mass formula; justification; pairing	KNP3.3
2. Summary of Relevant Quantum Concepts *(1 lecture)*	
Quantum mechanics for step potential, $E < V_0$	KNP2.3,MP5.7
1-D infinite and finite wells; simple harmonic oscillator	KNP2.3,MP5.4,5.5
Angular momentum and parity quantum numbers	KNP2.5,2.6
Nuclear excited states	KNP3.6
Spin and parity of nuclear states	KNP3.4

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3. Radioactive Decay *(2 lectures)*

Decay Law; mean life; half-life; decay constant	KNP6.1,MP12.5
Production of radioactivity; secular equilibrium	KNP6.3,MP13.2
Daughter activities; secular and transient equilibrium	KNP6.4
Types of radioactive decay; α, β, γ, fission; branching ratios	KNP6.5,MP12.5,12.6
Natural radioactivity	KNP6.6,MP12.10

4. Alpha and Gamma Decay *(2 lectures)*

Basic α–decay process; energetics; kinematics	KNP8.1,8.2,MP12.7
Decay systematics; Geiger-Nuttall rule	KNP8.3
Theory of α–emission; barrier penetration	KNP8.4,MP5.7
Angular momentum and parity in α–decay	KNP8.5
Energetics of γ –decay	KNP10.1,MP12.9
Electric and magnetic moments; multipole radiation	KNP10.2
Lifetimes for γ –decays; Weisskopf estimates	KNP10.3
Selection rules; change in angular momentum and parity	KNP10.4

5. Beta Decay and Electron Capture *(2 lectures)*

Isobar mass curves	KNP3.3
Energy release; need for the neutrino	KNP9.1,MP12.8
Fermi theory; shape of the spectrum; Fermi-Kurie plot	KNP9.2
Selection rules; allowed decays; forbidden decays	KNP9.4

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6. Nuclear Models *(2 lectures)*

Evidence for nuclear shells; magic numbers	KNP5.1
3-D infinite well; 3-D harmonic oscillator	KNP2.3
Nuclear shell model potential; spin-orbit force	KNP5.1
Pauli principle and pairing, in shell model	KNP5.1
Valence nucleons in odd-even nuclei	KNP5.1

7. Nuclear Reactions *(2 lectures)*

Conservation laws and kinematics	KNP11.1,11.2,MP13.3
Reaction Q-value; mass-energy equivalence	KNP11.2
Reaction cross sections: total, differential; barn	KNP11.4
Experimental techniques; Coulomb scattering	KNP11.5,11.6
Review of compound nuclear, and resonant reactions	KNP11.10

8. Fission and Reactors *(2 lectures)*

How energetics favour fission and barriers inhibit it	KNP13.1,MP13.4
Mass distribution of fragments; excess neutrons	KNP13.2 ,MP13.4
Prompt (fission) and delayed (by β–decay) neutrons	KNP13.2
energies of fission fragments, neutrons, β– and γ –decays	KNP13.3
Controlled fission; chain reactions; moderation	KNP13.5 ,MP13.4
Basic reactor physics; criticality; four factor formula	KNP13.5
Reactors: control rods, crucial role of delayed neutrons	KNP13.6,MP13.4

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9. Quark Structure of Nucleons and Mesons *(2 lectures)*

Quarks as a basis for particle structure	KNP18.3
Isospin	KNP17.2,18.2,11.3
Pions as carriers of the nuclear force; pion production	KNP17.2
Kaons and Strangeness	KNP17.5
CP violation and K0 decay	KNP17.6

10. Bosons, Leptons and Quarks *(2 lectures)*

Families of particles from three basic quarks	KNP18.3
The exchange bosons and the leptons	KNP18.1
Quark colours	KNP18.4,18.6
Conservation laws – energy and momentum	KNP18.2
Decays of mesons and baryons in the quark model	KNP18.5,17.5

11. The Standard Model and Beyond *(2 lectures)*

Beyond three quarks – charm, top and bottom	KNP18.6
J/ψ particles	KNP18.6
Flavour changing neutrinos	
Neutrino mass	
The Higgs boson at LHC	

12. Review and Key Points *(1-2 lectures)*

[END of SYLLABUS]

2NPP Nuclear and Particle Physics

Atoms comprise nuclei and electrons - known since 1910
Nuclei comprise protons and neutrons - known since 1932

radioactivity

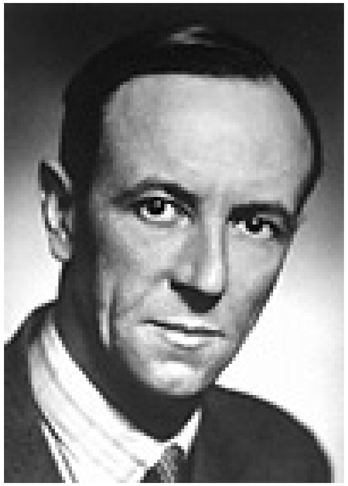
Marie Curie
Nobel Physics 1903
Nobel Chemistry 1911

the electron

J J Thomson
Nobel Physics 1906

the nucleus

Ernest Rutherford
Nobel Chemistry 1909
Founder of Nuclear Physics



the neutron

James Chadwick
Nobel Physics 1935

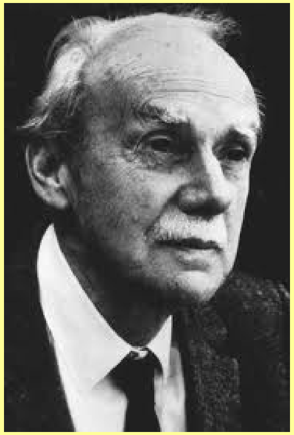
Z = number of protons
N= number of neutrons
A = N+Z = mass number
neutral atom has Z electrons
m(nucleon) ≈ 2000 × m(electron)
For element X write $^{A}_{Z}X_{N}$

