A brief history of nuclear physics: from the discovery of the nucleus to element 118.

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Goals

- Some history...

- Some news....

Outline

- *From Radioactivity to the Discovery of the Proton :* Radioactivity & Nuclear Dimensions

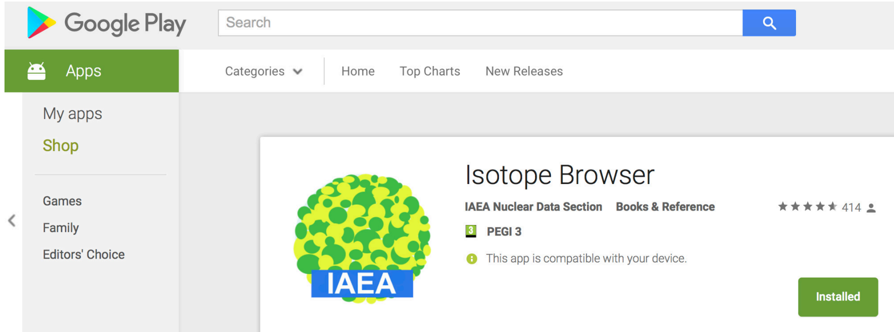
- *From the Discovery of the Proton to today :* Nuclear Mass, Stability & Interaction

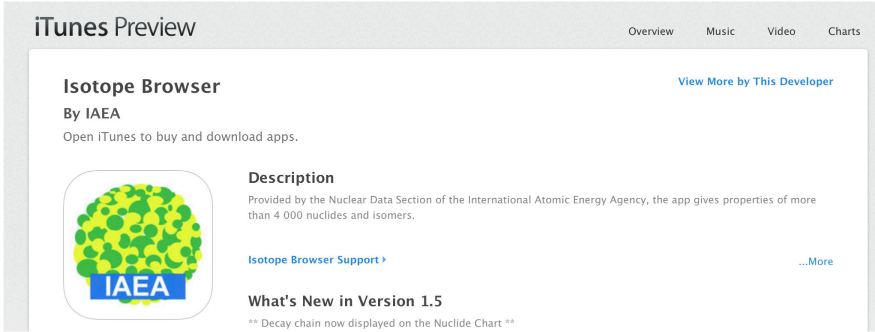
Some good tools

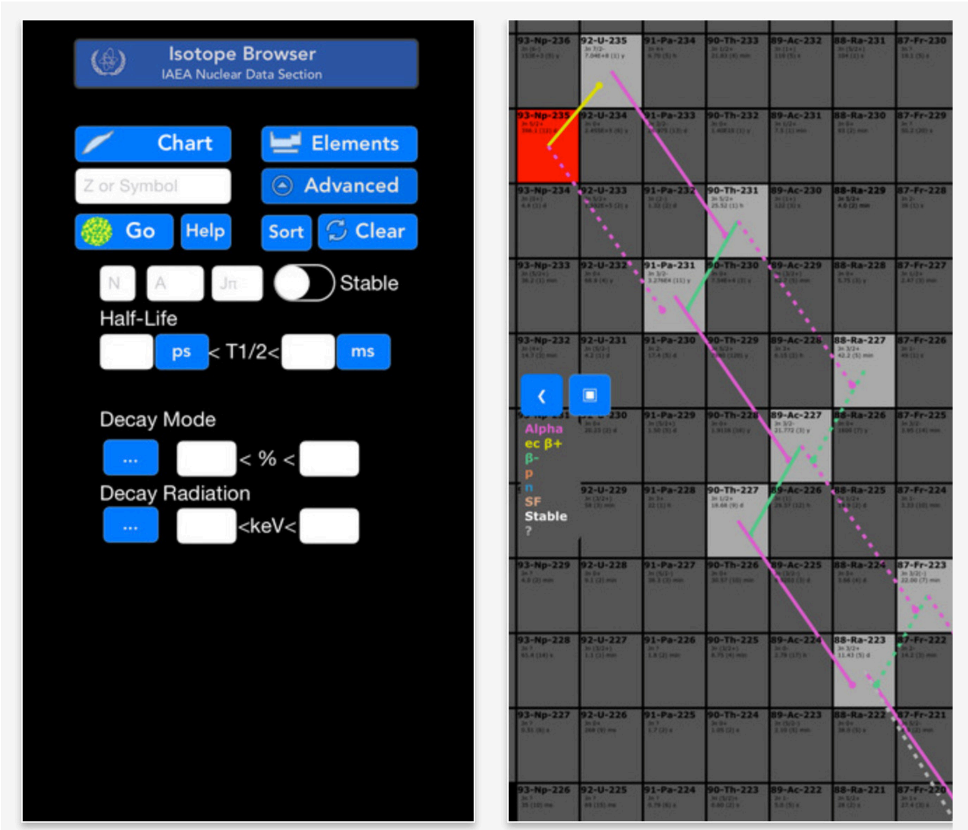
- National Nuclear Data Center (NNDC)

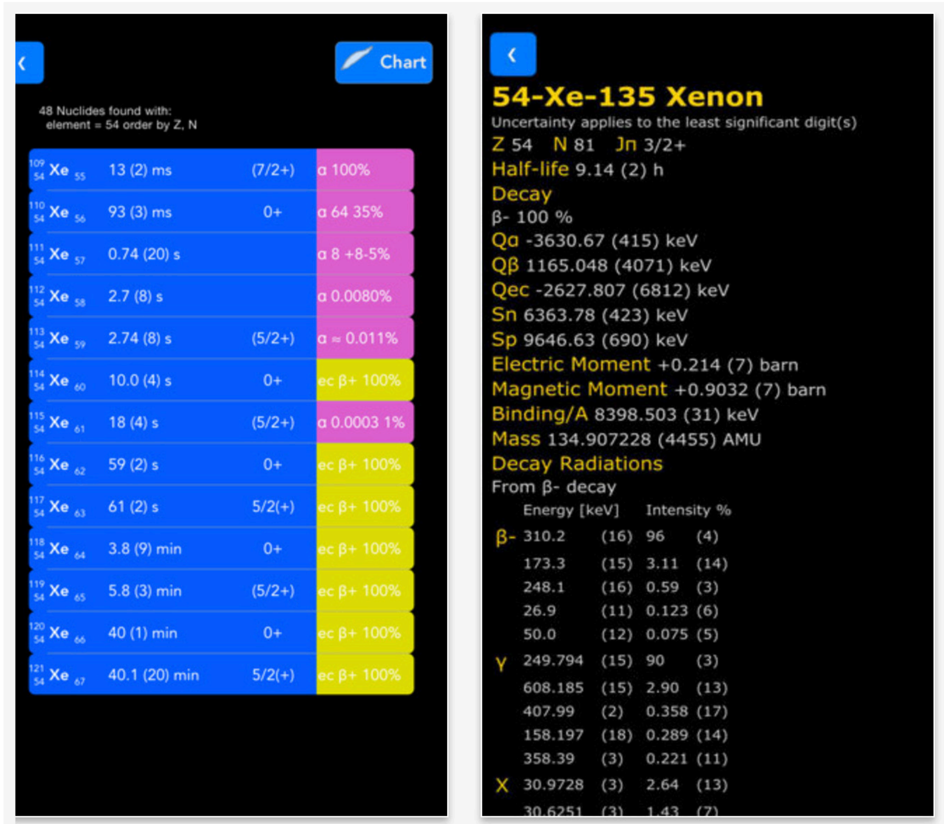
  http://www.nndc.bnl.gov

Some good applications

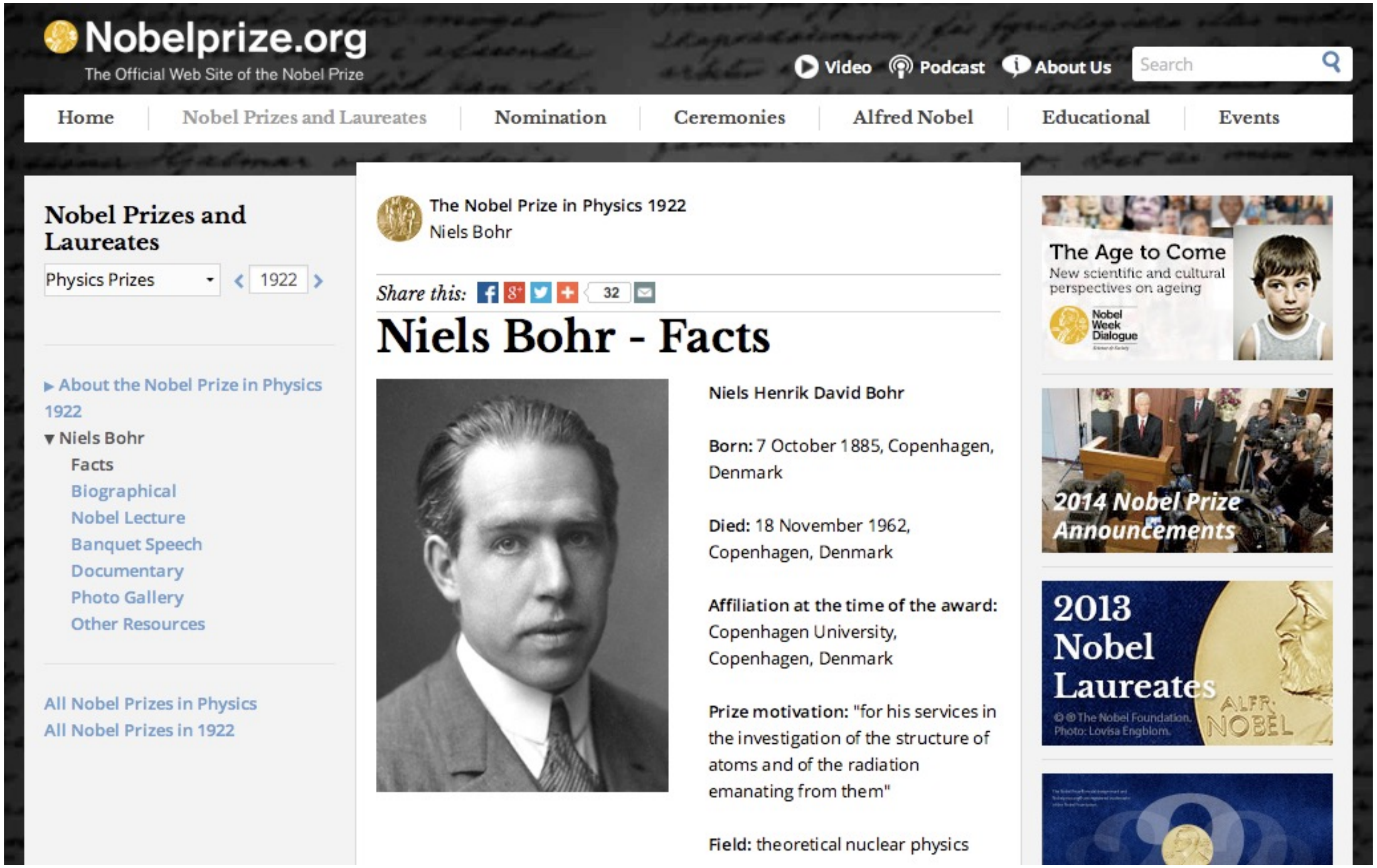








Some good reads...

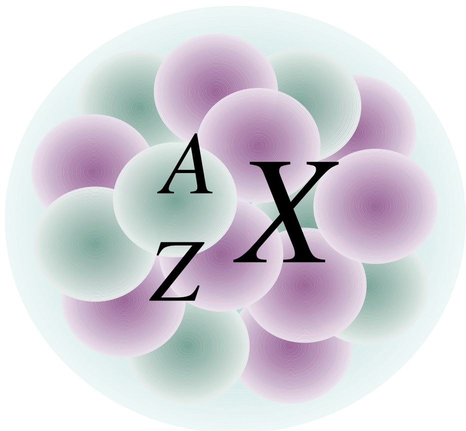


- ❖K. Krane, Introductory Nuclear Physics
- ❖ R. Casten, Nuclear Structure from a Simple Perspective
- ❖ A. Bohr & B. Mottelson, Nuclear Structure Vol. I & II

Part 1 – Introduction, Radioactivity & Nuclear Dimensions

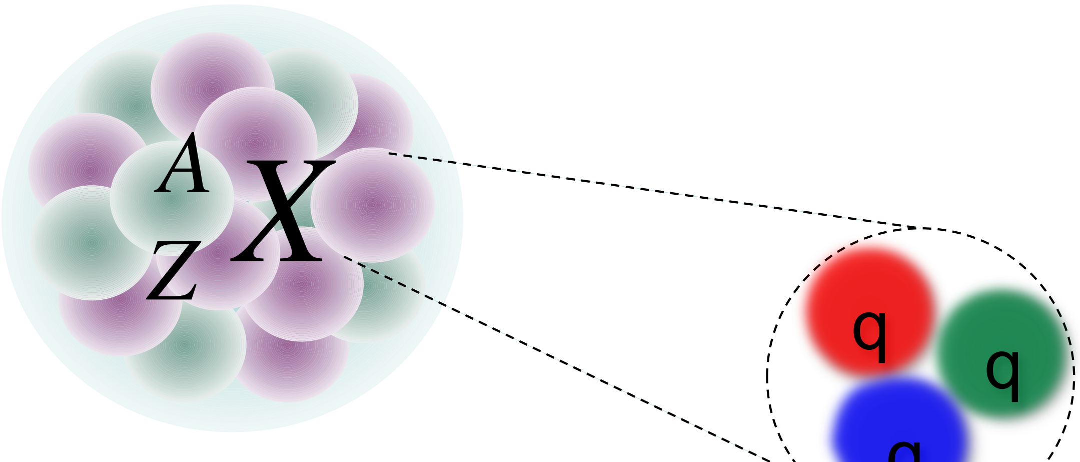
The nucleus

Z protons, N neutrons
Mass number $A = Z+N$
Atomic number Z
Mass of the nucleus accounts for more than 99% of the mass of the atom
Charge of the nucleus $+Ze$ ($e=1.6\ 10^{-19}$ C)
Nucleons are fermions: spin 1/2, Pauli's exclusion principle

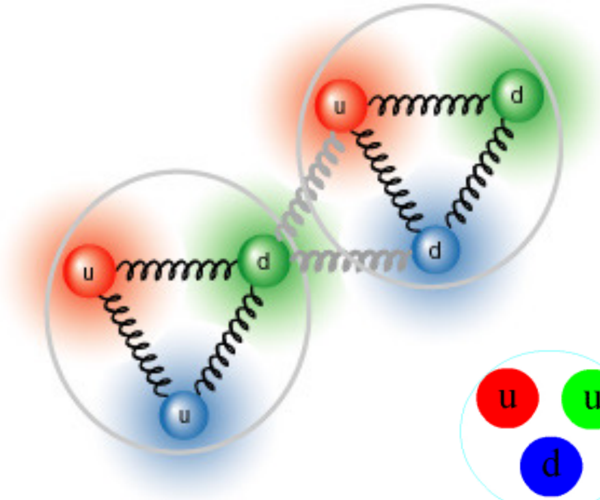


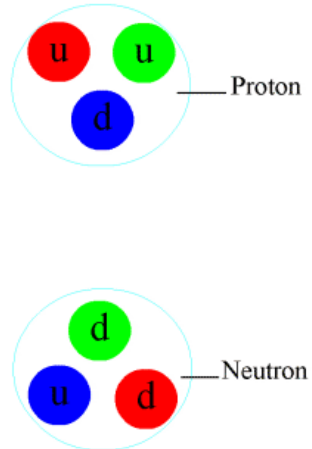
A interacting nucleons
3 forces: weak, electromagnetic & strong

A complex system



Nucleons are not elementary particles





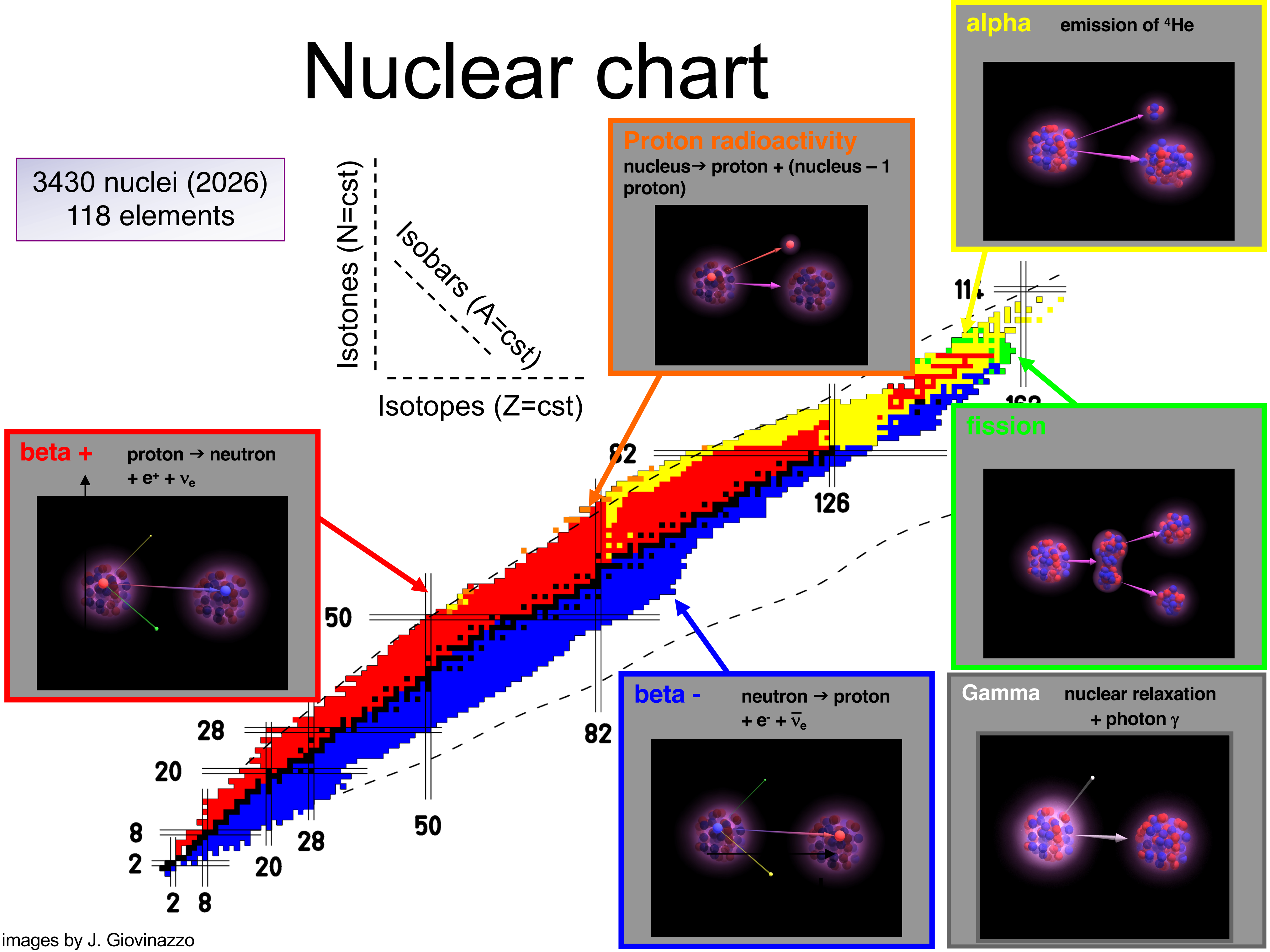
Understand and predict the organisation of nucleons inside the nucleus and the resulting nuclear properties

=

Challenge of nuclear physics

Nuclear chart

3430 nuclei (2026)
118 elements

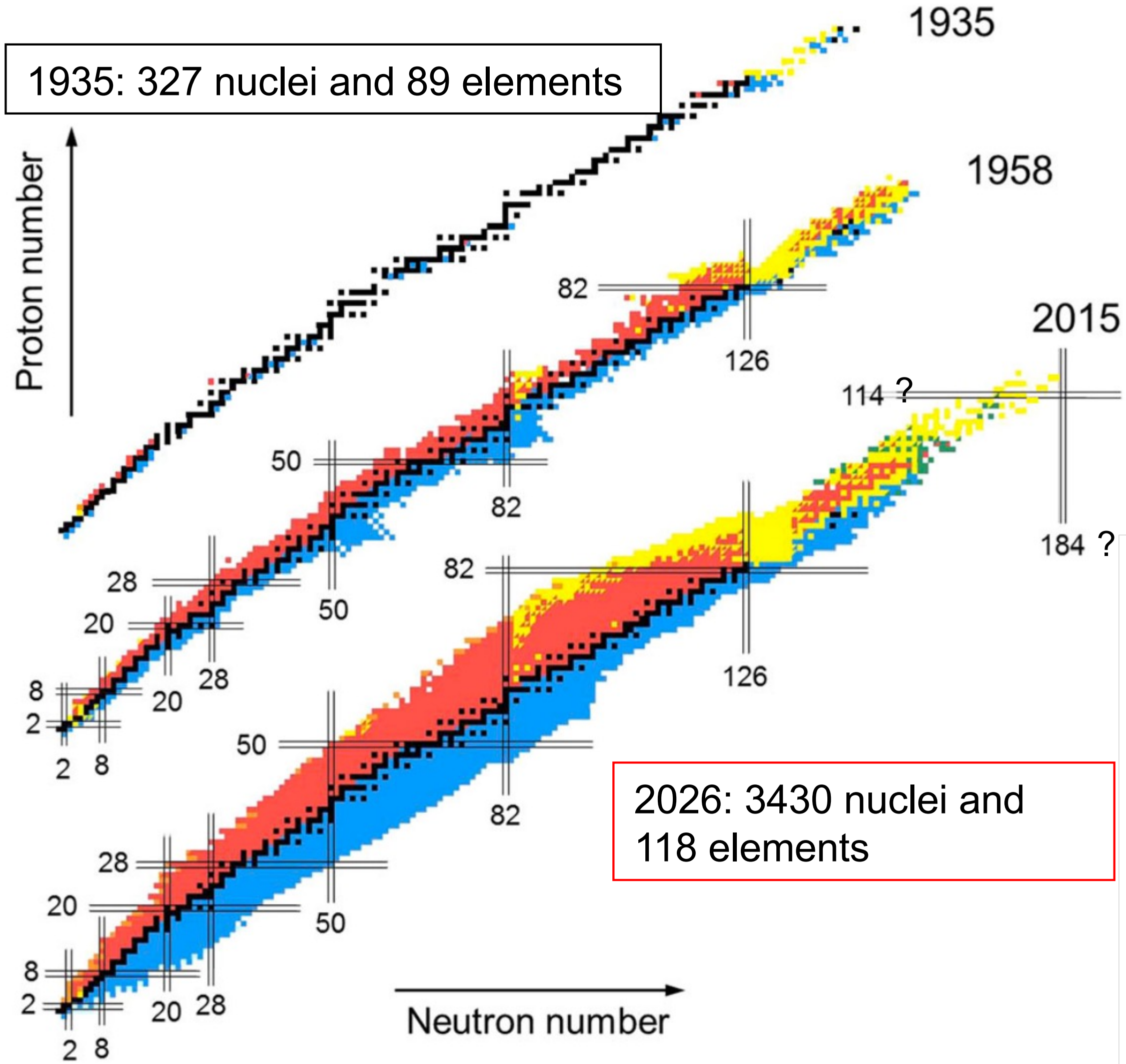


images by J. Giovinazzo

Evolution of the nuclear landscape

Adamian, G.G., Antonenko, N.V., Diaz-Torres, A. et al., Eur. Phys. J. A (2020) 56:47, http://creativecommons.org/licenses/by/4.0/.

