Physics 150 — 10/10/11 → 10/15/11

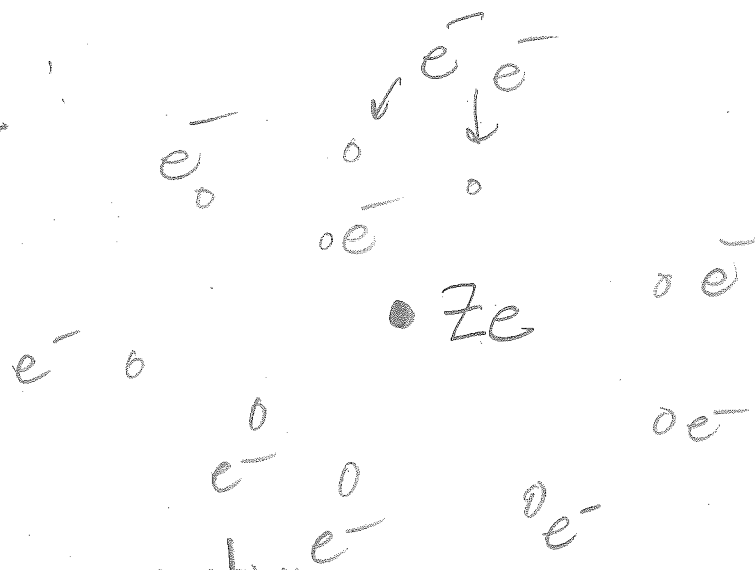
Nucleons (proton + neutron) in Nuclei

Idea: dense packing

totally different than electrons in a atom

Picture:

Atom:



e^- in motion, of course

but $e^- - e^-$ interactions are "a perturbation, not "the big effect"

In nuclei, the nucleon-nucleon interaction is large, short range, hard repulsive core, attractive outside

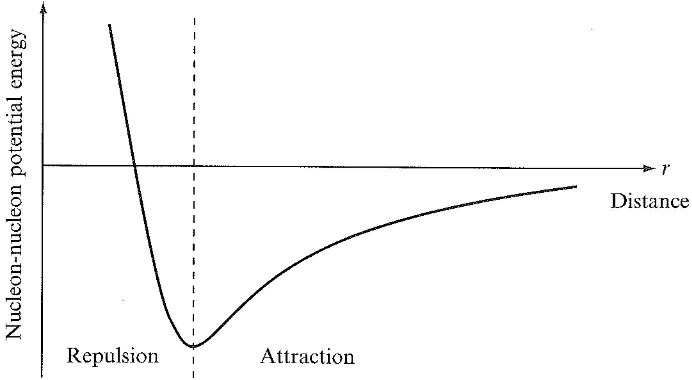
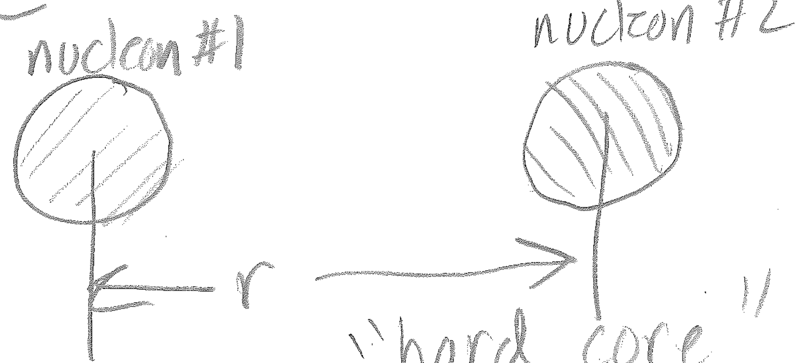
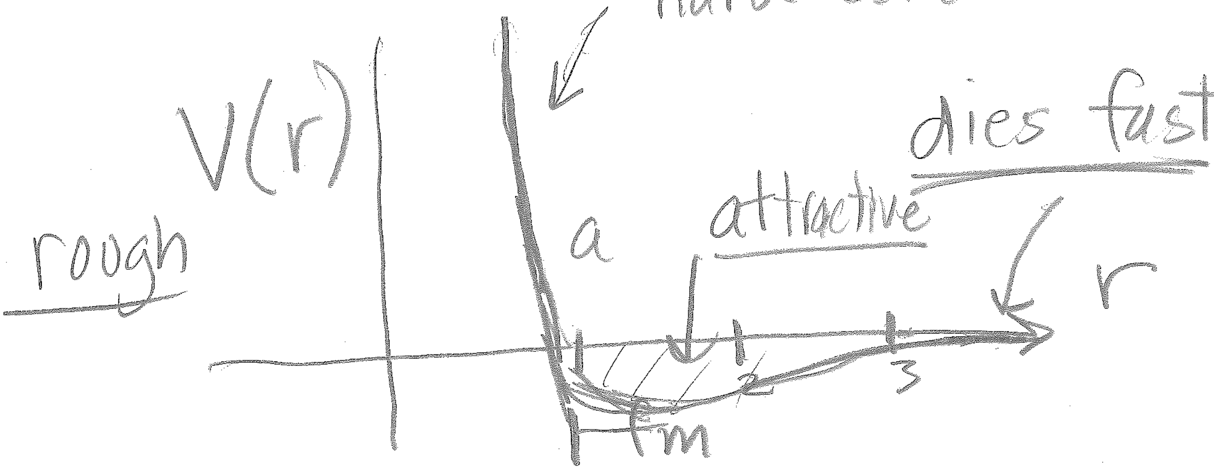


Figure 2.1 Schematic representation of the potential energy (PE) as a function of distance between two nucleons. As the nucleons approach each other, they experience an attractive force, which leads to a decrease in PE. At shorter distances ($\lesssim 0.5\,\text{fm}$), the force becomes repulsive and the PE increases. A minimum in PE occurs where the attractive and repulsive forces are equal and opposite.

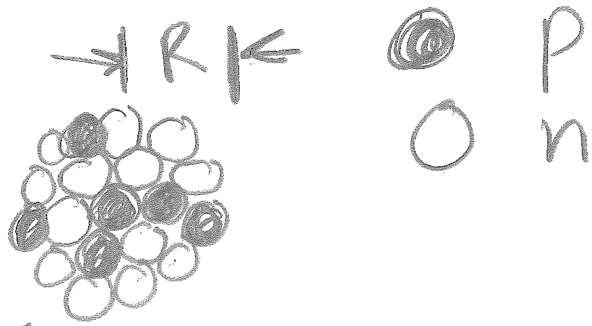
CRUDELY





$$1\ \text{fm} = 10^{-13}\ \text{cm} = 10^{-15}\ \text{m}$$

Nuclei Tend to Look Like



dense pack

N = # neutrons

Z = # protons

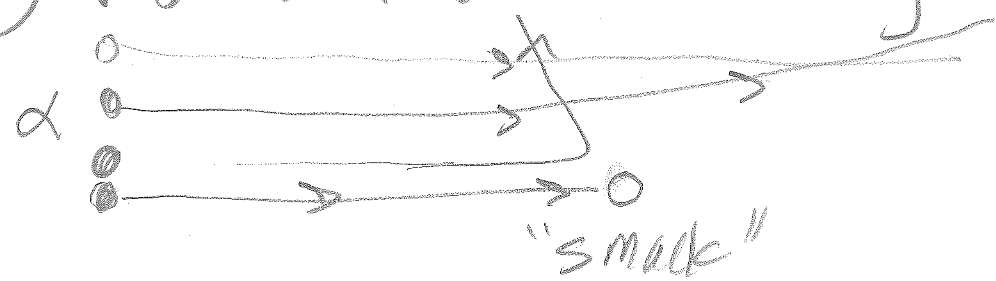
$$A = N + Z$$

$$A \propto \text{volume} = \frac{4\pi}{3} R^3$$

or $$A = \frac{4\pi}{3} R^3 \cdot \rho_0$$

ρ_0 and or R determined by experiment!

