The Heart of the MATTER

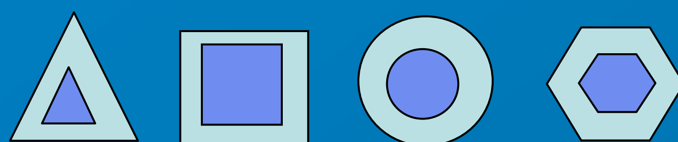
The Discovery of Subatomic Particles

The Eternal Quest:
What are the ultimate building blocks of matter?

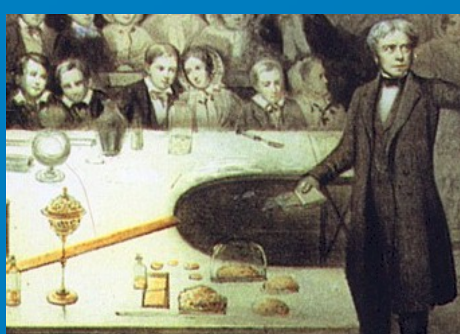
During middle ages, an idea that did not work postulated

the 4 "elements" earth, fire, water, air.

Forgotten earlier ideas of the Greek antique. Democritus (app. 400 B.C.) had an interesting variation of the 4-element hypothesis:



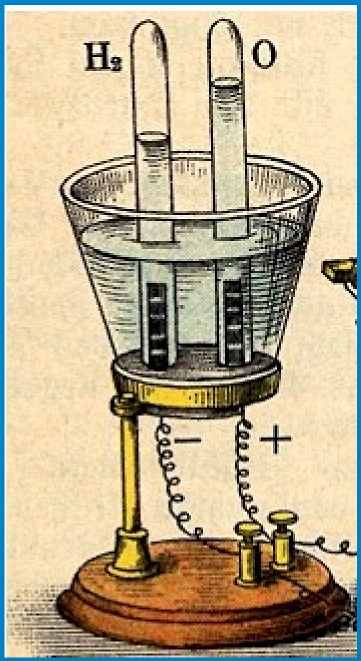
Smallest indivisible (ατομοσ) units of elements



Dalton's atomic hypothesis (1803-1807): Atoms are smallest building blocks, characteristic but identical for given chemical element

Integer proportions in chemical compounds

Chemical Properties and Reactions



Proof: Dissociation of chemical compounds.

Combination in integer proportions

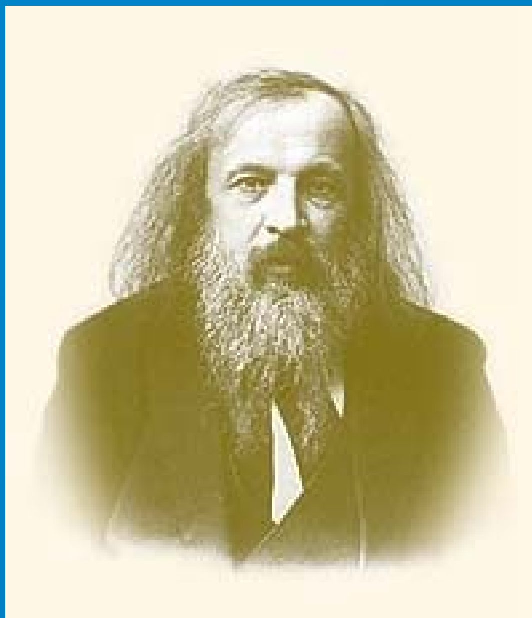
$$nA + mB \Rightarrow A_n B_m$$

e.g. $$4H + 2O \Rightarrow 2H_2O$$

Conservation of mass: Number of atoms of each species is conserved. No single atom gets lost in a chemical reaction, there is no transformation of matter, atoms of the chemical elements are only arranged differently.

Systematic study by Mendeleev (1869): Noticed patterns in the combination ratios of elements and their periodic reoccurrence.

Mendeleev's Periodic Table



Mendeleev's Table

PERIODIC SYSTEM OF THE ELEMENTS IN GROUPS AND SERIES.

Series	0	I	II	III	IV	V	VI	VII	VIII
1	—	Hydrogen H 1·008	—	—	—	—	—	—	
2	Helium He 4·0	Lithium Li 7·03	Beryllium Be 9·1	Boron B 11·0	Carbon C 12·0	Nitrogen N 14·04	Oxygen O 16·00	Fluorine F 19·0	
3	Neon Ne 19·9	Sodium Na 23·05	Magnesium Mg 24·3	Aluminium Al 27·0	Silicon Si 28·4	Phosphorus P 31·0	Sulphur S 32·06	Chlorine Cl 35·45	
4	Argon Ar 38	Potassium K 39·1	Calcium Ca 40·1	Scandium Sc 44·1	Titanium Ti 48·1	Vanadium V 51·4	Chromium Cr 52·1	Manganese Mn 55·0	Iron Cobalt Nickel Fe Co Ni (Cu) 55·9 59 59
5		Copper Cu 63·6	Zinc Zn 65·4	Gallium Ga 70·0	Germanium Ge 72·3	Arsenic As 75	Selenium Se 79	Bromine Br 79·95	
6	Krypton Kr 81·8	Rubidium Rb 85·4	Strontium Sr 87·6	Yttrium Y 89·0	Zirconium Zr 90·6	Niobium Nb 94·0	Molybdenum Mo 96·0	—	Ruthenium Rhodium Palladium Ru Rh Pd (Ag) 101·7 103·0 106·5
7		Silver Ag 107·9	Cadmium Cd 112·4	Indium In 114·0	Tin Sn 119·0	Antimony Sb 120·0	Tellurium Te 127	Iodine I 127	
8	Xenon Xe 128	Cesium Cs 132·9	Barium Ba 137·4	Lanthanum La 139	Cerium Ce 140	—	—	—	— — —
9		—	—	—	—	—	—	—	
10	—	—	—	Ytterbium Yb 173	—	Tantalum Ta 183	Tungsten W 184	—	Osmium Iridium Platinum Os Ir Pt (Au) 191 193 194·9
11		Gold Au 197·2	Mercury Hg 200·0	Thallium Tl 204·1	Lead Pb 206·9	Bismuth Bi 208	—	—	
12	—	—	Radium Rd 224	—	Thorium Th 232	—	Uranium U 239		
HIGHER SALINE OXIDES	R	R_2O	RO	R_2O_3	RO_2	R_2O_5	RO_3	R_2O_7	RO_4
HIGHER GASEOUS HYDROGEN COMPOUNDS					RH_4	RH_3	RH_2	RH	

Periodic Table of the elements (Mendeleev 1869): Arrangement in rows and columns according to weight and recurring chemical properties. Some problems!