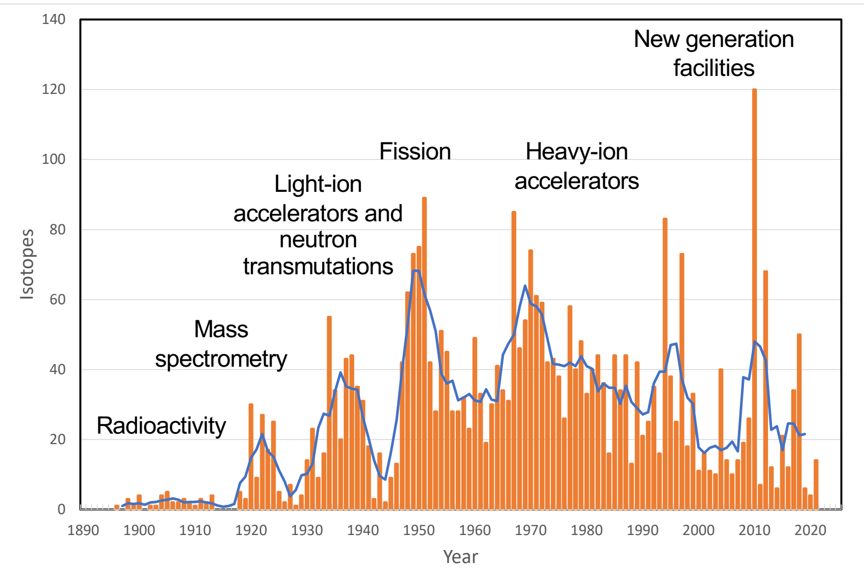
1935: 327 nuclei and 89 elements



2026: 3430 nuclei and 118 elements

Rank	Country	# of Isotopes
1	USA	1345
2	Germany	569
3	United Kingdom	300
4	Japan	294
5	Russia	255
6	France	215
7	Switzerland	122
8	Canada	67
9	Sweden	60
10	Finland	49
11	China	42
12	Netherlands	36
13	Belgium	17
14	Argentina	13
15	Denmark	12

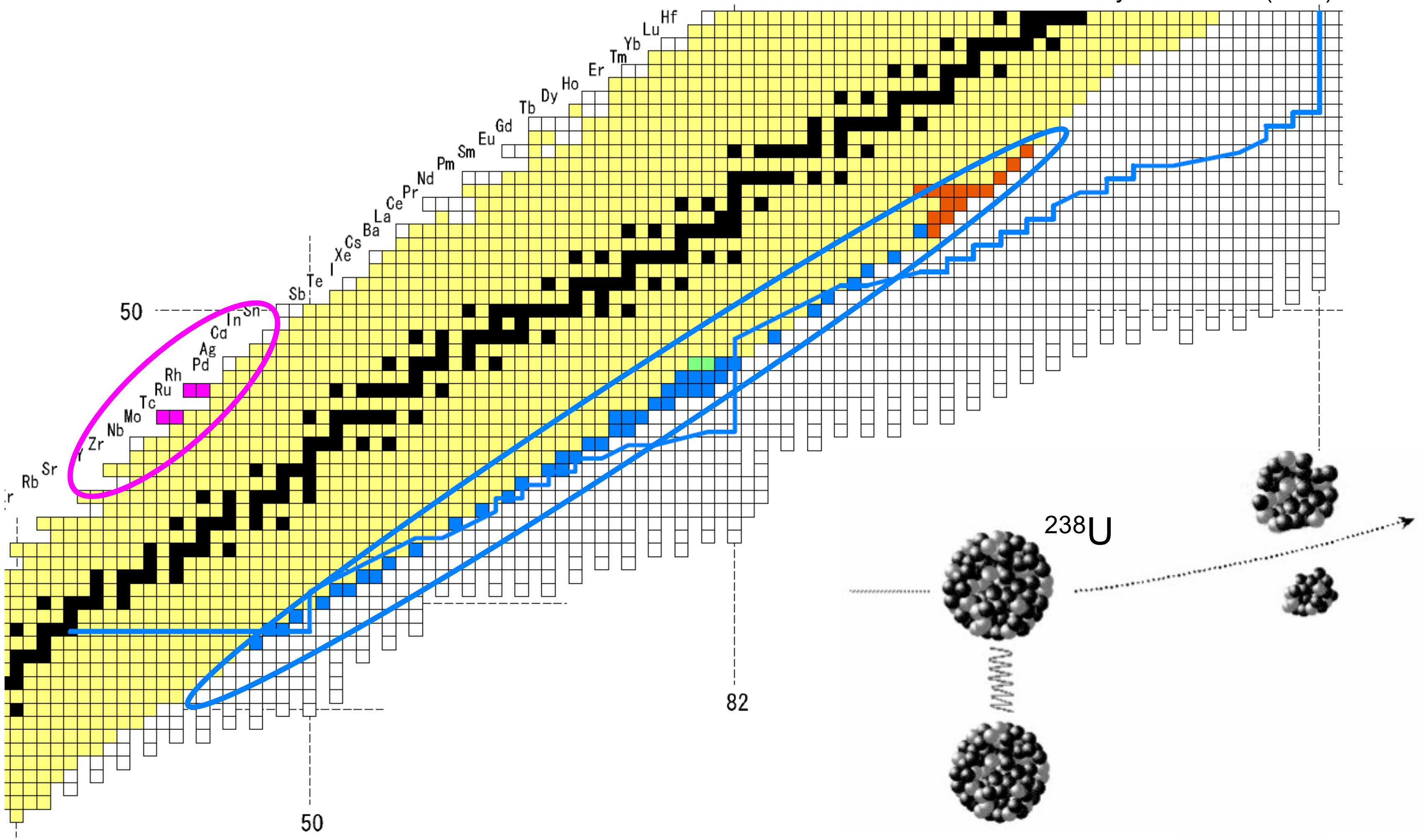
https://frib.msu.edu/public/nuclides



M. Thoennessen, private comm.

Discovery of New isotopes

T. Ohnishi et al. , J. Phys. Soc. Jpn. 79 (2010) 073201
D. Kameda et al.: Phys. Rev. C 86 (2012) 054319



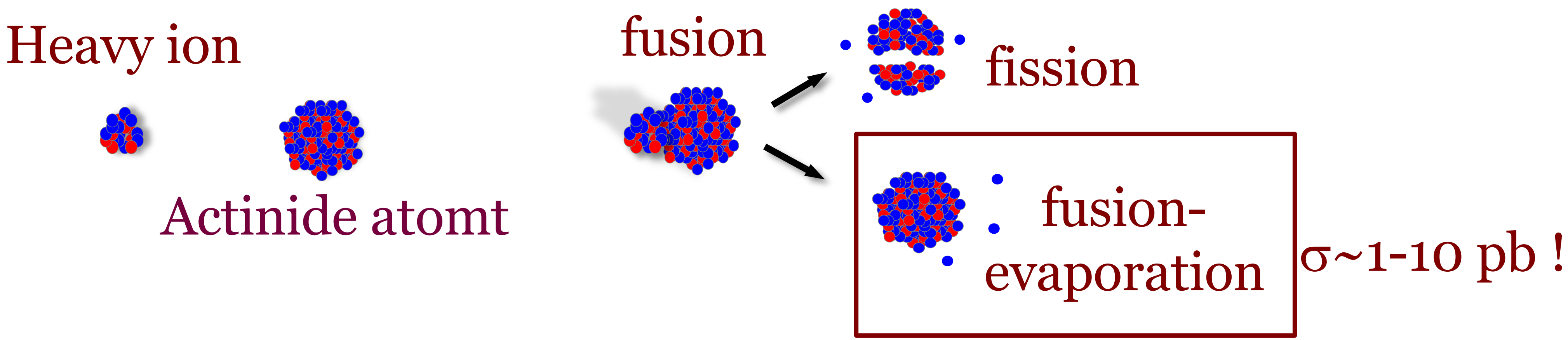
2007,2008,2011 (^{238}U): 61 new isotopes

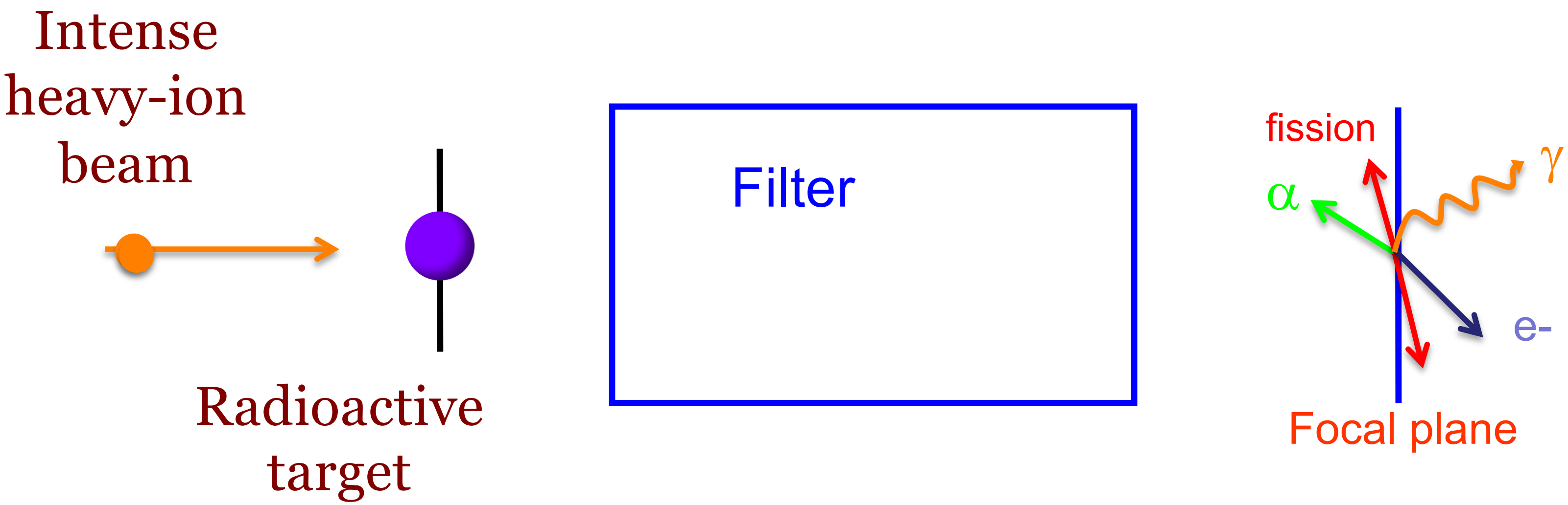
2014-2022 (^{238}U): 91 new isotopes

2011 (^{124}Xe): 4 new isotopes

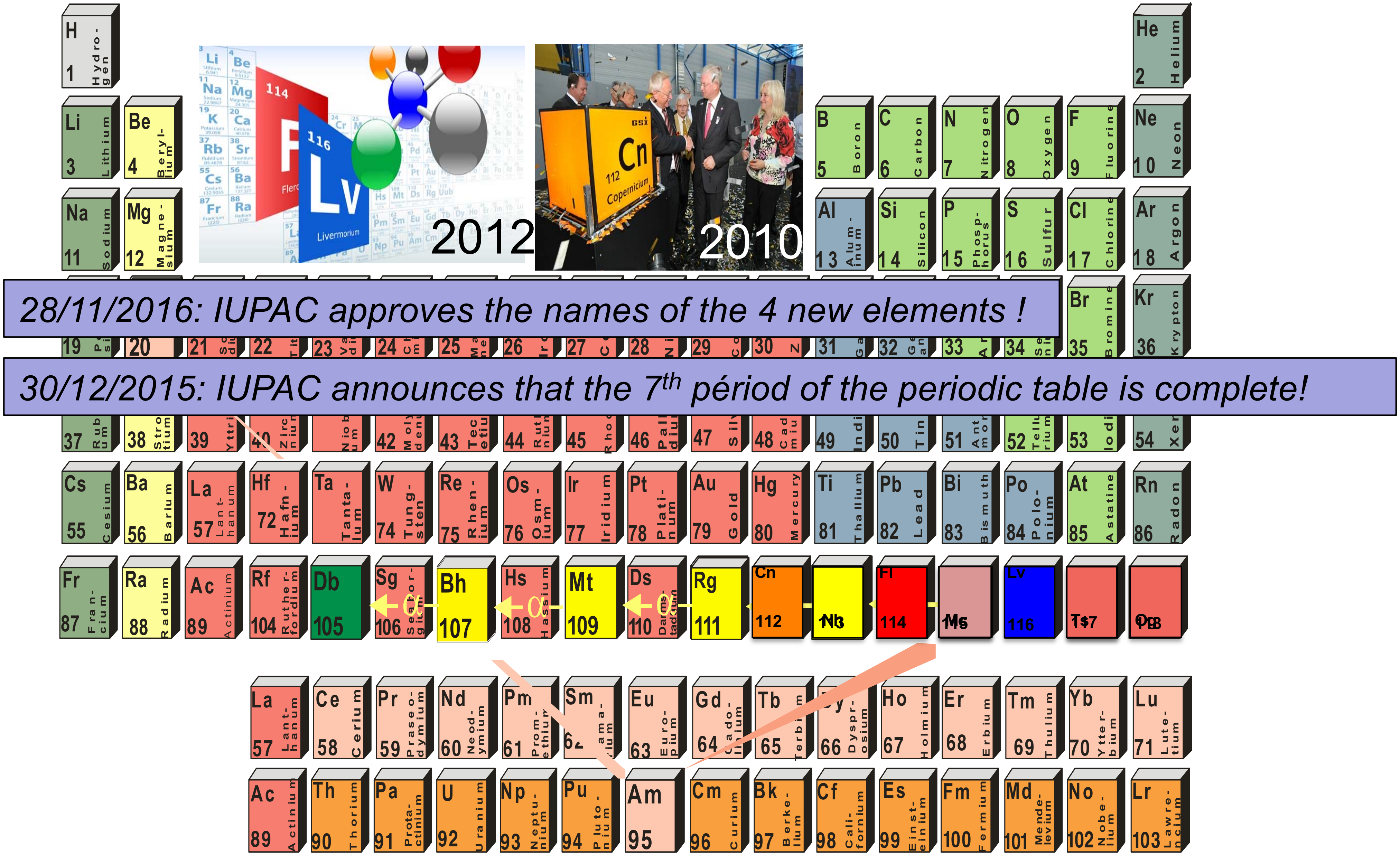
2016-2021 (^{124}Xe): 10 new isotopes

Synthesis of New Elements





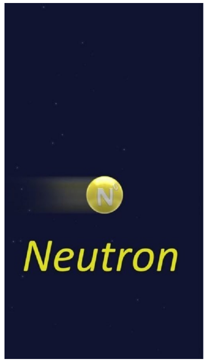
Super Heavy Elements



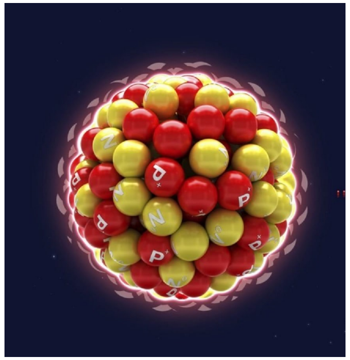
28/11/2016: IUPAC approves the names of the 4 new elements !

30/12/2015: IUPAC announces that the 7th périod of the periodic table is complete!

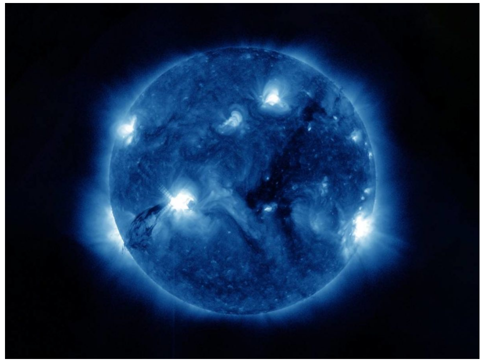
New state of nuclear matter (?)



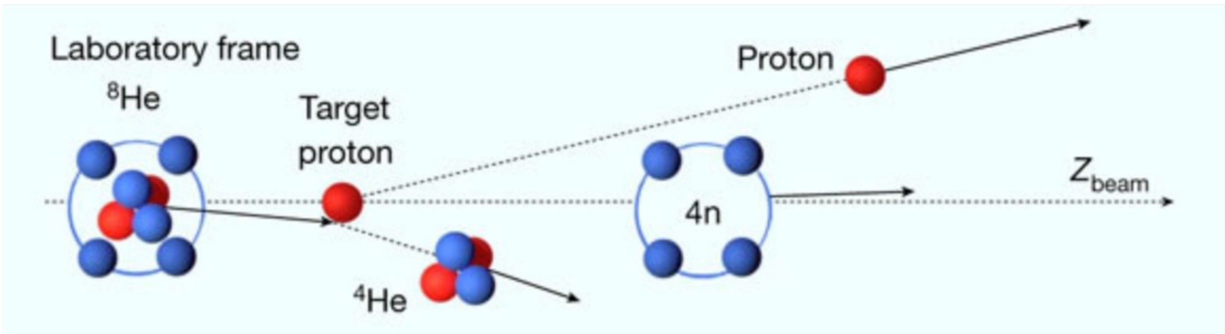
n unstable



n stable/unstable

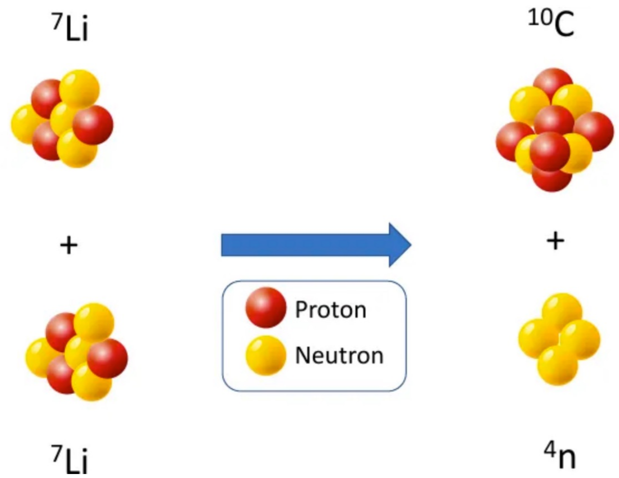


n stable



Observation of a correlated 4-neutron system, $T_{1/2}=(3.8 \pm 0.8) \times 10^{-22}$ s

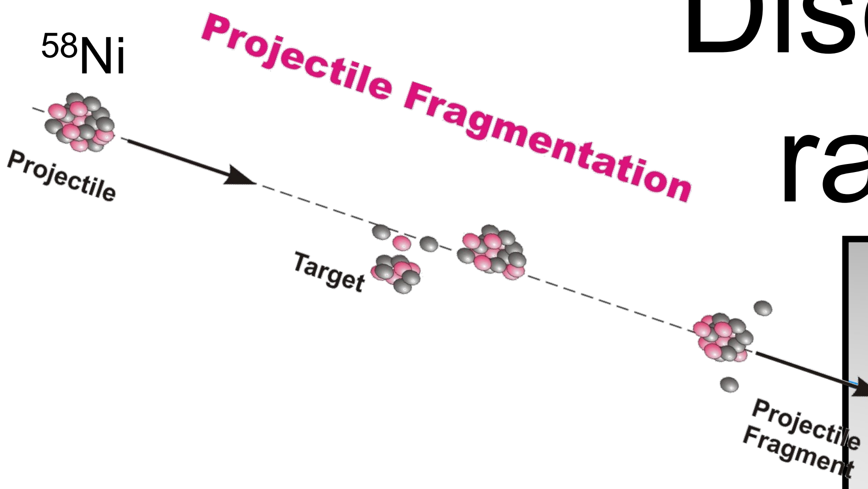
M. Duer et al., Nature 606, 678 (2022)

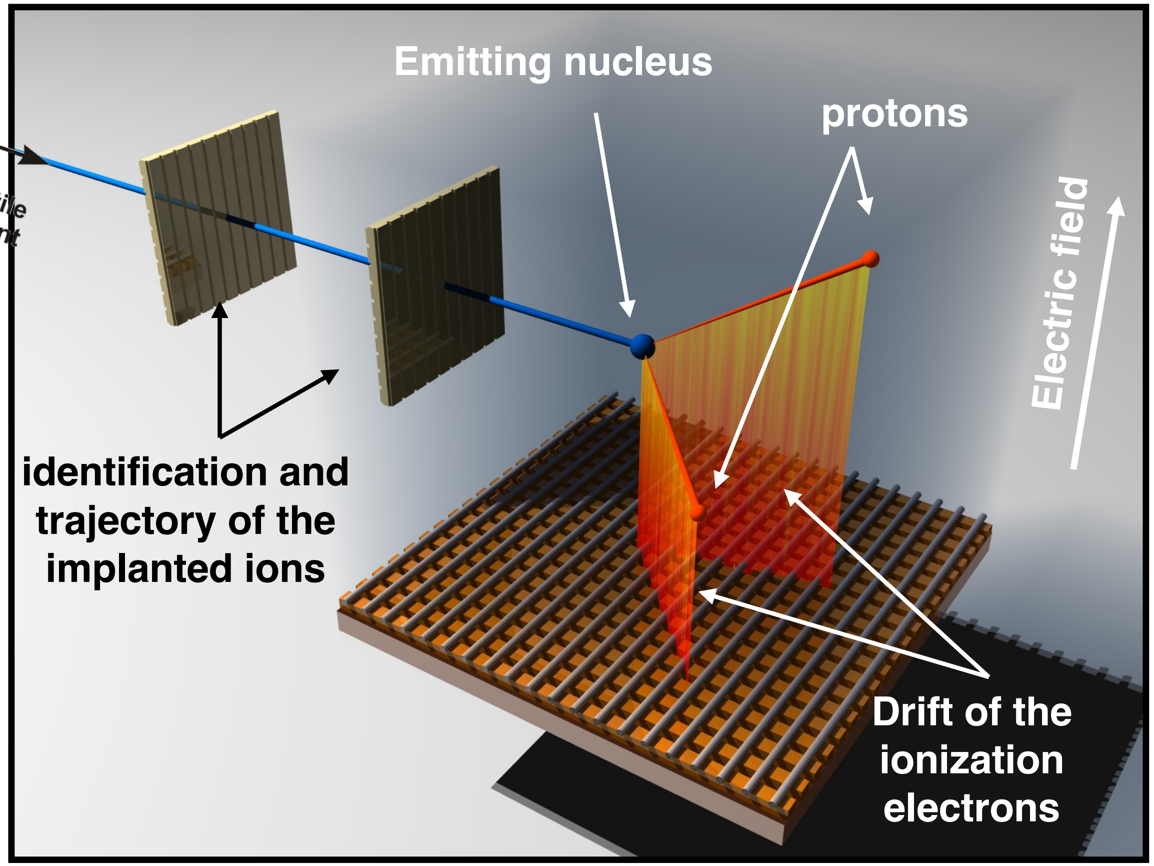


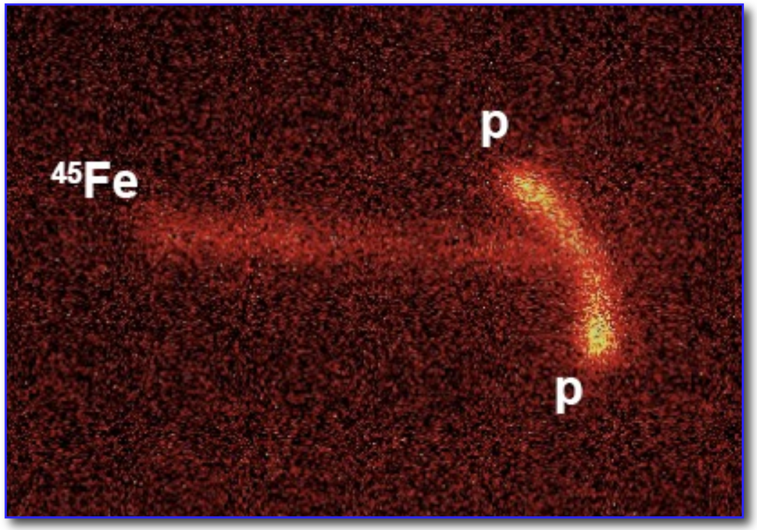
Observation of a bound 4-neutron system, $T_{1/2} \sim T_{1/2}(n)$

T. Faestermann et al., Phys. Lett. B 824,136799 (2022)

Discovery of new radioactivities







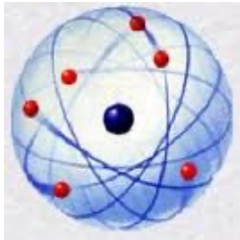
J. Giovinazzo et al., Phys. Rev. Lett. 89, 102501 (2002)
M. Pfützner et al., Eur. Phys. J. A14, 279 (2002)

4 other cases observed since: ^{54}Zn, ^{48}Ni, ^{19}Mg, ^{67}Kr

115 years ago.....