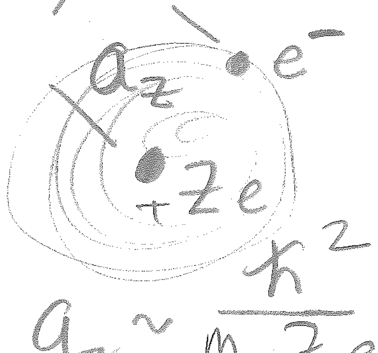
① Rutherford Scattering

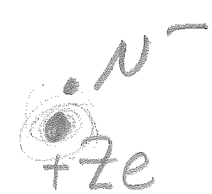


$$R \simeq 10^{-13}\,\text{cm}$$

② Muonic Atoms

μ^- like e^- but $m_\mu \sim 200\, m_e$





$$a_Z \sim \frac{\hbar^2}{m_e Z e^2} \sim \frac{0{,}5 \cdot 10^{-8}\,\text{cm}}{Z}$$

$$a_{\mu Z} \sim \frac{0{,}5 \cdot 10^{-8}\,\text{cm}}{200\, Z} \sim \underbrace{\frac{3 \cdot 10^{-11}\,\text{cm}}{Z}}_{\text{a bit big, close enough}}$$

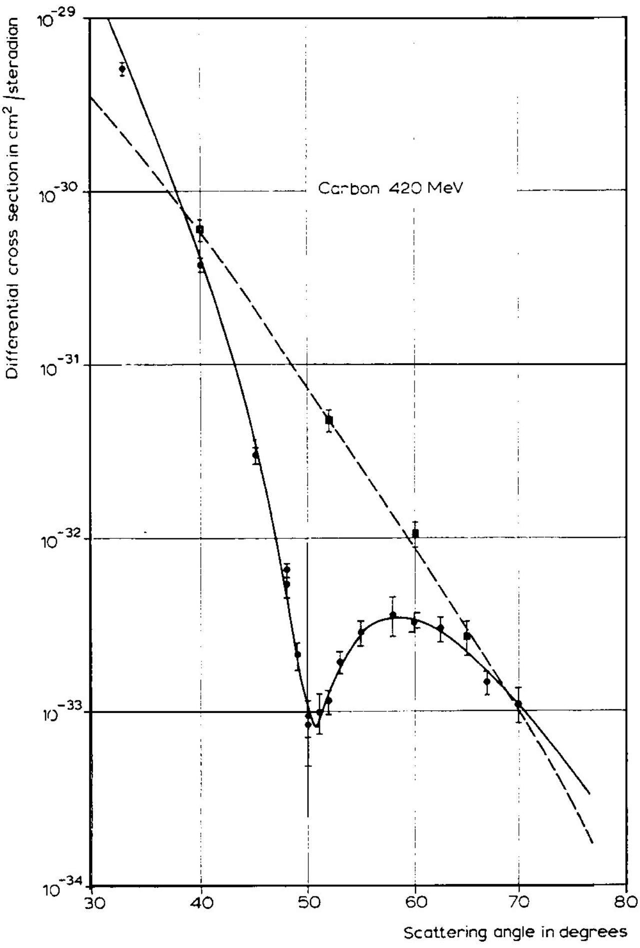
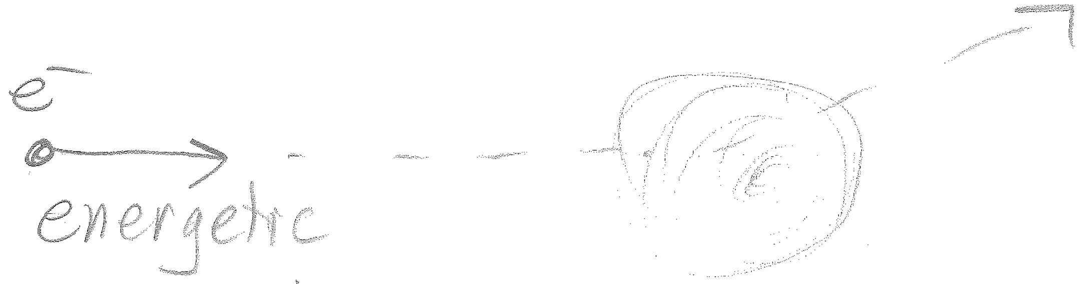


Fig. 5. This figure shows the elastic and inelastic curves corresponding to the scattering of 420-MeV electrons by ^{12}C. The *solid circles,* representing experimental points, show the elastic-scattering behavior while the *solid squares* show the inelastic-scattering curve for the 4.43-MeV level in carbon. The *solid line* through the elastic data shows the type of fit that can be calculated by phase-shift theory for the model of carbon shown in Fig. 8.

(3) e^- Nucleon Diffractive Scatterings

"diffraction"



energetic

$\lambda <$ nuclear size

Nucleus

$\lambda < 10^{-13}\,cm$

$$p > \hbar k = \frac{\hbar \cdot 2\pi}{\lambda} = \frac{2\pi \hbar c}{\lambda} \cdot \frac{1}{c}$$

$$\hbar c \simeq 200 \text{ MeV} \cdot \text{fm}$$

$$p \gtrsim \frac{6 \cdot 200 \cdot \text{fm}}{1 \ \ \text{fm}} \ \ \frac{\text{MeV}}{c}$$

$$p \gtrsim 1200 \ \text{MeV}/c$$

happened .. 400 MeV/c sufficient

Hofstadter 1961 Nobel Prize

Result : $\rho_0 \simeq \dfrac{1}{6} \dfrac{\text{nucleon}}{\text{fm}^3}$

$$R = \left(\frac{3}{4\pi\rho_0} A\right)^{1/3} = \left(\frac{9}{2\pi}\right)^{1/3} \text{fm} \cdot A^{1/3}$$

$$\boxed{R = (1.1 \text{ fm}) \cdot A^{1/3}}$$

(1 – 1.5 fm) within error etc

Binding Energy of Nucleons in Nuclei

Phenomenological ... like ... Lyman
Balmer
Paschen
Bracket
Pfund

Hydrogen

$\boxed{\text{Idea \#1}}$

$E = mc^2$

$$m_{nuc}(Z,N) = \underbrace{Z m_p + N m_n}_{\text{constituents}} - \underbrace{\frac{B(Z,N)}{c^2}}_{(\text{Binding energy})/c^2}$$

Atoms, not nuclei ...

$$m_a(Z,N) = Z(m_p + m_e) + N m_n - \frac{B(Z,N)}{c^2} - \frac{b_e}{c^2}$$

(Experimentally, sometimes atoms easier to get than naked nuclei, WHY?)

b_e: (A) Thomas-Fermi

guess $Z^3 = Z^2 \cdot Z$

$$b_e \sim 20.8\, Z^{7/3} \text{ eV}$$

note... per electron,

$$\frac{b_e}{Z} = 20.8\, \underline{Z^{4/3}} \text{ eV}$$

increases!

WHY?

(B) Better Empirical

$$b_e \sim 14.33\, Z^{2.39} \text{ eV}$$

or $\sim 14.44\, Z^{2.39} - (1.5547 \cdot 10^{-6}) Z^{5.35}$ eV

Here, $B(Z,N)$, for nuclei, is our concern, $b_e < 1$ MeV, $Z < 106$

NEGLECT b_e!, $Z \cdot m_e$

Measurement ...

- Mass Spectrometry
  → 1922 Nobel Prize, Chemistry
  Francis Aston
  Learned to surf in 1909
- B(Z,N) pretty obvious! Still Going ON!

Idea #2

my notation

$$\frac{B(Z,N)}{A} \sim \text{constant} = K$$

(not like electrons!)

consequence...   Since $A = N + Z$

$$m_{nuc} = \left(m_p - \frac{K}{c^2}\right)Z + \left(m_n - \frac{K}{c^2}\right)N$$

very close

$m_p c^2 = 938.3$ MeV $m_n c^2 = 939.6$ MeV

same to 1.4 ‰ (per mille)

$$m_{nuc} \simeq (m_N - \frac{K}{c^2})(Z+N=A)$$

$\sim 939\ MeV/c^2$?

Aston found...

$$m_{nuc} \simeq (m_U - \frac{m_e}{2}) A$$

Carbon 12 used

$$m_U = \frac{1}{12} m(^{12}C)$$

$$\boxed{m_U c^2 \cong 931.5\ MeV}$$

important

so

$$m_N - \frac{K}{c^2} = m_U - \frac{m_e}{2}$$

$$K \cong (m_N - m_U + \frac{m_e}{2}) c^2$$

$$\simeq 939 - 931.5 + \frac{0.511}{2}$$

$$\boxed{\begin{aligned} K &\simeq 7.8\ MeV \\ &\simeq 8\ MeV \end{aligned}}$$

Binding Energy/Nucleon

Aside: $N_A \cong 6.02 \cdot 10^{23}$

Compute: $N_A \cdot m_u = N_A \dfrac{m_u c^2}{c^2}$

$$= \frac{6.02 \cdot 10^{23} \cdot 9.315 \cdot 10^{8}\,\text{eV} \times 1.602 \cdot 10^{-19}\ \text{J/eV}}{(2.998 \cdot 10^{8})^2}$$

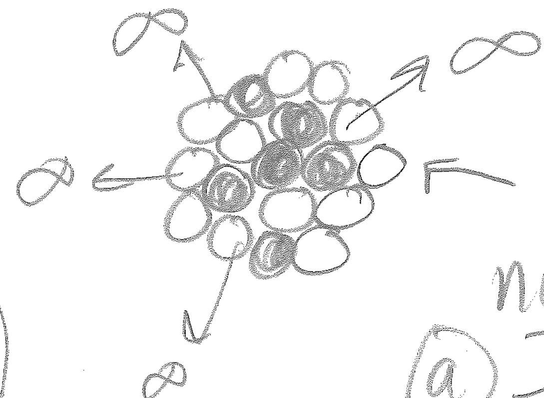
$$= 0.00099949 \cong 0.001\ \text{kg}$$

$\boxed{N_A m_u = 1\ \text{gram}} \Leftarrow$!!! definition of mole!!!