Protons & neutrons
are together known
as nucleons

ISOTOPES Z constant e.g. ${}^{16}_{8}O$, ${}^{17}_{8}O$, ${}^{18}_{8}O$

ISOTONES N constant e.g. ${}^{22}_{10}Ne$, ${}^{23}_{11}Na$, ${}^{24}_{12}Mg$

ISOBARS A constant e.g. ${}^{40}_{18}Ar$, ${}^{40}_{19}K$, ${}^{40}_{20}Ca$



Paul Dirac
Nobel Physics1933
antiparticles

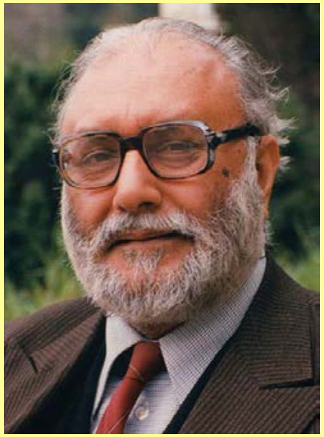
ATOMIC MASS UNIT amu

1 amu $\equiv$ 1 u $\equiv$ (mass of neutral ${}^{12}_{6}C$ atom) / 12

$1\ uc^2 = 931.50$ MeV (using $E= mc^2$)
$1\ u = 1.6606 \times 10^{-27}$ kg
1 u $\approx$ mass (neutron) $\approx$ mass (proton)