" The scattering of α and β particles by matter and the structure of the atom"

Philosophical Magazine Series 6, vol. 21 May 1911, p. 669-688



1911 Chemistry Nobel Prize is awarded to Marie Curie

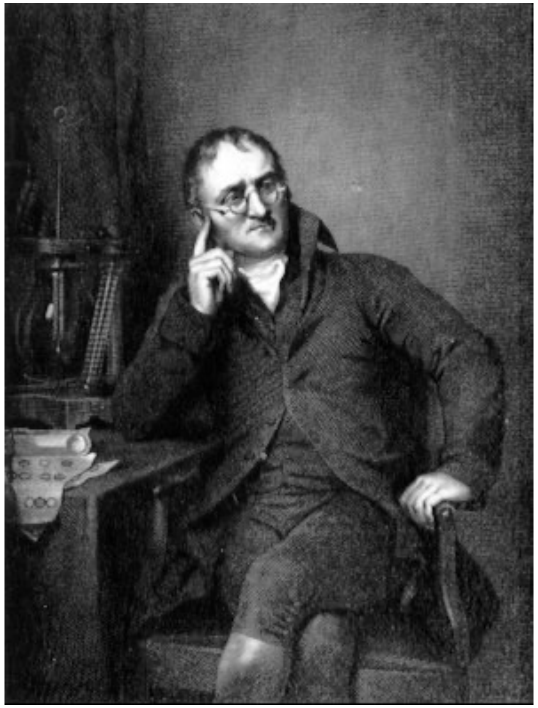
"in recognition of her services to the advancement of chemistry by the discovery of the elements radium and polonium, by the isolation of radium and the study of the nature and compounds of this remarkable element"

At the dawn of the 20th century

“There is nothing new to be discovered in physics now.
All that remains is more and more precise measurement.”

Phrase attributed to William Thomson (Lord Kelvin), 1900
British Association for the advancement of Science

Constituents of matter



John Dalton

1803 :
-matter is made of **atoms**

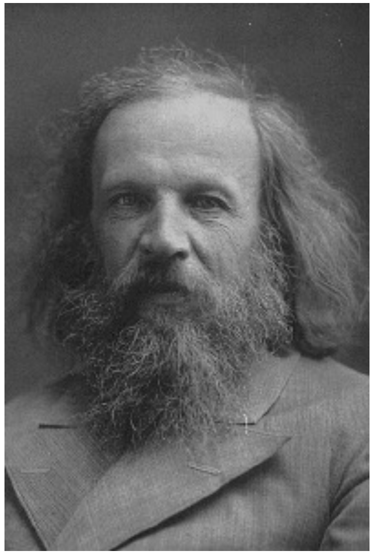
-atoms of the same element are identical

La « boule de billard »
de Dalton, 1803

-atoms of an element can combine with those of other elements to form compounds

-atoms of different elements have different masses

Classification of elements



Dmitri Ivanovich Mendeleev

Regularities in the chemical properties of the elements

ОПЫТЪ СИСТЕМЫ ЭЛЕМЕНТОВЪ,

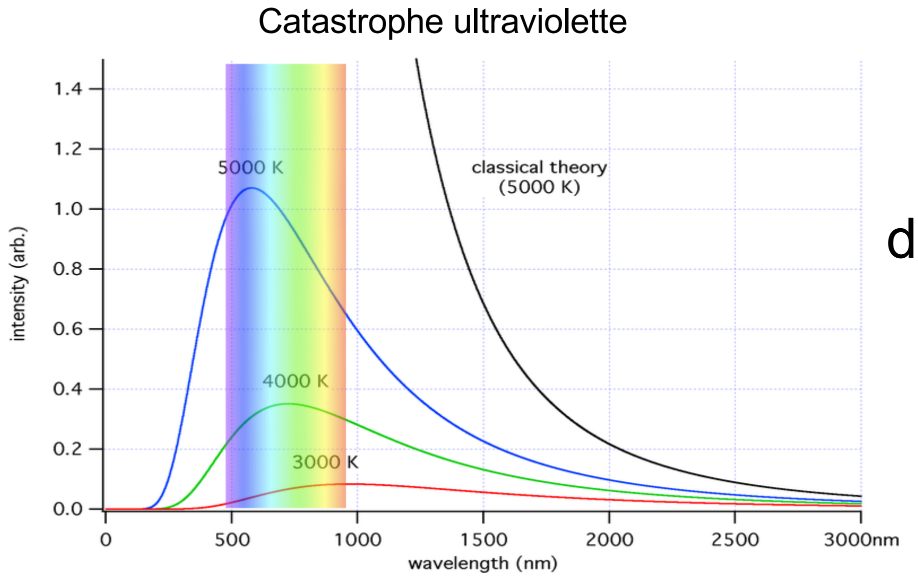
ОСНОВАННОЙ НА ИХЪ АТОМНОМЪ ВѢСѢ И ХИМИЧЕСКОМЪ СХОДСТВѢ.

			Ti=50	Zr=90	?=180.
			V=51	Nb=94	Ta=182.
			Cr=52	Mo=96	W=186.
			Mn=55	Rh=104,4	Pt=197,4.
			Fe=56	Rn=104,4	Ir=198.
			Ni=Co=59	Pl=106,6	Os=199.
H=1			Cu=63,4	Ag=108	Hg=200.
	Be=9,4	Mg=24	Zn=65,2	Cd=112	
	B=11	Al=27,4	Ga ?=68	Ur=116	Au=197?
	C=12	Si=28	Ge ?=70	Sn=118	
	N=14	P=31	As=75	Sb=122	Bi=210?
	O=16	S=32	Se=79,4	Te=128?	
	F=19	Cl=35,5	Br=80	I=127	
Li=7	Na=23	K=39	Rb=85,4	Cs=133	Tl=204.
		Ca=40	Sr=87,6	Ba=137	Pb=207.
		Sc ?=45	Ce=92		
		?Er=56	La=94		
		?Yt=60	Di=95		
		?In=75,6	Th=118?		

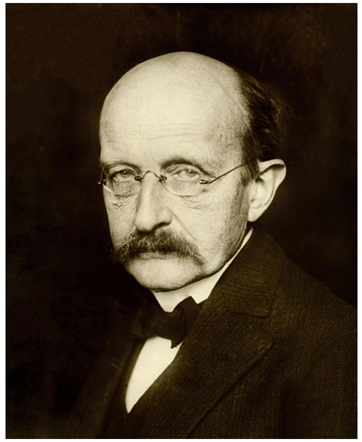
Д. Менделѣевъ (1869)

The place of an element in the table is given by the number **Z** (=atomic number, from Atom**Z**ahl)

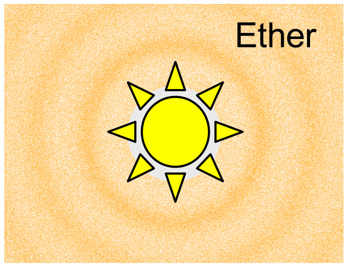
A few clouds in the sky.....

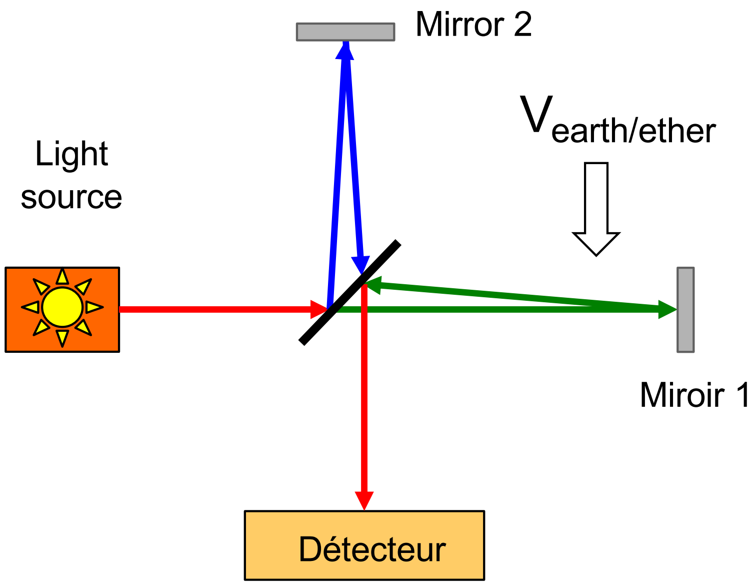


Matter can only absorb or emit radiation energy in discrete packets proportional to the frequency of the radiation: energy **quanta**



Max Planck

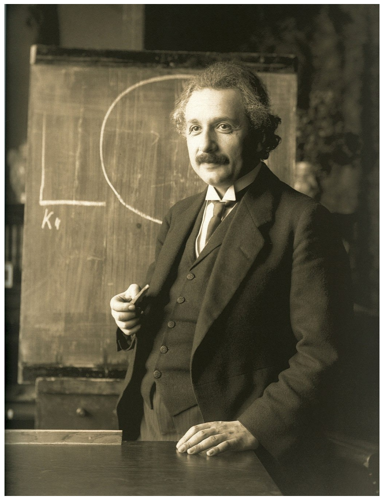




Michelson Morley experiment

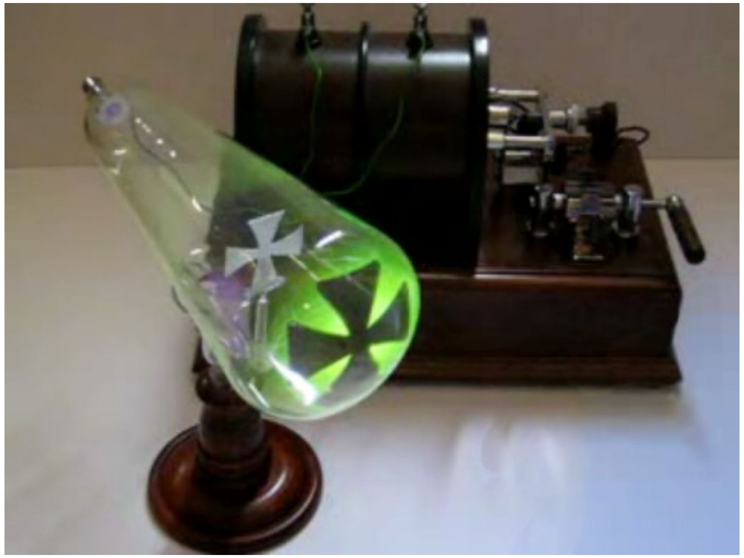
Special Relativité :
The laws of physics are the same in every inertial frame of reference, and the speed of light is a constant

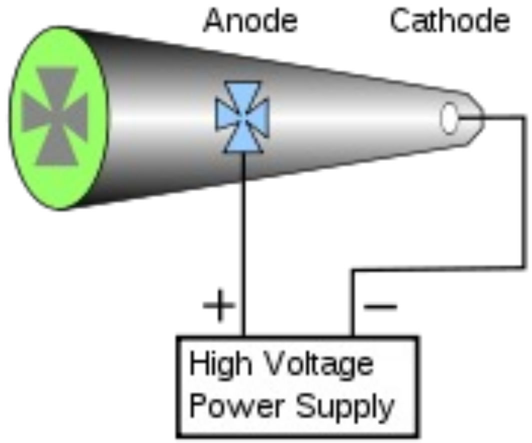
$$E=mc^2$$

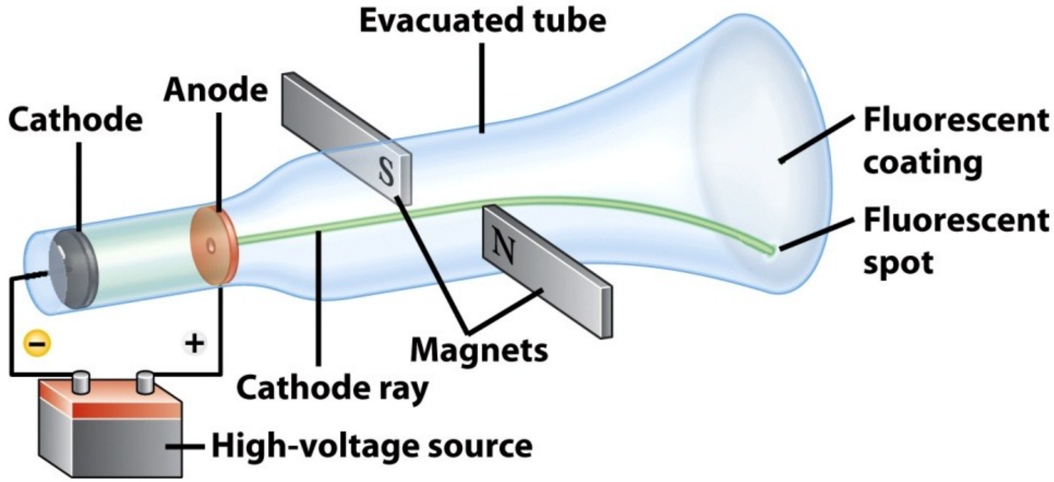


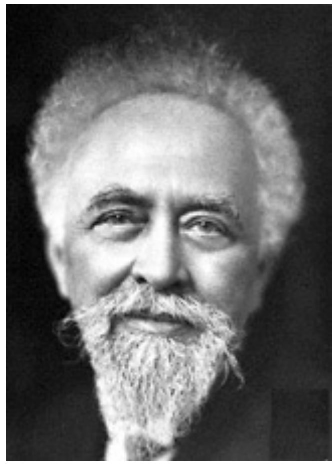
Albert Einstein

The cathode tube leads the revolution



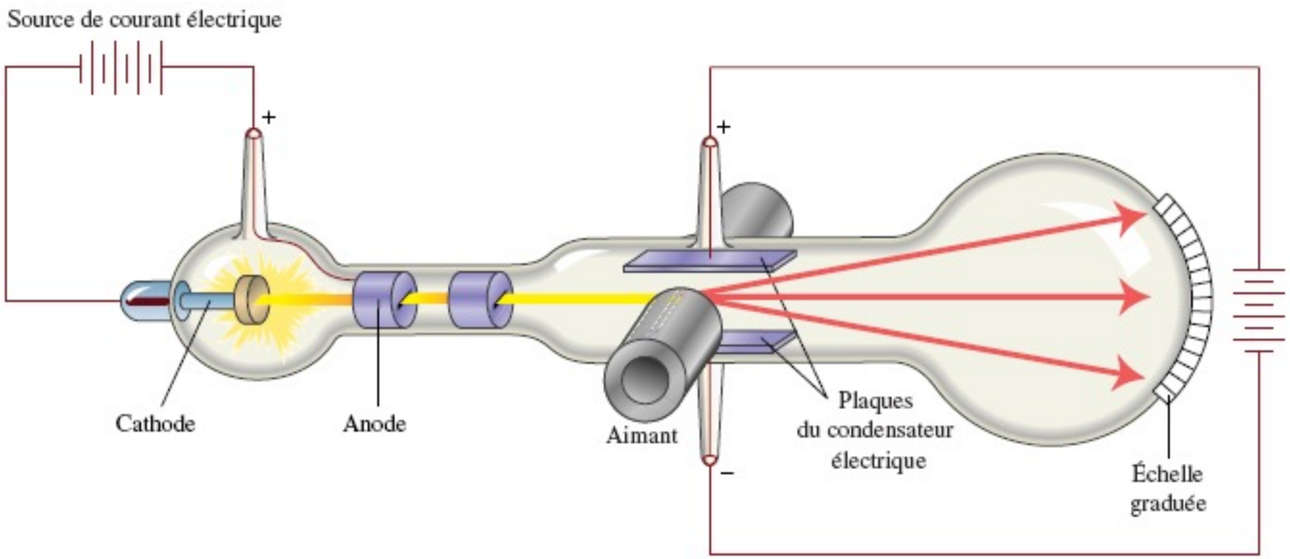


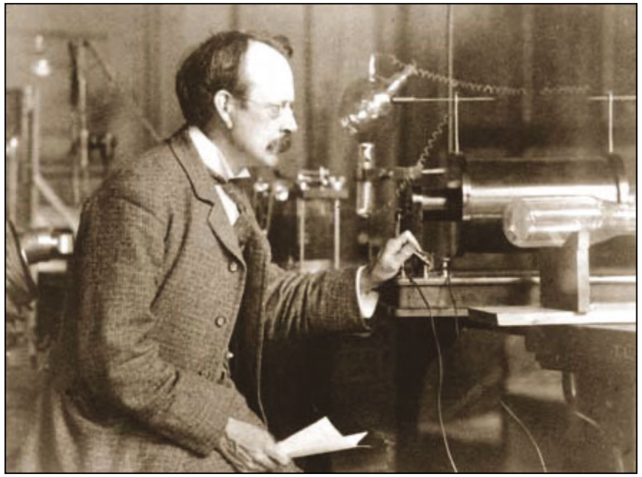




1895: Jean Perrin demonstrates that cathode rays are negatively charged particles

Atoms are no longer indivisible !



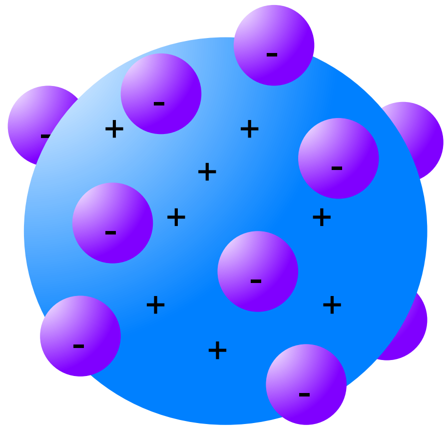


John Joseph Thomson

J.J. Thomson measures the charge/mass ratio of the charged particles

1898: J.J. Thomson concludes that what he calls 'corpuscules' (= electrons) are the constituents of atoms

'plum pudding' model

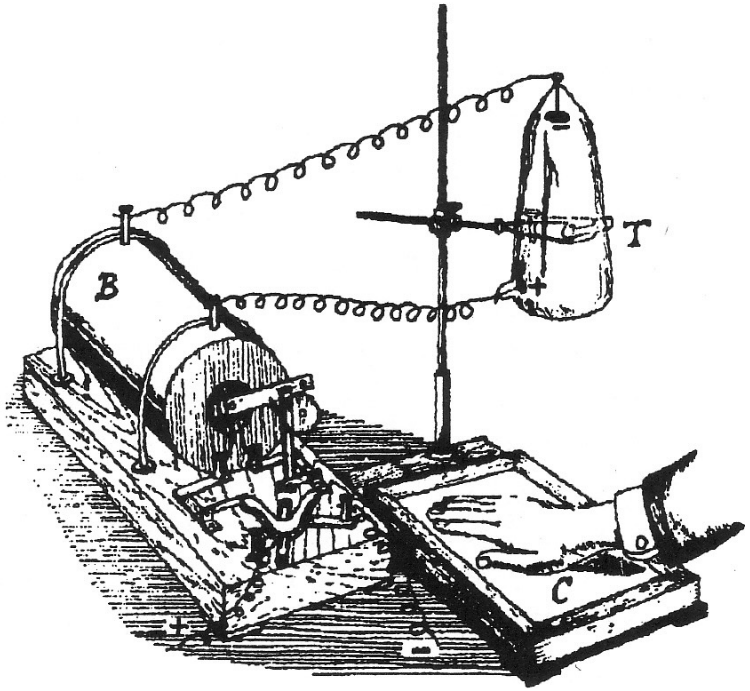


From cathode rays to X rays

1895 W. Röntgen

Discovery of X rays

Wilhelm Röntgen

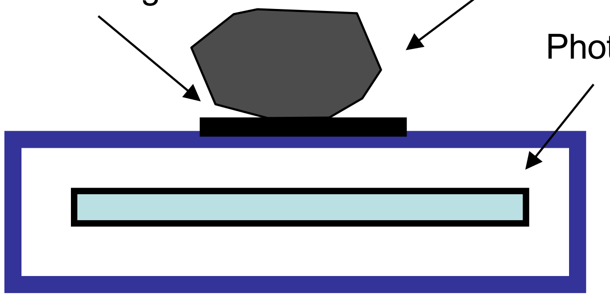


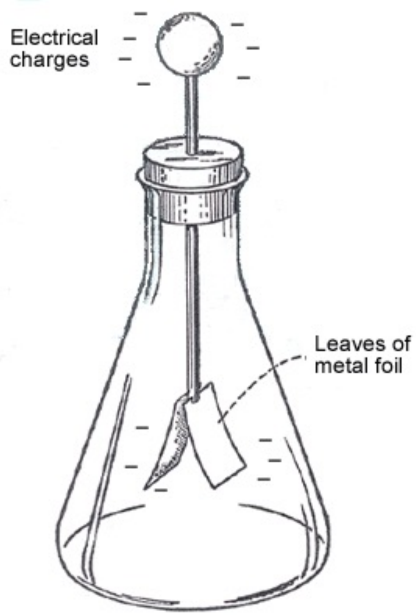
W. Röntgen receives the 1st Nobel Prize in Physics in 1901

From X rays to Uranium rays

1896 H. Becquerel Discovery of a new kind of radiation emitted by Uranium

Henri Becquerel





Uranium rays ionize the air and cause the discharge of an electroscope

From Uranium rays to radioactivity

1898 Marie & Pierre Curie

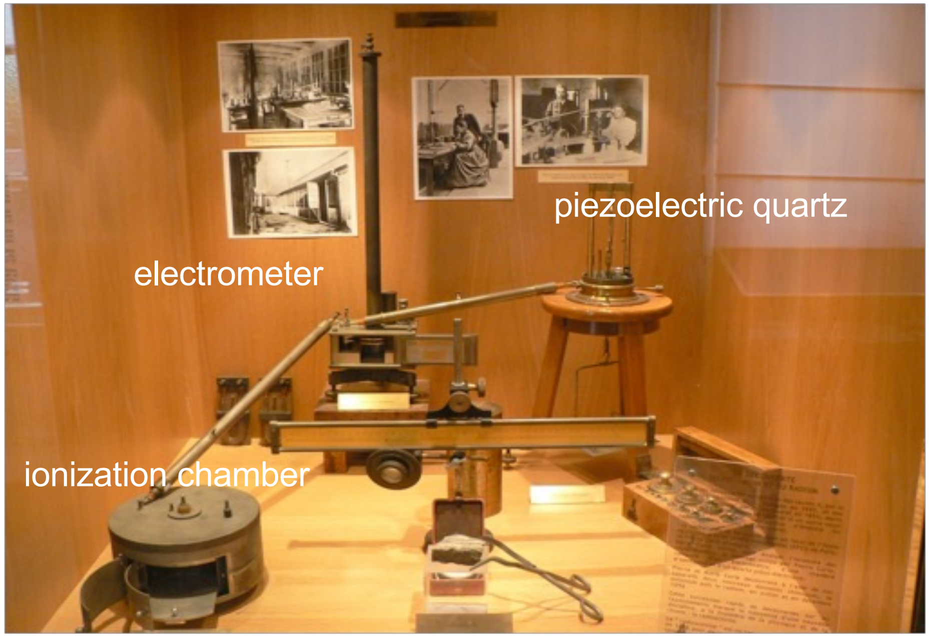
extraction of Polonium (Bismuth fraction) and Radium (Barium fraction)