Idea #3

Physical Picture of $\dfrac{B(Z,N)}{A} \simeq$ constant.

nucleons go on forever



mostly attractive force between nucleons:

(a) Independent of whether p or n

(b) Only between nearest neighbors

Surpise!

This picture gives $\boxed{B(Z,N)/A \simeq 16\ \text{MeV}}$

Substantially greater than 8 MeV!

Other terms/considerations tend to increase energy, reduce binding energy

Idea #4 Nucleons on the surface lack outer neighbor.. binding energy less

$$B(Z,N) \simeq aA - bA^{2/3}$$

volume $\propto A \propto R^3$ surface $\propto A^{2/3} \propto R^2$

$$\boxed{b \simeq 18 \text{ MeV}}$$

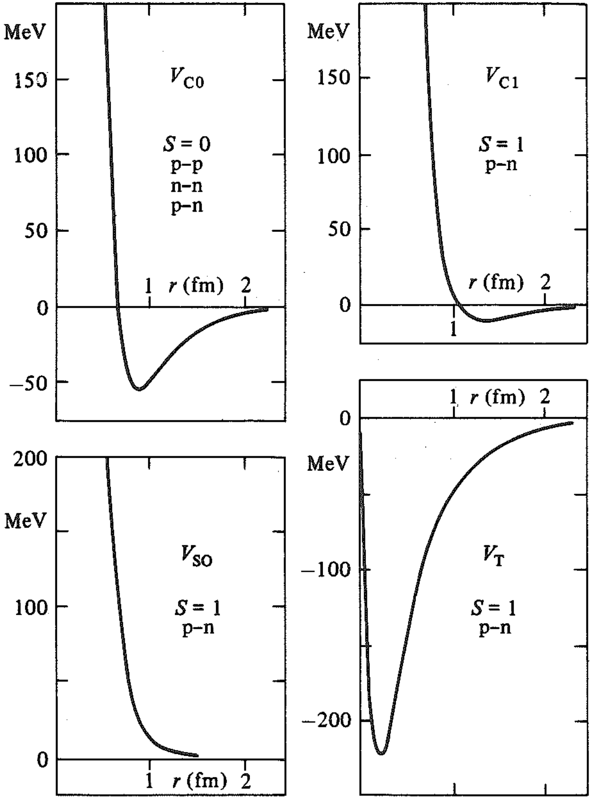
(more precise depends on details)

Idea #5 Electrostatic Repulsion of Only Protons

$$B(Z,N) \simeq aA - bA^{2/3} - d\frac{Z^2}{A^{1/3}}$$

$$d \simeq 0.714 \text{ MeV}$$

3.2 The most important components of the 'Paris potential'. (After Lacombe, M. *et al.* (1980), *Phys. Rev.* **C21**, 861.)



$\boxed{\text{Idea \#6}}$ n-p interaction is more attractive then n-n or p-p.

$\boxed{\text{WHY}}$? Pauli Principal...

For wavefunction of n-n + p-p **not** to vanish when nucleons atop one another, spin state must be $\underbrace{S_{tot}=0}_{\text{asym}}$

$\Rightarrow$ potential not strong enough to even bind n-n or p-p!

$\boxed{\text{n-p}} \rightarrow$ not identical particles!
$S_{tot}=1$ possible!
Way deeper potential!!

$$B(Z,N) = aA - bA^{2/3} - d\frac{Z^2}{A^{1/3}} - s\frac{(N-Z)^2}{A}$$

$\boxed{\text{Idea \#7}}$ $\delta \simeq 11$ MeV

Pairing

		n/p n/p
$+$	$\frac{\delta}{A^{1/2}}$	odd-odd
	0	odd-even
$-$	$\delta/A^{1/2}$	even-even

- 0 $N=Z$
- goes up as square of difference
- pure N (or Z) $\propto A$

Putting Everything Together

$$m_a c^2 = \underbrace{\left(N m_n + Z(m_p + m_e)\right)}_{\text{constituents}} c^2$$

$m_n c^2 \simeq 939.6$ MeV
$m_p c^2 \simeq 938.3$ MeV
$m_e c^2 \simeq 0.511$ MeV

$$\underbrace{-aA + bA^{2/3} + d\frac{Z^2}{A^{1/3}} + \frac{s(N-Z)^2}{A} + \frac{\delta}{A^{1/2}}}_{\text{nuclear binding}}$$

$$-fZ^{2.39} \leftarrow \text{electronic binding}$$

a	$\simeq$	16	MeV	(15.835)
b	$\simeq$	18	"	(18.33)
d	$\simeq$	0.71	"	(0.714)
s	$\simeq$	23	"	(23.28)
δ	$\simeq$	11	"	(11.2)
f	$\simeq$	0	MeV	(0.000014)

Subsequent Concepts

$\boxed{\#1}$ Take A as given, solve for Z that minimizes the atomic mass. $N = A - Z$

$$m_A c^2 = A(m_n c^2 - a) + bA^{2/3} + sA + \frac{\delta}{A^{1/2}}$$
$$+ \left((m_p + m_e - m_n)c^2 - 4s\right)Z$$
$$+ \left(\frac{4s}{A} + \frac{d}{A^{1/3}}\right)Z^2$$
$$= \alpha - \beta Z + \gamma Z^2$$

$$\alpha \equiv A(m_n c^2 - a) + bA^{2/3} + sA + \frac{\delta}{A^{1/2}}$$

$$\beta \equiv 4s - (m_p + m_e - m_n)c^2$$

$$\gamma = \frac{4s}{A} + \frac{d}{A^{1/3}}$$

minimize

$$\frac{d(m_A c^2)}{dZ} = -\beta + 2\gamma Z = 0 \Rightarrow Z_{min} = \frac{\beta}{2\gamma} = \frac{[4s + (m_n - m_p - m_e)c^2]A}{2(4s + dA^{2/3})}$$

