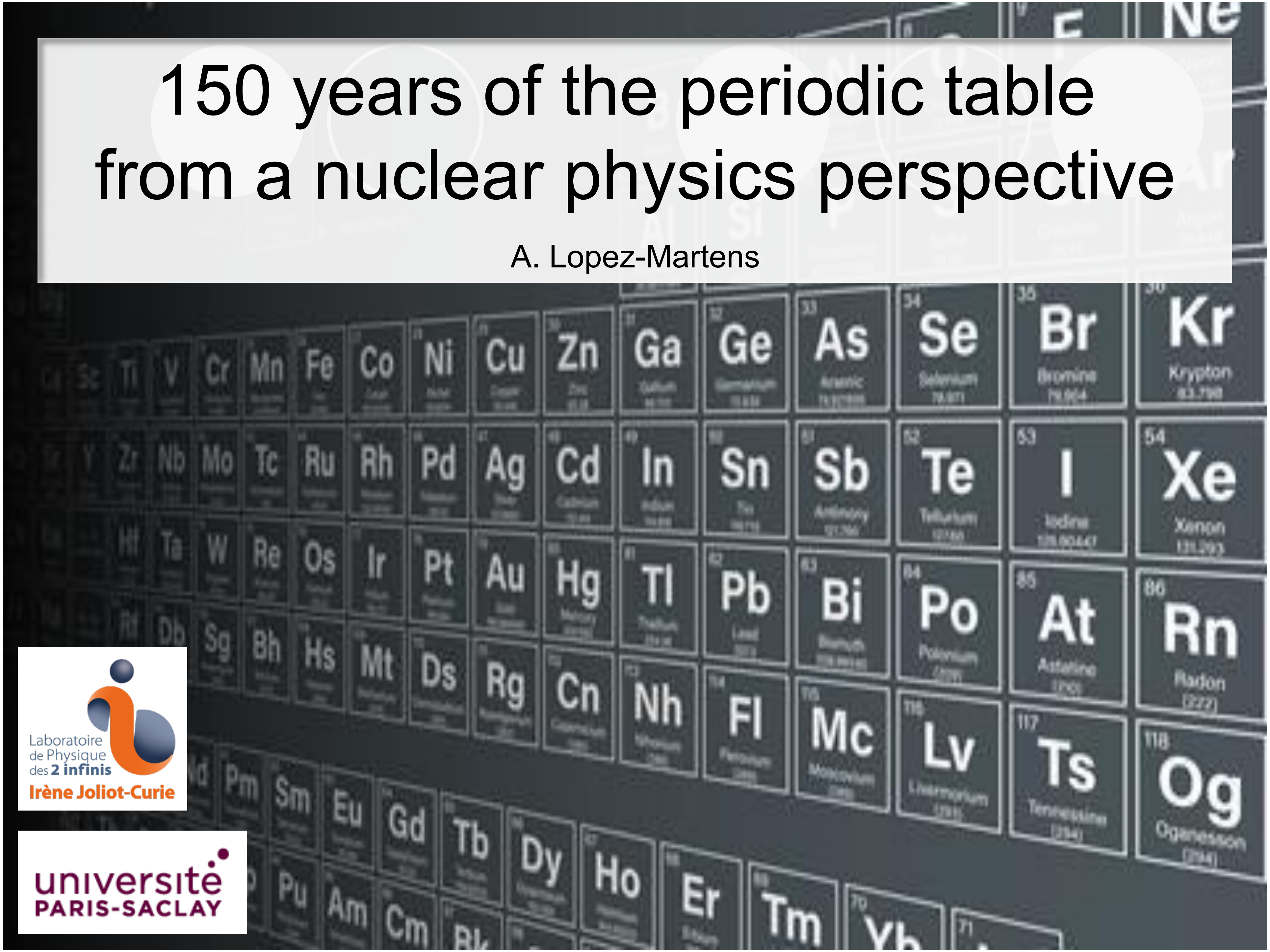
150 years of the periodic table from a nuclear physics perspective

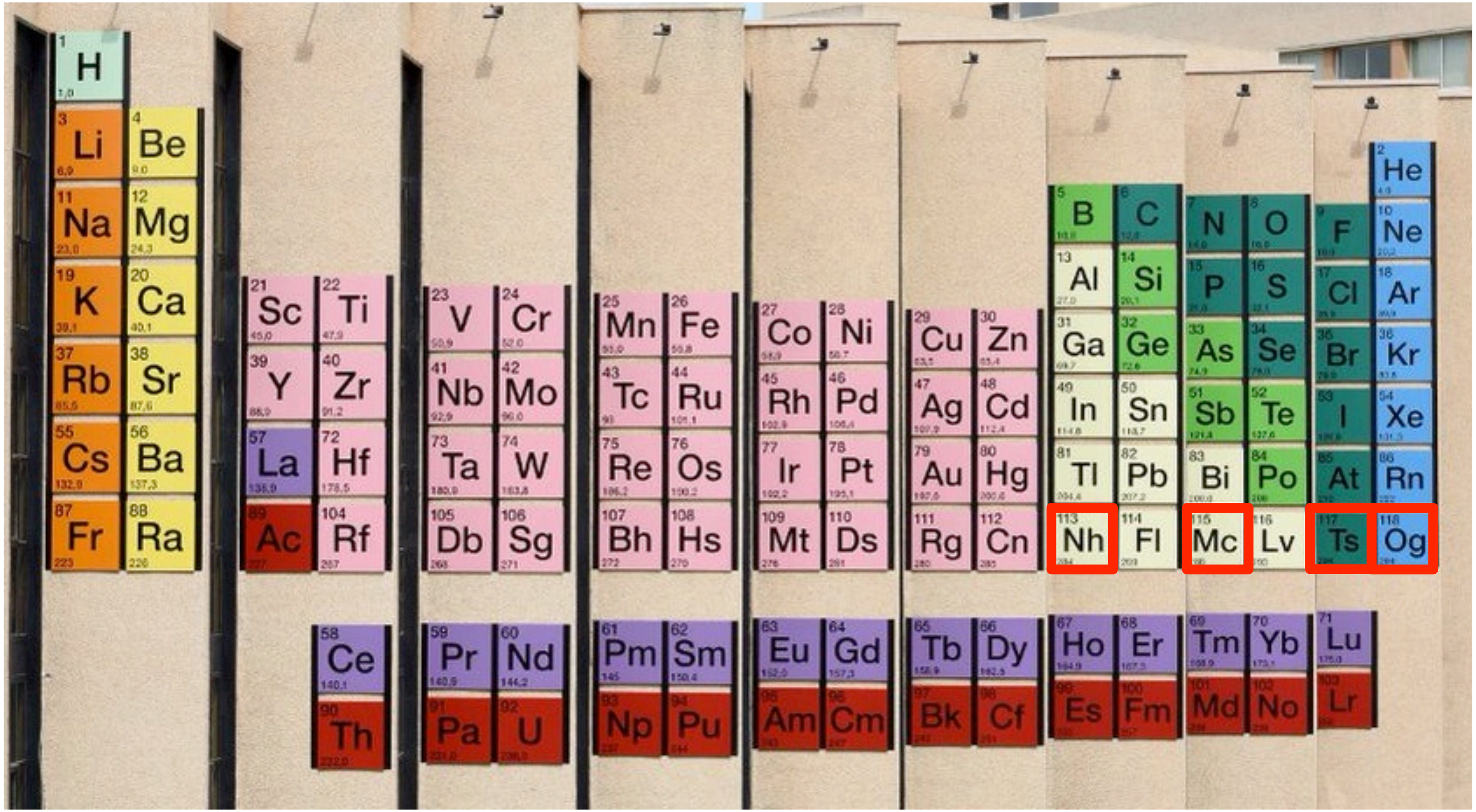
A. Lopez-Martens



Laboratoire de Physique des 2 infinis Irène Joliot-Curie
université PARIS-SACLAY

2019 IYPT

150 years of the Periodic Table

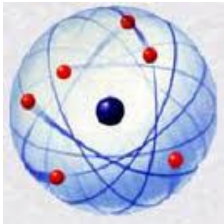


Chemistry Department, University of Murcia

100 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



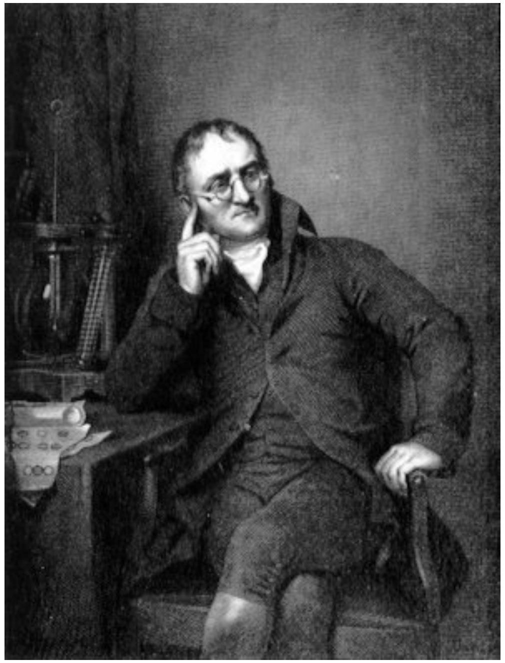
The Nobel Prize in Chemistry 1911 was awarded to Marie Curie *"in recognition of her services to the advancement of chemistry by the discovery of the elements radium and polonium, by the isolation of radium and the study of the nature and compounds of this remarkable element"*.

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."