Marie Curie

Pierre Curie

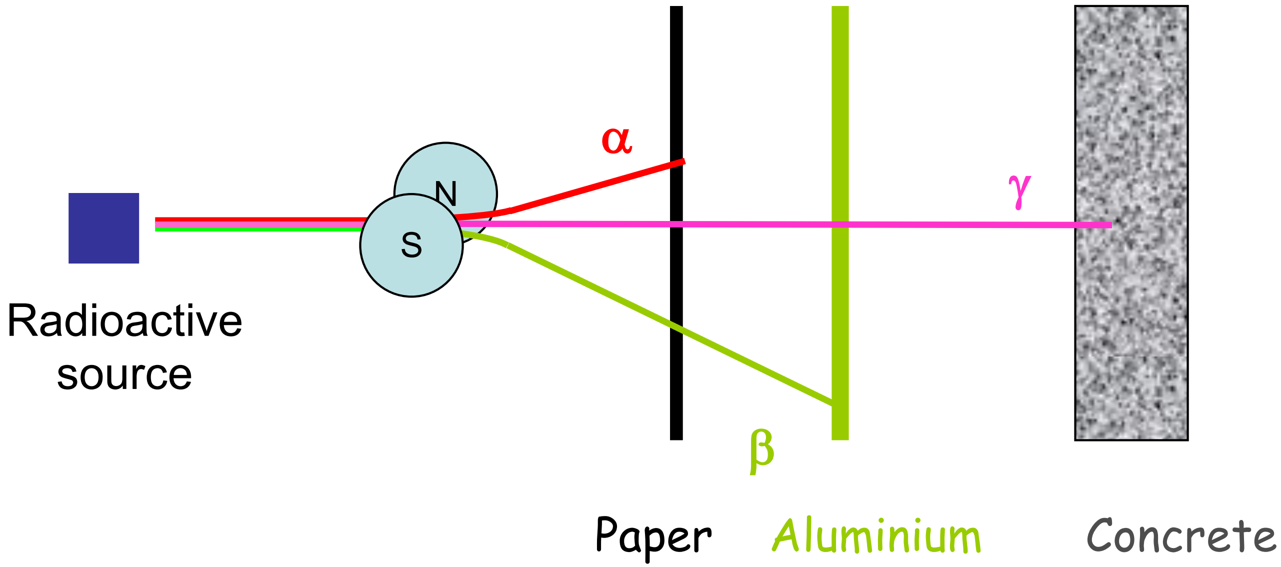
M. Curie calls the phenomenon:
'radioactivity'

Laboratoire à l'Ecole de Physique et Chimie Industrielle de Paris



Radioactivity is manifold

1898	E. Rutherfod	alpha, beta radiation
1900	P. Villard	gamma radiation



Ernest Rutherford

Paul Villard

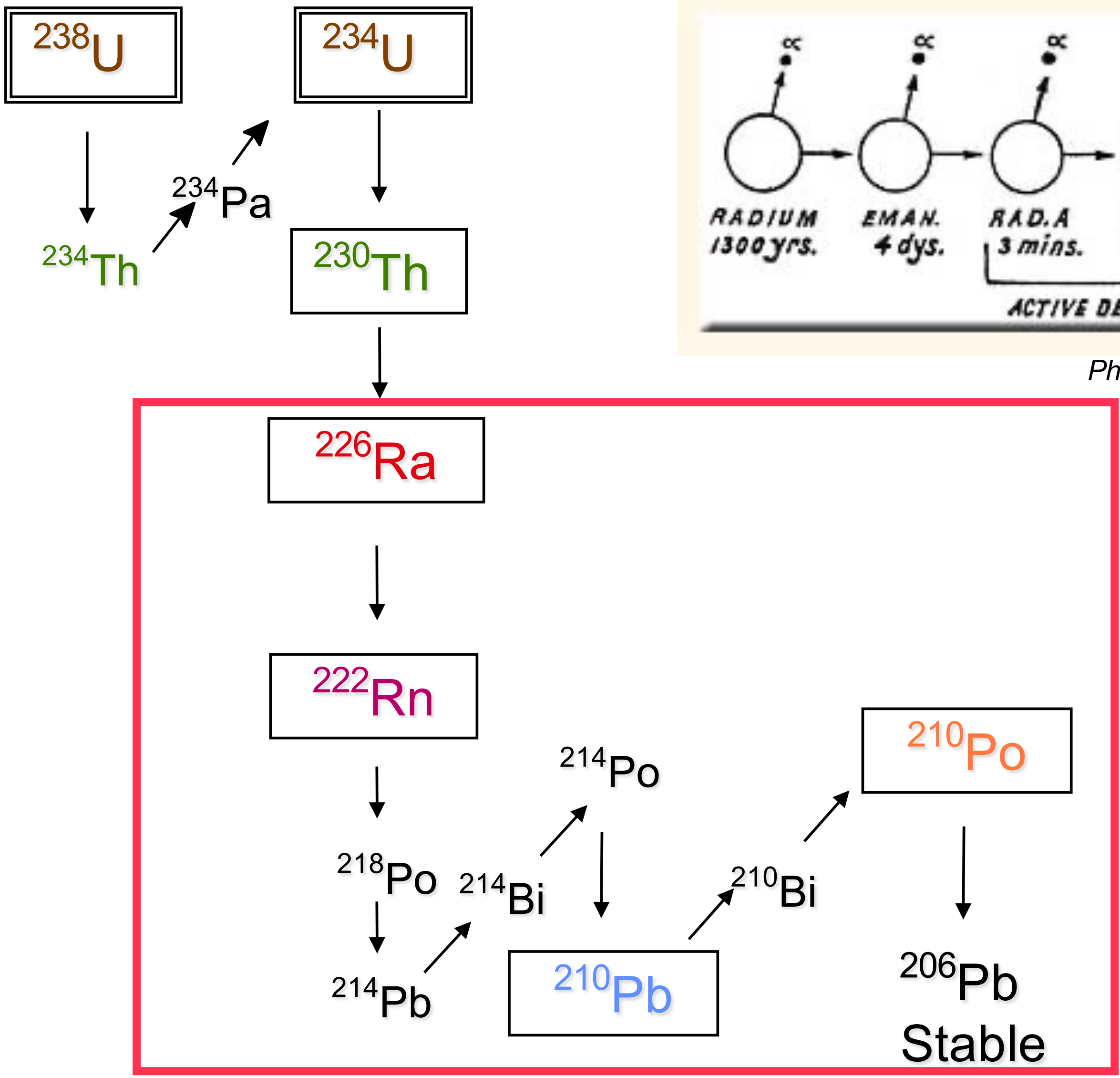
α = Helium ions He^{2+}

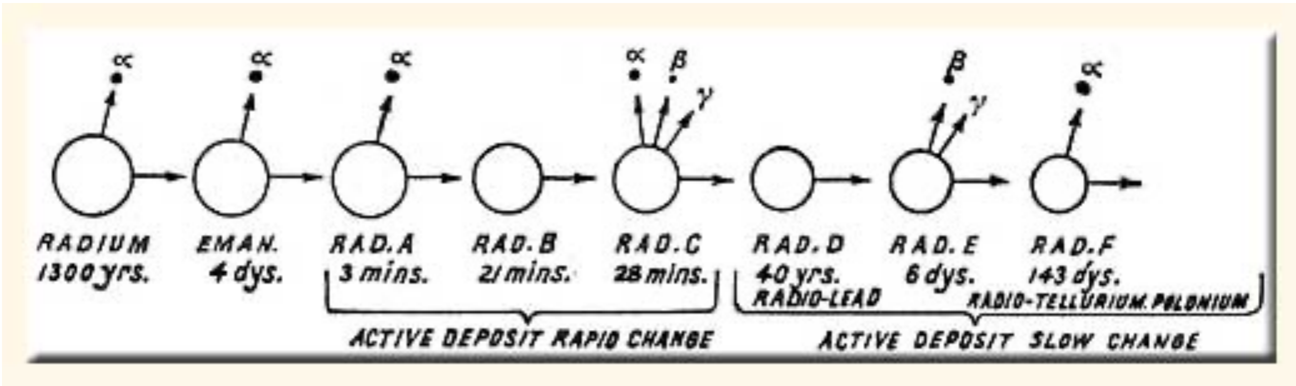
β= high-energy e^-

γ= photons – like X rays

Atoms transform !

1902 E. Rutherford & F. Soddy transmutation of atoms



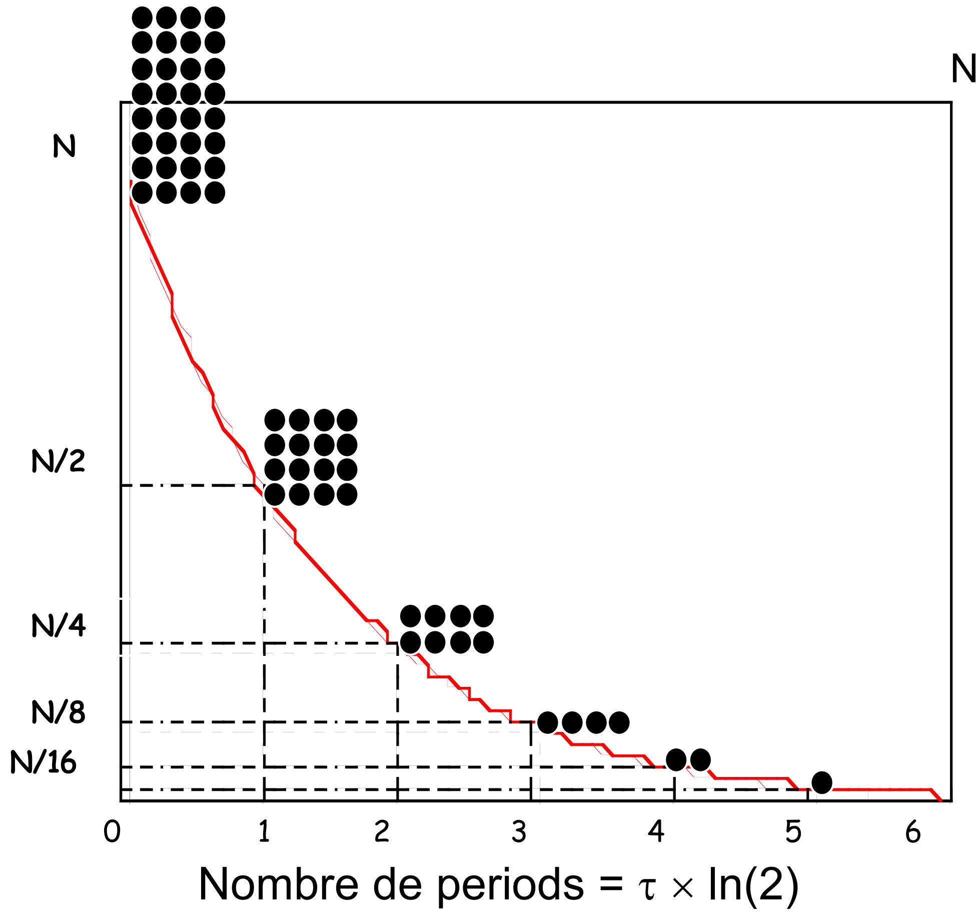


Philosophical Transactions of the Royal Society of London, 1905

β, γ radioactivity

α radioactivity

Radioactive decay



Number of nuclei at time t

Initial number of nuclei

Decay constant

$$N(t) = N_0 \exp(-\lambda t)$$

$$Activité = \lambda N(t) = N(t)/\tau$$

Lifetime

1910:

1 curie (Ci) = activity of 1g of Radium

1 Ci = 37 billion decays/s

1 Bq = 1 decay/s

Some examples of activities:

Man : 130 Bq/kg

House made of granit: 4 billion Bq

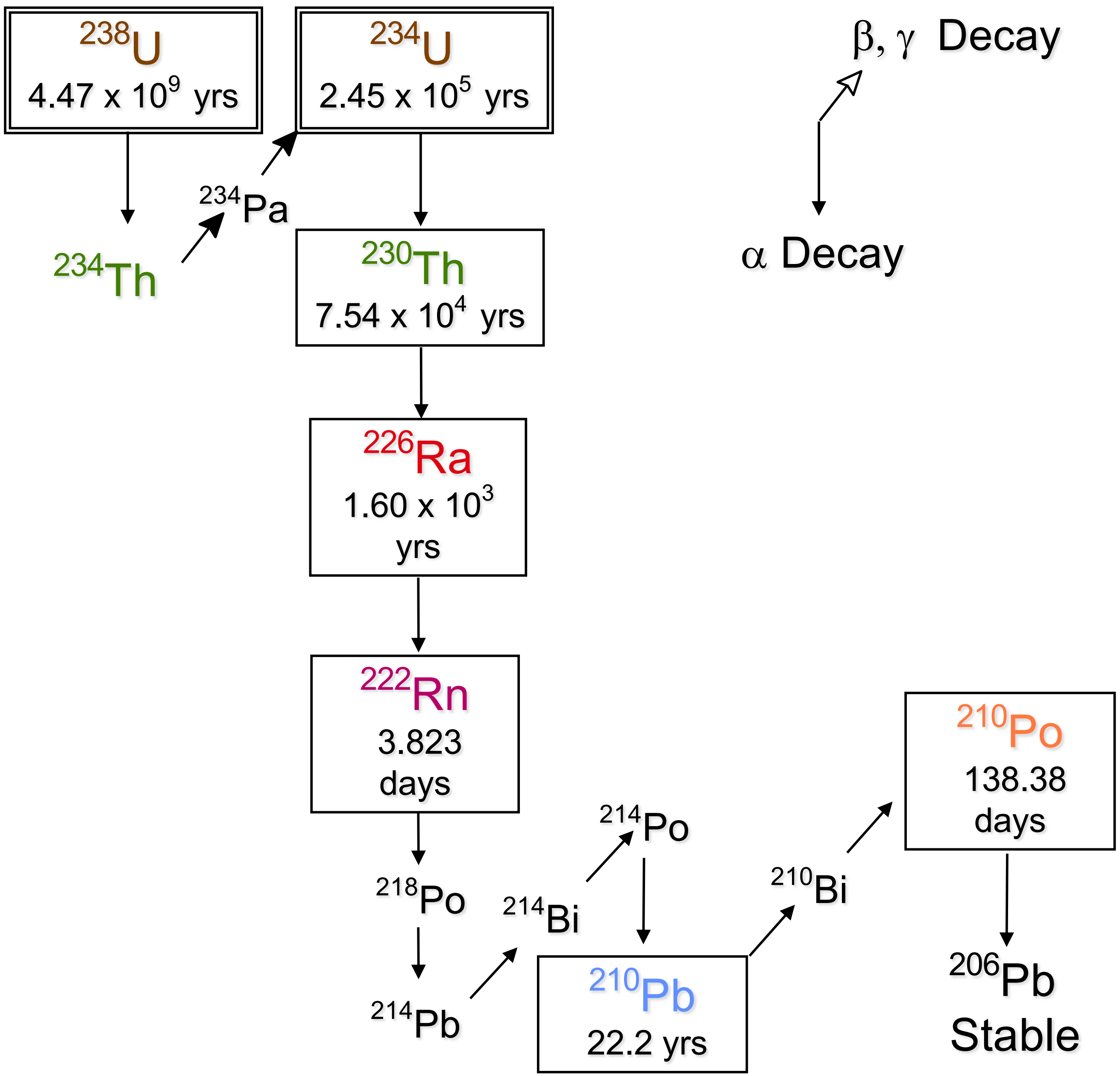
Concrete: 500 Bq/kg

Milk: 80 Bq/kg

Thyroid Scintigraphy : 37 million Bq

Spent reactor fuel: 10 billion billion Bq

Telluric radiation



Age of the earth:
~4.5 10^{9} years

Half-lives:

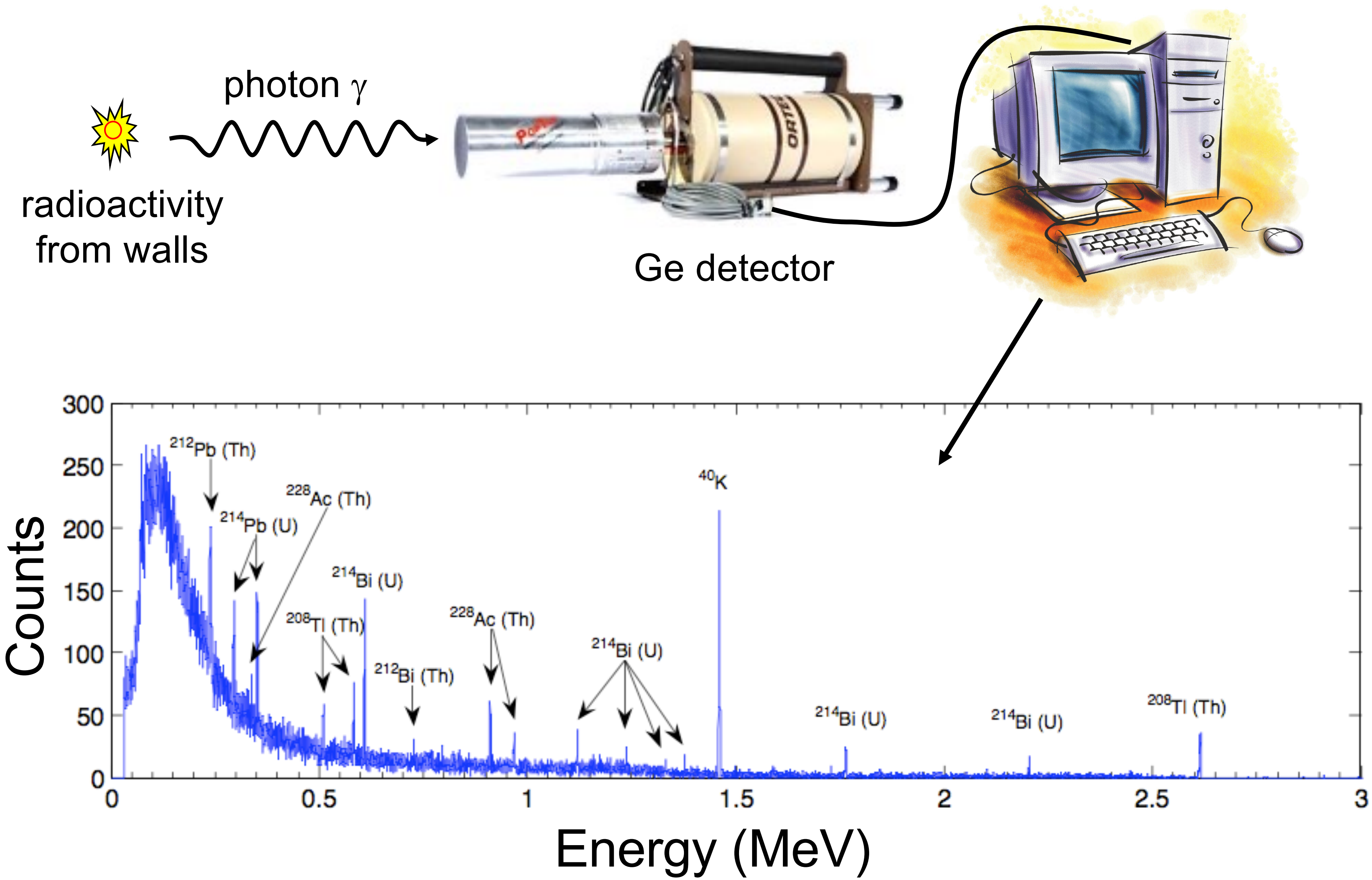
^{232}Th: 1.40 10^{10} y

^{235}U: 7.04 10^{8} y

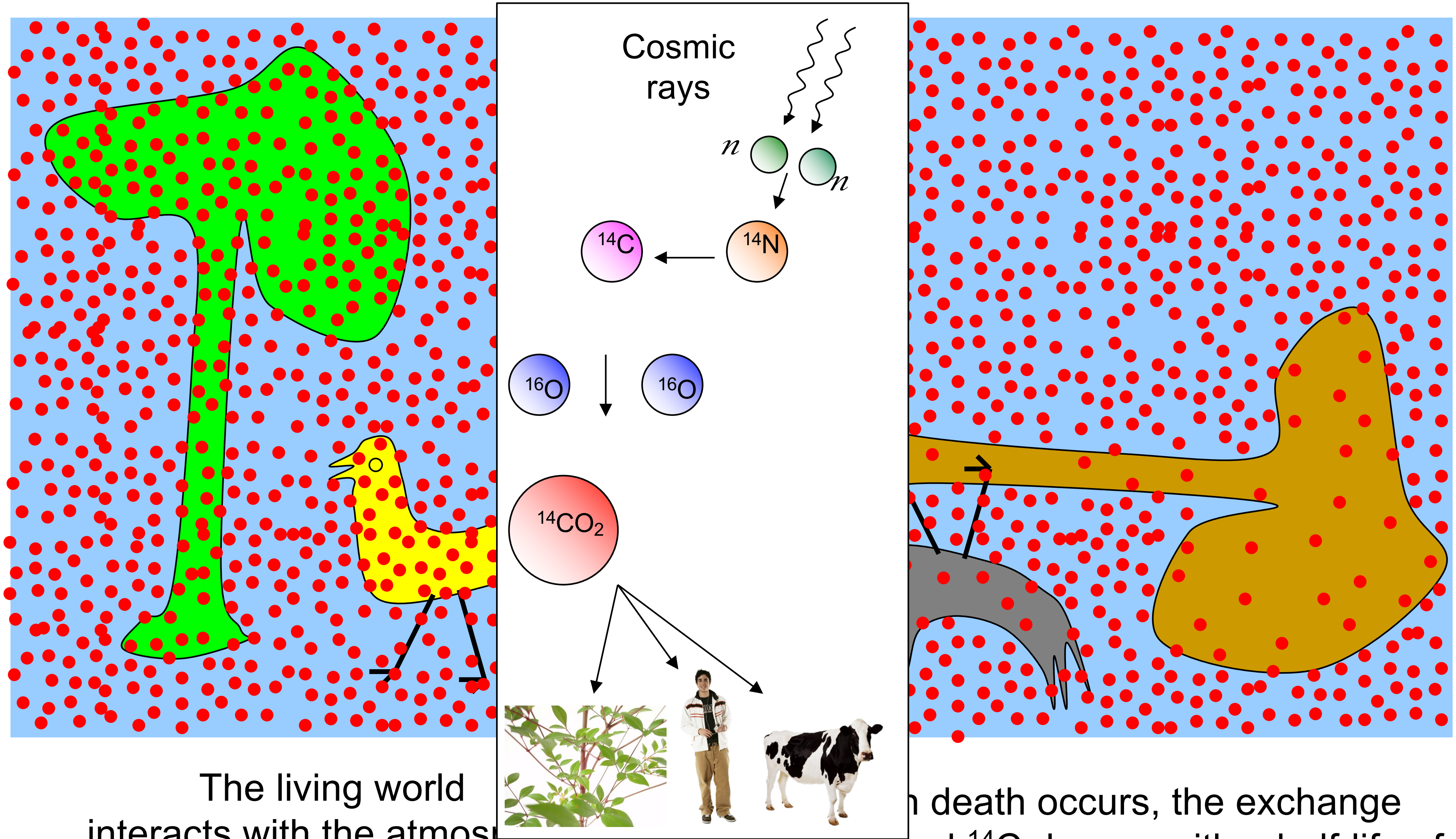
^{238}U: 4.47 10^{9} y

^{40}K: 1.2 10^{9} y

Telluric radiation



Comogenic radiation



The living world interacts with the atmosp

n death occurs, the exchange stops, and ^{14}C decays with a half-life of 5,730 years: R decreases

Abundance ratio $R = {}^{14}C/{}^{12}C \approx 10^{-12}$

Ötzi, the Iceman

In September 1991, hikers discovered Ötzi (the Iceman) in the Italian Alps. An activity of 0.121 Bq per 1 g of C was measured

South Tyrol Museum of Archaelogy, Bolzano

Radioactivity and Energy

1903: Pierre Curie and his collaborator Albert Laborde find that radium gives off enough heat to melt more than its weight of ice in an hour

Where does this energy come from ?