Murray Gell-Mann
Nobel Physics1969
Quark Model

Burton Richter
Nobel Physics1976
Charm – J/ψ

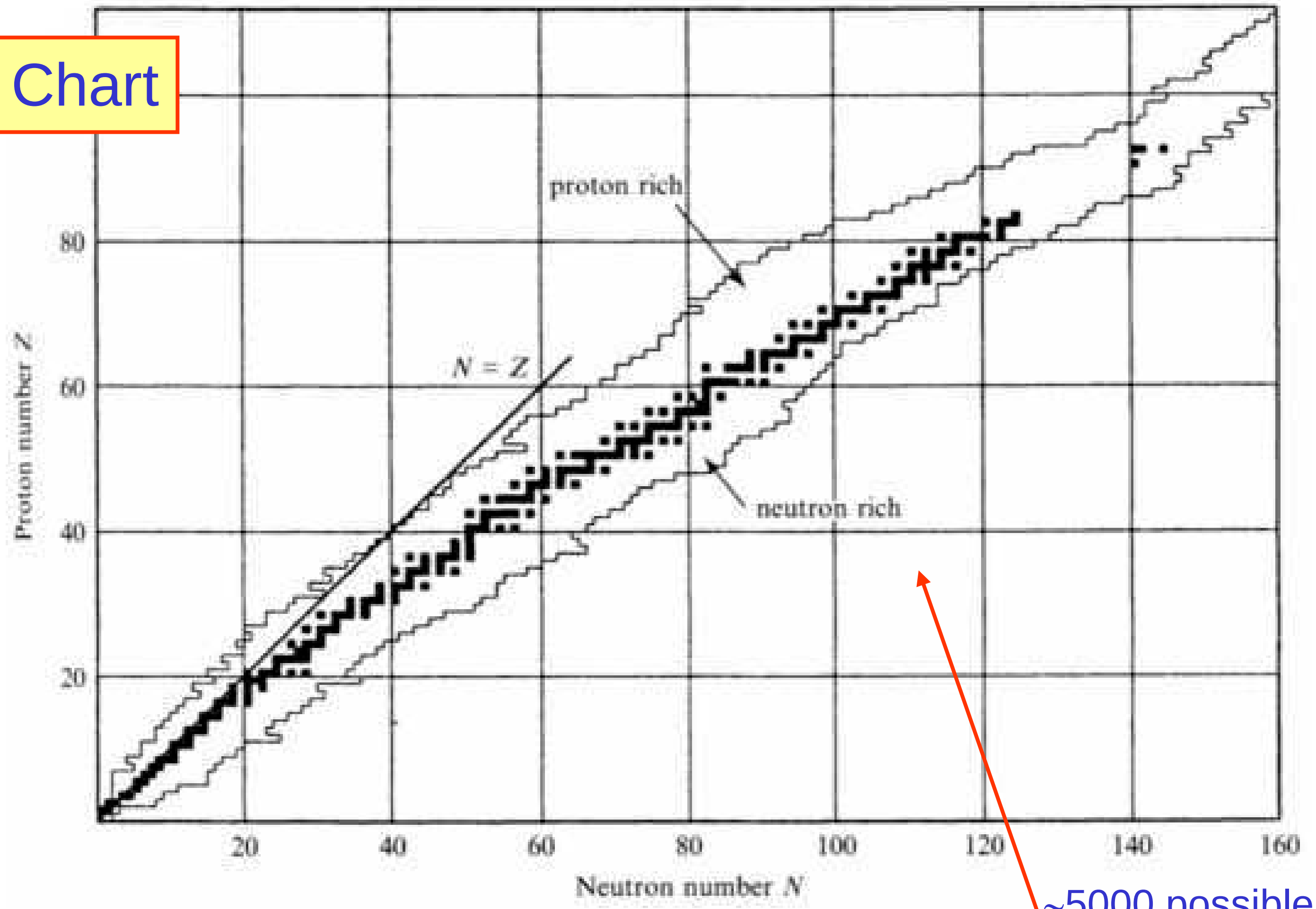


Abdus Salam
Nobel Physics1979
Electroweak

Chris Llewellyn Smith
CERN DG 1994-1998
Octet of Gluons

protons are made of three quarks: two ups and a down
neutrons are made of three quarks: two downs and an up
up and down quarks are just the lightest pair – there are two heavier generations
electrons are just the lightest leptons – there are two heavier generations
gluons are exchange bosons that bind the quarks together
photons and Z bosons and W+/W– bosons all allow electroweak interactions

The Nuclear Chart



~5000 possible

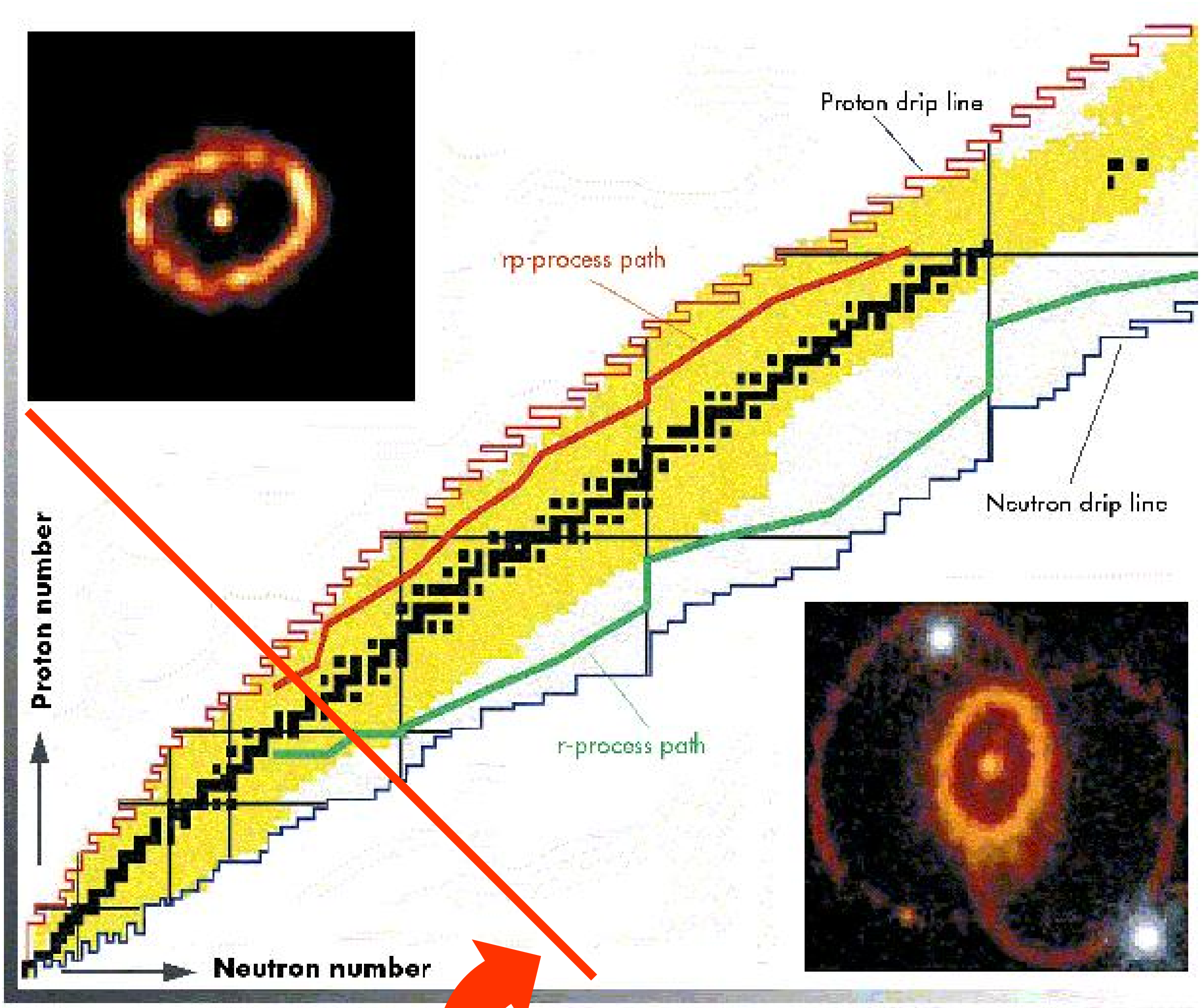
Stable isotopes
(which are not radioactive)
are in black - 283 of them
(limits of observed nuclei are shown)
Stable isotopes get more
neutron rich as Z increases