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**

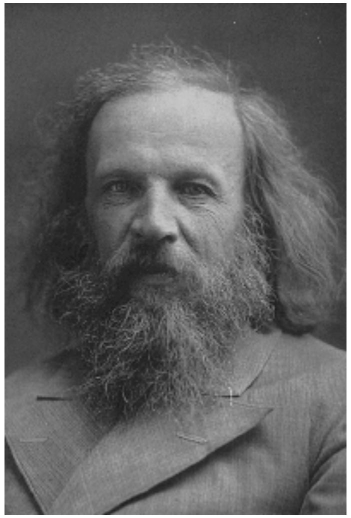
-atoms of the same element are identical

Dalton's billiard ball, 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.

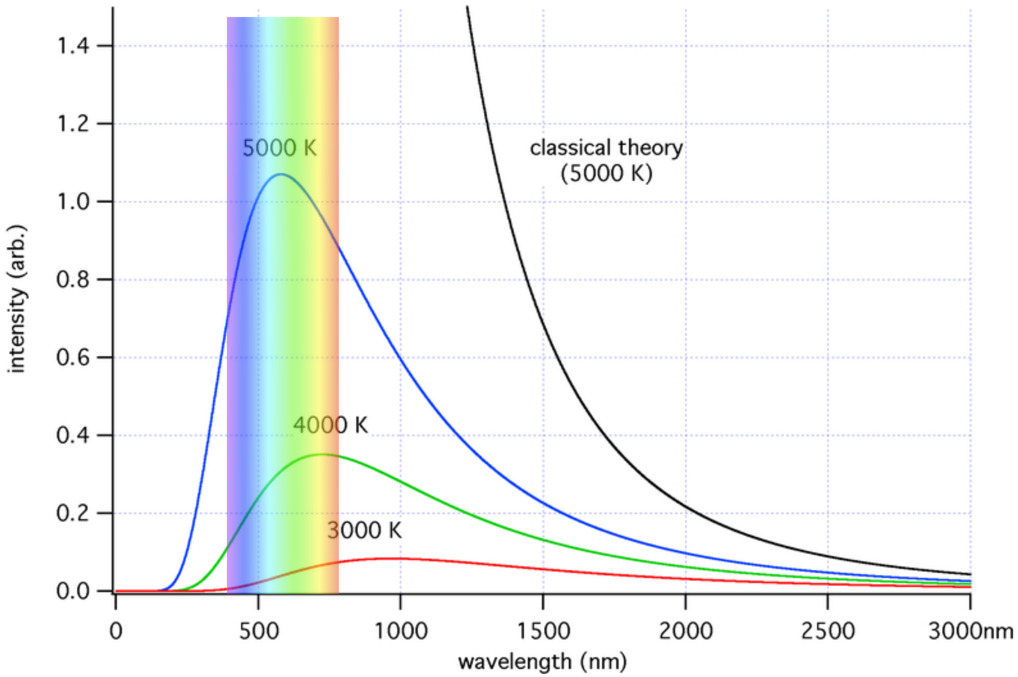
			Ti=50	Zr=90	?=180.
			V=51	Nb=94	Ta=182.
			Cr=52	Mo=96	W=186.
			Mn=55	Rh=104,4	Pt=197,4.
			Fe=56	Rn=104,4	Ir=198.
			Ni=Co=59	Pl=106,6	Os=199.
H=1			Cu=63,4	Ag=108	Hg=200.
	Be=9,4	Mg=24	Zn=65,2	Cd=112	
	B=11	Al=27,4	Ga ?=68	Ur=116	Au=197?
	C=12	Si=28	Ge ?=70	Sn=118	
	N=14	P=31	As=75	Sb=122	Bi=210?
	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?		

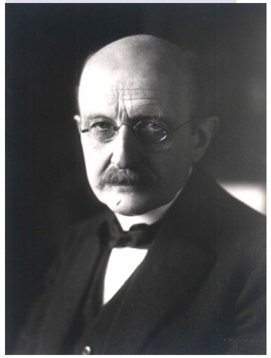
Д. Менделѣевъ (1869)

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.....

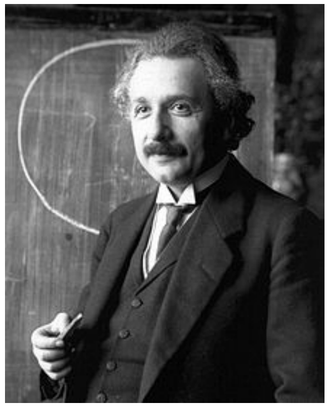
ultraviolet catastrophe: spectral distribution of thermal radiation from matter





Max Planck

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

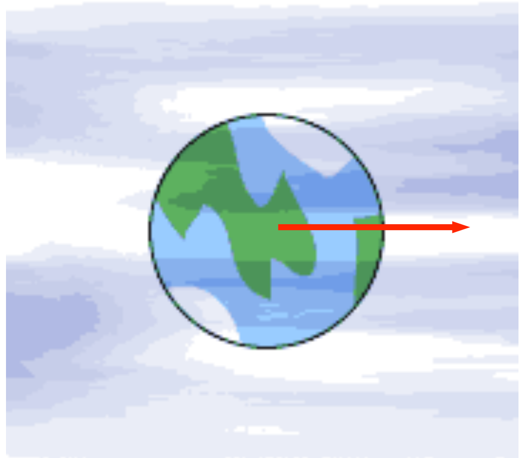


Albert Eisntein

According to A. Einstein, Planck's quantization arises from the granular nature of light: light is made up of **photons**

Aether

Light must travel in a medium: aether
The speed of light in Maxwell's equations is obtained with respect to the aether



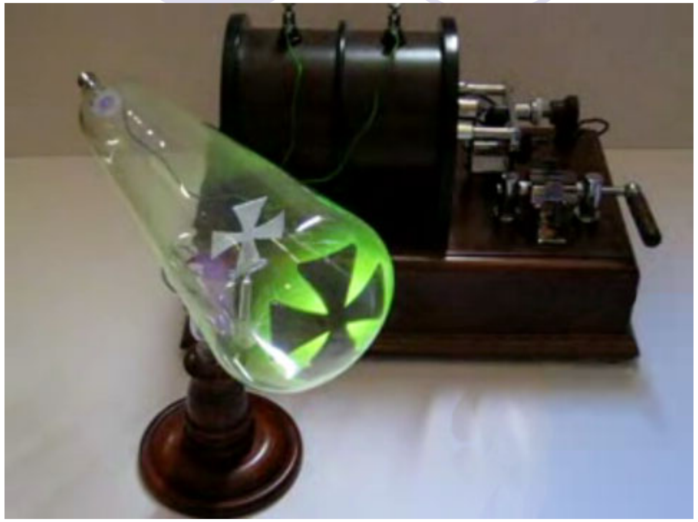
⇨ any object moving in the aether should measure a different speed of light

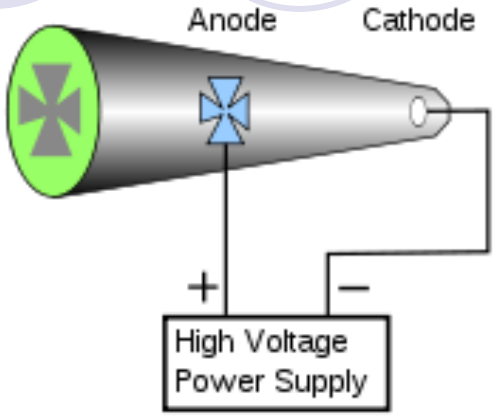
1887: failure of the Michelson-Morley interferometry experiment

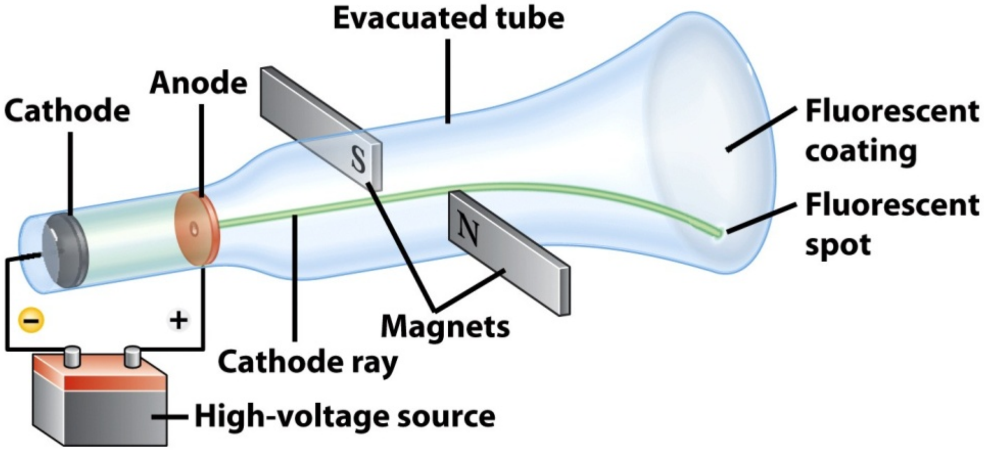
A. Einstein reconciles Newton's mechanics and Maxwell's electromagnetism with the theory of special relativity: "On the Electrodynamics of Moving Bodies"