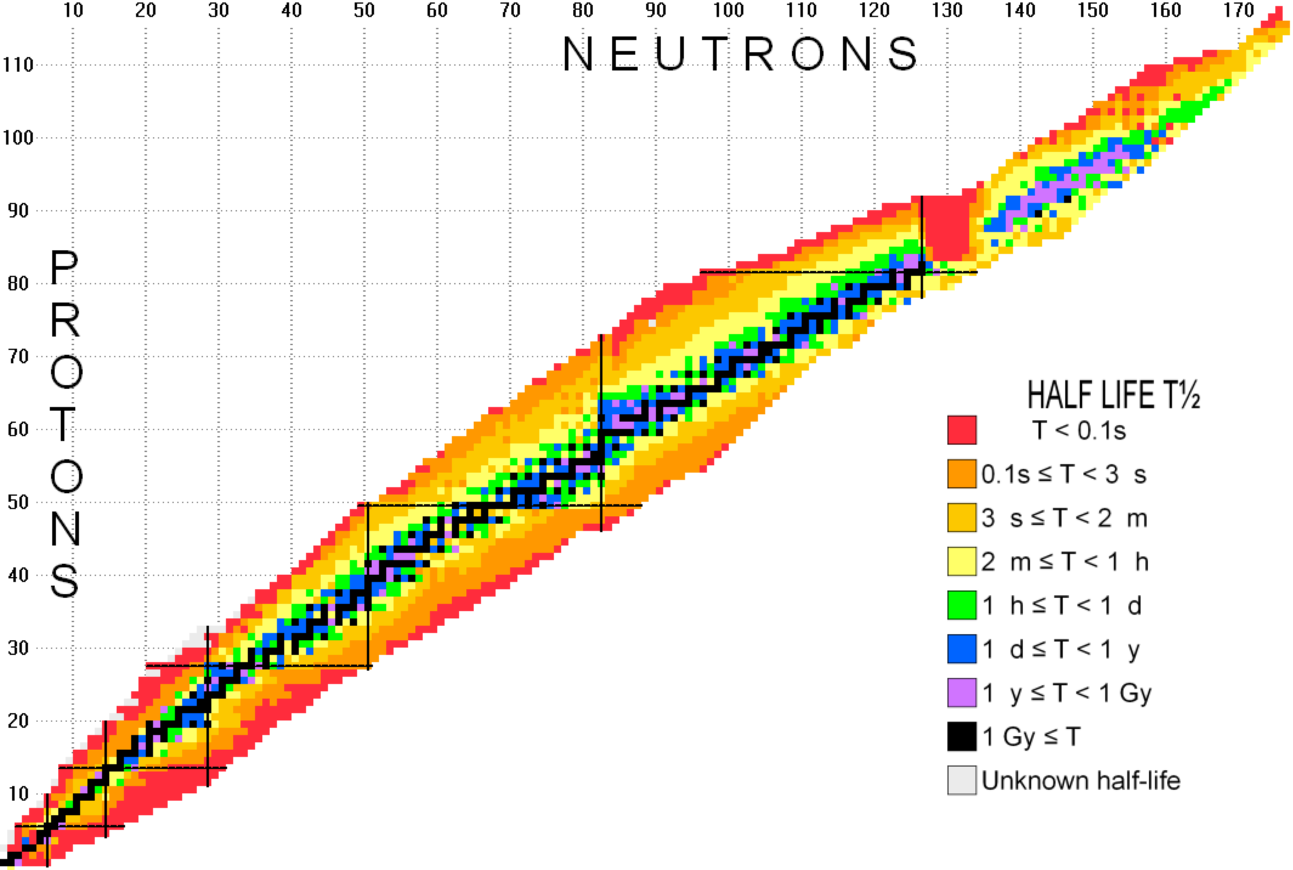


Figure 2: Chart of the nuclides for half-lives (created by NUCLEUS-AMDC).

Limiting Cases

(A) • A small

• note $4s = 92$ MeV

$$(m_n - m_p - m_e)c^2 = 939.6 - 938.3 - 0.5 \simeq 0.8 \text{ MeV}$$

$$\therefore \quad Z_{min} \simeq \frac{1}{2} A$$

$${}^{4}_{2}He, \ {}^{16}_{8}O, \text{ etc.}$$

(B) • A grows,

$$Z_{min} < \frac{1}{2} A$$

so $N_{min} > \frac{1}{2} A$

Heavy Nuclei are neutron rich

#1 a "Valley of Stability"

Z vs N

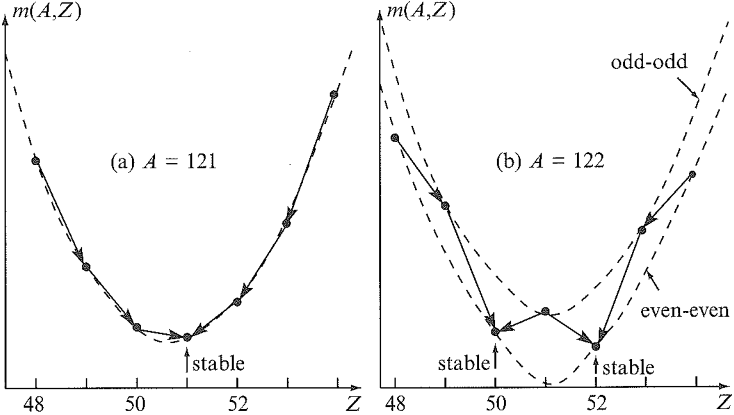
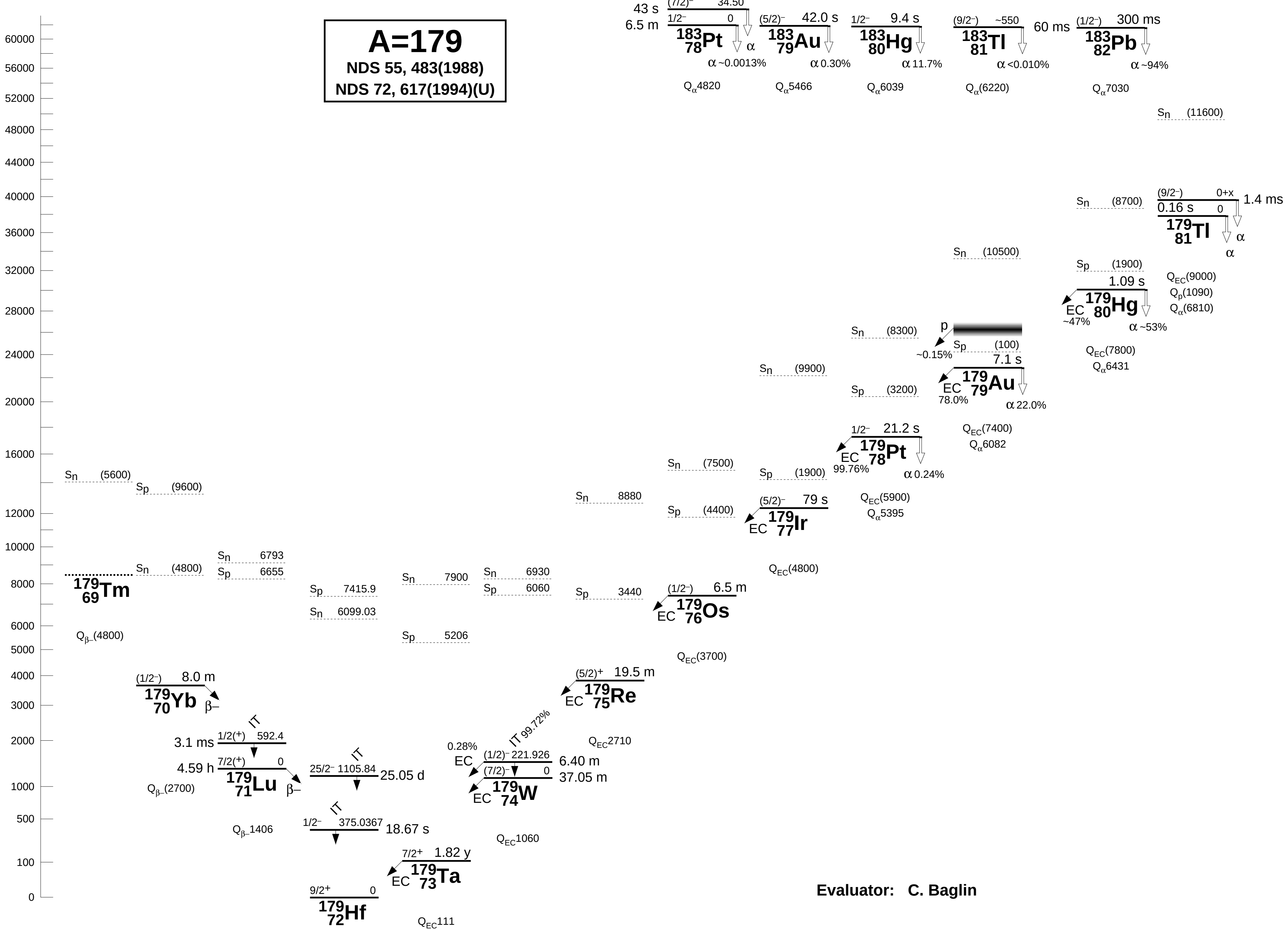
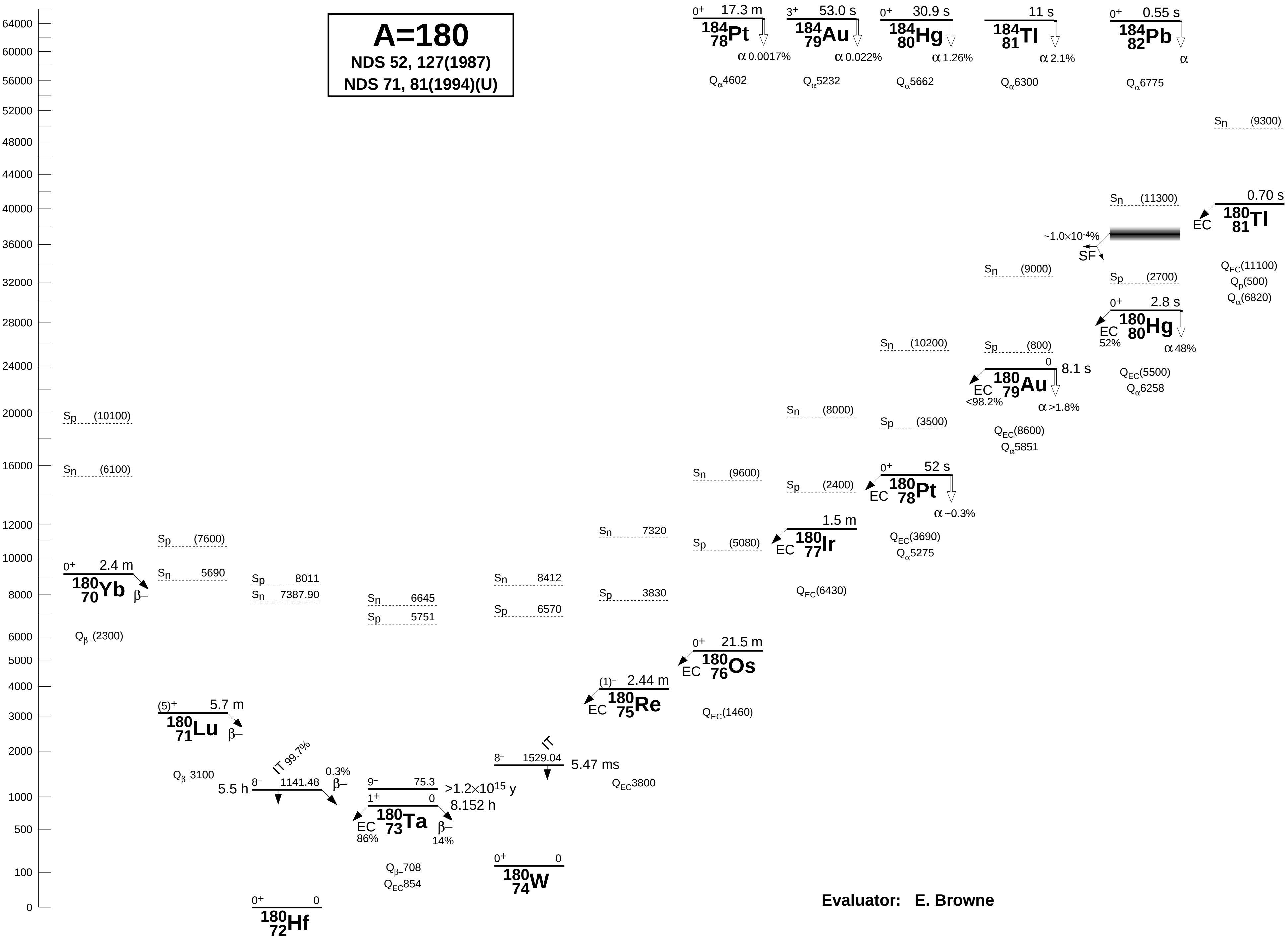