Modern Periodic Table

Correct ordering is according to "atomic number" Z, the number of electrons and protons in the atom.

Periodic Table of the Elements

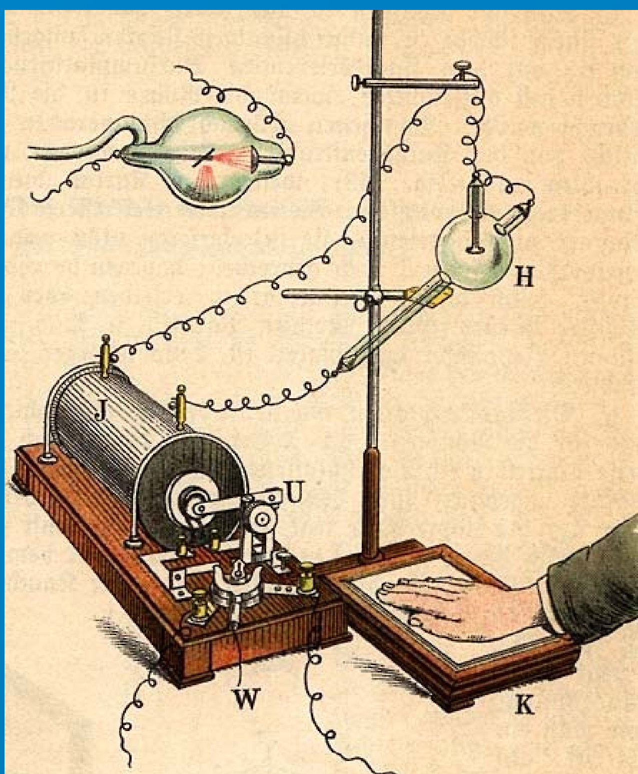
	IA	IIA	IIIB	IVB	VB	VIB	VIIB	VII			IB	IIB	IIIA	IVA	VA	VIA	VIIA	0
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	57 *La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	89 +Ac	104 Rf	105 Ha	106 Sg	107 Ns	108 Hs	109 Mt	110 110	111 111	112 112	113 113					

* Lanthanide Series	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
+ Actinide Series	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

Cathode ray tube

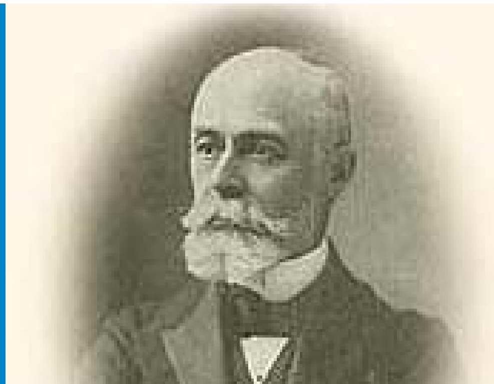
Röntgen's Mysterious X Rays

Study of phosphorescence in gas discharge tubes ("Cathode ray tubes") produces penetrating X rays, originating at anode and with energy characteristic of anode material.



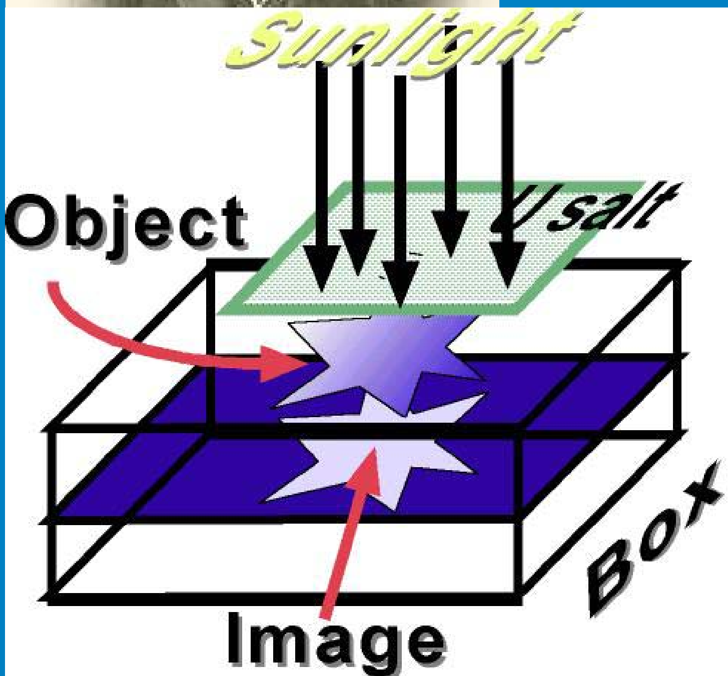
X-ray machines are used in medical imaging. Bones absorb X rays more readily than tissue.

Image of hand of Röntgen's wife.



Natural Radioactivity

Becquerel discovered (1896) that certain crystals (e.g., U salt) emit penetrating radiation (like X rays).



Hypothesis: Uranium salt irradiated with sunlight emits penetrating phosphor-essence radiation, which darkens photo-graphic plates.

Experiment: Place absorbing object (metal star) on closed box containing photographic plate. Expose setup to U salt in bright sunlight. Observe shadow of shape.

Finding: Object is imaged on plate inside closed box, when exposed to U salt. Surprise: works also in the dark. Sunlight is not required. **U salt radiates spontaneously.**

Studying Natural Radioactivity

Marie (and Pierre) Curie studied (1897-1904) the property of "pitchblende", obtained in mining of uranium.

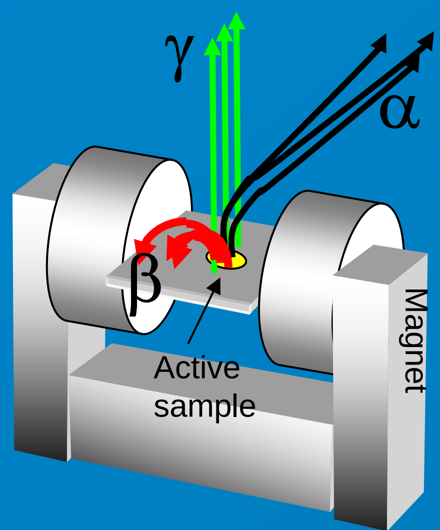
Motivation by Becquerel's discovery.