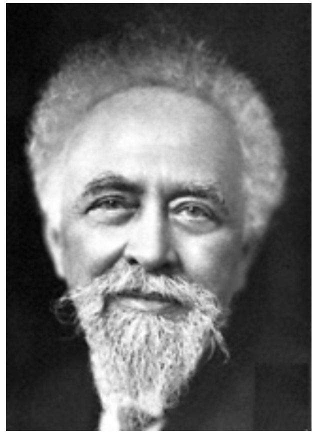
$$E = mc^2$$

The cathode tube leads the revolution



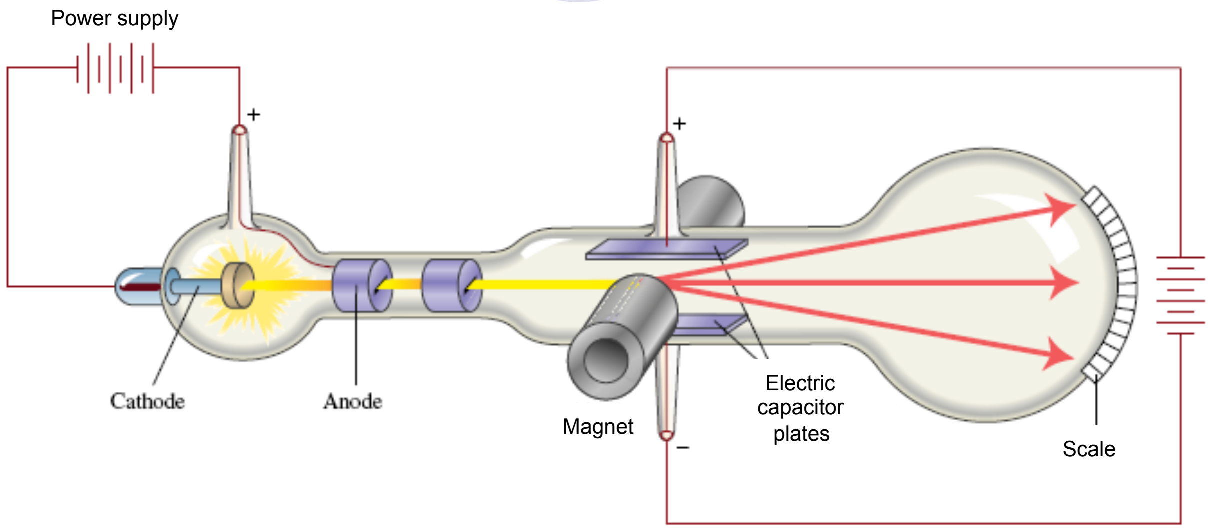


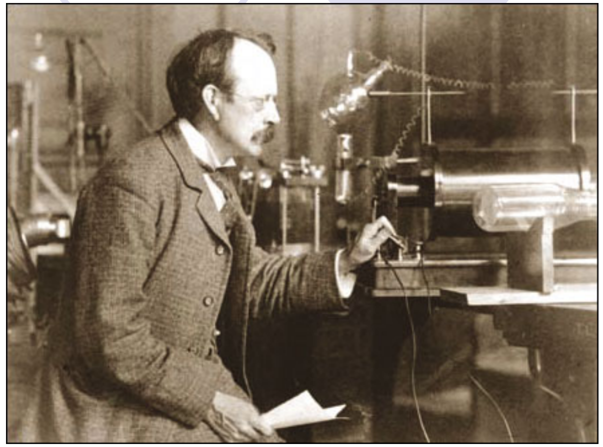




1895: Jean Perrin demonstrates that cathode rays are negatively charged particles

Atoms are no longer indivisible !



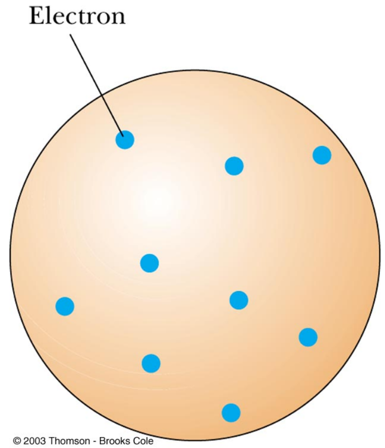


John Joseph Thomson

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

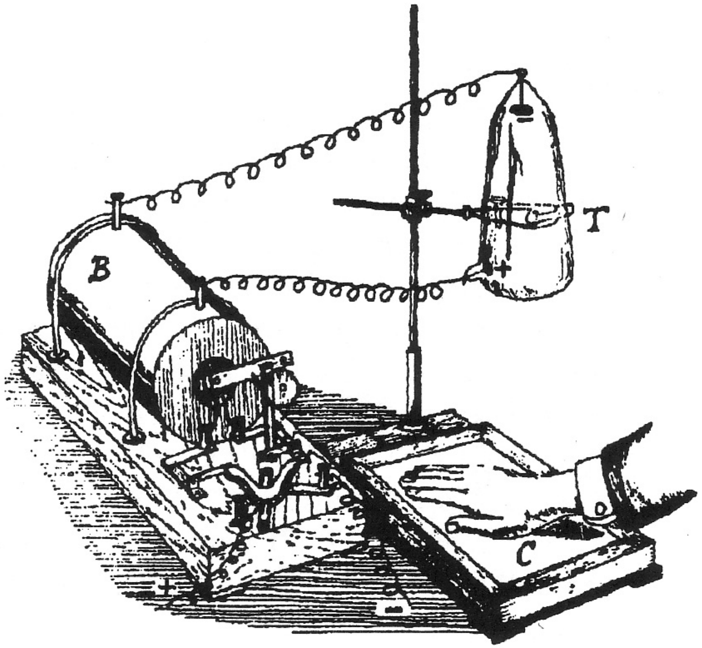
‘plum pudding’ model



From cathode rays to X rays

1895 W. Röntgen discovery of X rays

Wilhelm Röntgen

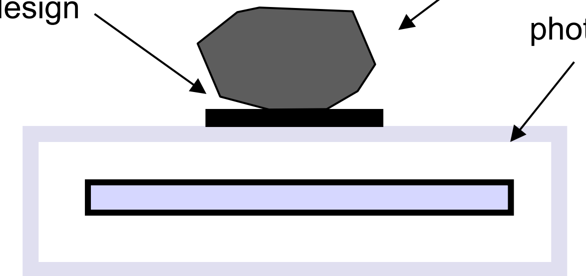


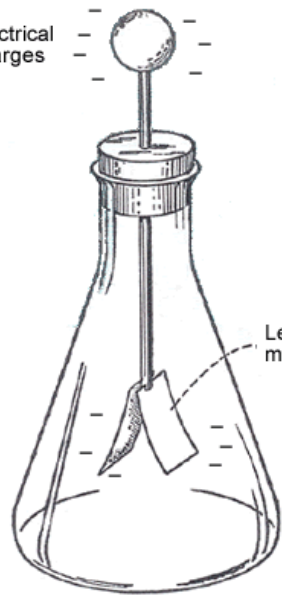
W. Röntgen receives the 1st Nobel Prize in Physics in 1901

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

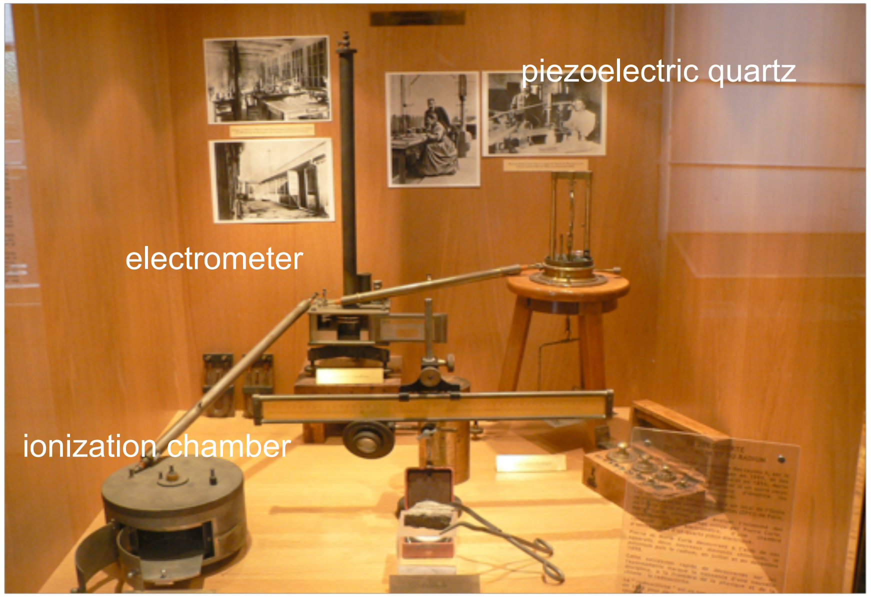
From Uranium rays to radioactivity

1898 Marie & Pierre Curie

extraction of polonium (Bi fraction) and radium (Ba fraction)

Marie Curie

Pierre Curie



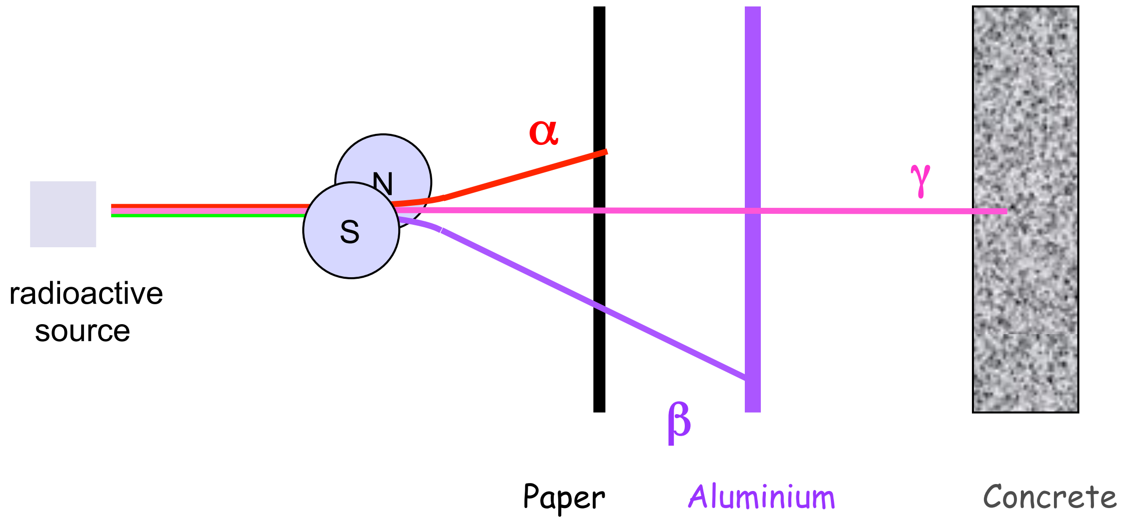
Laboratory at the Ecole de Physique et Chimie industrielle de Paris