Figure 2.4 Stability of nuclei in isobaric mass sequences. The nuclear mass $m(A, Z)$, calculated using the SEMF, is plotted as a function of atomic number for (a) $A = 121$ and (b) $A = 122$. Note that when A is even, points for the different isobars fall on two parabolas because of the pairing energy term in the SEMF. Beta-decay transitions are indicated by arrows.



A=179
NDS 55, 483(1988)
NDS 72, 617(1994)(U)
60000
56000
52000
48000
44000
40000
36000
32000
28000
24000
20000
16000
12000
10000
8000
6000
5000
4000
3000
2000
1000
500
100
0
179 69 Tm
Sn (5600)
Qβ– (4800)
Sp (9600)
Sn (4800)
(1/2–) 8.0 m
179 70 Yb
β–
Qβ– (2700)
Sn 6793
Sp 6655
IT
3.1 ms 1/2(+) 592.4
4.59 h 7/2(+) 0
179 71 Lu
β–
Qβ– 1406
Sp 7415.9
Sn 6099.03
IT
25/2– 1105.84 25.05 d
IT
1/2– 375.0367 18.67 s
9/2+ 0
179 72 Hf
Sn 7900
Sp 5206
7/2+ 1.82 y
EC
179 73 Ta
QEC 111
Sn 6930
Sp 6060
0.28%
EC
IT 99.72%
(1/2)– 221.926 6.40 m
(7/2)– 0 37.05 m
EC
179 74 W
QEC 1060
Sn 8880
Sp 3440
(5/2)+ 19.5 m
EC
179 75 Re
QEC 2710
Sn (7500)
Sp (4400)
(1/2–) 6.5 m
EC
179 76 Os
QEC (3700)
Sn (9900)
Sp (1900)
(5/2)– 79 s
EC
179 77 Ir
QEC (4800)
Sn (8300)
Sp (3200)
1/2– 21.2 s
EC 99.76%
179 78 Pt
α 0.24%
QEC (5900)
Qα 5395
Sn (10500)
p
~0.15%
Sp (100)
7.1 s
EC 78.0%
179 79 Au
α 22.0%
QEC (7400)
Qα 6082
Sn (8700)
Sp (1900)
1.09 s
EC ~47%
179 80 Hg
α ~53%
QEC (7800)
Qα 6431
Sn (11600)
(9/2–) 0+x 1.4 ms
0.16 s 0
179 81 Tl
α
α
QEC (9000)
Qp (1090)
Qα (6810)
43 s (7/2)– 34.50
6.5 m 1/2– 0
183 78 Pt
α
α ~0.0013%
Qα 4820
(5/2)– 42.0 s
183 79 Au
α 0.30%
Qα 5466
1/2– 9.4 s
183 80 Hg
α 11.7%
Qα 6039
(9/2–) ~550 60 ms
183 81 Tl
α <0.010%
Qα (6220)
(1/2–) 300 ms
183 82 Pb
α ~94%
Qα 7030
Evaluator: C. Baglin

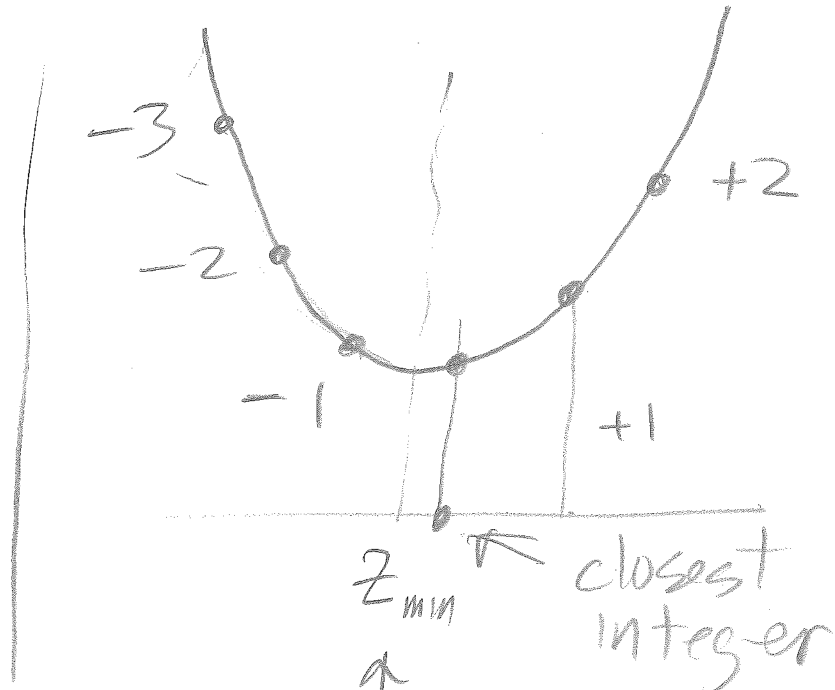

A=180
NDS 52, 127(1987)
NDS 71, 81(1994)(U)
0+ 17.3 m 184 78 Pt α 0.0017% Qα4602
3+ 53.0 s 184 79 Au α 0.022% Qα5232
0+ 30.9 s 184 80 Hg α 1.26% Qα5662
11 s 184 81 Tl α 2.1% Qα6300
0+ 0.55 s 184 82 Pb α Qα6775
Sn (9300)
Sn (11300)
0.70 s 180 81 Tl EC
~1.0×10-4% SF
QEC(11100) Qp(500) Qα(6820)
Sn (9000)
Sp (2700)
0+ 2.8 s 180 80 Hg EC 52% α 48%
QEC(5500) Qα6258
Sn (10200)
Sp (800)
0 8.1 s 180 79 Au EC <98.2% α >1.8%
QEC(8600) Qα5851
Sn (8000)
Sp (3500)
0+ 52 s 180 78 Pt EC α ~0.3%
QEC(3690) Qα5275
Sn (9600)
Sp (2400)
1.5 m 180 77 Ir EC
Sp (5080)
QEC(6430)
Sn 7320
Sp 3830
0+ 21.5 m 180 76 Os EC
QEC(1460)
(1)– 2.44 m 180 75 Re EC
QEC3800
Sn 8412
Sp 6570
8– 1529.04 5.47 ms IT
0+ 0 180 74 W
Sn 6645
Sp 5751
9– 75.3 >1.2×10^15 y
1+ 0 8.152 h 180 73 Ta EC 86% β– 14%
Qβ–708 QEC854
Sp 8011
Sn 7387.90
8– 1141.48 5.5 h IT 99.7% 0.3% β–
0+ 0 180 72 Hf
Sp (7600)
Sn 5690
(5)+ 5.7 m 180 71 Lu β–
Qβ–3100
Sp (10100)
Sn (6100)
0+ 2.4 m 180 70 Yb β–
Qβ–(2300)
64000 60000 56000 52000 48000 44000 40000 36000 32000 28000 24000 20000 16000 12000 10000 8000 6000 5000 4000 3000 2000 1000 500 100 0
Evaluator: E. Browne