ISOTOPES Z constant

ISOTONES N constant

ISOBARS A constant

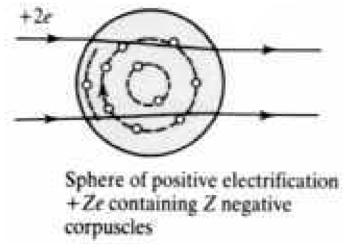
Segrè chart - showing stable and unstable nuclei

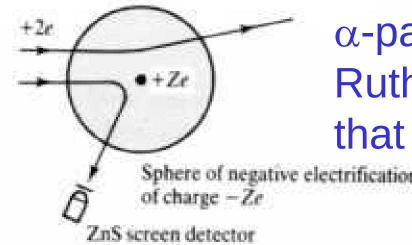


283 stable
5000 predicted
2500 made

Line of constant A has slope = -1

Nuclear Sizes

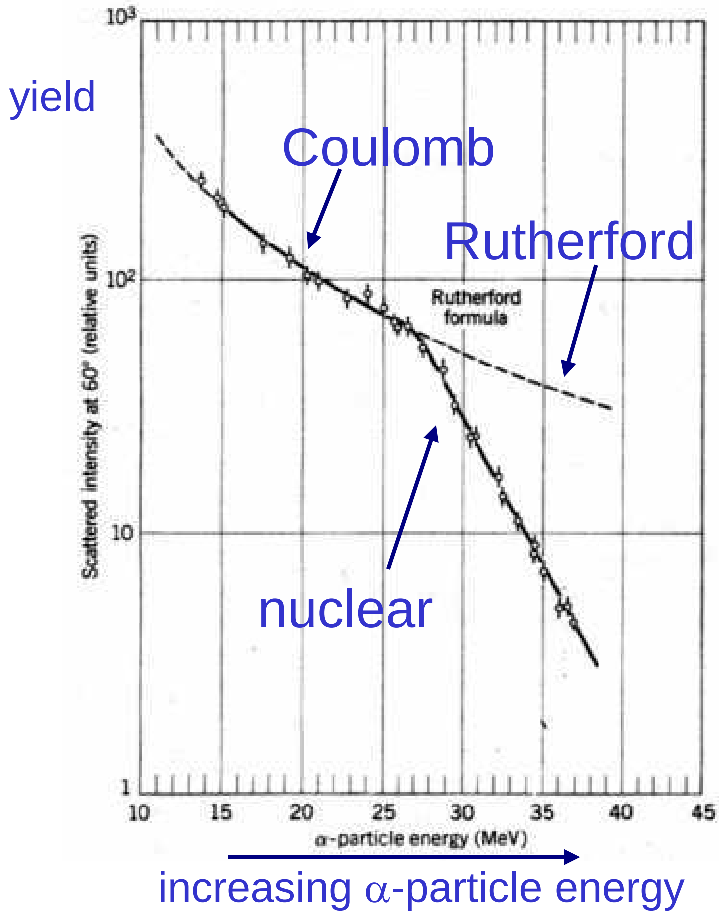




α-particle scattering by Rutherford first showed that the nucleus must exist

The yield will deviate from the Rutherford formula when the nuclei actually touch...

α-particles
incident on Pb foil…



Results

$R \approx r_0 A^{1/3}$

$r_0 = 1.2$ to 1.4
$\times 10^{-15}$ m

$1\ \text{fm} \equiv 10^{-15}$ m

The Nuclear Force

The nuclear force is different from gravity or electromagnetic (Coulomb forces)

Since protons repel each other, it must be stronger than the Coulomb force at distances of order 1 fm (10^{-15} m)

Since neutrons are strongly held inside nuclei, it must have similar effects on both neutrons and protons (mirror nuclei such as $^{17}F_8$ and $^{17}O_9$ $\Rightarrow$ charge independence)

Force is due to exchange of pions (Yukawa 1935) and other mesons. Pion discovered in cosmic rays (1946), mass $\approx$ (1/7) $\times$ m(nucleon)

The pions are systems of a quark and an anti-quark bound together by gluon exchange (QCD theory)

Nuclear Isotopes

Not all atoms of the same chemical element have exactly the same mass.
Deduced in 1911 by Soddy, who gave the name **isotopes** to the different masses.
First direct observation using electromagnetic separation achieved by Fred Aston in 1919.

Mass Spectrometer

Atoms of the element are ionized, and the charged ions go into a **velocity selector** which has **orthogonal** electric and magnetic fields set to exert equal and **opposite** forces on ions of a particular velocity.
(if the velocity is smaller, then the magnetic force is smaller; if it is bigger then the magnetic force is greater; these ions are then deflected)
The magnet then separates the ions according to mass since the bending radius is
$R = (m \times v) / (q \times B)$ where q = charge of ion.