M. Curie calls the radiation:
'radioactivity'

Radioactivity is manifold

1898 E. Rutherfod alpha, beta radiation

1900 P. Villard gamma radiation



Ernest Rutherford

Paul Villard

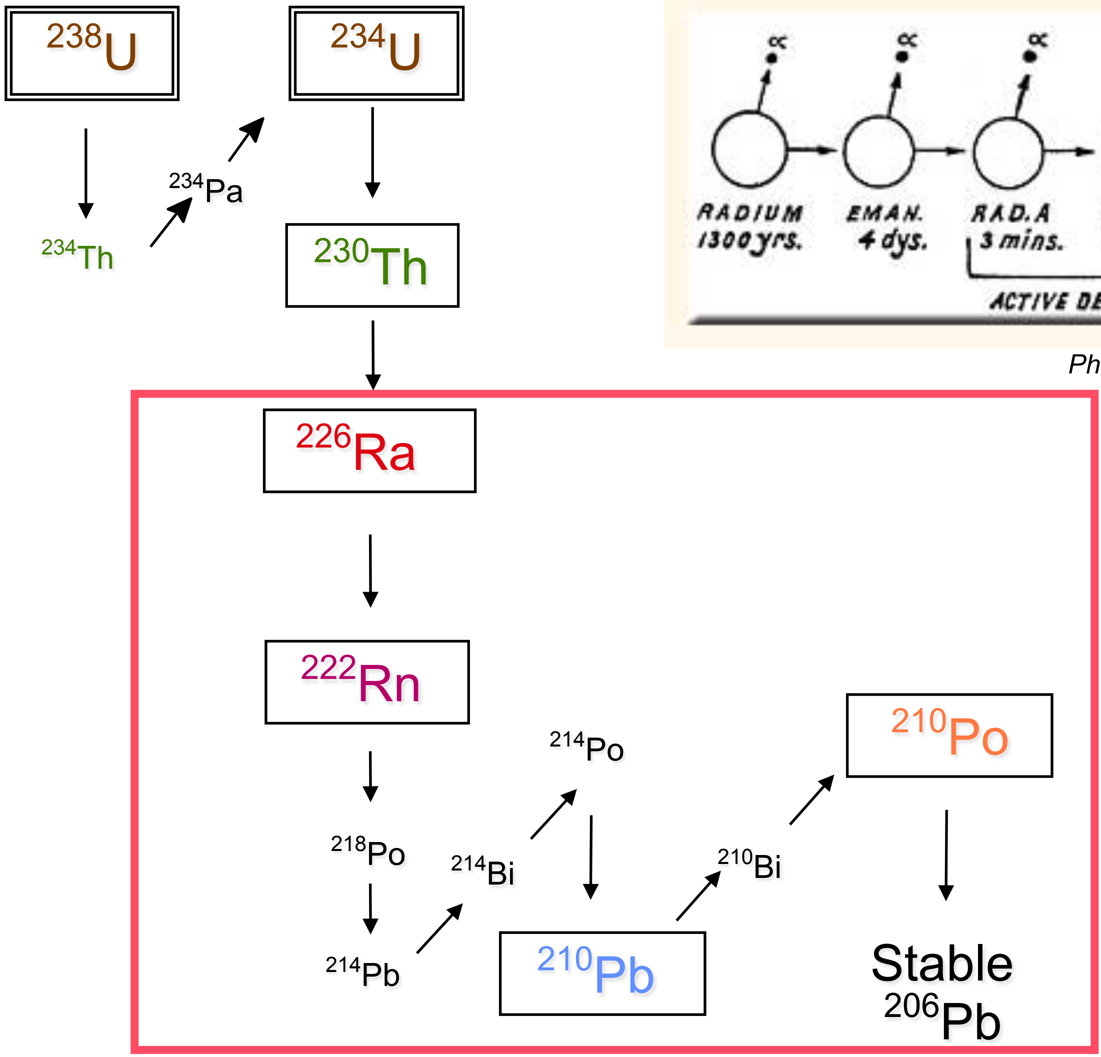
α = hélium ion He^{2+}

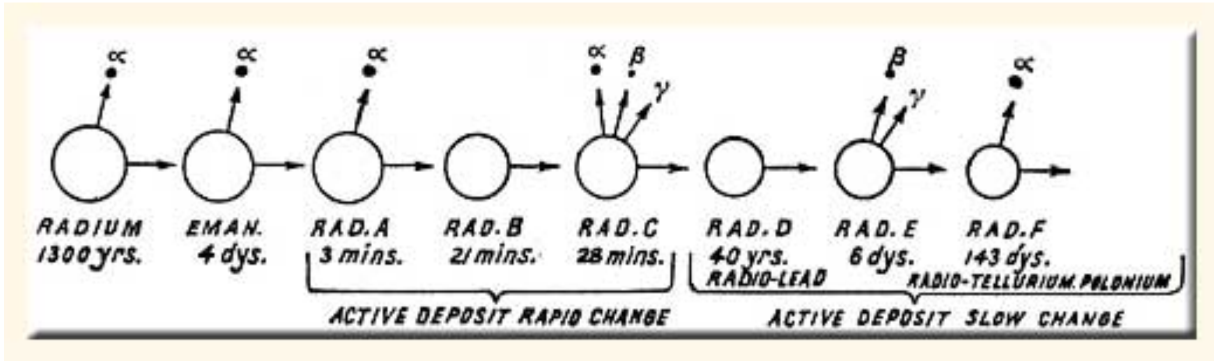
β= high energy e^-

γ= photons - like X rays

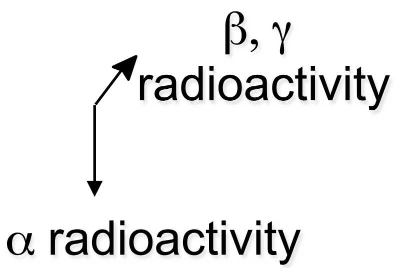
Atoms transform !

1902 E. Rutherford & F. Soddy transmutation of atoms



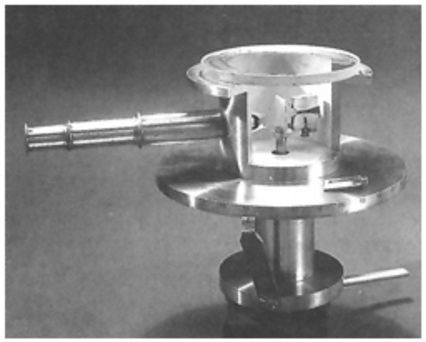


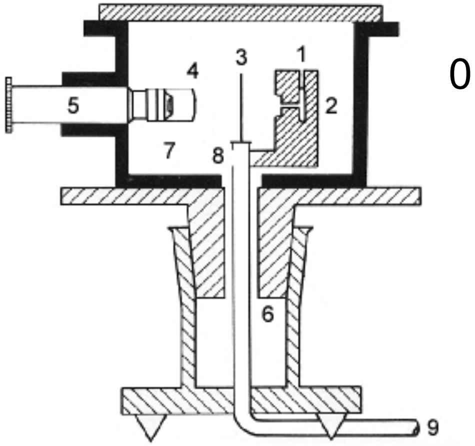
Philosophical Transactions of the Royal Society of London, 1905