#1b Fix A, plot mass versus Z

Easier: Even-Odd

Odd A

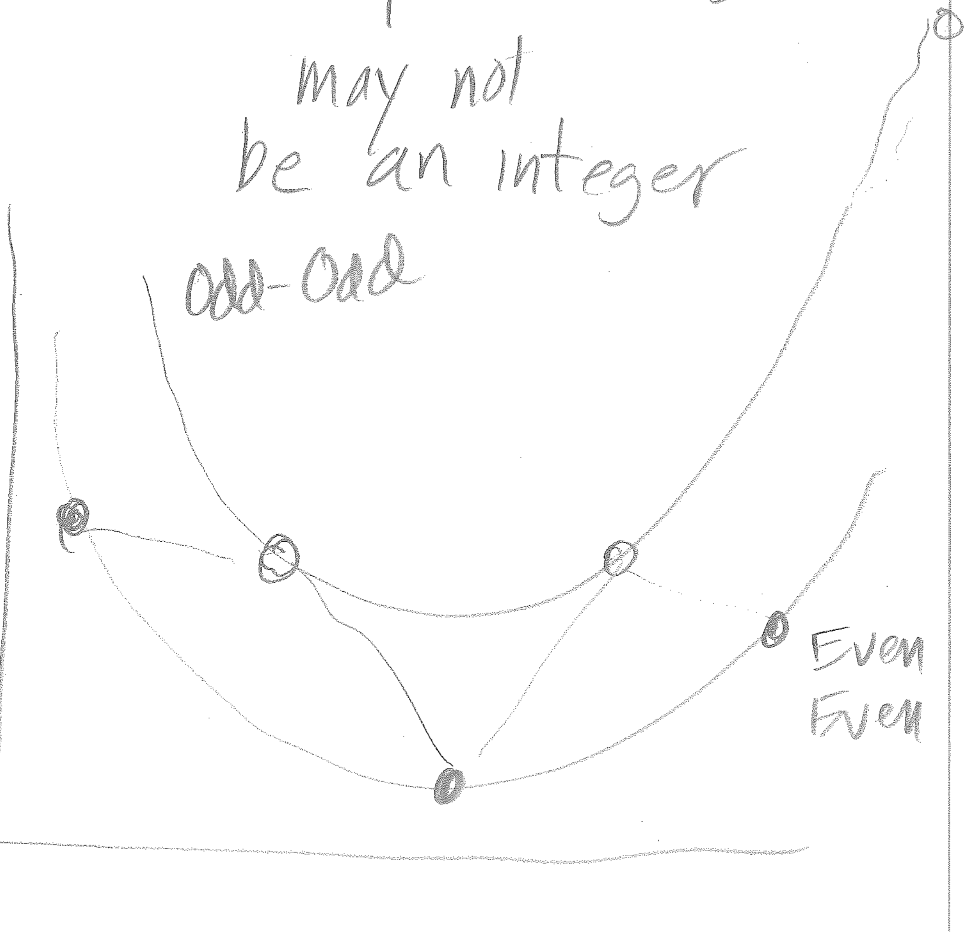
$m_A c^2$



may not be an integer

Even A

Key Question... Are More Energetic Ones Stable?



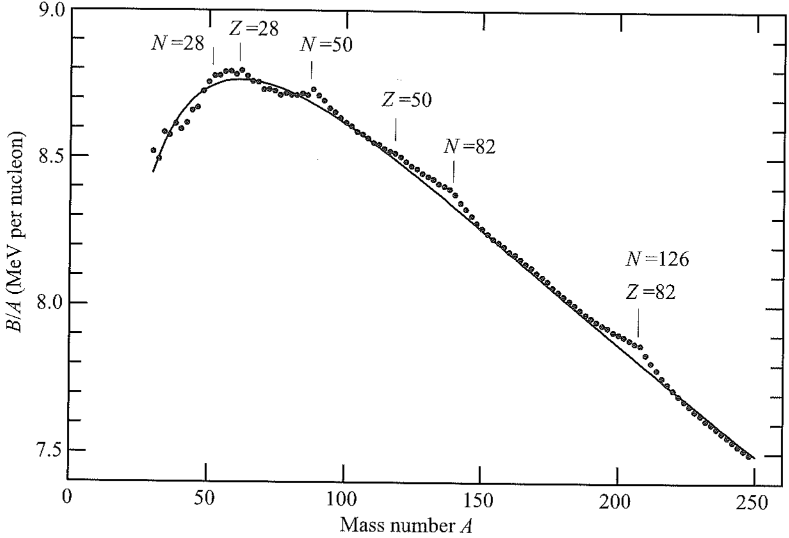
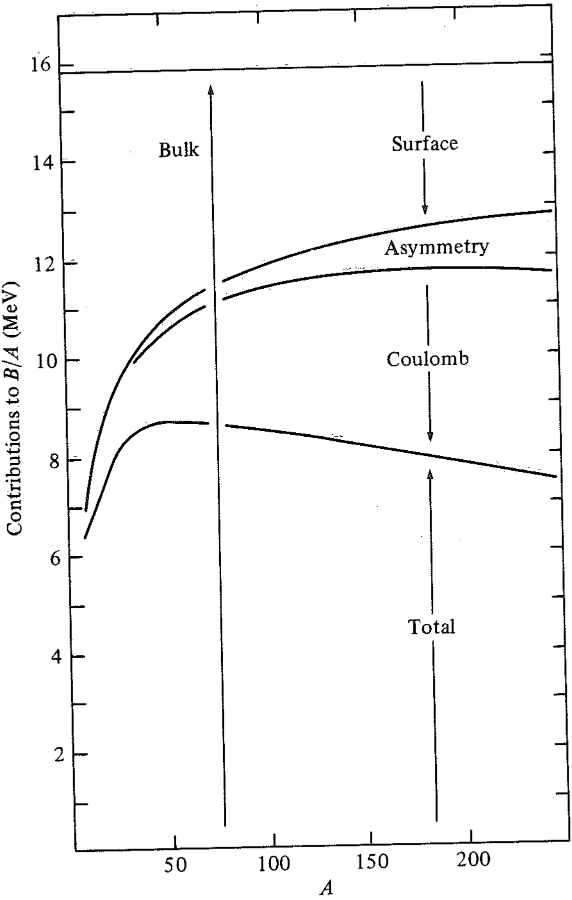


Figure 2.3 Experimental values of binding energy per nucleon B/A plotted as a function of mass number A. The smooth curve represents the semi-empirical mass formula with $a_v = 15.56$ MeV, $a_s = 17.23$ MeV, $a_a = 23.28$ MeV and $a_c = 0.7$ MeV. Each point represents an odd–even nucleus or an average of neighbouring nuclei (for A even) so that there is no effect due to the pairing term. Significant differences between experimental values and the SEMF occur near indicated values of N and Z.

Abundance of Si
is normalized to 10^6
Log10(Abundance)
Z, Atomic number
H
He
Li
Be
B
C
N
O
F
Ne
Na
Si
P
S
Ar
Ca
Sc
Ti
V
Fe
Co
Ni
Cu
Zn
Ga
Ge
As
Zr
Nb
Mo
Sn
In
Te
Xe
Ba
Pr
W
Re
Pt
Au
Hg
Pb
Bi
Th
U

4.8 The contributions to B/A. Note that the surface, asymmetry and Coulomb terms all subtract from the bulk term.



$\boxed{\#1c}$ Stuff Z_{min} back in and get $m_A c^2(A)_{Min}$

People really subtract off the constituent rest energies and then get...

$$\frac{B_{min}(A)}{A} \Leftarrow$$ "curve of binding energy"

(Title of Book by John MacPhee)

$\Rightarrow$ Most Abundant Elements also Most Tightly Bound (Iron!)