« There is reason to believe that an enormous store of latent energy is resident in the atoms of radioactive elements. If it were ever possible to control at will the rate of disintegration of the radioelements, an enormous amount of energy could be obtained from a small amount of matter. »

'Radioactivity', E. Rutherford, Ed. Cambridge at the University Press (1904)

1914: H.G. Wells publishes "The world set free"

Radioactivity and age of the earth

Lord Kelvin:
- ~tens of millions of years
- cooling from an initially molten state
- quantitative arguments

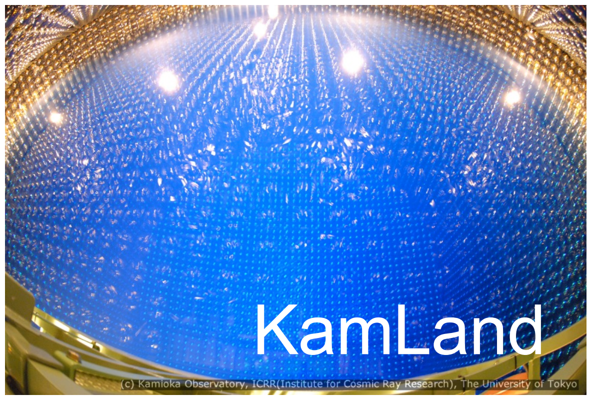
Geologists and biologists:
- ~hundreds of millions of years
- fossils, evolution, speed of sedimentation....
- Qualitative arguments

Discovery of radioactivity:

The decay of radioactive minerals in the earth is a source of heat which helps to invalidate Kelvin's calculations (in addition to the fact that he had not taken convection into account)

Geothermal heat flow: 44.2 ± 1.0 TW
Contribution from radiative nuclei of ^{238}U, ^{232}Th and ^{40}K: ~50%

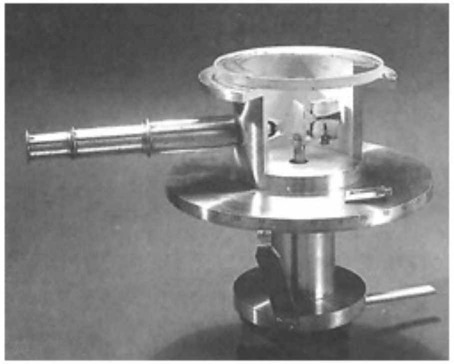
Nature Geoscience 4 (2011) 647

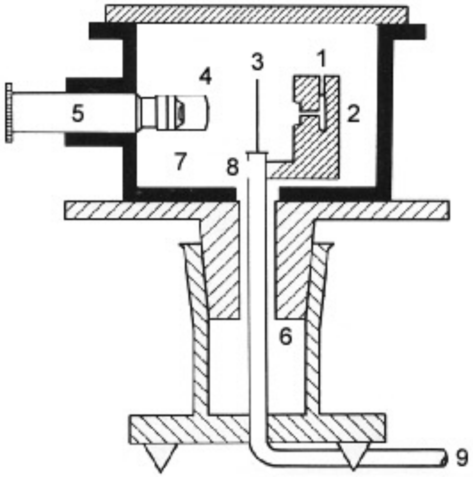


The discovery of radioactivity revolutionized science and society in a profound and lasting way.

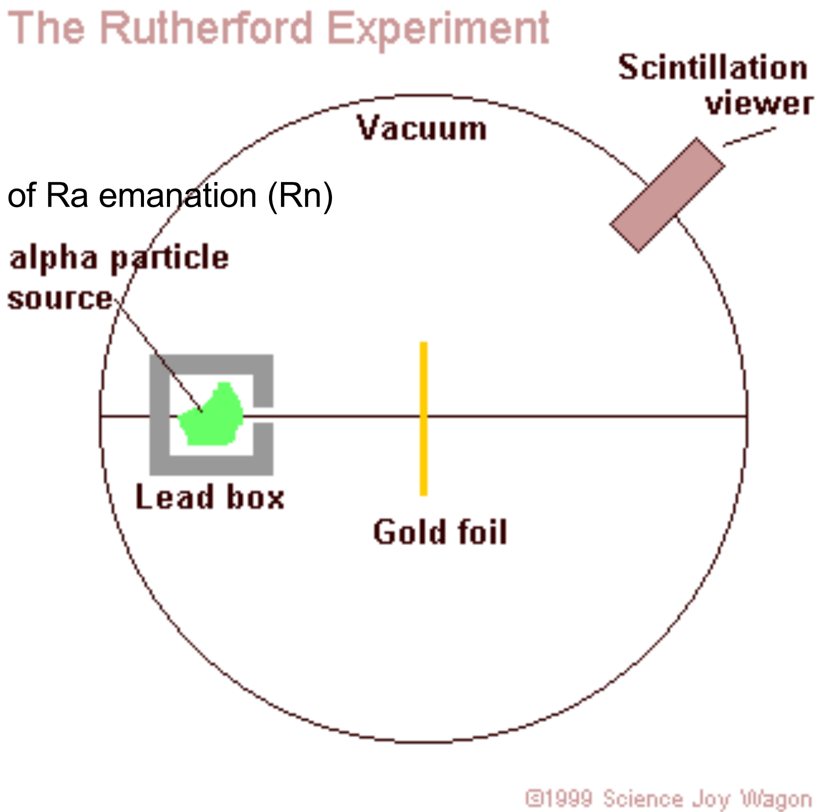
But that wasn't the end of it...

Scattering of alpha particles





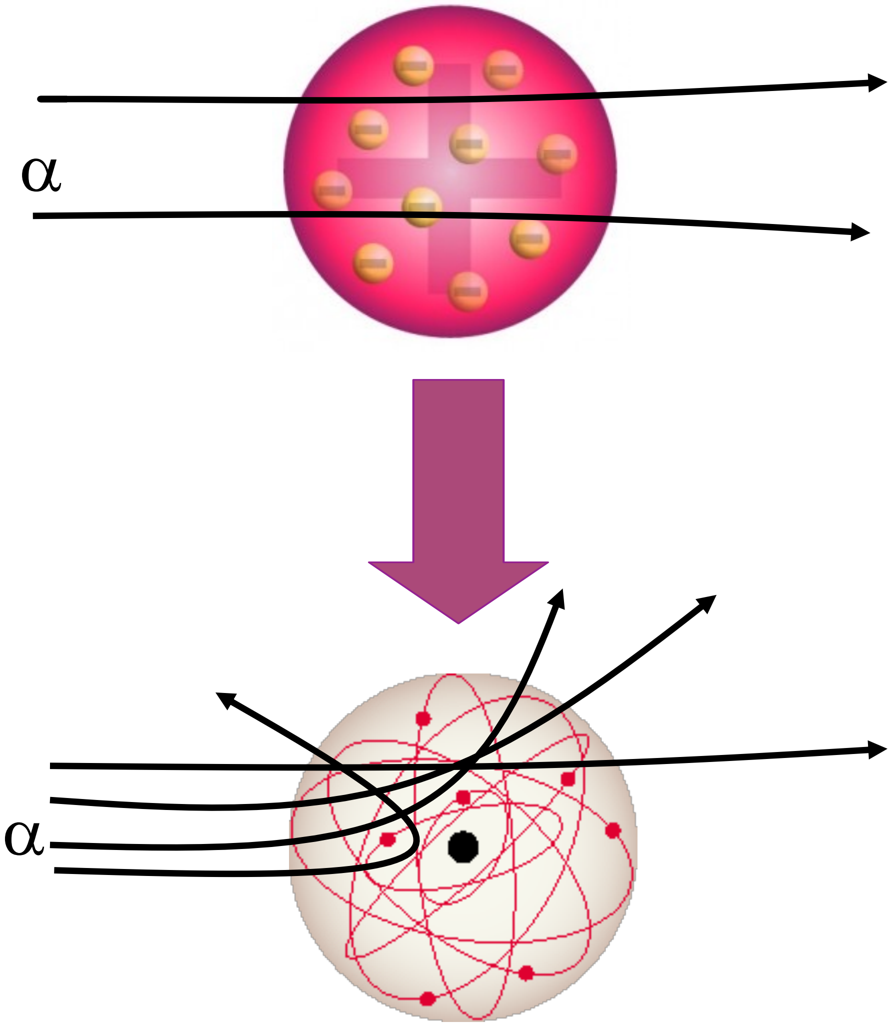
Experiment performed by H. Geiger and E. Marsden
(1909, University of Manchester)



"It was almost as incredible as if you fired a 15-inch shell at a piece of tissue paper and it came back and hit you! "

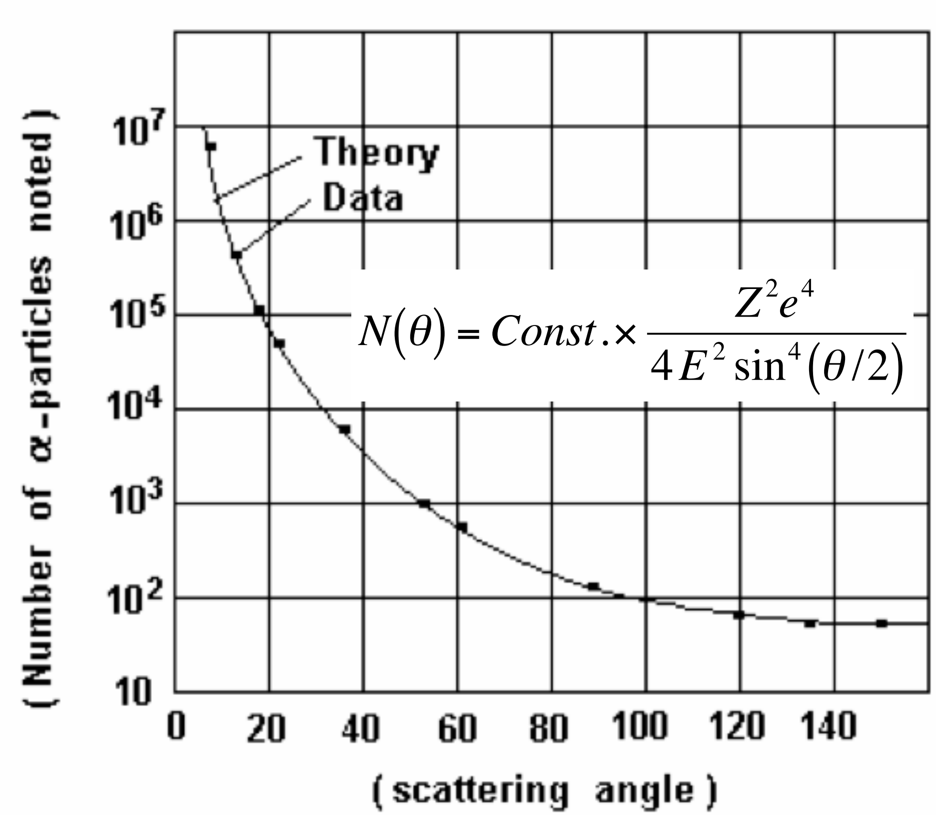
The nucleus is born !

'plum pudding' model

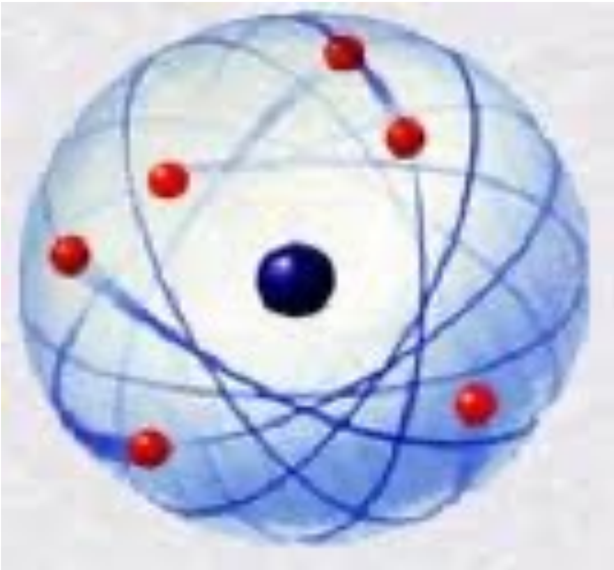


Nuclear model

Philosophical Magazine Series 6,
vol. 21 May 1911, p. 669-688



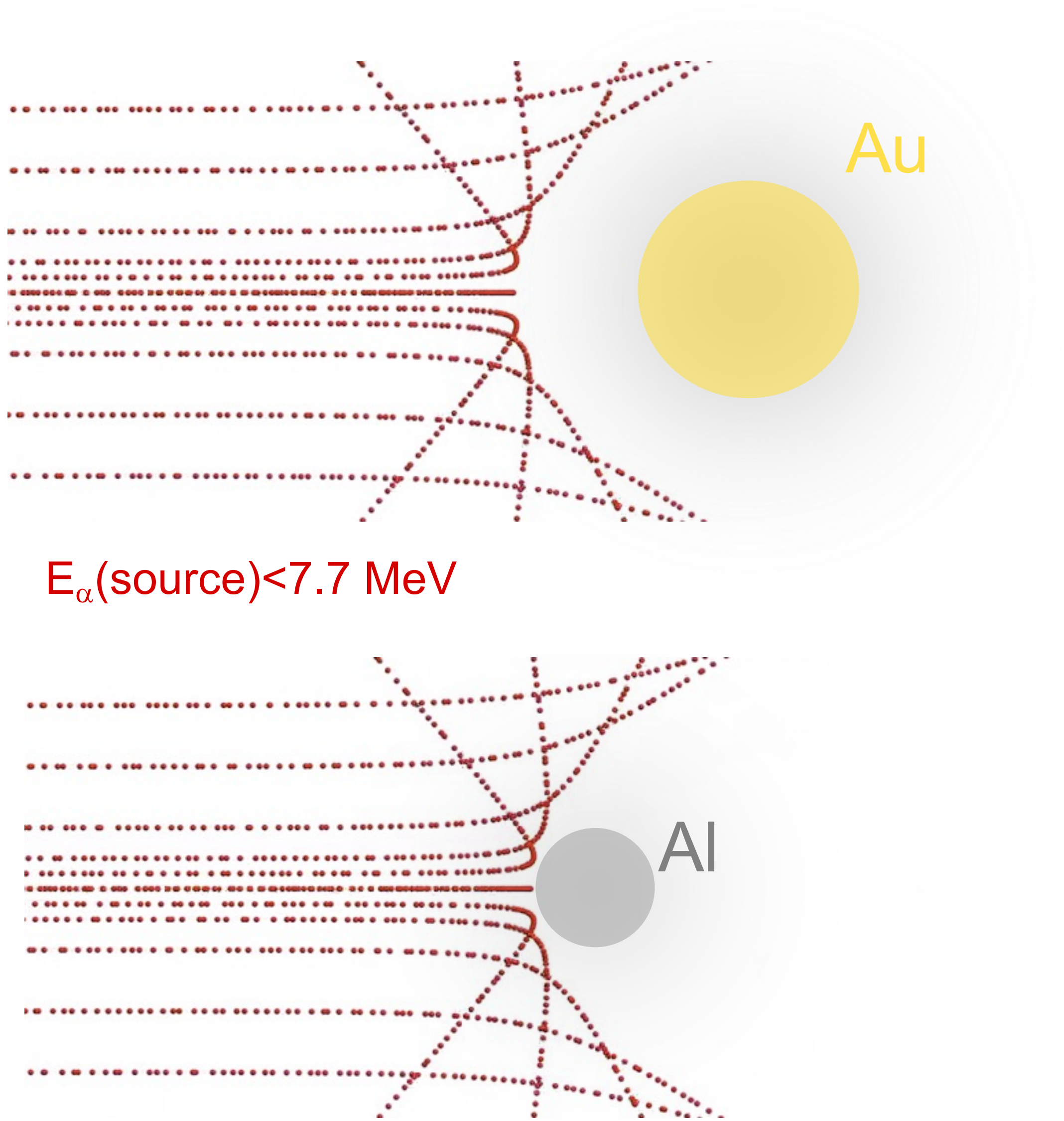
Consequences of Rutherford's model



10^{-14} m

10^{-10} m

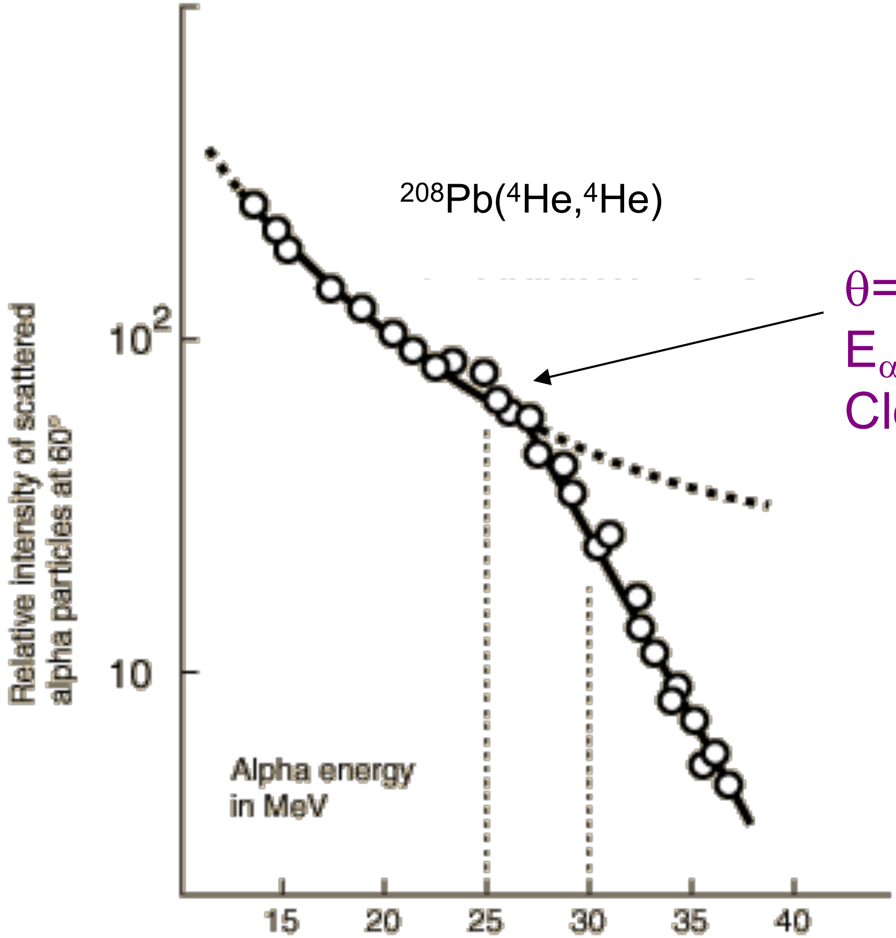
Matter is empty !



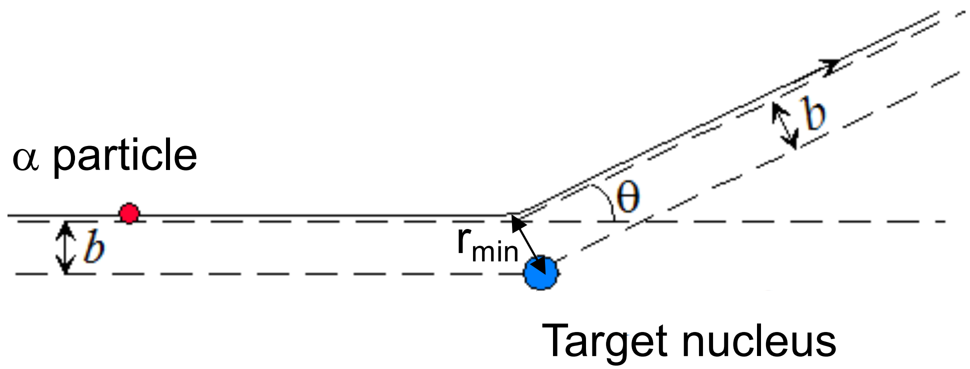
Closer to the nucleus

At higher energies, α particles can get very close to a heavy nucleus and feel the effects of the nuclear force

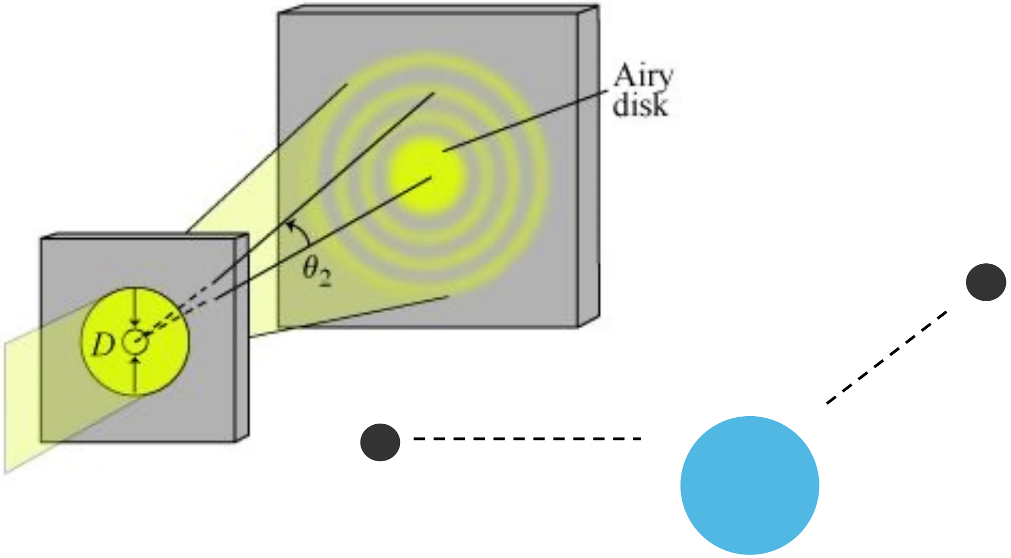
Eisberg, R. M. and Porter, C. E., Rev. Mod. Phys. 33, 190 (1961)



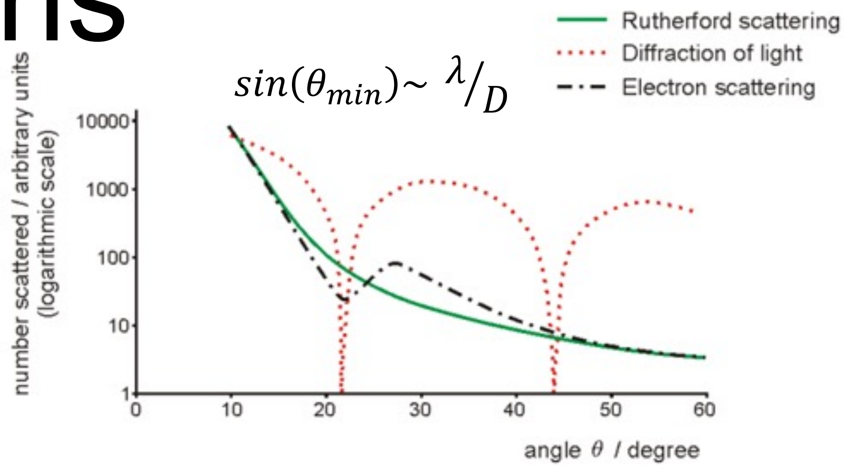
$\theta=60^\circ$,
$E_\alpha=27.5$ MeV
Closest approach: $r_{min}=12.9$ fm



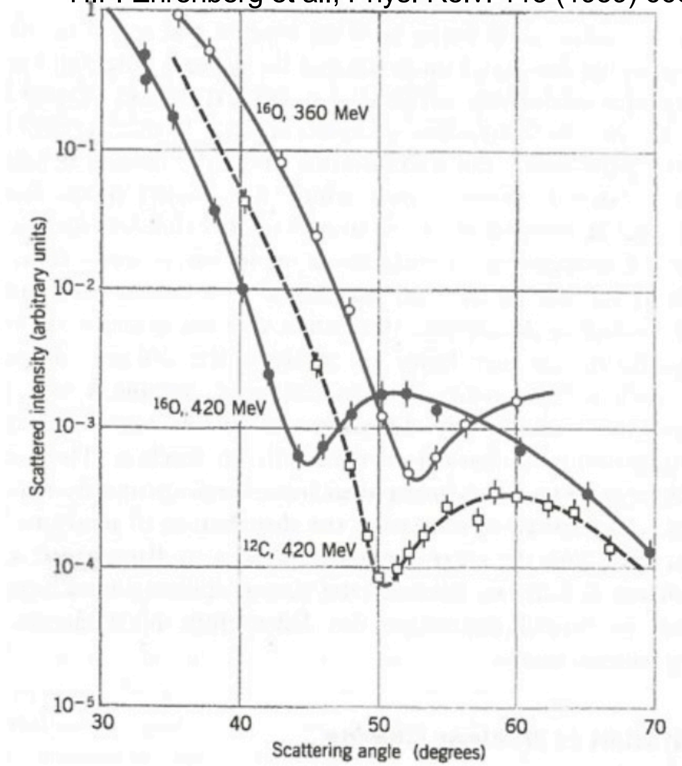
Scattering experiments with electrons



$sin(\theta_{min}) \sim \lambda/_D$



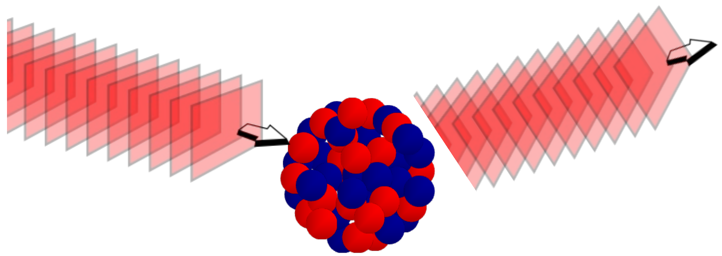
H.F. Ehrenberg et al., Phys. Re.v. 113 (1959) 666