The rate of transmutation follows an exponential law

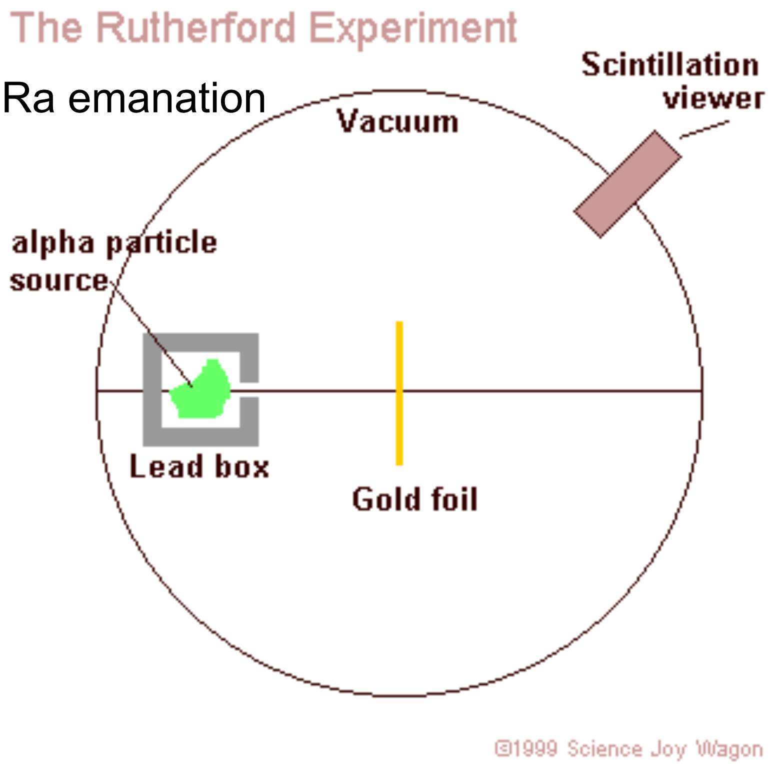
Scattering of alpha particles





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

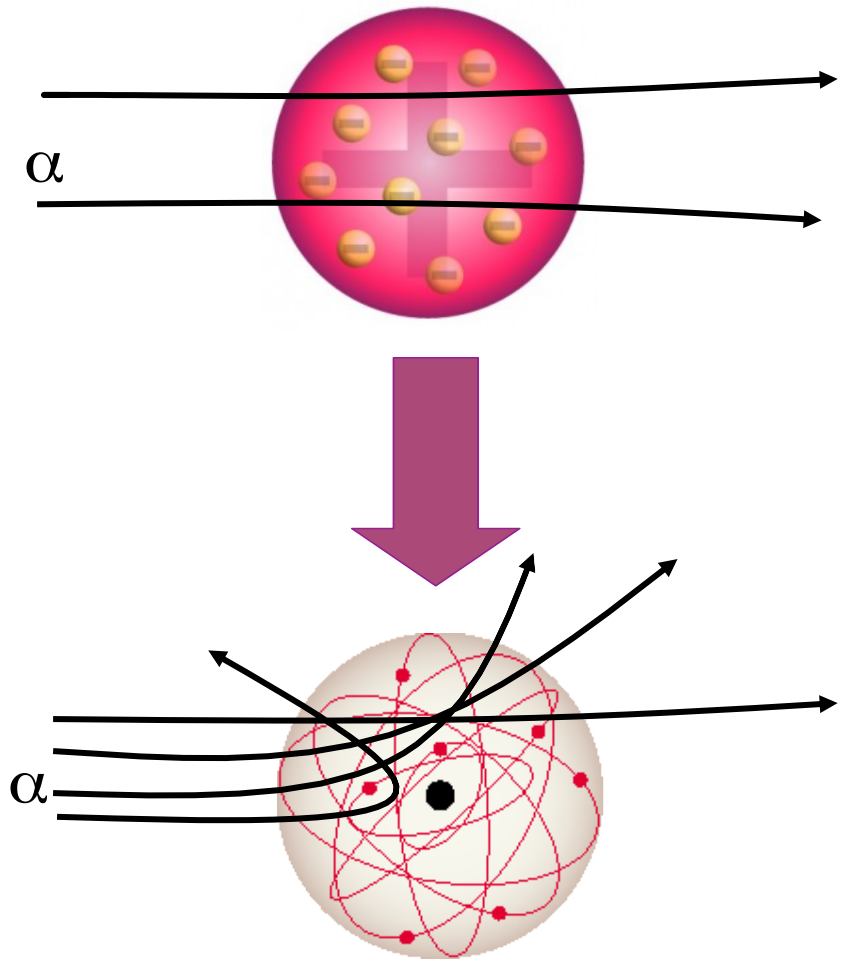
0.1 Ci Ra emanation



"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! "

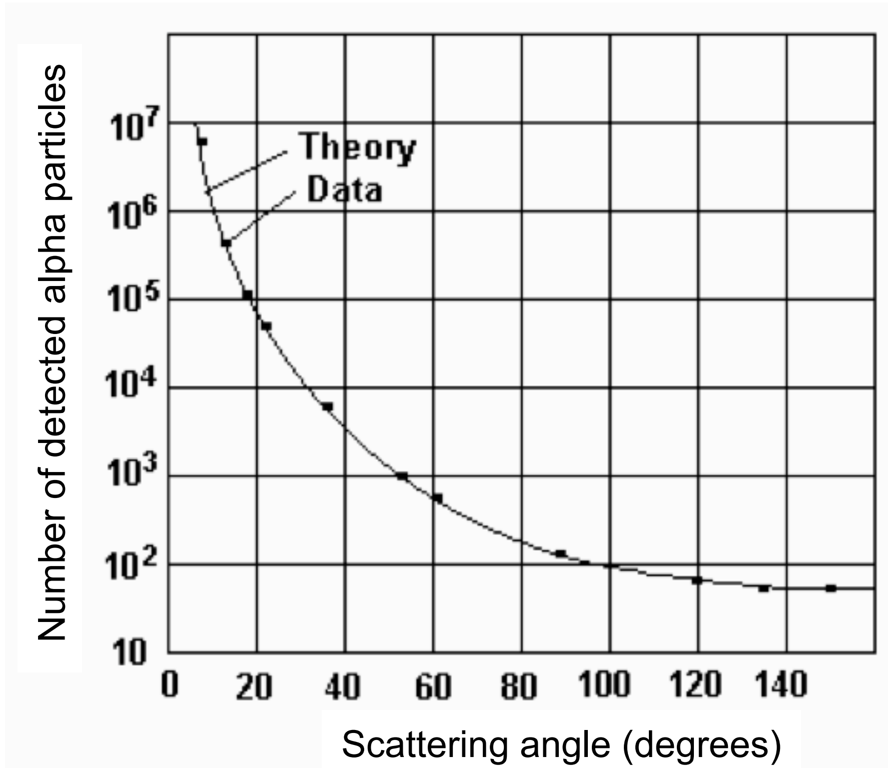
The nucleus is born !

'plum pudding' model

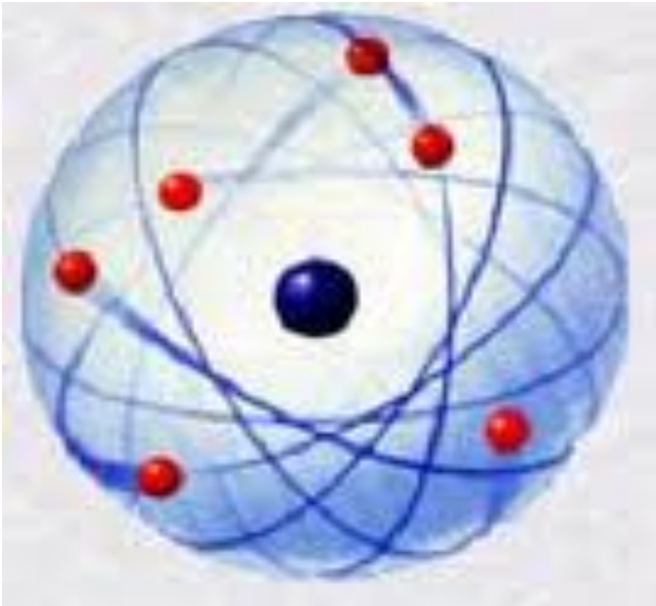


Nuclear model

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



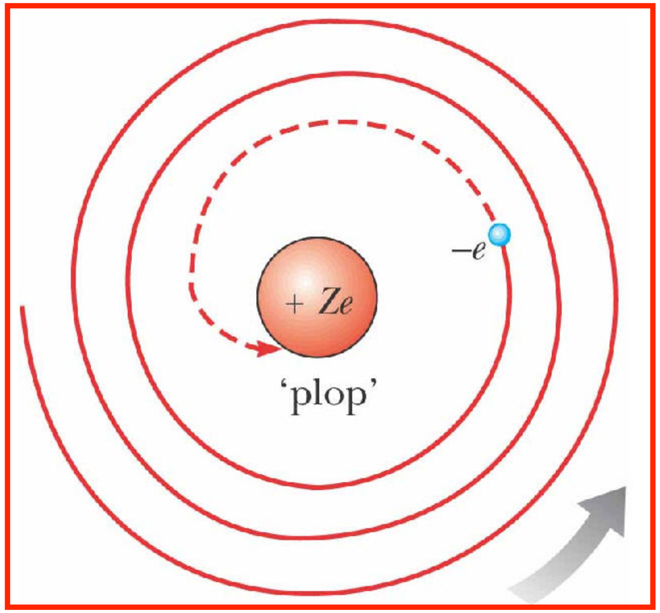
Consequences of Rutherford's model



10^{-14} m

10^{-10} m

Matter is empty !



The atom is unstable !

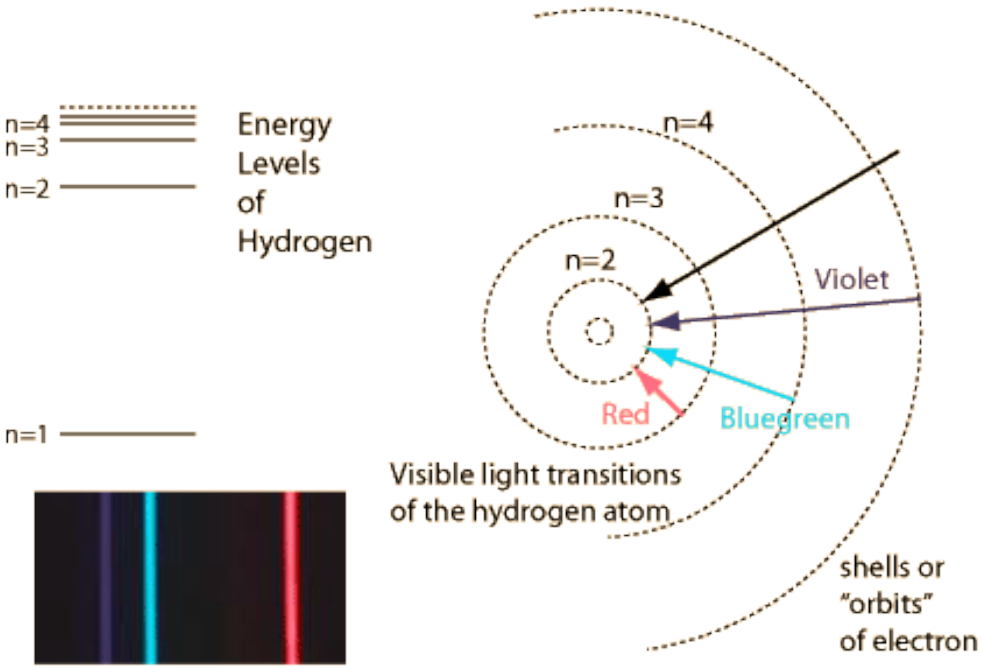
Bohr solves the problem with Planck's quanta