Review of Basic Concepts

Nuclei comprise protons and neutrons

$m_p c^2 = 938.28$ MeV

$m_n c^2 = 939.57$ MeV

$m_N \approx 1$ u

Atoms are nuclei + electrons $m_e c^2 = 0.511$ MeV $m_e \approx 1/2000$ u

Sizes: Atoms ~ 10^{-10} m

Nuclei ~ 10^{-14} m = 10 fm (fermi)

Isotopes

same proton number

$$\left\{ \begin{array}{l} {}^{14}_{6}C_8 \xrightarrow{\tau_{1/2} \sim 5700\text{ yr}} {}^{14}_{7}N_7 \\ {}^{12}_{6}C_6 \end{array} \right.$$

Protons and neutrons can ***change*** into each other

Isobars (i.e. same A) can have ***different masses***

$${}^{239}_{94}Pu_{145} \xrightarrow{\tau_{1/2} \sim 24110\text{ yr}} {}^{235}_{92}U_{143} + {}^{4}_{2}He_2$$

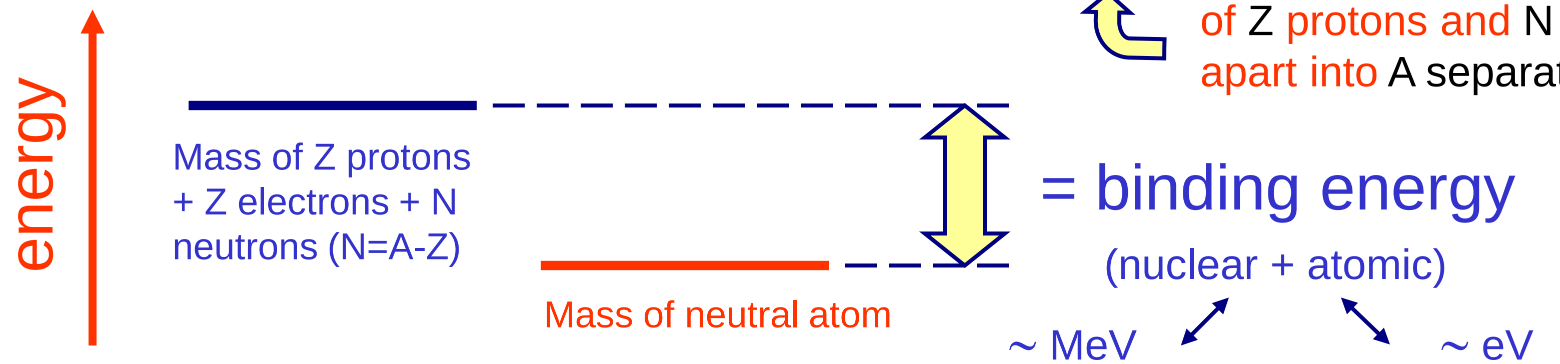
The same numbers of protons and neutrons can be grouped together ***differently***, to have ***different overall masses***

Atomic Masses

$M(Z,A)$ = mass of ***neutral atom*** of element Z as isotope A

$$M(Z,A) \approx Z \times m(\,{}^{1}_{1}\mathrm{H}\,) + N \times m_n - B_{\mathrm{nuclear}}$$

The binding energy is the energy needed to take a nucleus of Z protons and N neutrons apart into A separate nucleons