Case of ^{16}O at 360 MeV:

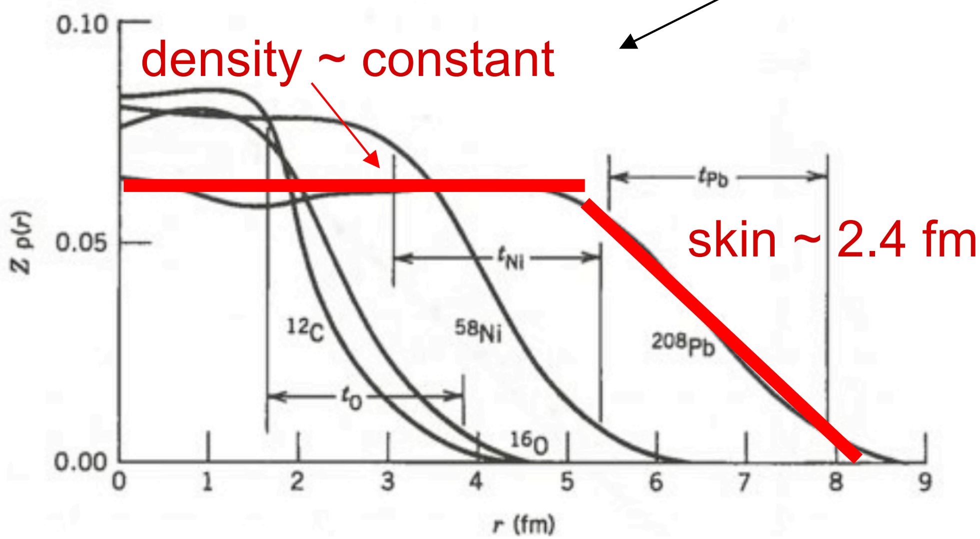
1st minimum at $\theta = 52^o \sim \sin^{-1}(\lambda/D)$
$E_e = 360$ MeV
$p = E/c$ ($E \gg mc^2$)
$\lambda = h/p$ ⇨ R=D/2 =2.6 fm

Charge distribution



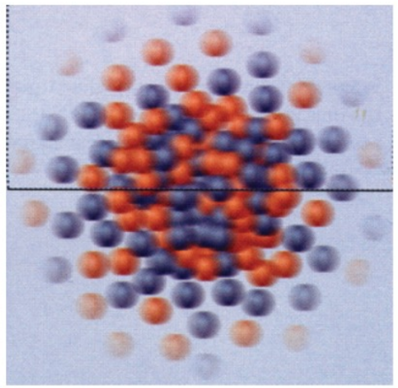
$$\frac{dN}{d\Omega}(\theta) = |F(\theta)|^2 \left[\frac{dN}{d\Omega}(\theta)\right]_{\text{Mott}}$$

Form factor



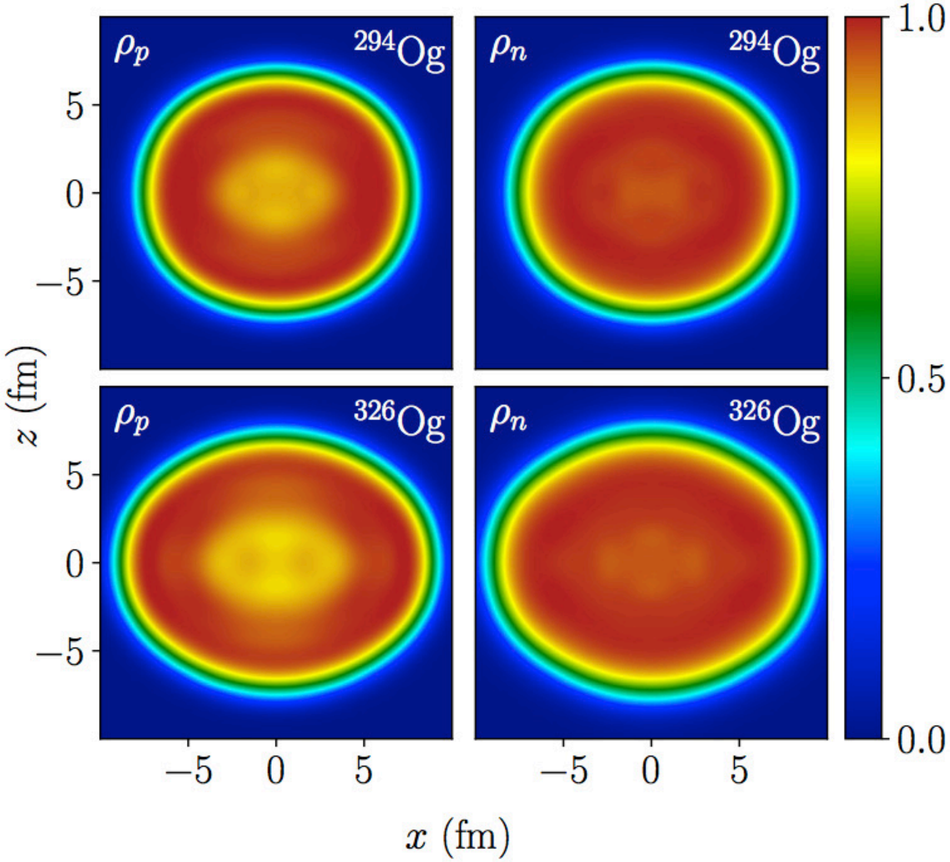
K. S. Krane, Introductory Nuclear Physics, John Wiley & Sons

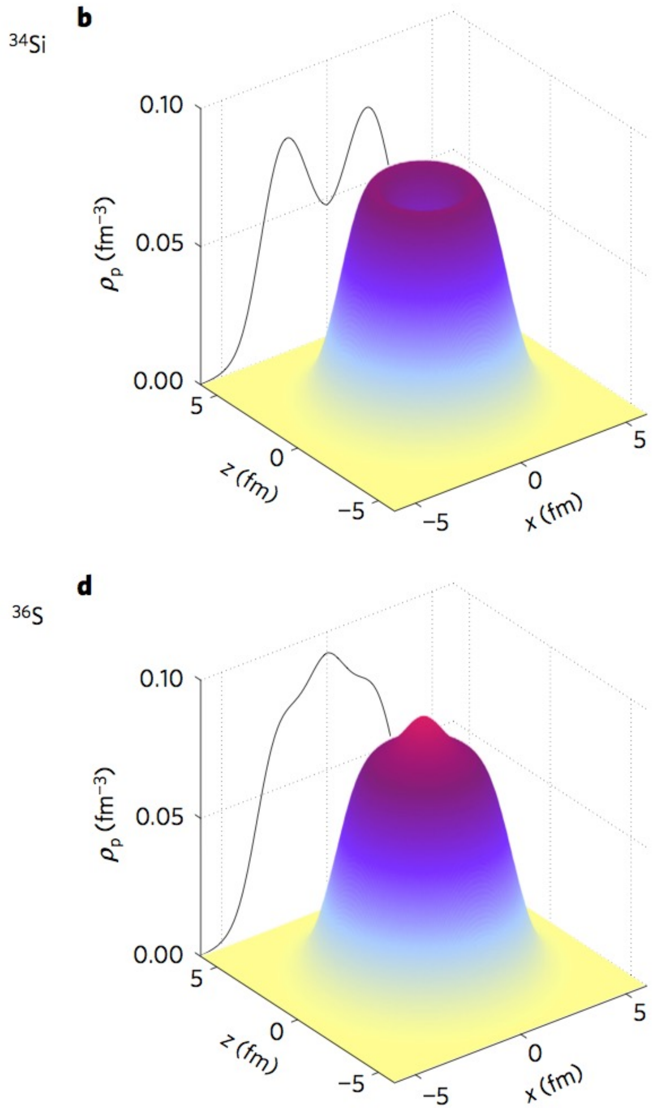
Nuclide	Fraction in "Skin"
^{12}C	0.90
^{24}Mg	0.79
^{56}Fe	0.65
^{107}Ag	0.55
^{139}Ba	0.51
^{208}Pb	0.46
^{238}U	0.44



Central depression and bubble nuclei ?

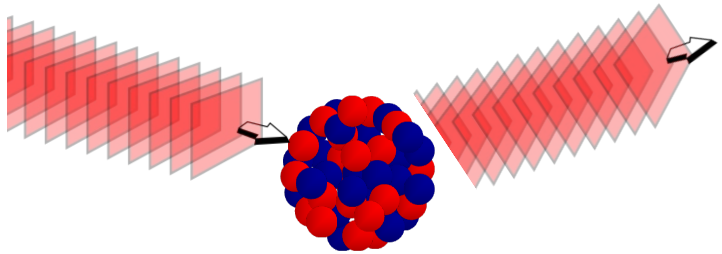
B. Schuetrumpf et al., Phys. Rev. C 96 (2017) 024306





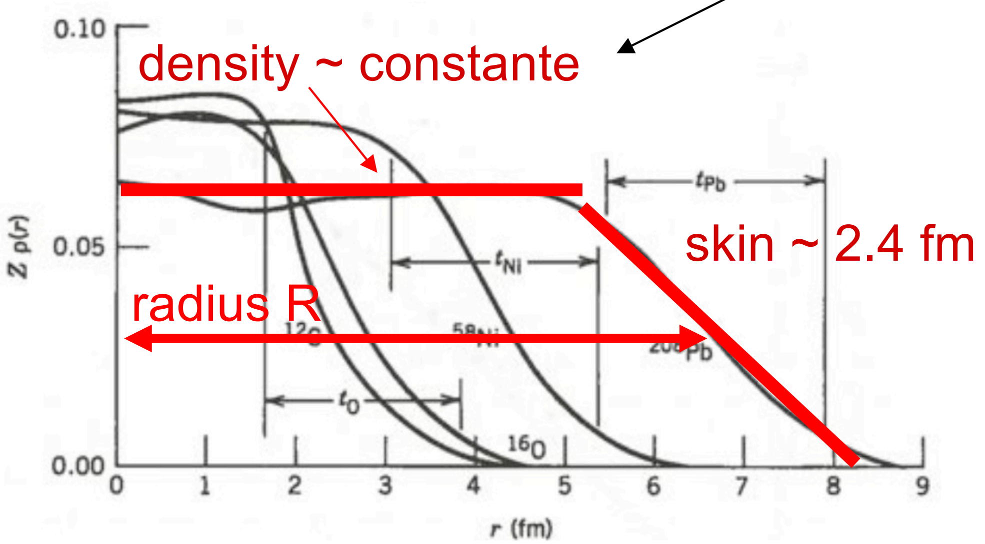
A. Mutschler et al., Nature Physics 13 (2017) 152

Charge distribution



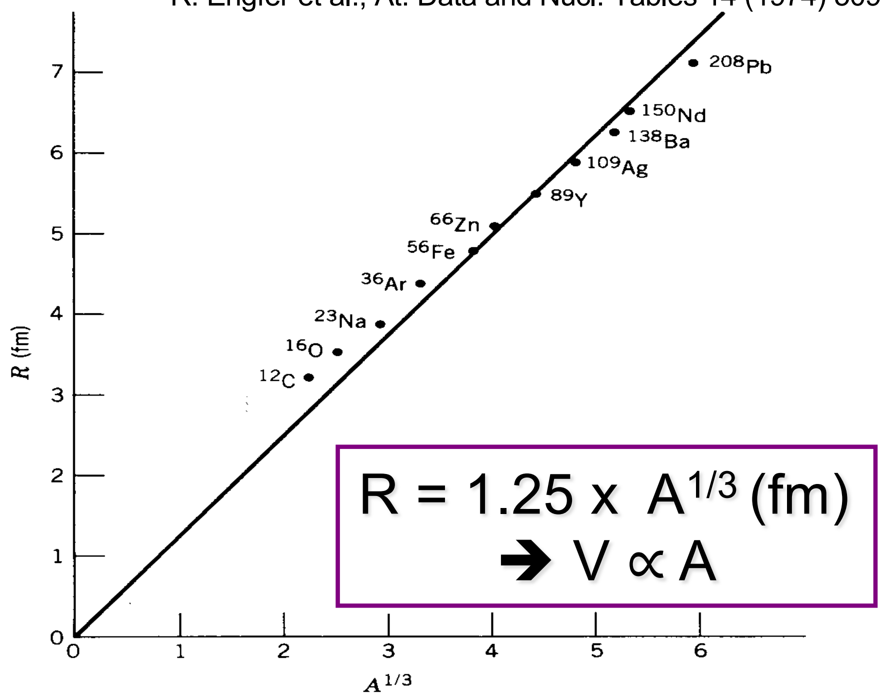
$$\frac{dN}{d\Omega}(\theta) = |F(\theta)|^2 \left[\frac{dN}{d\Omega}(\theta)\right]_{Mott}$$

facteur de forme



K. S. Krane, Introductory Nuclear Physics, John Wiley & Sons

R. Engfer et al., At. Data and Nucl. Tables 14 (1974) 509

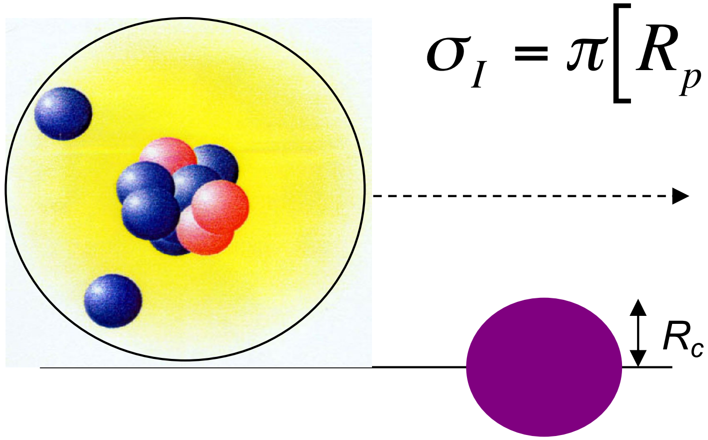


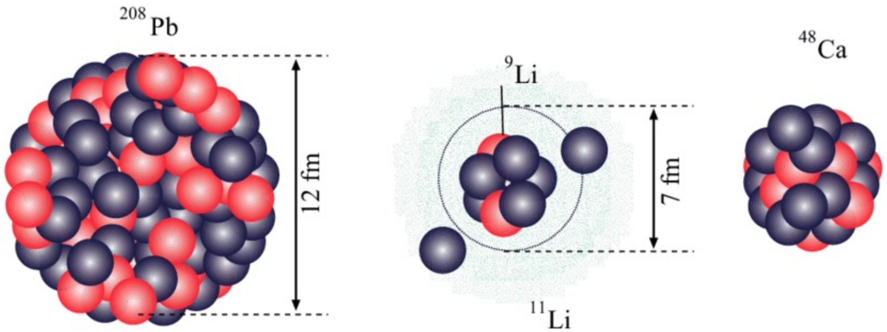
$R = 1.25 \times A^{1/3}$ (fm)

➔ $V \propto A$

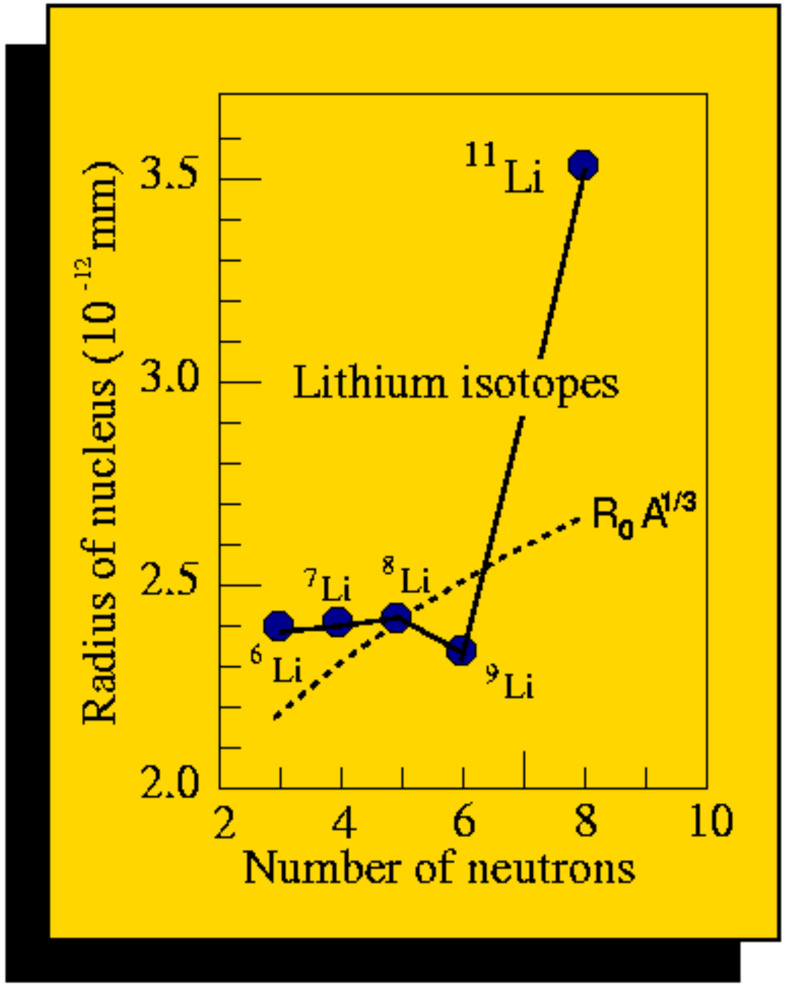
Some notable exceptions…

$$\sigma_I = \pi\left[R_p + R_c\right]^2$$



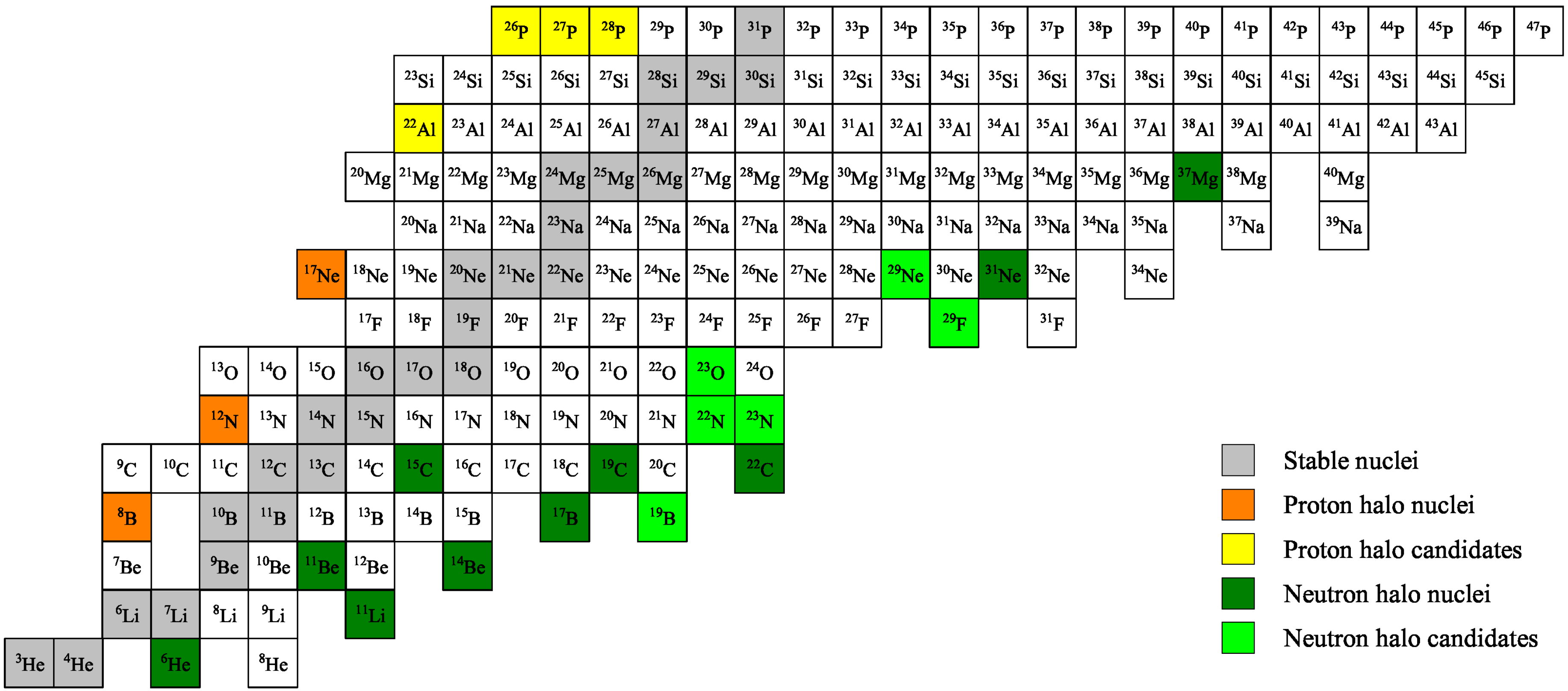


I. Tanihata et al.,. PRL 55 (1985) 2676



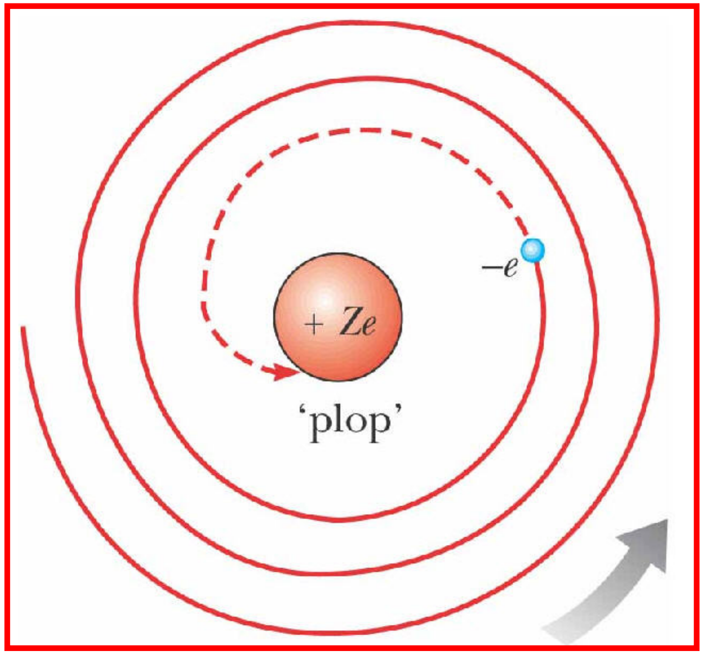
^{11}Li is a Borromean nucleus: if one of the three components is removed, the system is no longer bound (^{10}Li and 2n are not bound)

Halo nuclei



Y. Xiang et al., *Symmetry* **2023**, *15*(7), 1420;

Consequences of Rutherford's model



The atom is unstable

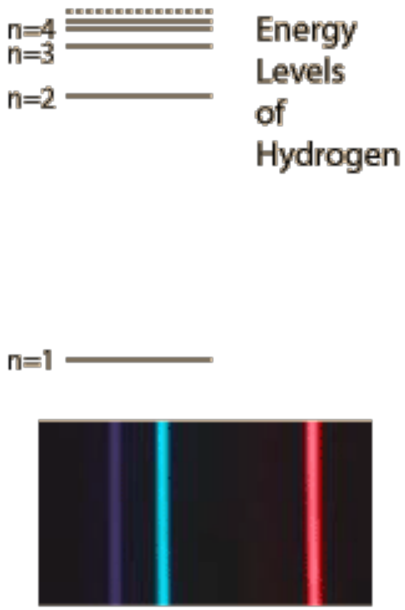
Bohr solves the problem with Planck’s quanta