- angular momentum is quantized ⇔ only certain orbits (**shells**) 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

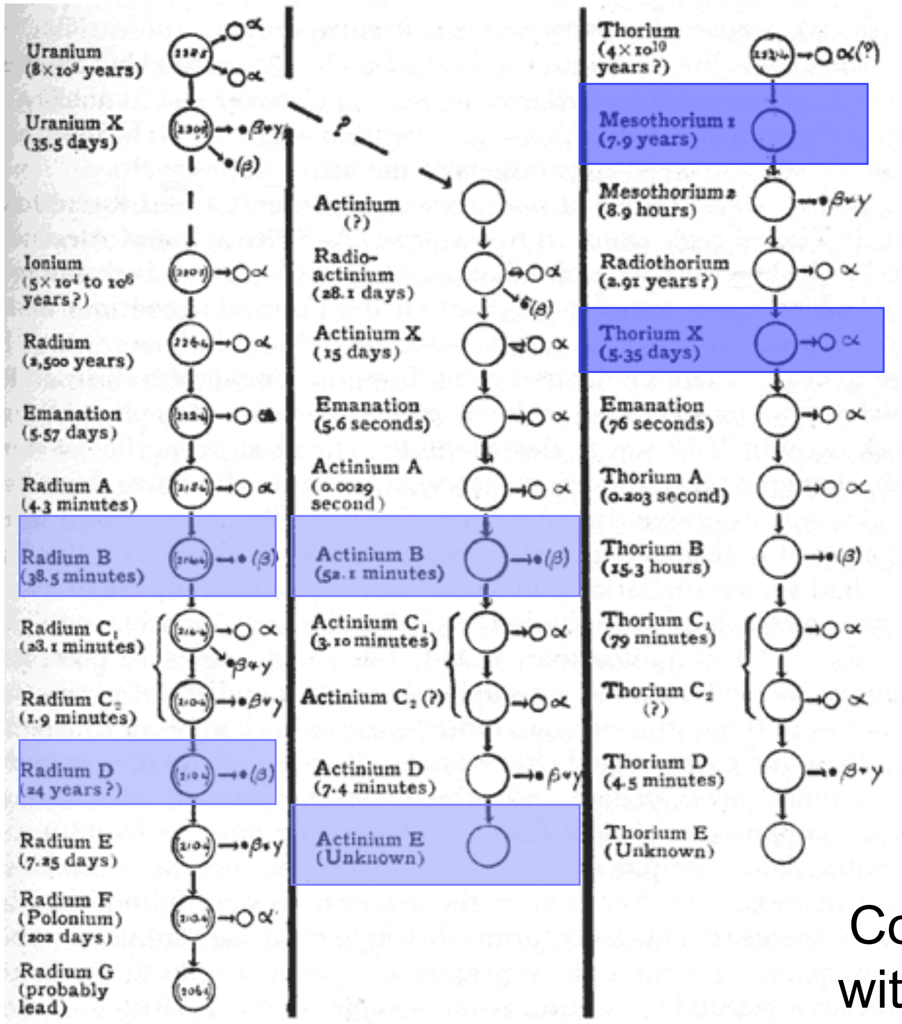
Philosophical Magazine **26**, 1-25 (1913)

Niels Bohr

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



Dalton's atom undermined



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

More than 40 radio-elements discovered in 15 years

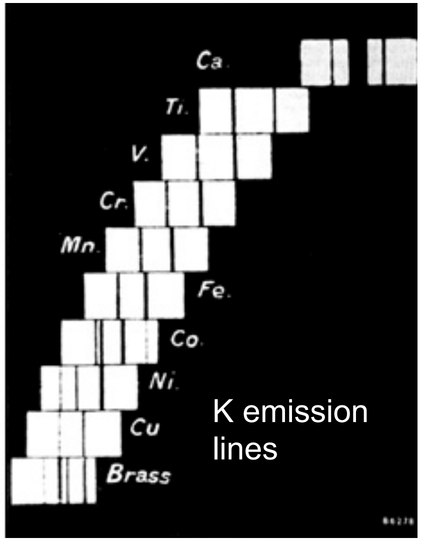
Problem: There are only 7 empty spaces in the periodic table between Bi and U!

Inseparability of certain radio-elements

1913 Frederick Soddy

Concept of **isotope**: radioactive elements with different masses but with the same chemical properties

The periodic table finds its thread

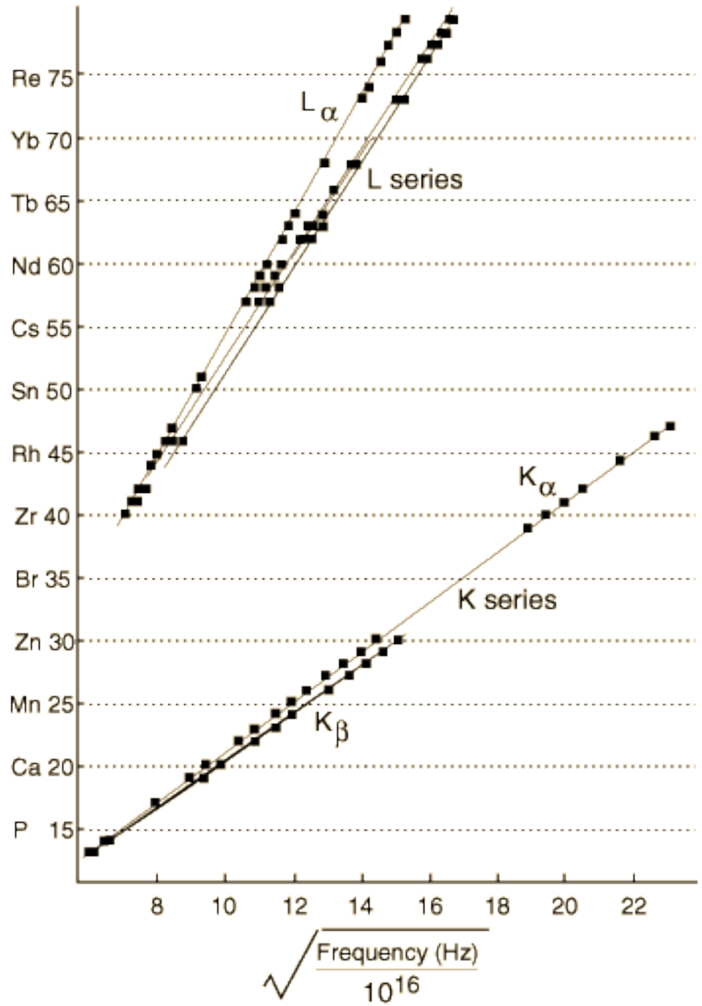


1914 Henry Moseley

Measurement of the high frequency 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 alchemist's dream come true

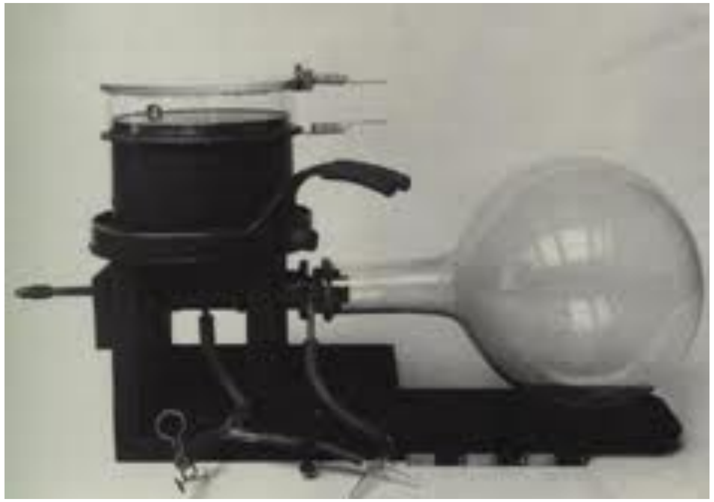
1919 E. Rutherford

1st man-made transmutation

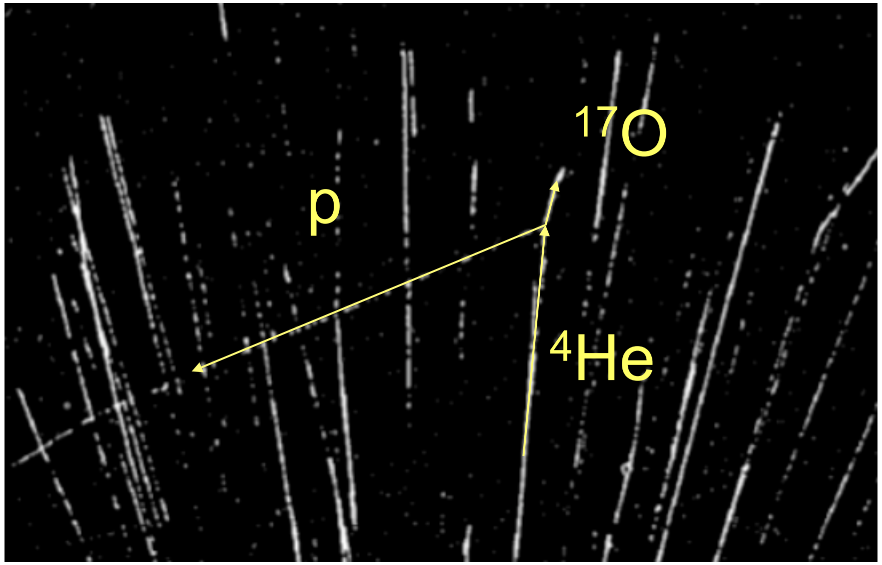
α + Nitrogen → Hydrogen

Rutherford calls H^+ **proton**

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

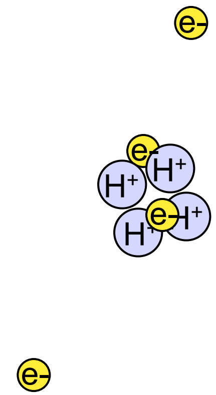


Cloud chamber (C.T.R. Wilson, 1912)