$\Rightarrow$ Eotvos Experiment

Gravity Really couples to Rest Energy, not N or Z or their L.C.

#2 Instability

#2a Weak

(i) β^- decay (Neutron Rich)

$$(A, Z) \rightarrow (A, Z+1) + e^- + \bar{\nu}_e$$

$$m_{nuc}(A, Z) > m_{nuc}(A, Z+1) + m_e$$

or $$m_a(A, Z) > m_a(A, Z+1)$$

Right hand move on graph

(ii) β^+ decay (Proton Rich)

$$(A, Z) \rightarrow (A, Z-1) + e^+ + \nu_e$$

$$m_{nuc}(A, Z) > m_{nuc}(A, Z-1) + m_e$$

$$m_a(A, Z) > m_a(A, Z-1) + 2m_e$$

Left hand move on graph

note the $2m_e$!

(iii) e^- capture

$$(A, Z) + e^- \rightarrow (A, Z-1) + \nu_e$$

$$m_a(A, Z) > m_a(A, Z-1)$$

goes when $2m_e$ gap not their

$\boxed{\#2b}$ α decay

$$(A, Z) \rightarrow (A-4, Z-2) + \underbrace{{}^4_2He}_{28.3\ MeV}$$

Binding Energy

$$\boxed{B(A, Z) < B(A-4, Z-2) + 28.3\ MeV}$$

${}^{238}U$, ${}^{232}Th$ $\Leftarrow$ naturally occuring

$\Rrightarrow$ Deduction of Quantum Tunnelling

$\boxed{\#2c}$ Fission (Meitner)

$$(A, Z) \rightarrow \underbrace{(A_1, Z_1) + (A_2, Z_2)}_{\text{more tightly bound, curve of binding energy}} + Qn$$

${}^{235}U \longrightarrow$

${}^{239}Pu \longrightarrow$

more tightly bound, curve of binding energy

spare neutrons

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Award Ceremony Speech

Presentation Speech by Professor H. Pleijel, Chairman of the Nobel Committee for Physics of the Royal Swedish Academy of Sciences, on December 10, 1938

Your Majesty, Your Royal Highnesses, Ladies and Gentlemen.

With what we know today of the structure of atoms, we understand perfectly the hopeless task undertaken by alchemists of old, striving to transmute the different elements one to another, and to transform lead and mercury into gold. With the means at their command, they could not work on the essential part of the atom, that is to say the nucleus. The chemical binding forces and most of the physical phenomena, such as radiation, etc., originate in the outermost parts of the atom, in the light, negatively charged electrons orbiting around the nucleus. The characteristic feature of atoms and what makes atoms different from each other, however, is the number of positive unit charges of electricity, or the number of protons, contained in the nucleus. It is this charge which holds together the light, negative electrons that spread, like the planets round the sun, in circular layers round the central nucleus.

At the present level of our knowledge, everything points to the fact that the nuclei of the atoms are composed of particles of two types, one being a heavy particle that has been given the name of *neutron* as it lacks electric charge, and the other being called *proton*, of the same mass as the neutron but with a positive unit charge. A proton is nothing but the nucleus of the lightest atom, i.e. hydrogen. A helium nucleus has two protons and two neutrons; the atom of carbon has six protons and six neutrons, and so on. The atoms are numbered according to the number of protons, or unit charges in the nucleus, with hydrogen as number 1 and uranium as number 92, which is the heaviest element known to date.

Meanwhile, it has been found that the nucleus of an atom can contain a number of neutrons less than or in excess of the normal. These atoms, that present the same physical and chemical qualities as the normal atom except that the weight is different, have received the name of *isotopes*. As an example of an isotope, we can cite the heavy-hydrogen atom discovered by Urey which is a constituent of so-called heavy water. There exist hydrogen isotopes with one or two neutrons in the nucleus.

After all the fruitless attempts at the transmutation of one element into another, the firm conviction grew last century that the different atoms, 92 in number, were indestructible and immutable units of the structure of matter. There was thus great sensation when the Frenchman Becquerel, in 1892, discovered that the element uranium distintegrated giving off strong radiation. Research on this radiation proved that it consisted among others of the helium nuclei that were emitted at very high speed from the uranium atoms. Thus, when one part of the uranium nuclei disintegrates explosively, new substances are formed that disintegrate in their turn, giving off radiations, and so on, until a final stable product is formed which is found to be lead. Among the substances included in this chain, there is the highly radioactive substance radium, which Madame Curie discovered and succeeded in producing. Soon after the radioactivity of uranium was discovered, it was established that this same characteristic occurred in another element, thorium, and later it appeared that this was also the case with the element called actinium. The end-product of the disintegration of these two last-named elements is lead also. However, the lead obtained in these three series is not identical, in so far as the number of constituent neutrons is concerned. The lead that comes from the uranium has 124 neutrons in

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FACTS AND LISTS

the nucleus, that which comes from thorium has 126 and that which comes from actinium has 125. So we have three isotopes of lead. Lead as found in nature is usually a mixture of these three types.

It must be noted in this respect that however strong the effect of a substance that is radioactive, it is in many instances only a very small part of the number of atoms that disintegrates. Thus, for a half of the number of uranium atoms to disintegrate, it would take four and a half thousand million years. For radium, the corresponding length of time would be one thousand six hundred years. Other radioactive materials would by contrast only take seconds or days for half of the number of atoms to disintegrate.

As the idea of immutability of the atoms of the elements had to be abandoned, one was back at the age-old problem of the alchemists, the transmutation of the elements. Lord Rutherford was the first to put forward the idea that it would be possible, with the help of the heavy-helium nuclei that are thrown off at great speed by the natural radioactive substances, to split atoms. He met with success in several cases. For the sake of example, we will be content to mention that if a nitrogen nucleus has been struck by the bombarding helium nuclei, a hydrogen nucleus is ejected from the former, and that the rests together with the captured helium nucleus form an oxygen nucleus. By this means helium and nitrogen were thus changed into oxygen and hydrogen. The atom of oxygen that was obtained by this method was however not the ordinary oxygen atom, an atom that has eight neutrons in the nucleus, but an oxygen atom with nine neutrons. This meant that an oxygen isotope had been obtained. This occurs in nature, although rarely; among 12,500 ordinary oxygen atoms, one oxygen isotope is found.

Rutherford's experiments on the splitting of atoms have later been continued by the husband-and-wife team Joliot-Curie, among others, who also used helium nuclei as projectiles. They found that often when new isotopes were formed, these isotopes were radioactive, and distintegrated emitting radioactive radiations. This discovery was of great importance, for it opened up the possibility of obtaining, by artificial processes, substances capable of replacing radium, a material that was both very costly and hard to come by.

Using helium nuclei and also hydrogen nuclei as projectiles, however, one can not split atoms with atomic numbers higher than 20; therefore, only part of the lighter elements of the series of atoms can so be split.

It was granted to today's Nobel Prize winner, Professor Fermi, to succeed in shattering even the heavier and the heaviest elements in the Periodic System.

Fermi used neutrons as projectiles in his experiments.

We have earlier spoken of the neutron as one of the two building-stones in atom nuclei. The existence of the neutron is however only a recent discovery. Rutherford had suspected the existence of a heavy particle without electric charge and had even given it the name neutron; it was given to one of his pupils, Chadwick, to find the neutron in the extremely strong radiation given off by beryllium subjected to the effect of a radioactive substance. The neutron has qualities that make it particularly suitable as a projectile in atomic fission. Both the helium nucleus and the hydrogen nucleus carry electric charges. The strong electric forces of repulsion developed when such a charged particle comes within reach of an atomic nucleus, deflect the projectile. The neutron being uncharged continues on its course without suffering any hindrance until it is stopped by direct impact on a nucleus. As the dimensions of the nuclei are extremely small compared with the distances that separates the different parts of the atoms, such impacts are of rare occurrence. As a result, beams of neutrons, experiment has shown, can pass through armour-plates metres thick without appreciable reduction in speed taking place.

The result which Fermi was able to achieve by using neutron bombardments have proved to be of inestimable value, and have shed new light on the structure of atom nuclei.

At first, the source of radiation was a mixture of beryllium powder and a radioactive substance. Today, neutrons are artificially produced by bombarding beryllium or lithium with heavy-hydrogen nuclei, whereby these substances emit neutrons with high energy. The neutron beams so produced are particularly powerful.