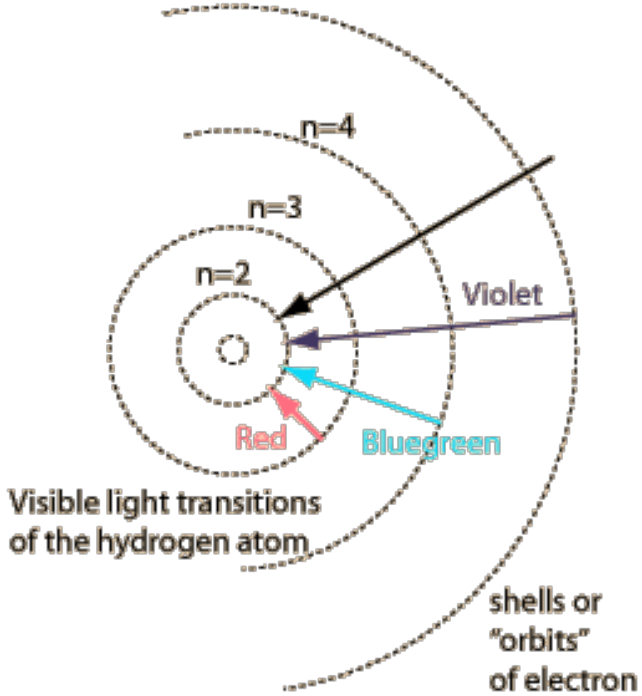
- angular momentum is quantized ⇔ only certain orbits of energy E_n (n=1,2,3,...) are allowed
- n is the principal quantum number
- electronic jumps from one orbit to another are accompanied by the emission (or absorption) of a photon of given wavelength

Niels Bohr

Philosophical Magazine **26**, 1-25 (1913)

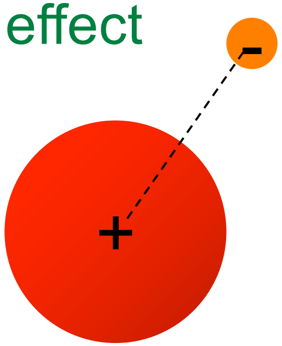
$E_n \propto - Q^2/n^2$





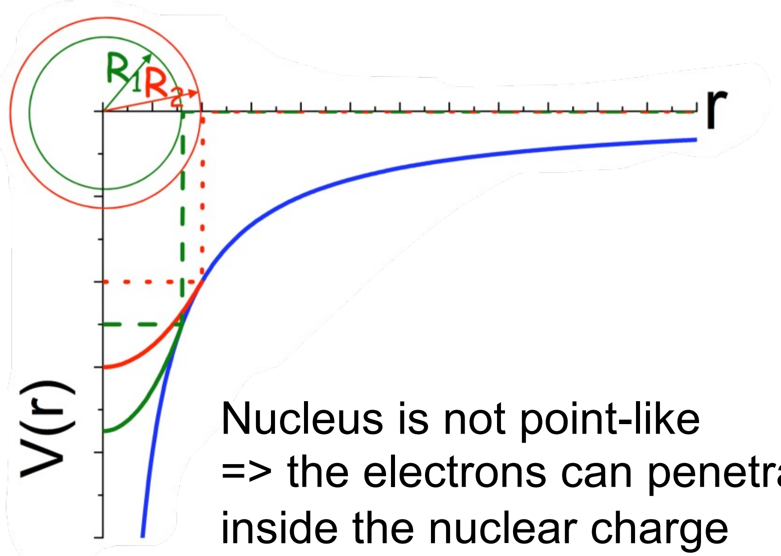
Isotopic shifts

Mass effect



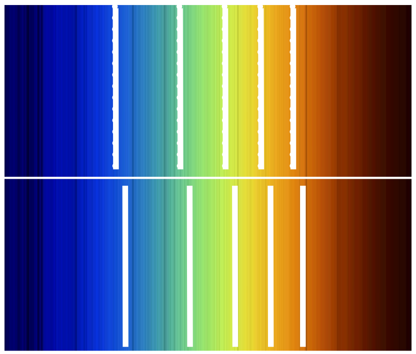
Nucleus is not infinitely massive
=> reduced electronic mass

Field effect



Nucleus is not point-like
=> the electrons can penetrate inside the nuclear charge distribution

Isotope A



Isotope A‘

Mass effect

$$\delta\nu^{A,A'} = M\frac{A'-A}{AA'} + F\delta < r^2 >^{A,A'}$$

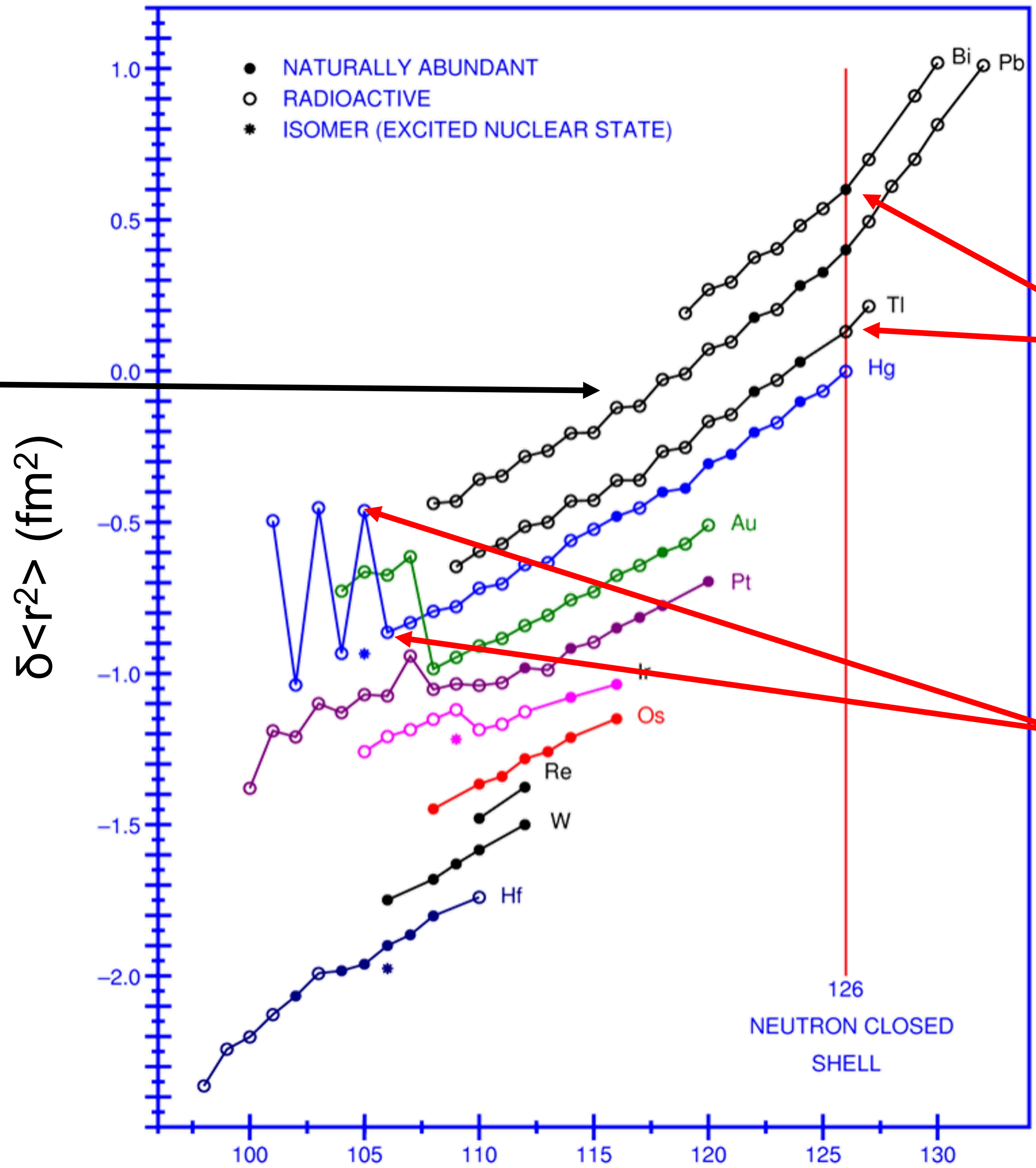
Field effect

Atomic factors

→ small energy shifts in atomic transitions when A changes: **isotopic shift**

Mean squared radius

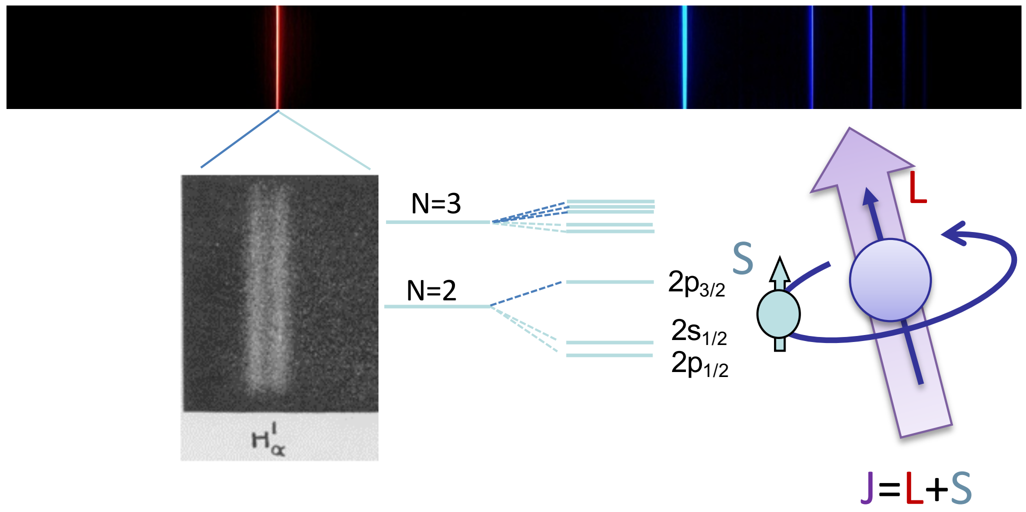
Odd-even staggering



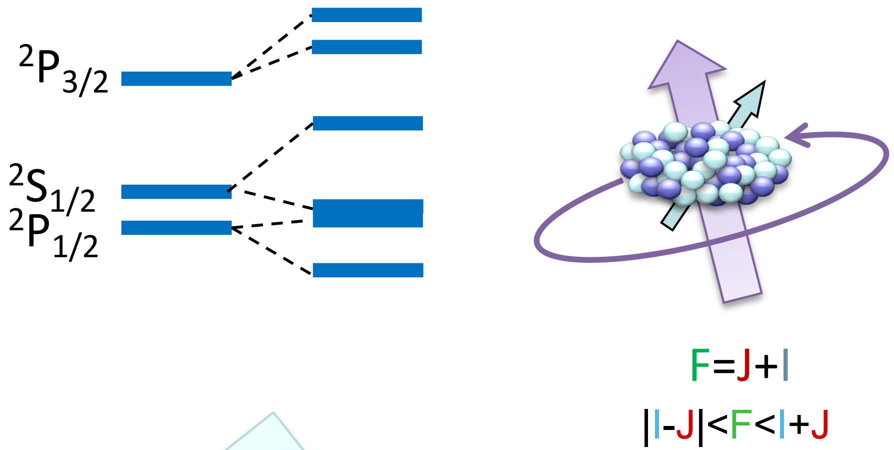
Kink

Change in shape

Fine and Hyperfine structure

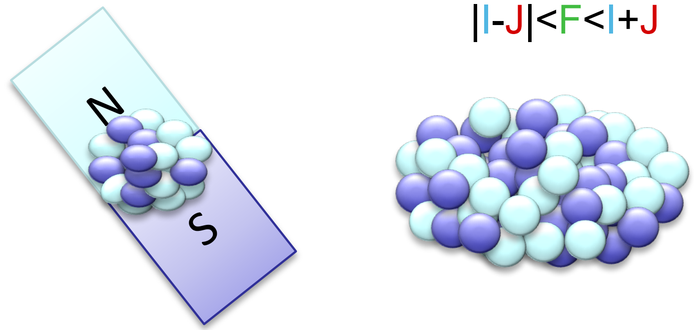


- A resolution ~5,000 times higher reveals a fine structure in the hydrogen spectrum due to spin-orbit interaction



- A 1,000-fold increase in resolution reveals an even finer structure due to the coupling of the nucleus with the electron's orbit

→ The hyperfine structure of atomic spectra provides information about the spin and the magnetic and electric moments of the nucleus



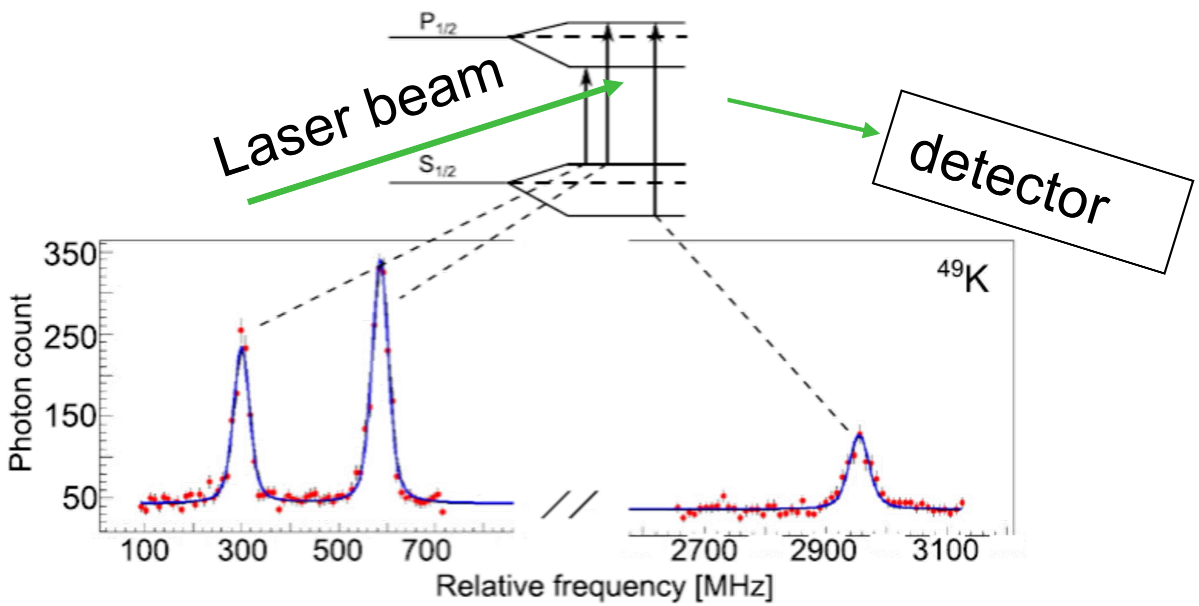
The spin of the nucleus

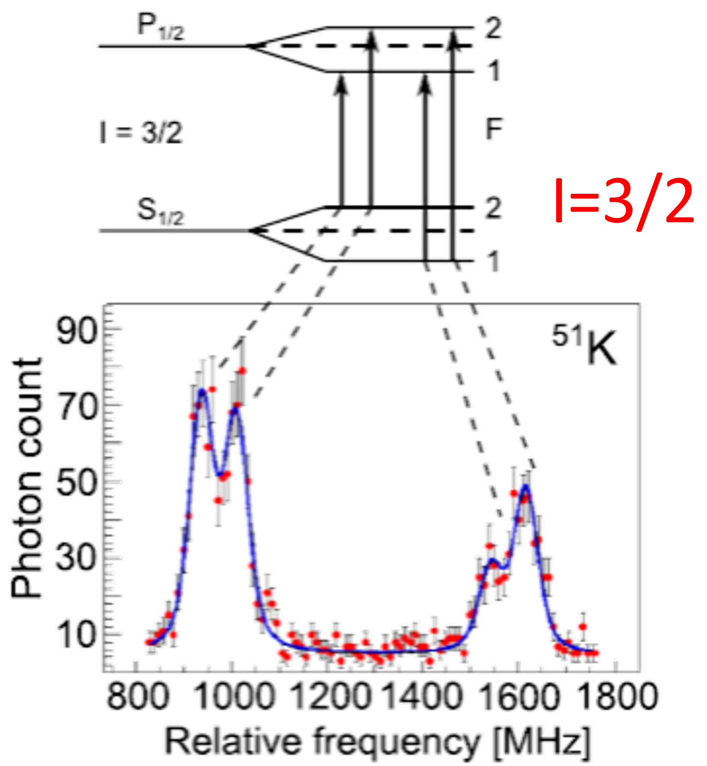
PRL **110,** 172503 (2013) PHYSICAL REVIEW LETTERS week ending 26 APRIL 2013

J. Papuga et al.,

Spins and Magnetic Moments of ^{49}K and ^{51}K: Establishing the $1/2^{+}$ and $3/2^{+}$ Level Ordering Beyond $N = 28$

I=1/2: only 3 transitions are authorized because the $F_i=0 \rightarrow F_j=0$ is forbidden





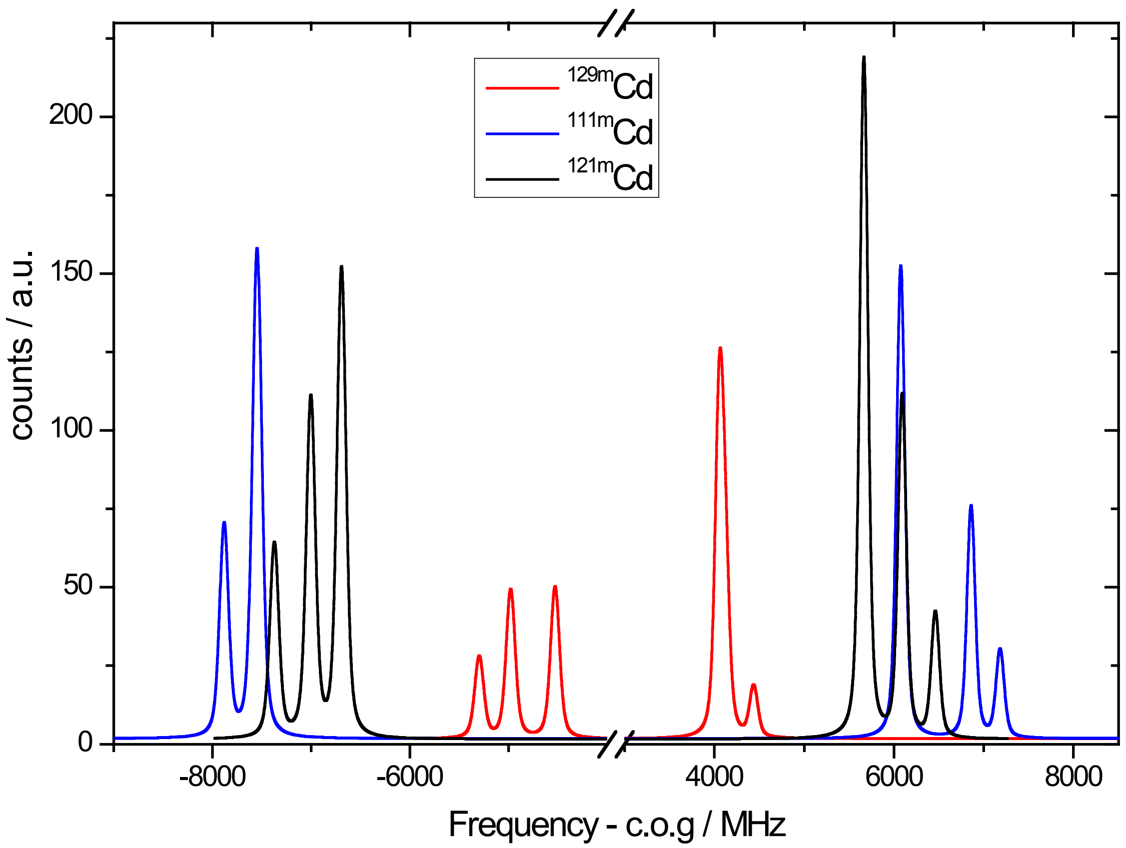
Deformation of the nucleus

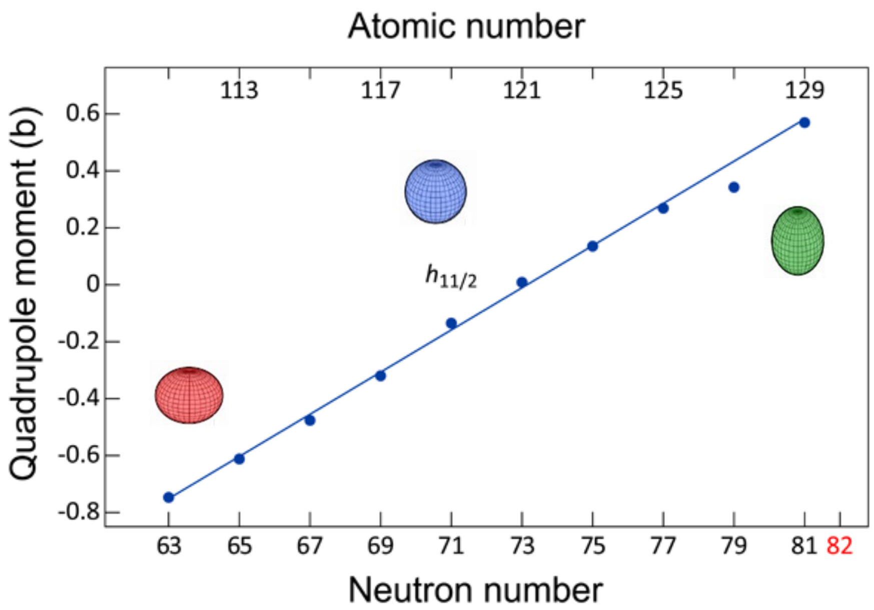
Selected for a Viewpoint in *Physics*
PRL **110**, 192501 (2013) PHYSICAL REVIEW LETTERS week ending 10 MAY 2013