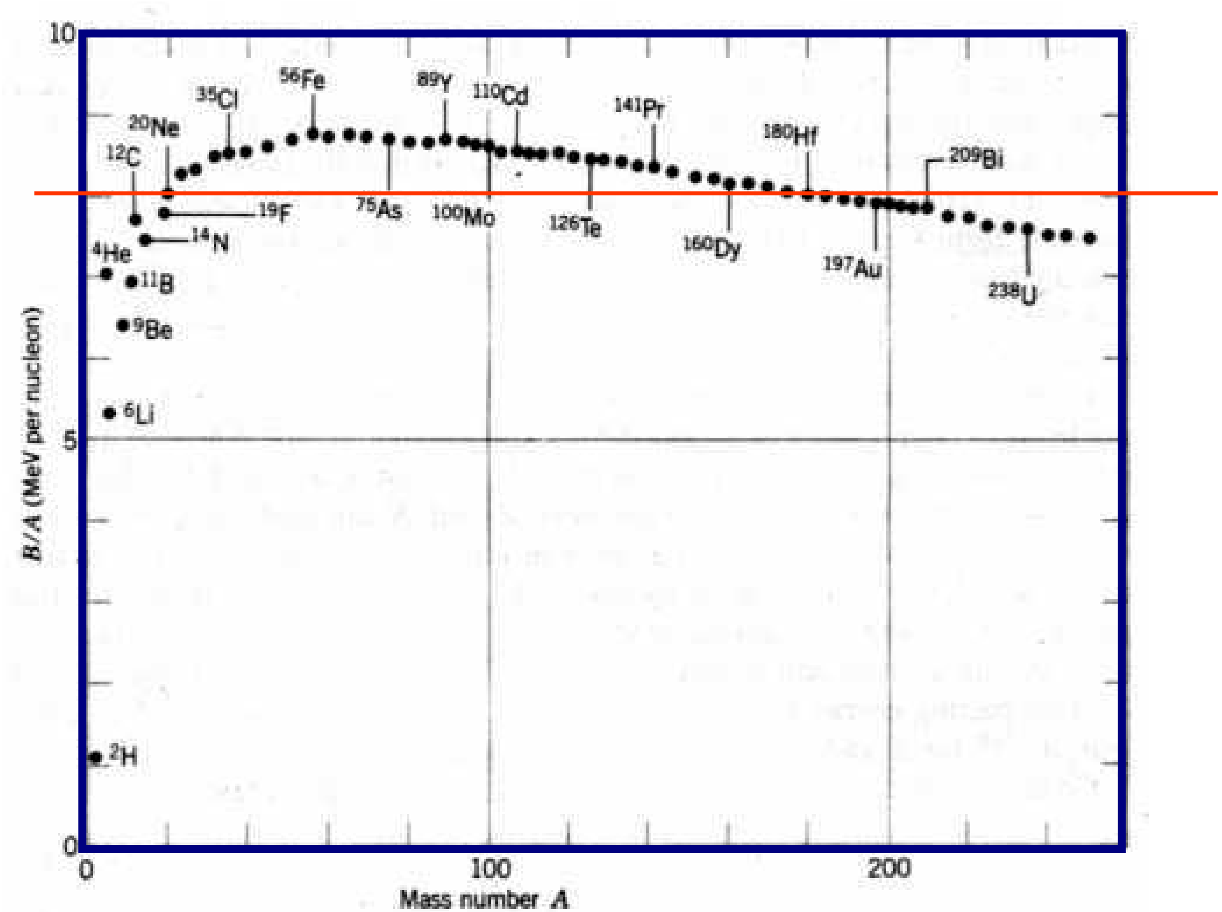


Mass excess, or mass defect : $\Delta = [\,M(Z,A) - A \times (1\ \mathrm{u})\,] \times c^2$

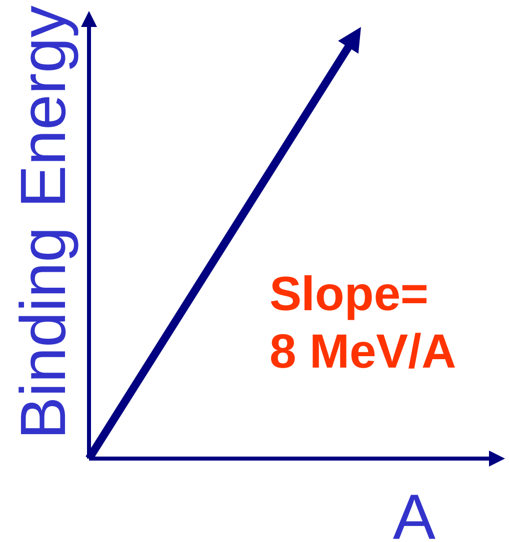
1 amu = 1 u = $(1/12) \times M(12,6) = (1/12) \times M(\,{}^{12}_{6}\mathrm{C}\,)$

Separation energies :

The variation of Binding Energy per nucleon with A



8 MeV/A

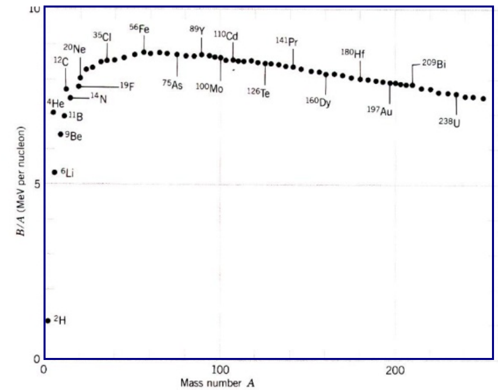


B (Z, A) $\approx$ 8 $\times$ A MeV $\Rightarrow$ binding is via a short range force

Deviations from the "constant" 8 MeV/A $\Rightarrow$ fission and fusion can release energy

The Semiempirical Mass Formula

This allows the general trends in nuclear masses to be understood in terms of their 5 main contributions



Volume term

Surface term

Coulomb term

Symmetry term

Pairing term

Since B/A ≈ constant (8 MeV/A), we can write

$B = a_V A$ to a first approximation

($r = r_0 A^{1/3}$ and volume $\propto r^3$ so volume $\propto A$)

Nucleons feel a binding force from all *neighbours*, and *surface nucleons* have *fewer neighbours*

correction $\propto$ $(4 \pi r^2)$ i.e. $- a_S A^{2/3}$

(compare surface tension on a liquid drop)

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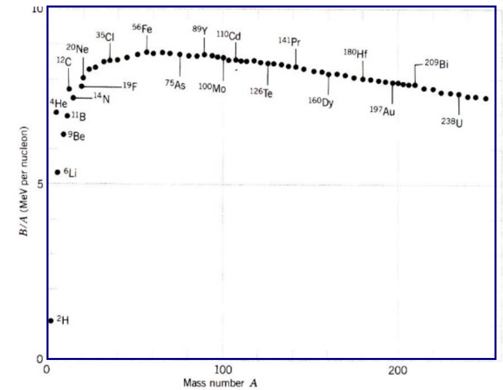

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Repulsion between protons reduces the binding, B

The number of ways to choose 2 protons = Z (Z-1)

Coulomb potential $\propto (1/ r)$ i.e. $- a_C Z (Z-1) A^{-1/3}$

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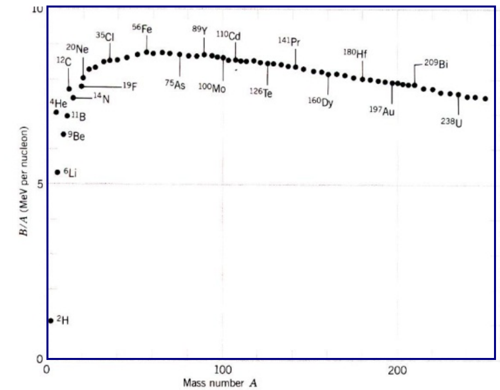