Found Thorium, Radium

Ra powerful radiator

Sensitive electrometers were used to measure weak ionization currents produced in air by the Ra or U salts.

Different Types of Radiation



Radioactive Ra sample in a magnetic field

α rays

deflected like positive particles, stopped in 0.001" Al foil. Identified later as He^{++} ions

β rays

deflected like negative particles, highly penetrating.

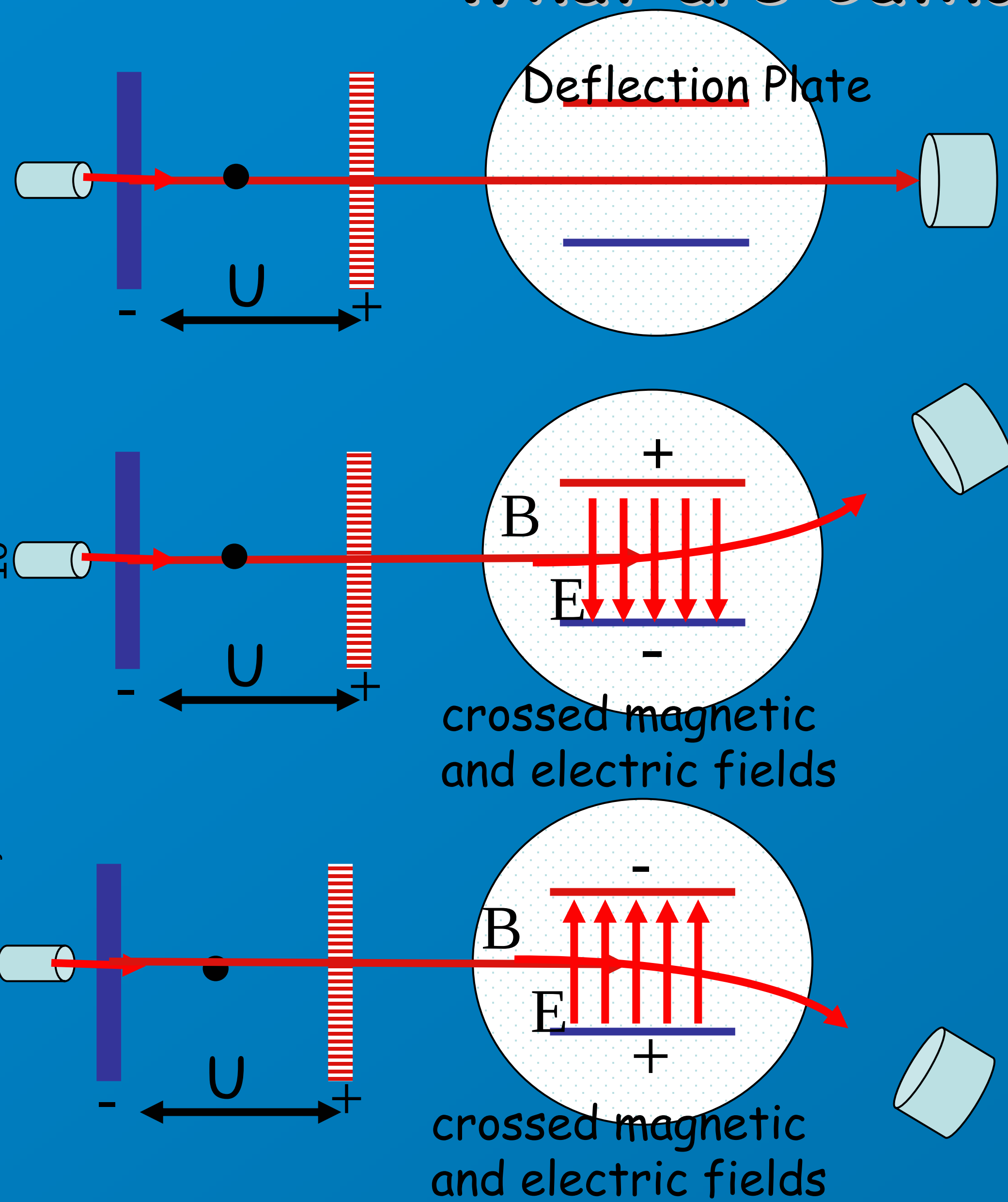
Identified later as e^- electrons

γ rays

not deflected, like rays of light

Identified later as energetic photons, light of short wave length

What are Cathode Rays?



J.J. Thomson (1894-97)
Deflection experiment in vacuum with crossed electric and magnetic fields. Predictions if rays were charged particles:

Lorentz Force:

$$\vec{F} = e \cdot \left(\vec{E} + \vec{v} \times \vec{B} \right)$$

Particle velocity

$$v = \sqrt{2K/m} = \sqrt{2eU/m}$$

It proved possible to balance the effects of electric and magnetic fields resulting in *no net deflection of rays.*

Cathode rays are charged particles!

Question:

What information can one obtain on a charged particle of kinetic energy K from observing a certain (which?) balance of electric and magnetic fields?

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Balance E and B so that no net deflection occurs for particle. Then, the Lorentz force must be zero, F = 0.

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Answer:

$$Lorentz\ Force\ in\ 1 dimension:$$

$$F = e \cdot \left(E + vB \right) = 0$$

$$\Rightarrow E = -vB,\ Particle\ speed\ |v| = E / B$$

$$K = eU\ \ kinetic\ energy \rightarrow v = \sqrt{2K / m} = \sqrt{2eU / m}$$

$$obtain\ e/m\ \ for\ particle.$$

The Electron

Cathode rays are negatively charged particles, “electrons”

$$J.J.Thomson: e/m = 1.76 \cdot 10^{11} C/kg$$

$$R.A.Millikan: e = -1.602 \cdot 10^{-19} C$$

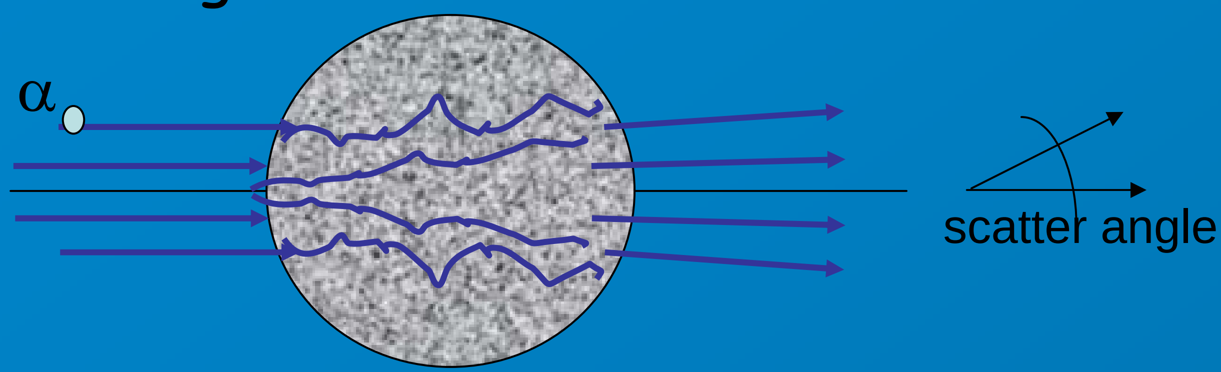
$$\rightarrow m = 9.11 \cdot 10^{-31} kg$$