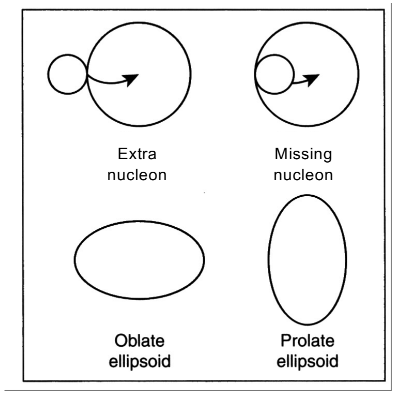
D. T. Yordanov et al.,

Spins, Electromagnetic Moments, and Isomers of $^{107-129}$Cd

Isomeric 11/2$^-$ state



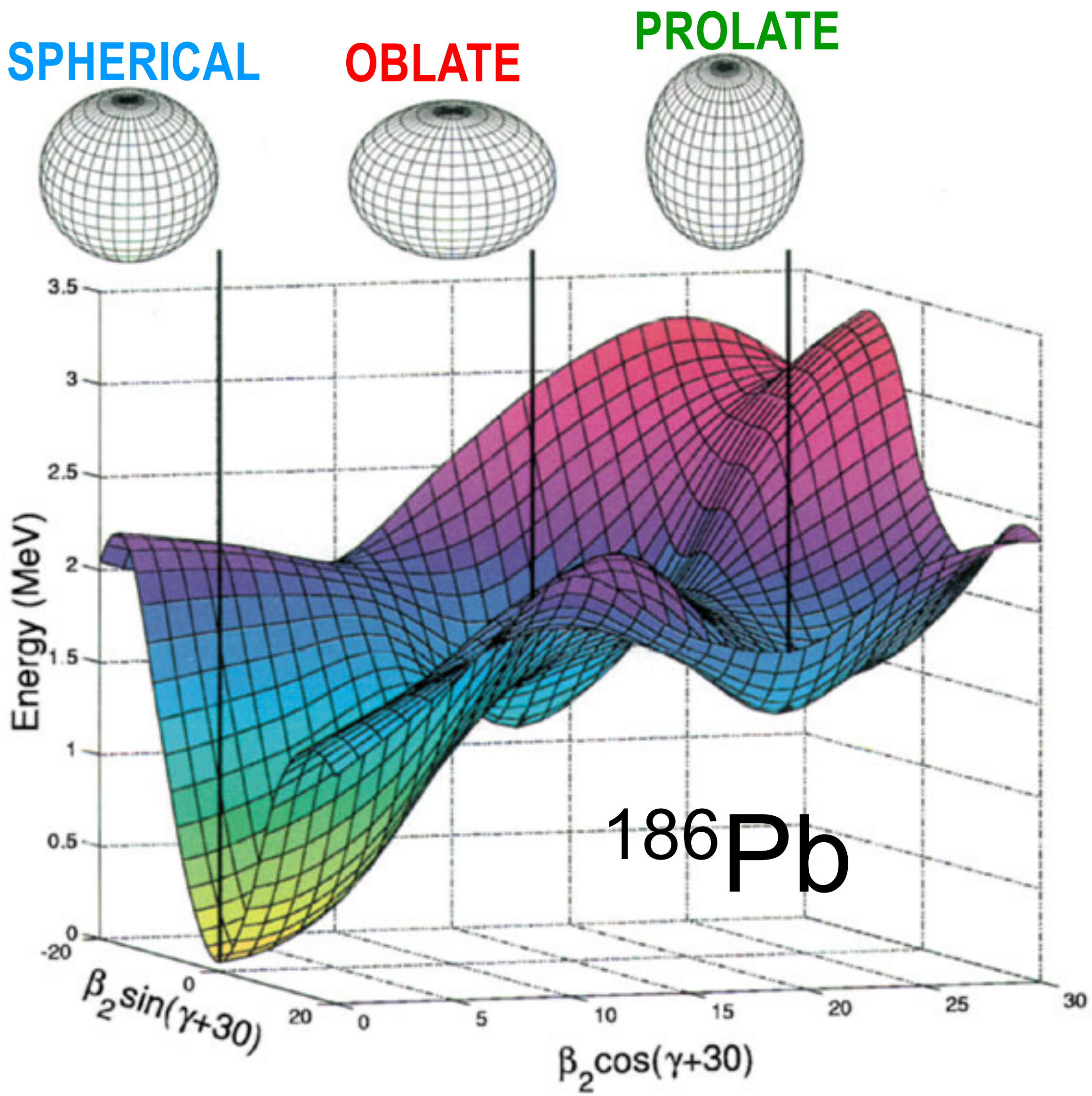


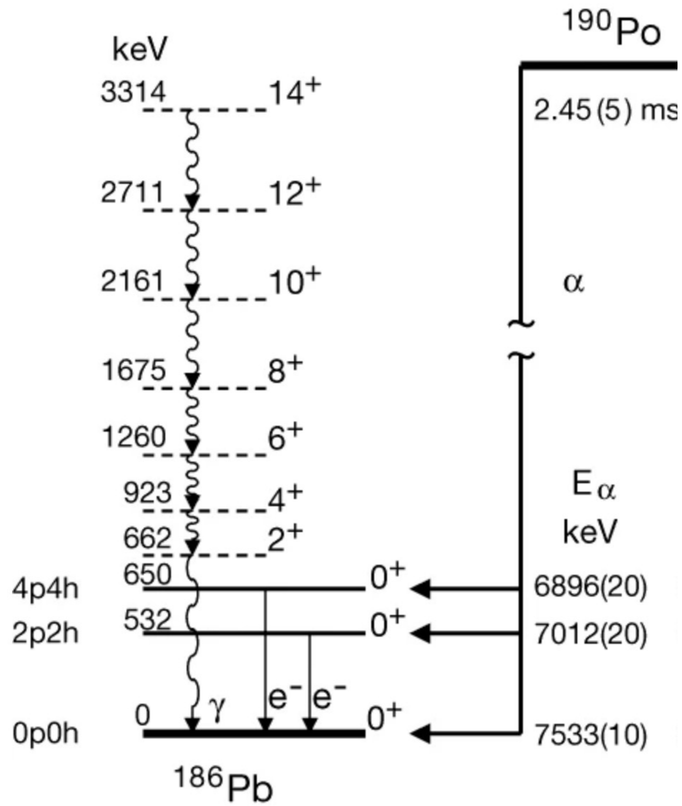


Behaviour expected in the extreme shell model: linear variation of Q due to filling of $h_{11/2}$ shell

Coexisting shapes

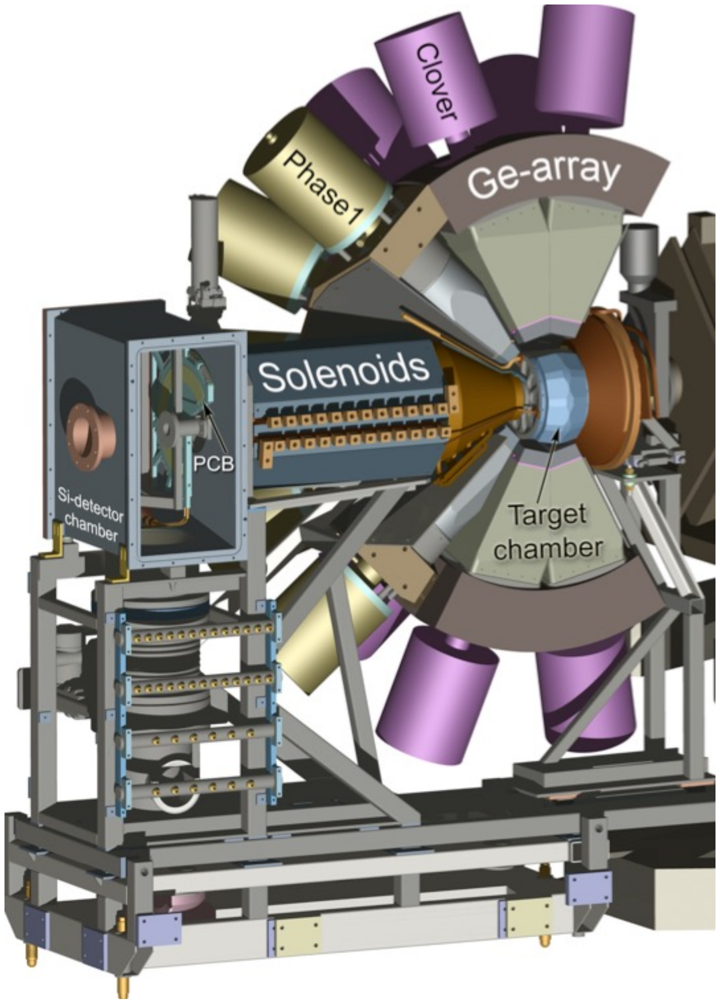
Three 0^+ states observed at low energy in the α decay of ^{190}Po

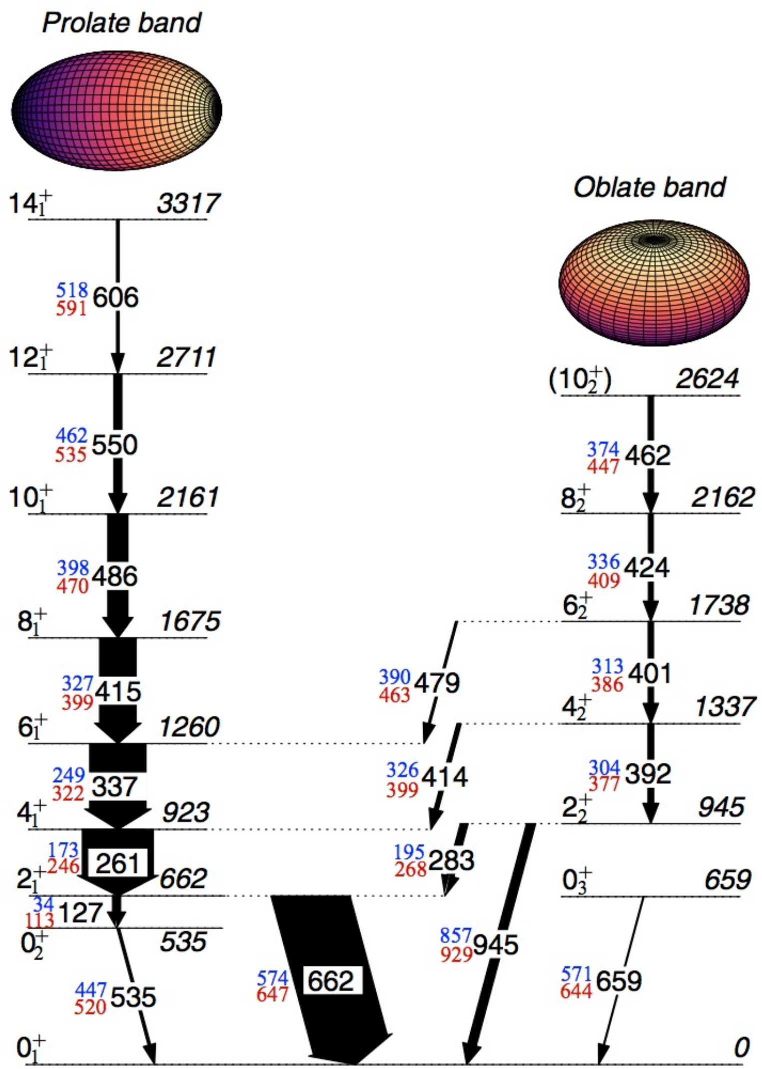




A. Andreyev et al. Nature 405 (2000) 430

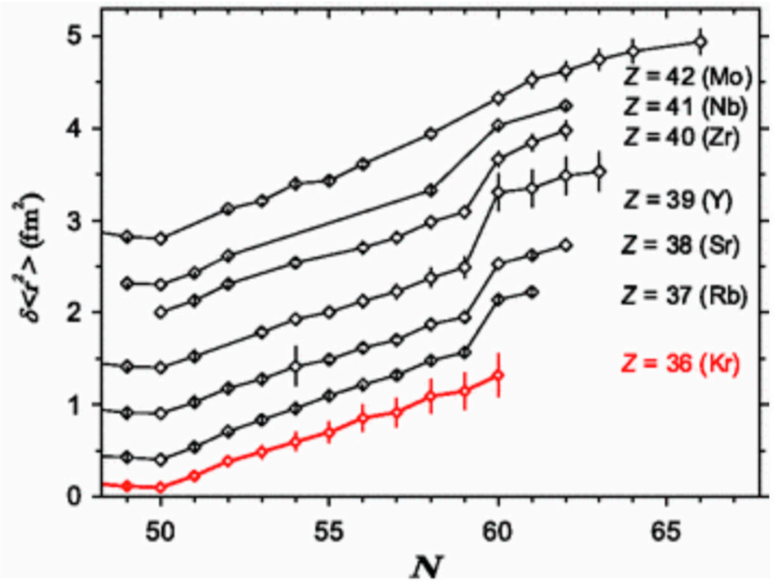
Reassigning shapes in ^{186}Pb





J. Ojala et al., Communication Physics 5, 213 (2022)

Changing shapes



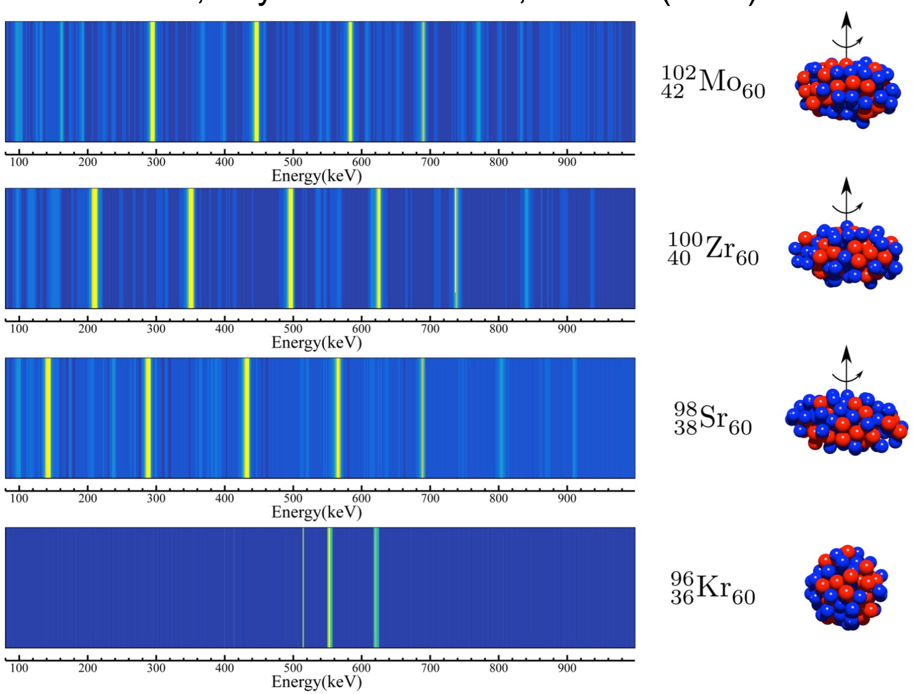
S. Naimi *et al.*, Phys. Rev. L 105, 032502 (2010)

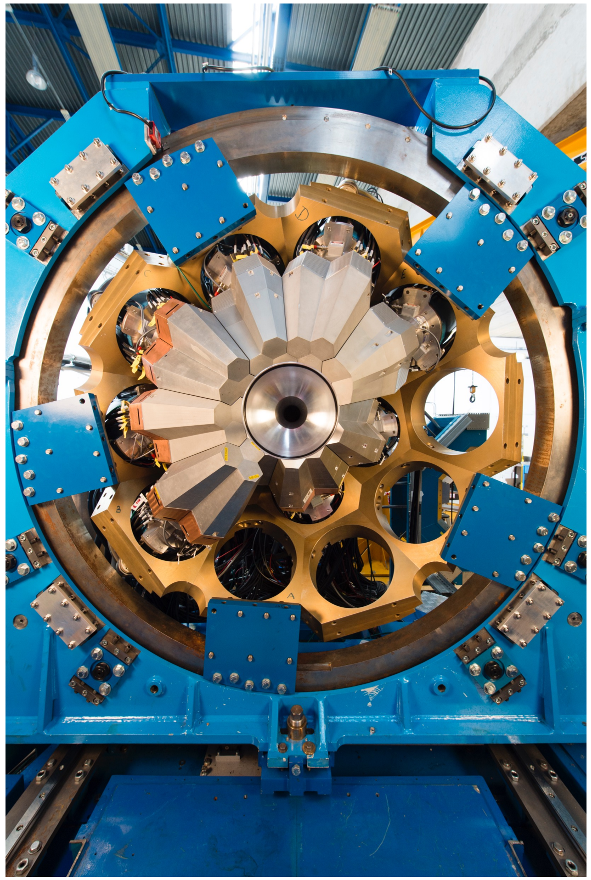
Mass and mean squared radius measurements:
Shape change at N=60 from Mo→Rb

What about Kr ?

γ-ray spectroscopy of ^{96}Kr with AGATA

J. Dudouet et al., Phys. Rev. Lett. 118, 162501 (2017)





Dalton’s atom undermined

Thorium

Mesothorium 1

Mesothorium 2

Radiothorium

Thorium X

Emanation

Thorium A

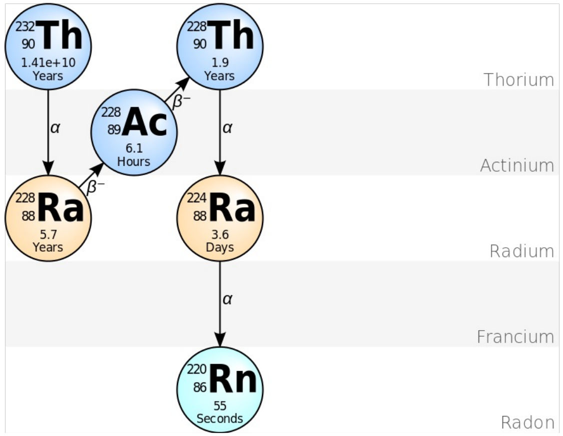
Thorium B

Thorium C1

Thorium C2

Thorium D

Thorium E



‘The Chemistry of Radio-Elements’, F. Soddy (1911)

More than 40 radioelements discovered in 15 years

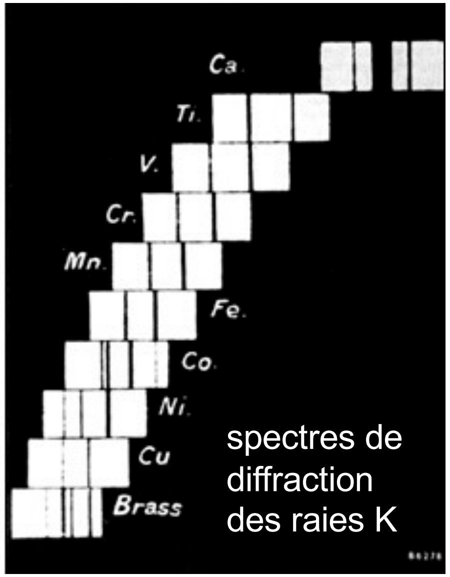
Problem: only 7 cases unoccupied slots in the periodic table

Inseparability of certain radioelements

Frederick Soddy

1913: Isotope concept: radioactive elements can have different masses but the same chemical properties

The periodic table finds its thread

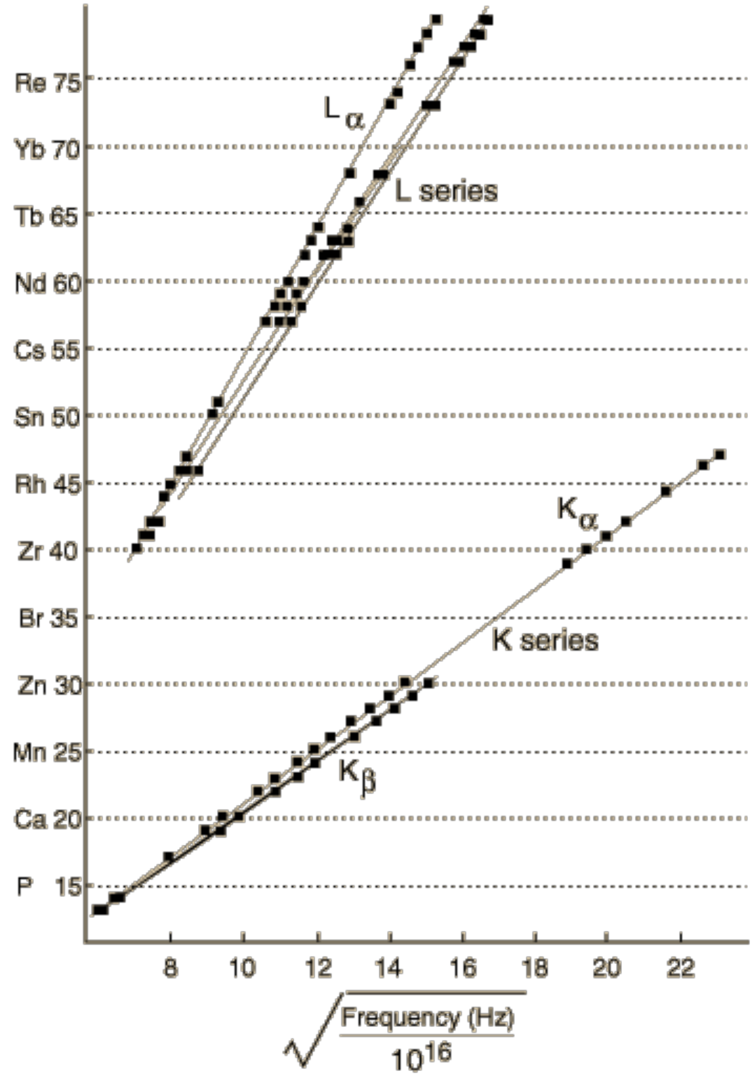


1914 Henry Moseley

Measurement of the high frequency X-ray spectra of many elements

⇨ atomic number Z = charge of the nucleus

⇨ regularities of the periodic table explained in terms of filling of electronic shells



Adapted from Moseley's original data (H. G. J. Moseley, Philos. Mag. (6) 27:703, 1914)

The alchemists of the 20th century

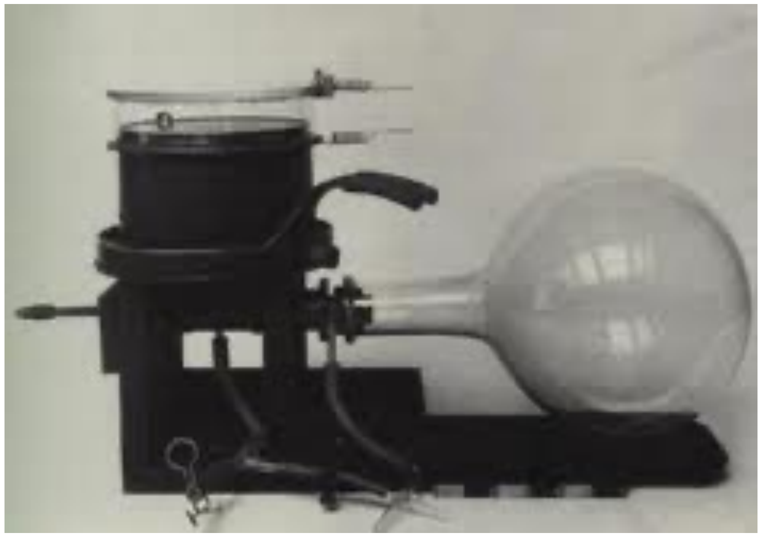
1919 E. Rutherford

1st artificial transmutation

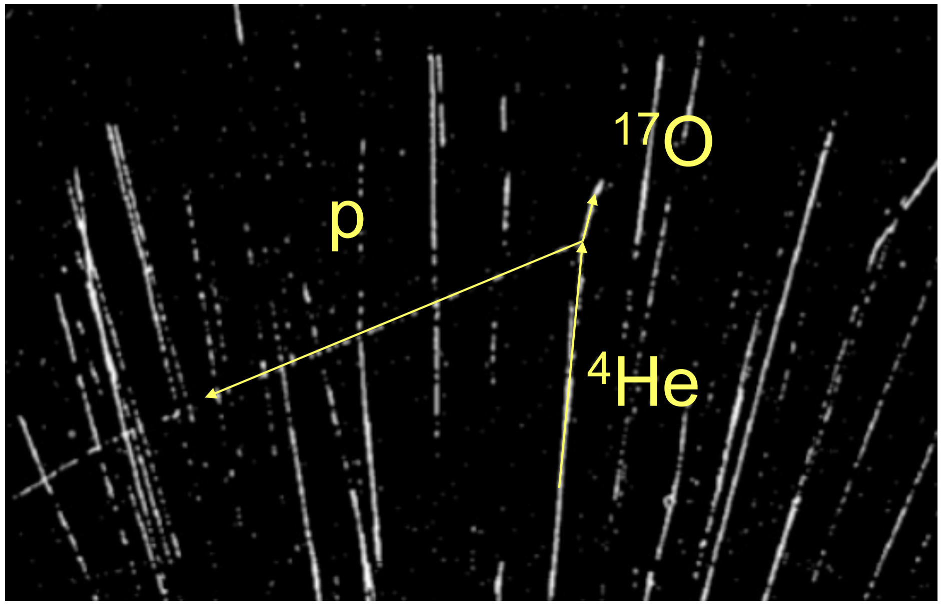
α + Azote $\rightarrow$ Hydrogène

Rutherford calls H^+ proton

1924 P. Blackett visualizes the transmutation $\alpha + {}^{14}N \rightarrow {}^{17}F^* \rightarrow {}^{17}O + p$

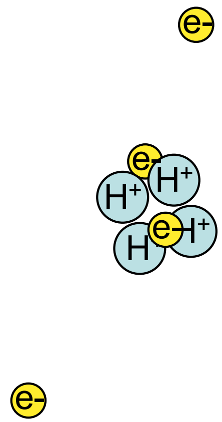


Cloud chamber (C.T.R. Wilson, 1912)



Structure of the nucleus (1920)

The nucleus is thought to be composed of A protons and (A-Z) electrons



E. Rutherford suggests the existence of an e^--p pair, which would have all the characteristics of a neutral particle

Bakerian Lecture, Proc. Roy. Soc. A, ***97****, 374 (1920)*

This information goes unnoticed around the world, except at the Cavendish Laboratory in Cambridge, where Rutherford is appointed director...