Structure of the nucleus

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

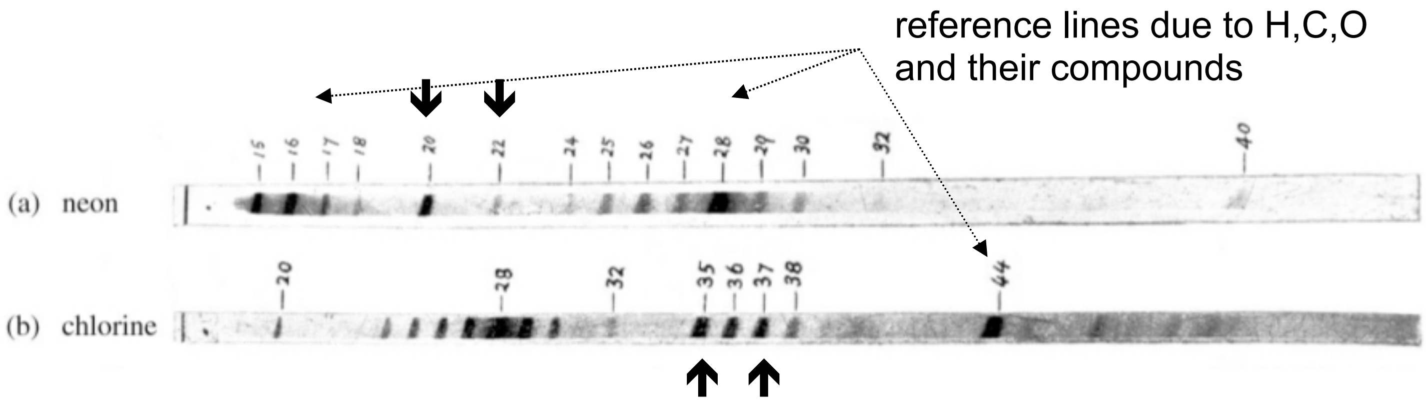
Bakerian Lecture, Proc. Roy. Soc. A, ***97****, 374 (1920)*

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

The beginnings of mass spectrometry

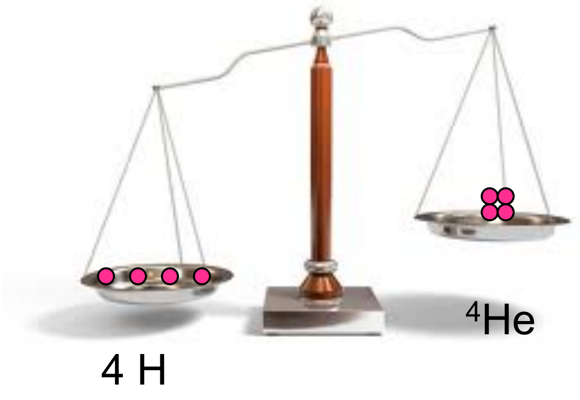
1919: F. Aston provides the experimental proof of the existence of isotopes and measures isotopic abundances *F.W. Aston, Nature 105 (1920) 617*

Francis Aston



He establishes that all masses ($M(^{16}O)=16$) are whole numbers, with the exception of Hydrogen (1.008)

Mass excess

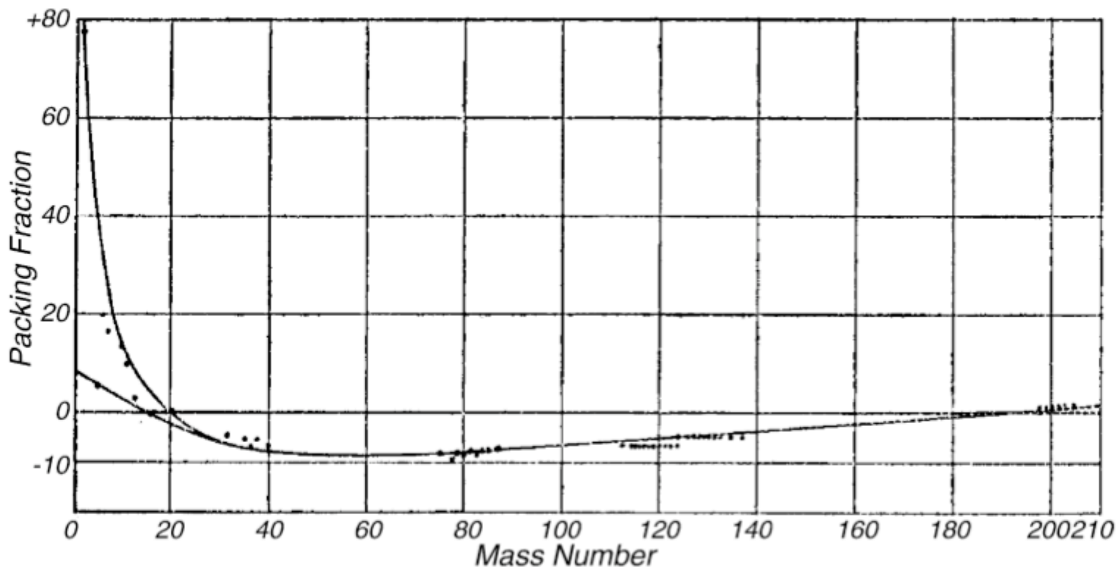


F. Aston proposes that mass is lost to form nuclei

A. Eddington suggests that the transformation of H into He is the source of the sun's energy

1927: With an improved spectrometer, Aston shows that masses are not quite whole numbers