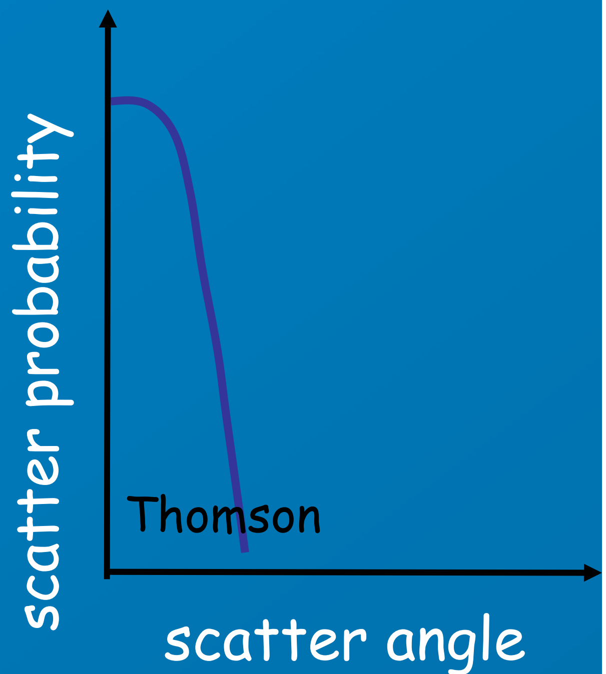
The elementary charge was the same found in Faraday’s earlier electro-chemical experiments.

Where do these electrons come from? Must come from inside the atom.

Atomic Models

Thomson's plum pudding model: positive and negative charges distributed over entire atom





Very little net scattering of α (He^{++}) particles predicted in Thomson's model, interaction averages out: $\langle V_{Coulomb} \rangle = 0$.

Multiple-scattering theory for Ra α particles and a Au nucleus:

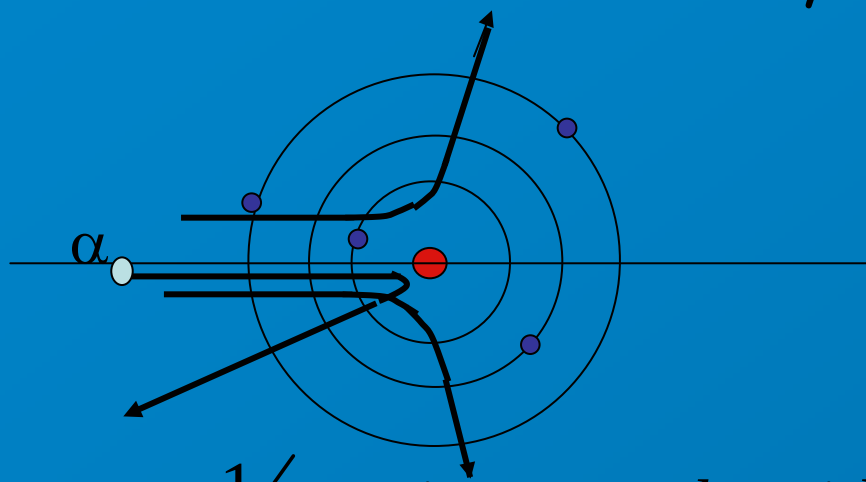
Most probable deflection $\Theta = 0.87^{o}$

Probability for back scattering

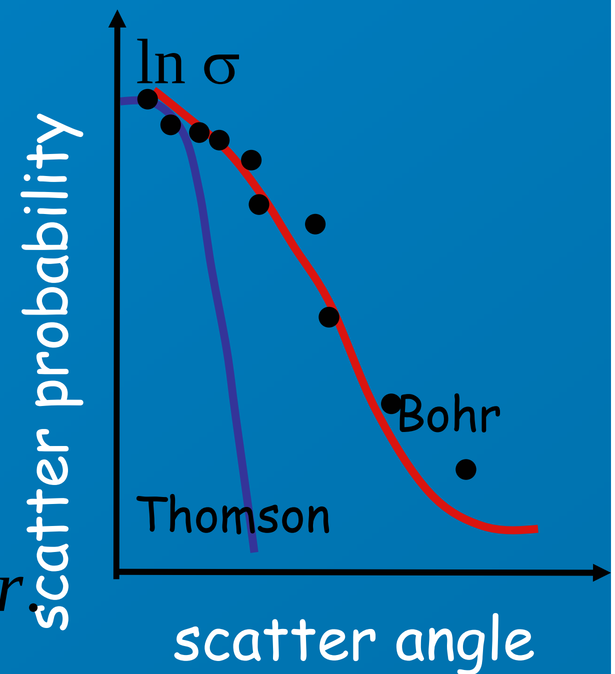
$P(180^{o}) = 3.10^{-2174}$!!! extremely improbable

Atomic Models

Bohr's planetary model: positive nucleus in center orbited by electrons



$$V_{Coulomb} \propto {}^{1}\!/_{r} \; \textit{varies strongly with distance } r.$$