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The number of ways to choose 2 protons = Z (Z-1).
Coulomb potential $\propto$ (1/ r) i.e. $- a_C\, Z\,(Z-1)\, A^{-1/3}$

For stable light nuclei
N $\approx$ Z
but less true for higher A

Hence, B is lower if
N $\neq$ Z
unless A is large

i.e. $- a_{SYM}\,(N - Z)^2 / A$

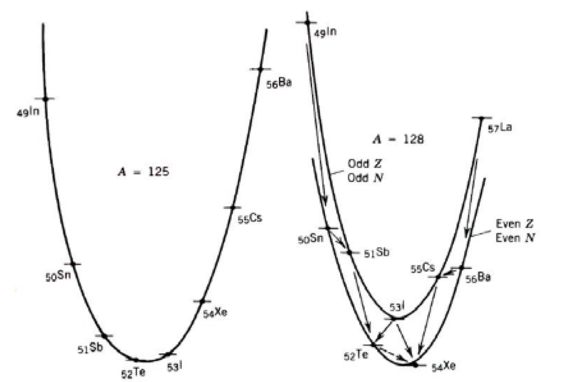
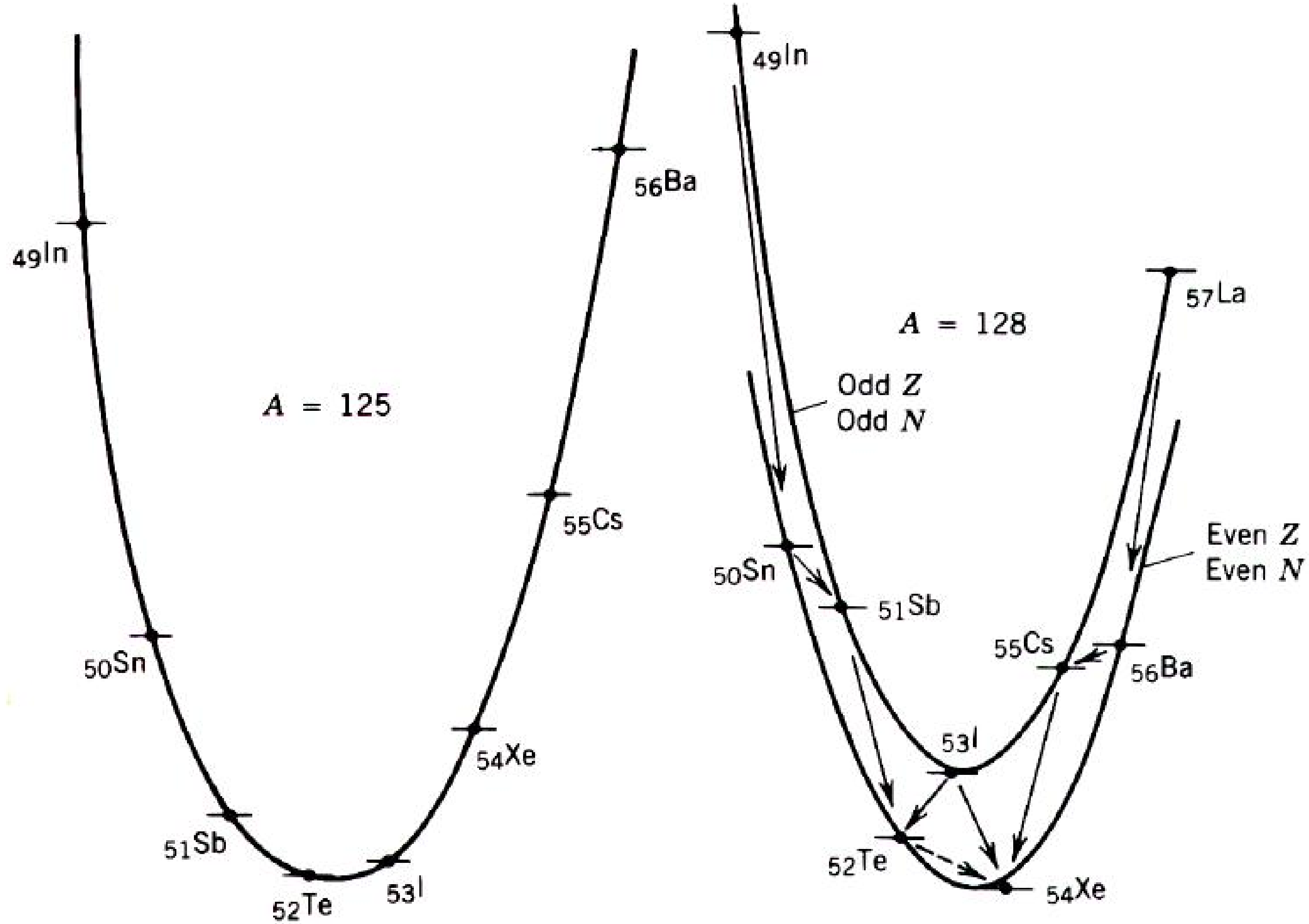


Figure 3.18 Mass chains for $A = 125$ and $A = 128$. For $A = 125$, note how the energy differences between neighboring isotopes increase as we go further from the stable member at the energy minimum. For $A = 128$, note the effect of the pairing term; in particular, ^{128}I can decay in either direction, and it is energetically possible for ^{128}Te to decay directly to ^{128}Xe by the process known as double β decay.