When using neutrons as projectiles, these are captured in the nucleus. In the case of the lighter elements, a hydrogen nucleus or a helium nucleus is ejected instead. With the heavier elements, however, the forces that interlink the atomic parts are so strong that, at least with neutron speeds that can be obtained by present methods, there is no ejection of any material part. The surplus energy disappears in the form of electromagnetic radiations (gamma-radiations). As there is no variation in the charge, an isotope is obtained of the initial substance. This isotope, in many cases unstable, disintegrates giving off radioactive radiations. Radioactive materials are thus obtained as a rule.

It was some six months after their first experiment with neutron irradiation that Fermi and his co-workers came by chance on a new discovery which proved to be of the greatest importance. They observed namely that the effect of neutron irradiation was often extremely increased, when the rays were allowed to pass through water or paraffin. Minute study of this phenomenon showed that the speed of the neutrons was slowed down on impact with the hydrogen nuclei which were present in these substances. Contrary to what one had reasons to believe, it appeared that the slow neutrons had a much more powerful effect than the fast neutrons. It was further found that the strongest effect was achieved at a certain speed, which is different for different substances. This phenomenon has therefore been compared with resonance found in optics and acoustics.

With low-speed neutrons, Fermi and his co-workers were successful in producing radioactive isotopes of all the elements with the exception of hydrogen and helium and part of the radioactive substances. More than four hundred new radioactive substances have thus been obtained. A certain number of these has effects stronger than radium as regards radioactivity. Of these substances, more than half were products of bombardment by neutrons. The half-lives of these artificial radioactive substances appear comparatively short, varying from one second to several days.

As we have said, during the irradiation of heavy elements by neutrons, the neutrons are captured and incorporated in the nucleus, and an isotope is thus formed of the primary substance, and this isotope is radioactive. When the isotope decays, however, negative electrons - as can be proved - are projected and new substances are formed with higher positive charges, and therefore substances with higher rank number.

This general pattern that Fermi has found to be the rule when heavy substances are subjected to irradiation by neutrons, took on special interest when applied by him to the last element in the series of elements, viz. uranium, which has rank number 92. Following this process, the first product of disintegration should be an element with 93 positive electric charges and a new element would thus have been found, lying outside the old series. Fermi's researches on uranium made it most probable that a series of new elements could be found, which exist beyond the element up to now held to be the heaviest, namely uranium with rank number 92. Fermi even succeeded in producing two new elements, 93 and 94 in rank number. These new elements he called Ausenium and Hesperium.

Along with Fermi's significant discoveries, and to a certain extent equivalent, can be placed his experimental skill, his brilliant inventiveness and his intuition. These qualities have found expression in the creation of refined research methods which made it possible to demonstrate the existence of these newly formed substances, which occur in extremely small quantities. The same goes for the measurement of the speed at which the different radioactive products disintegrate, particularly since in many cases several disintegration products with different half-lives are simultaneously involved.

Professor Fermi. The Royal Swedish Academy of Sciences has awarded you the Nobel Prize for Physics for 1938 for your discovery of new radioactive substances belonging to the entire field of the elements and for the discovery, which you made in the course of your studies, of the selective powers of the slow neutrons.

We offer our congratulations and we express the most vivid admiration for your brilliant researches, which throw new light on the structure of atomic nuclei and which open up new horizons for the future development of atomic investigation.

We ask you now to receive the Nobel Prize from the hands of His Majesty the King.

From *Nobel Lectures, Physics 1922-1941*, Elsevier Publishing Company, Amsterdam, 1965

Disintegration of Uranium by Neutrons: a New Type of Nuclear Reaction

Lise Meitner and O.R. Frisch

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On bombarding uranium with neutrons, Fermi and collaborators[1] found that at least four radioactive substances were produced, to two of which atomic numbers larger than 92 were ascribed. Further investigations[2] demonstrated the existence of at least nine radioactive periods, six of which were assigned to elements beyond uranium, and nuclear isomerism had to be assumed in order to account for their chemical behavior together with their genetic relations.

In making chemical assignments, it was always assumed that these radioactive bodies had atomic numbers near that of the element bombarded, since only particles with one or two charges were known to be emitted from nuclei. A body, for example, with similar properties to those of osmium was assumed to be eka-osmium ($Z = 94$) rather than osmium ($z = 76$) or ruthenium ($z = 44$).

Following up an observation of Curie and Savitch[3], Hahn and Strassmann[4] found that a group of at least three radioactive bodies, formed from uranium under neutron bombardment, were chemically similar to barium and, therefore, presumably isotopic with radium. Further investigation[5], however showed that it was impossible to separate those bodies from barium (although mesothorium, an isotope of radium, was readily separated in the same experiment), so that Hahn and Strassmann were forced to conclude that *isotopes of barium* ($Z = 56$) *are formed as a consequence of the bombardment of uranium* ($Z = 92$) *with neutrons*.

At first sight, this result seems very hard to understand. The formation of elements much below uranium has been considered before, but was always rejected for physical reasons, so long as the chemical evidence was not entirely clear cut. The emission, within a short time, of a large number of charged particles may be regarded as excluded by the small penetrability of the 'Coulomb barrier', indicated by Gamov's theory of alpha decay.

On the basis, however, of present ideas about the behaviour of heavy nuclei[6], an entirely different and essentially classical picture of these new disintegration processes suggests itself. On account of their close packing and strong energy exchange, the particles in a heavy nucleus would be expected to move in a collective way which has some resemblance to the movement of a liquid drop. If the movement is made sufficiently violent by adding energy, such a drop may divide itself into two smaller drops.

In the discussion of the energies involved in the deformation of nuclei, the concept of surface tension has been used[7] and its value has been estimated from simple considerations regarding nuclear forces. It must be remembered, however, that the surface tension of a charged droplet is diminished by its charge, and a rough estimate shows that the surface tension of nuclei, decreasing with increasing nuclear charge, may become zero for atomic numbers of the order of 100.

It seems therefore possible that the uranium nucleus has only small stability of form, and may, after neutron capture, divide itself into two nuclei of roughly equal size (the precise ratio of sizes depending on finer structural features and perhaps partly on chance). These two nuclei will repel each other and should gain a total kinetic energy of c. 200 Mev., as calculated from nuclear radius and charge. This amount of energy may actually be expected to be available from the difference in packing fraction between uranium and the elements in the middle of the periodic system. The whole 'fission' process can thus be described in an essentially classical way, without having to consider quantum-mechanical 'tunnel effects', which would actually be extremely small, on account of the large masses involved.

After division, the high neutron/proton ratio of uranium will tend to readjust itself by beta decay to the lower value suitable for lighter elements. Probably each part will thus give rise to a chain of disintegrations. If one of the parts is an isotope of barium[8], the other will be krypton (Z = 92 - 56), which might decay through rubidium, strontium and yttrium to zirconium. Perhaps one or two of the supposed barium-lanthanum-cerium chains are then actually strontium-yttrium-zirconium chains.

It is possible[8], and seems to us rather probable, that the periods which have been ascribed to elements beyond uranium are also due to light elements. From the chemical evidence, the two short periods (10 sec. and 40 sec.) so far ascribed to ^{239}U might be masurium isotopes (Z = 43) decaying through ruthenium, rhodium, palladium and silver into cadmium.

In all these cases it might not be necessary to assume nuclear isomersim; but the different radioactive periods belonging to the same chemical element may then be attributed to different isotopes of this element, since varying proportions of neutrons may be given to the two parts of the uranium nucleus.

By bombarding thorium with neutrons, activities are which have been ascribed to radium and actinium isotopes[8]. Some of these periods are approximately equal to periods of barium and lanthanum isotopes resulting from the bombardment of uranium. We should therefore like to suggest that these periods are due to a 'fission' of thorium which is like that of uranium and results partly in the same products. Of course, it would be especially interesting if one could obtain one of those products from a light element, for example, by means of neutron capture.

It might be mentioned that the body with the half-life 24 min[2] which was chemically identified with uranium is probably really ^{239}U and goes over into eka-rhenium which appears inactive but may decay slowly, probably with emission of alpha particles. (From inspection of the natural radioactive elements, ^{239}U cannot be expected to give more than one or two beta decays; the long chain of observed decays has always puzzled us.) The formation of this body is a typical resonance process[9]; the compound state must have a life-time of a million times longer than the time it would take the nucleus to divide itself. Perhaps this state corresponds to some highly symmetrical type of motion of nuclear matter which does not favor 'fission' of the nucleus.

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