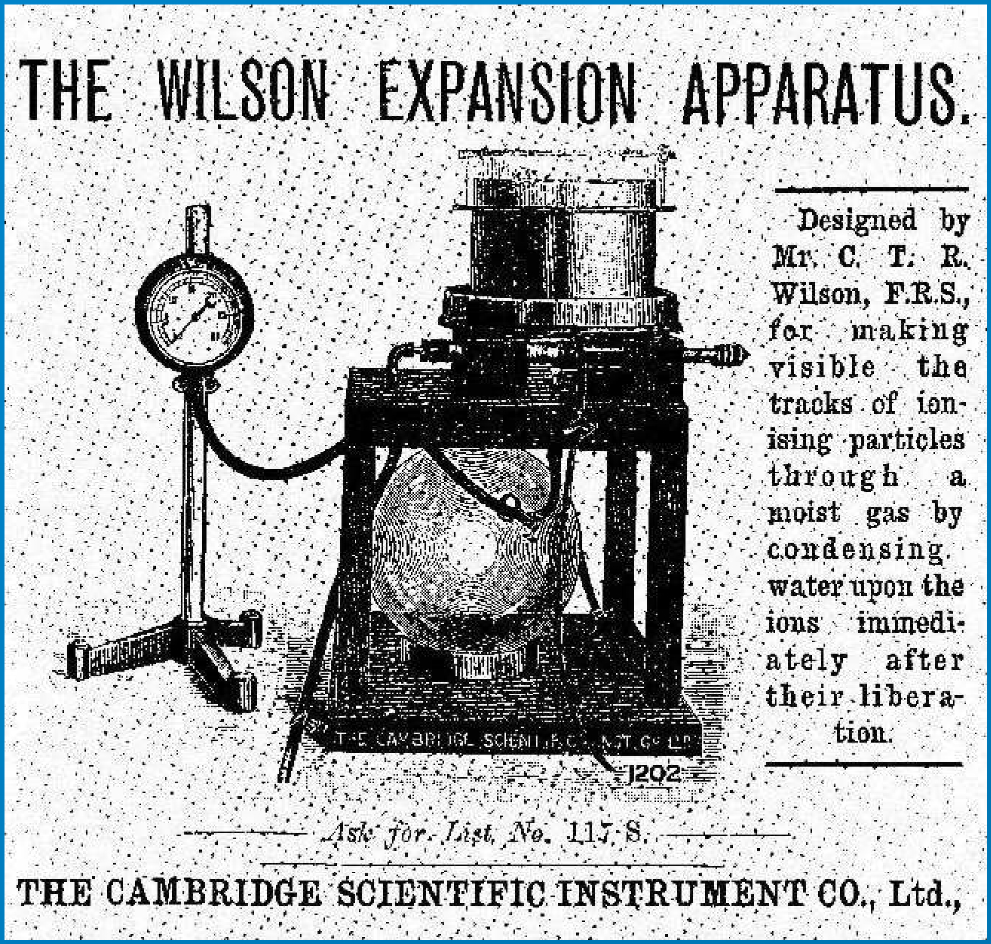


$$Rutherford \;\; scattering \;\; P(\theta) \propto \frac{1}{\sin^4(\theta/2)}$$

$$P(180^o) = \frac{1}{20000}$$

Experiment by Geiger, Marsden, Rutherford decides for Bohr Model

Early Detectors for Subatomic Particles



Early advertisement for cloud chanbers.

Chamber filled with organic vapor/moist gas.

When suddenly connected to evacuated expansion vessel, gas cooled below condensation point. Any impurity would function as a seed to form liquid droplets.

Tracks of ionizing particles produced such condensation seeds.

Examples

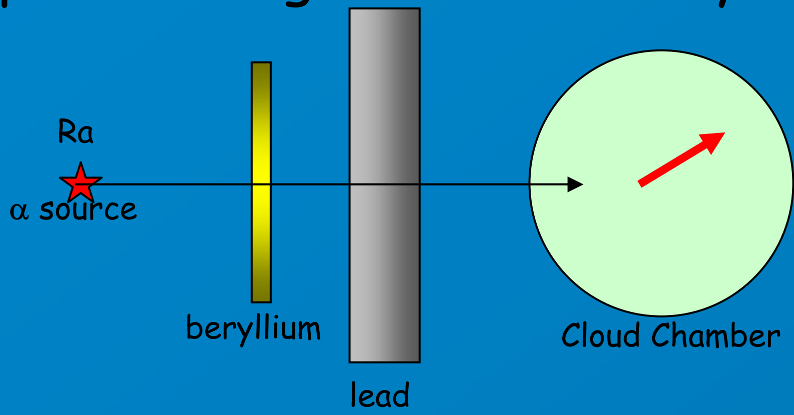
In Curie's laboratory.

Tracks of a particles from RaC′ (^{214}Po)

Tracks of different nuclear events.

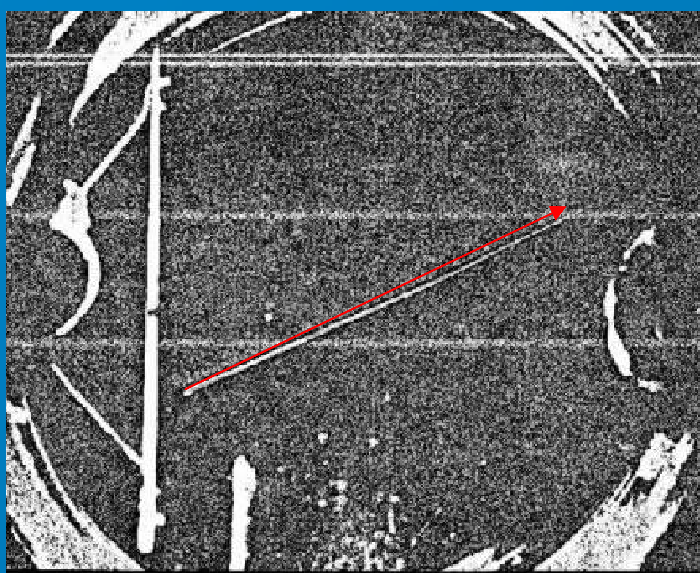
Discovery of the Neutron (Chadwick, 1932)

Bombardment of light elements with α particles produced penetrating radiation "beryllium rays". Not charged particles!