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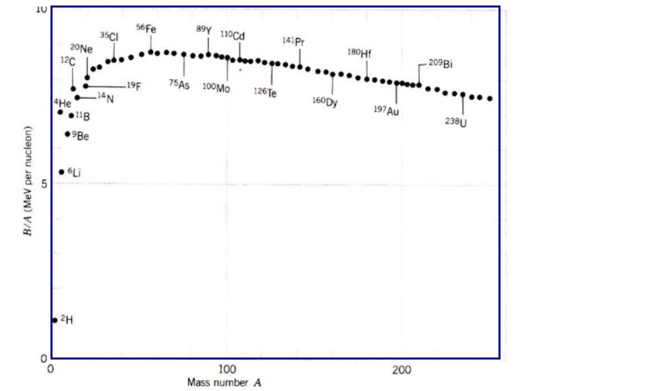

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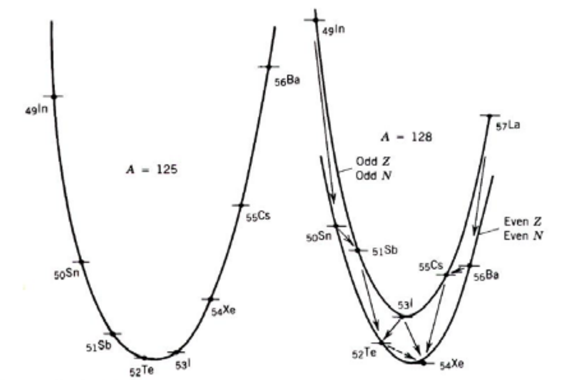

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Mass parabolas show that *odd nucleons cost energy*; pairing of protons (even Z) or neutrons (even N) is energetically favoured (i.e. lower mass) (higher B)

$$\text{i.e. Add } \delta = \begin{cases} + a_P \, A^{-3/4} & \text{Z and N both even} \\ 0 & \text{odd A} \\ - a_P \, A^{-3/4} & \text{Z and N both odd} \end{cases}$$

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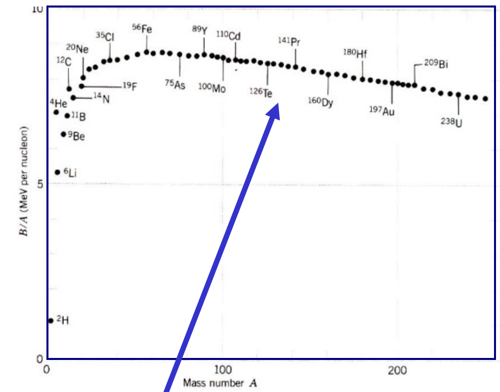
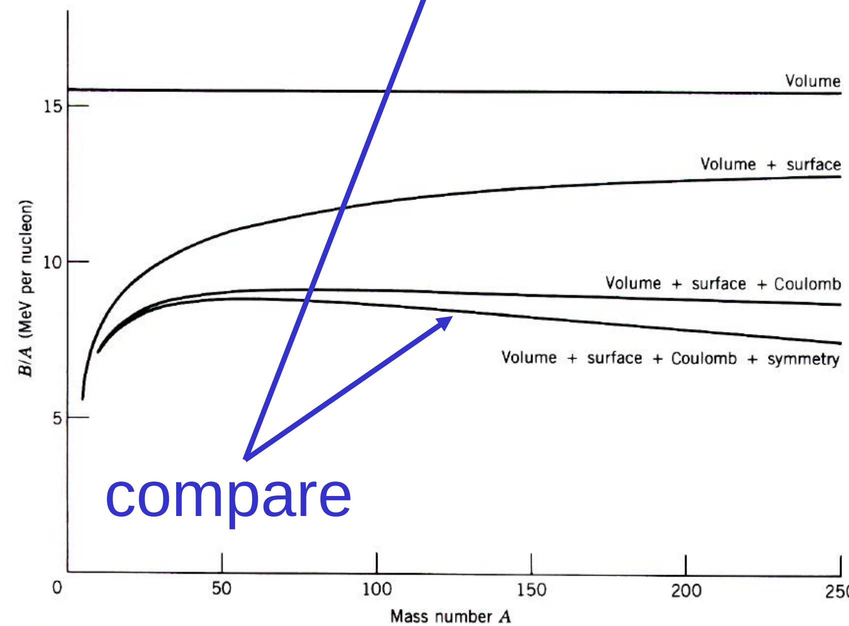


Volume term	$a_V = 15.5$ MeV
Surface term	$a_S = 16.8$ MeV
Coulomb term	$a_C = 0.72$ MeV
Symmetry term	$a_{SYM} = 23$ MeV
Pairing term	$a_P = 34$ MeV



compare

Figure 3.17 The contributions of the various terms in the semiempirical mass formula to the binding energy per nucleon.

$$B = a_V A - a_S A^{2/3} - a_C Z(Z-1) A^{-1/3} - a_{SYM} (N-Z)^2 /A + \delta$$