Beryllium rays penetrate sheets of metal, but are stopped by paraffin, unlike γ-rays. Can hit a proton in a cloud chamber (red trace)

→ neutral particle:"neutron"



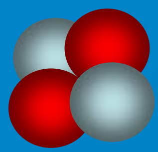
Cloud chamber: neutron track invisible, struck proton. Get mass of neutron from kinematic relation

$$E_{proton} = E_{neutron} \frac{4m_{neutron} \cdot \cos^2(\theta_{scatter})}{(m_{neutron} + m_{proton})^2}$$

Vary $\Theta_{scatter}$ and recoil nucleus

Basic Constituents of Atomic Nuclei

Helium



$$ {}^{A}_{Z}X_{N} = {}^{4}_{2}He_{2} $$

A nucleons: protons (H^+) plus neutrons

Z protons (equals the number of electrons in a neutral atom)

N=A-Z neutrons

Masses

$m_p = 1.673\cdot10^{-27}$kg = 938.279 MeV/c^2 = 1.00728 u (mass units)

$m_n = 1.675\cdot10^{-27}$kg = 939.573 MeV/c^2 = 1.00867 u

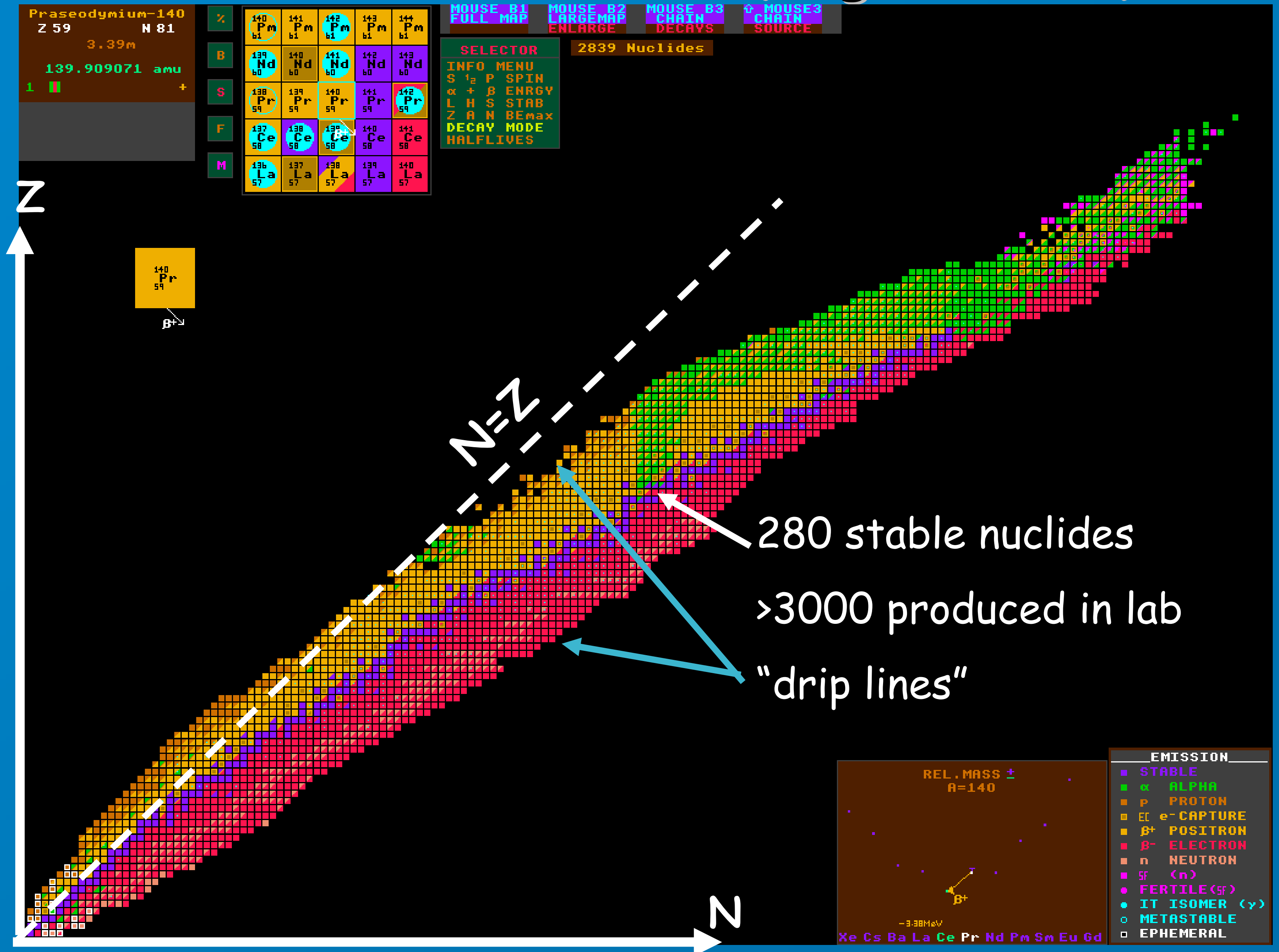
1u = m(^{12}C)/12 = $1.6606\cdot10^{-27}$kg = 931.502 MeV/c^2

Charges

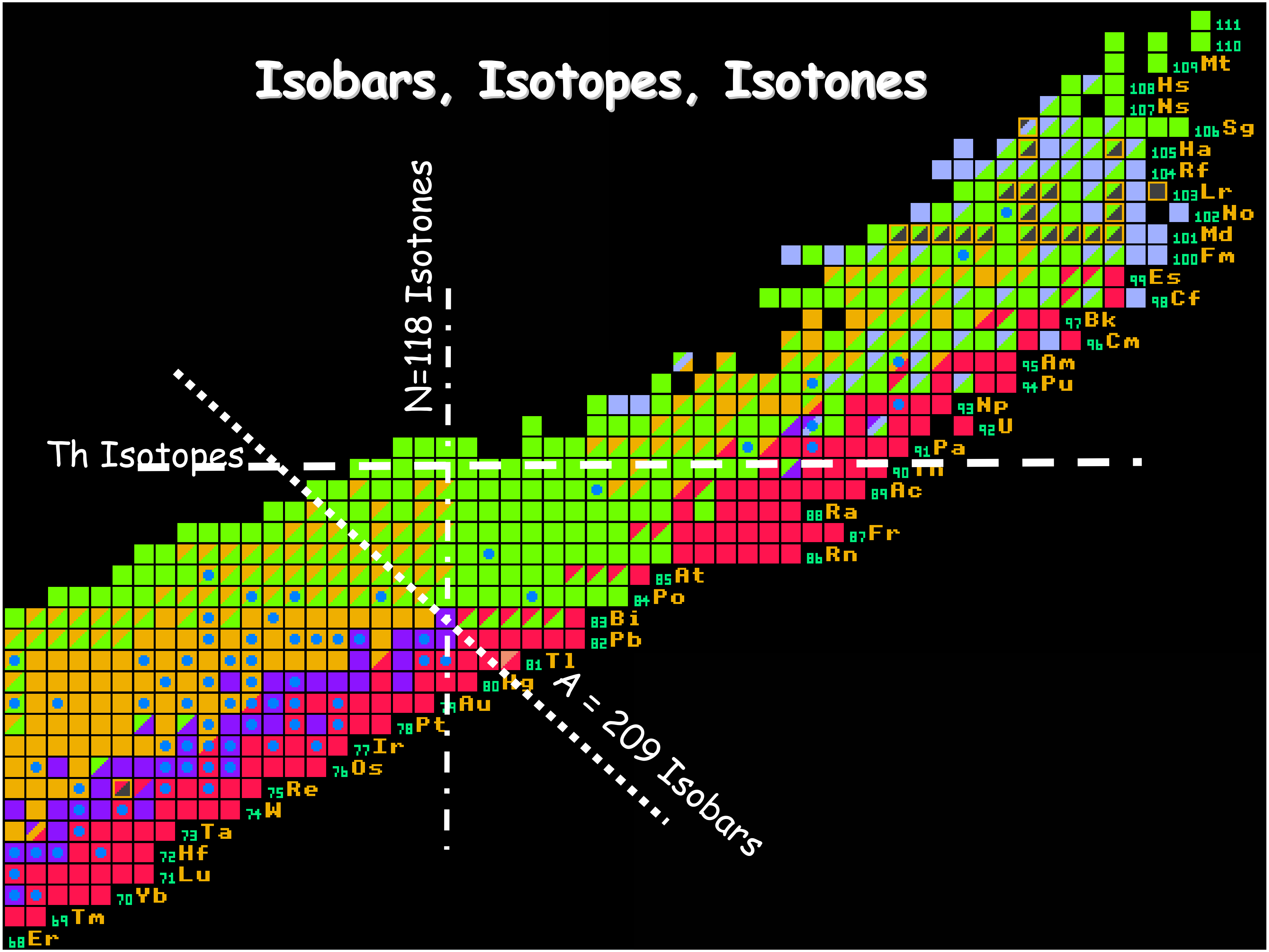
$e_p = +e = 1.602\cdot10^{-19}C$ (Coulomb) $e_n = 0$

Useful parameter $e^2 = 1.440\cdot10^{-15}$ MeV·m =1.440 MeV·fm

Chart of Nuclides (Segré Chart)



Isobars, Isotopes, Isotones



Consistency of Stable Nuclei

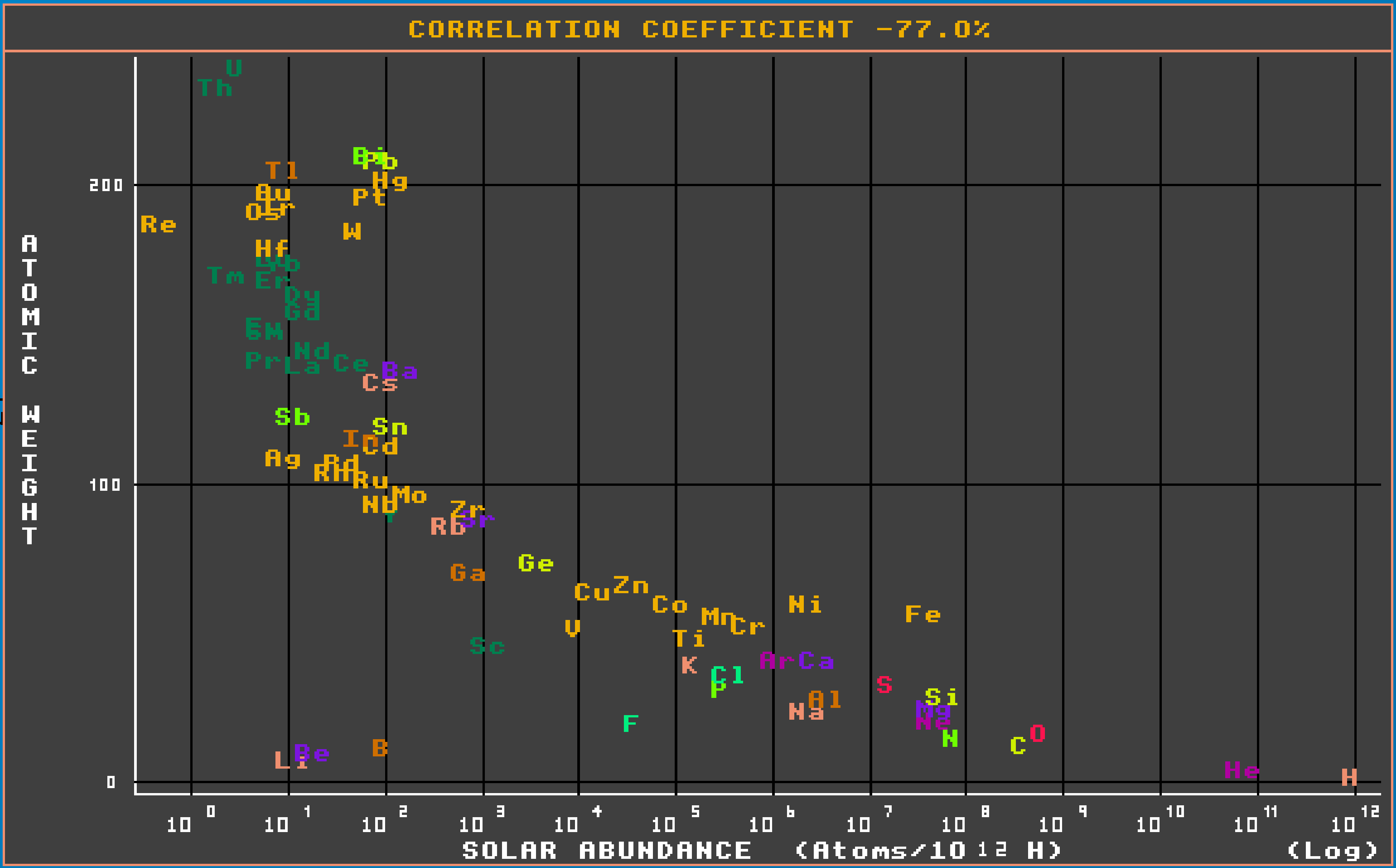
An important detail:

Of the 280 stable nuclides,

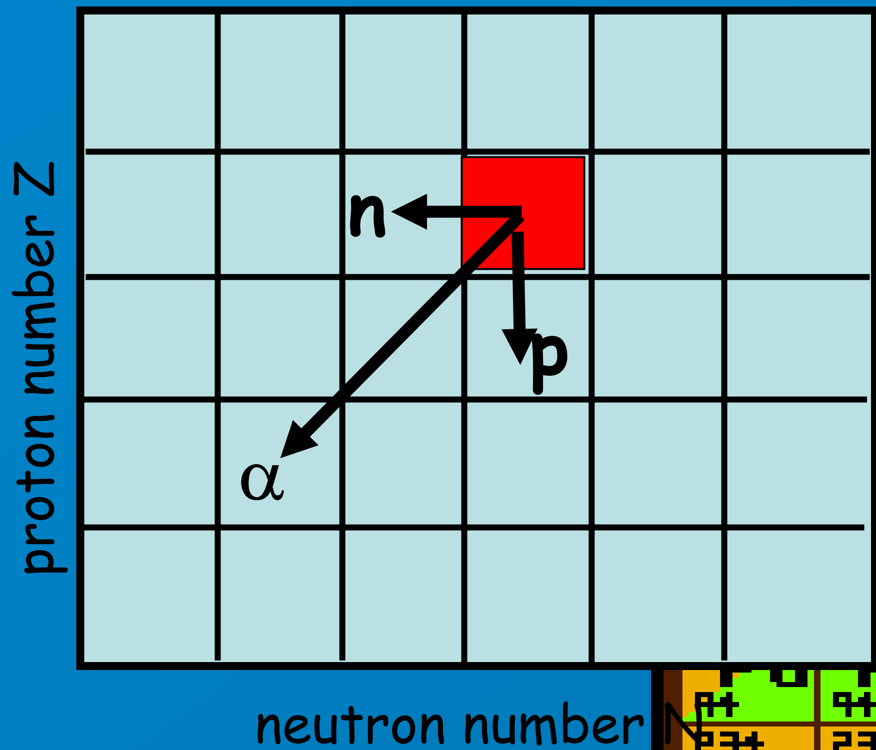
- 170 have N even Z even
- 50-60 have N or Z even, the other quantity odd
- 4 have N odd and Z odd (extremely rare!)

Preference of “paired” nucleons.

Solar Abundances of Elements



Transmutation of Nuclei



By nuclear decay

α-decay : $\Delta Z = -2 \quad \Delta N = -2$

p-decay : $\Delta Z = -1 \quad \Delta N = 0$

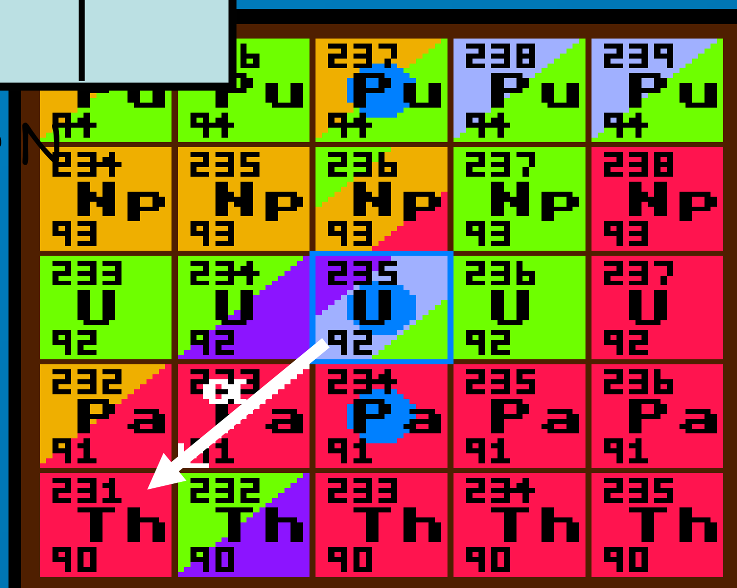
n-decay : $\Delta Z = 0 \quad \Delta N = -1$

β^+-decay : $\Delta Z = -1 \quad \Delta N = +1$

β^--decay : $\Delta Z = +1 \quad \Delta N = -1$

electron capture:

$\Delta Z = -1 \quad \Delta N = +1$



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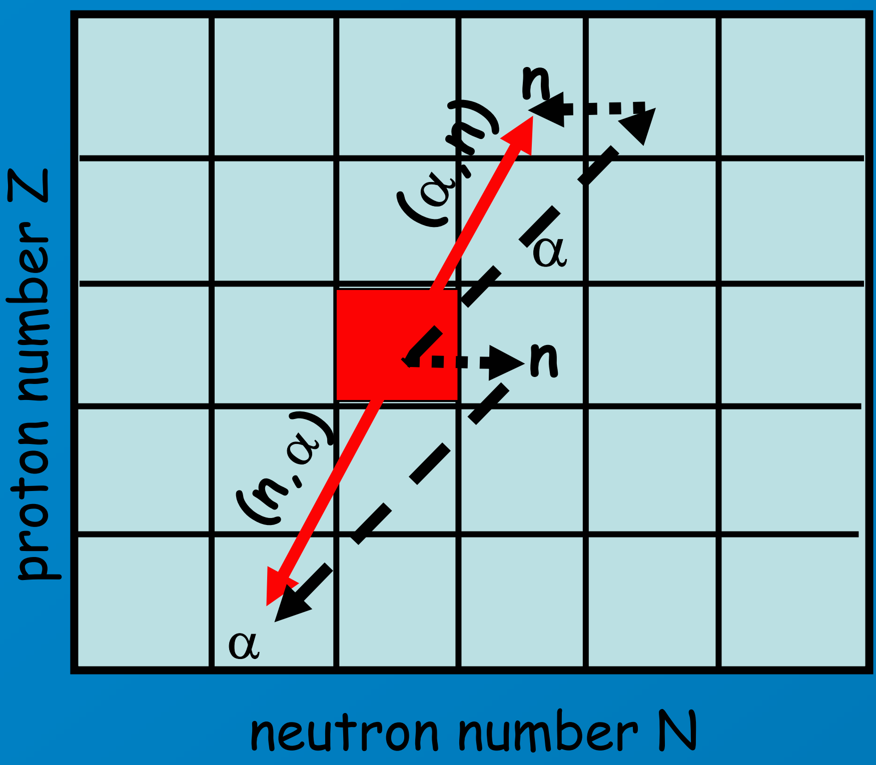

Important application:
Transmutation of nuclear waste (weapons, spent fuel)

By nuclear reactions, example:

Reaction $\,^{9}Be + \alpha \rightarrow \,^{12}C + n$

Notation $\,^{9}Be\left(\alpha, n\right)\,^{12}C$

Target

Projectile

Ejectile

Recoil,

Residue

Inverse reaction:

Reaction $\,^{9}Be + n \rightarrow \,^{6}He + \alpha$

Notation $\,^{9}Be\left(n, \alpha\right)\,^{6}He$

Large changes are possible with heavy-ion reactions