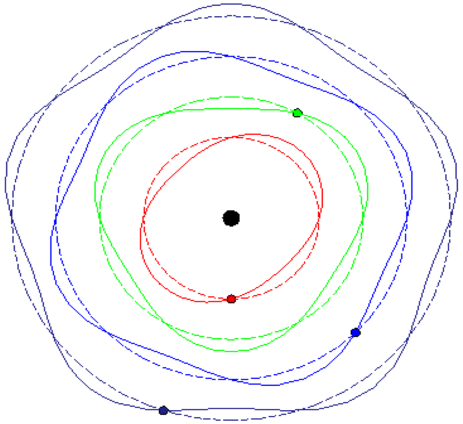
'packing fraction'= 10 000 (M – A)/A



Development of Quantum Mechanics

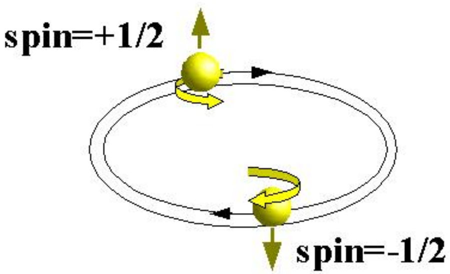
1924

L. de Broglie

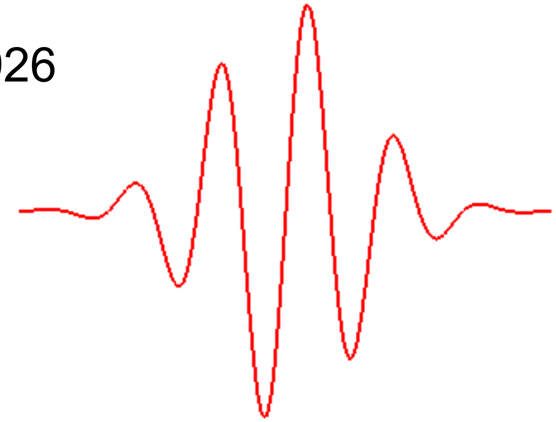


1924-1925

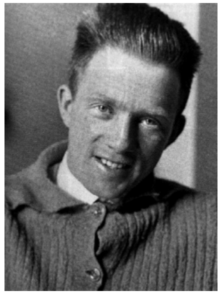
W. Pauli



1926



M. Born



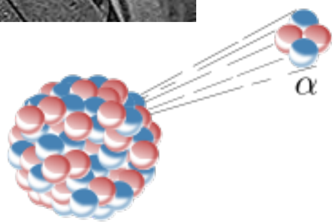
W. Heisenberg

E. Schrödinger

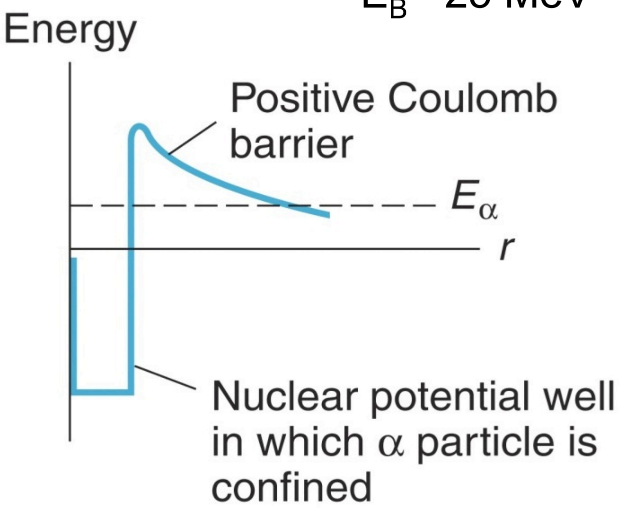
The theory of α decay

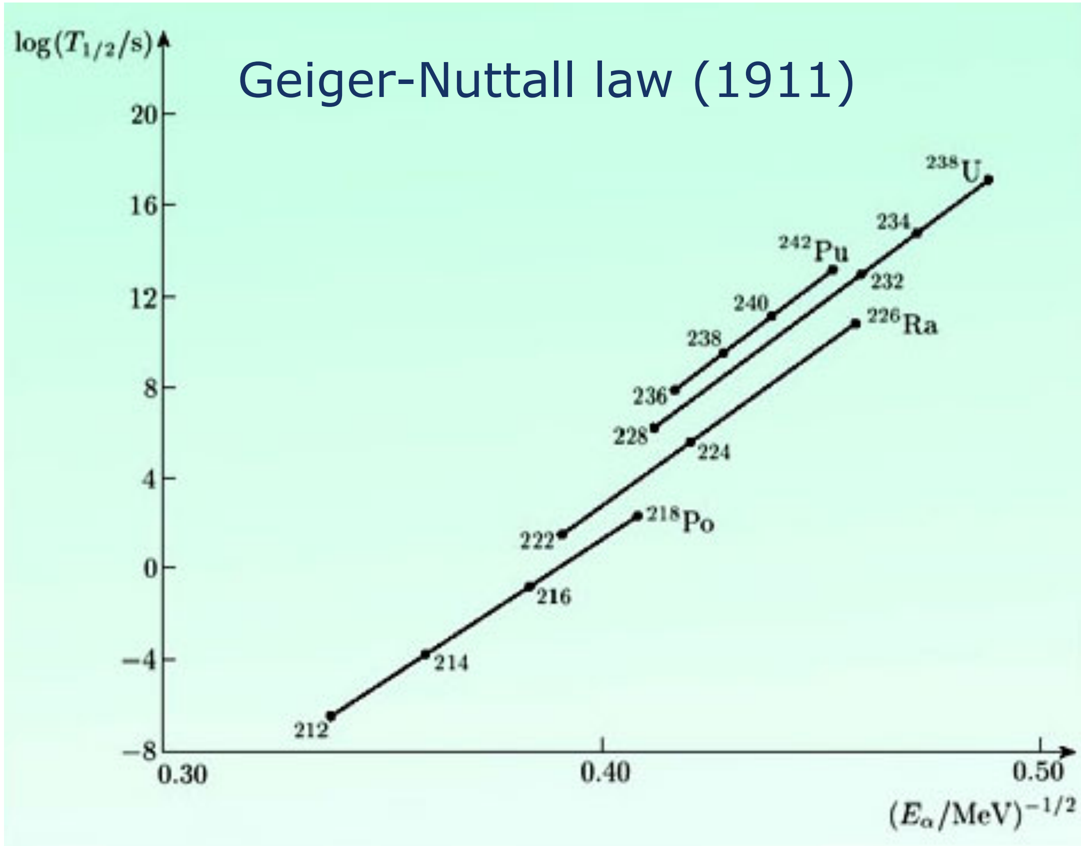
1928: G. Gamow proposes a model for α decay based on quantum mechanics

Z. Physik ***5**1, 204 (1928)*



^{212}Po
E_α=8.78 MeV
E_B~ 25 MeV





Antimatter

Special Relativity

Quantum Mechanics

$$\underbrace{\hspace{10em}}_{\text{relativistic electron}}$$

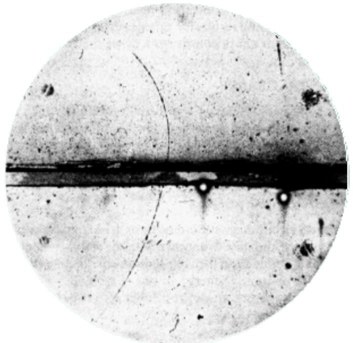
1929 : Dirac equation

The Dirac equation has 2 solutions ! $\left\{ \begin{array}{l} \text{electron} \\ \text{????} \end{array} \right.$

1930: P. Dirac invents the anti-electron

e^-	e^+
electron	anti-electron

1932 : C. Anderson discovers the anti-electron and calls it positron



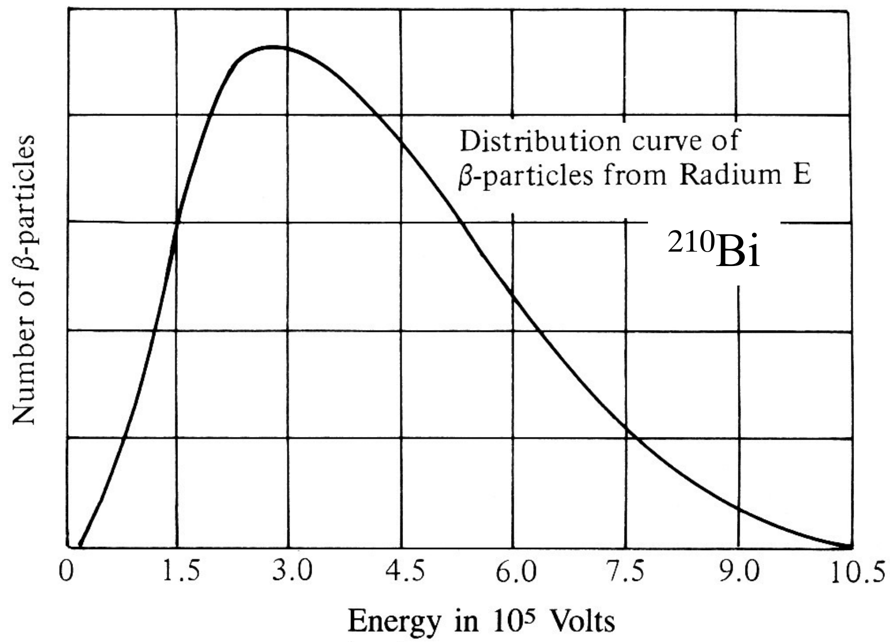
β decay and the neutrino hypothesis

1914 J. Chadwick measures a continuous β−decay spectrum

⇩

Is the law of conservation of energy violated ?

Chadwick to Rutherford: 'I can't find the ghost of a line. There must be a silly mistake somewhere...!'



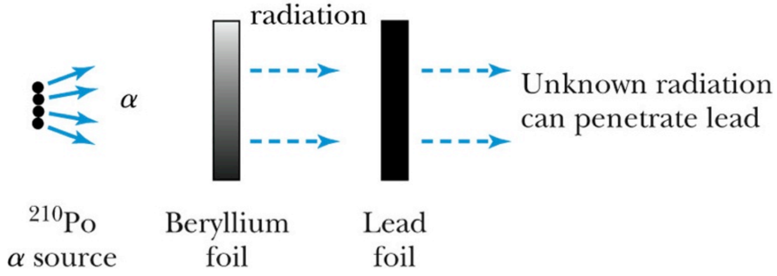
1927: Calorimetric experiment performed by C.D. Ellis and W.A. Wooster: average e^- energy < endpoint of β spectrum

1930: W. Pauli suggests the existence of a new neutral, ~massless particle, which he calls 'neutronen' and which would share the β-decay energy with the e^-

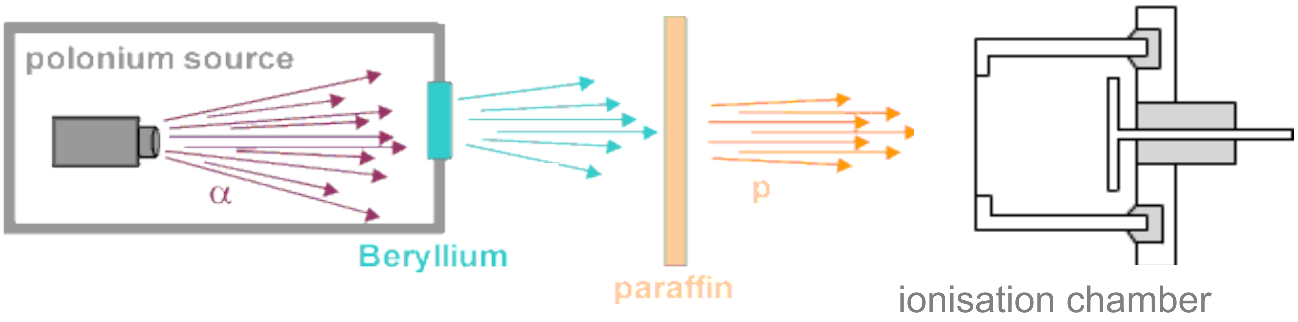
Discovery of the neutron

1930-32

W. Bothe & H. Becker discover a strange reaction



James Chadwick



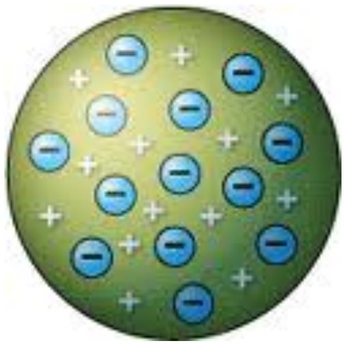
J. Chadwick shows that the mysterious radiation corresponds to a particle of mass ~1: the **neutron**

Proc. Roy. Soc., A, 136 (1932) 692

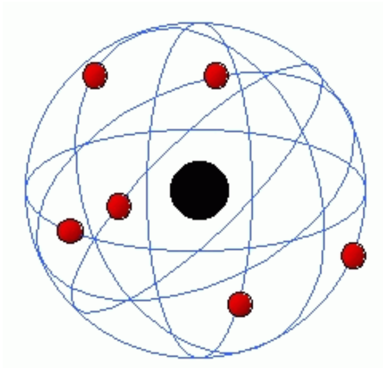
The nucleus is complete !

1932: D. Ivanenko, W. Heisenberg and E. Majorana propose models of the nucleus composed of Z protons and N neutrons. Heisenberg introduces isospin

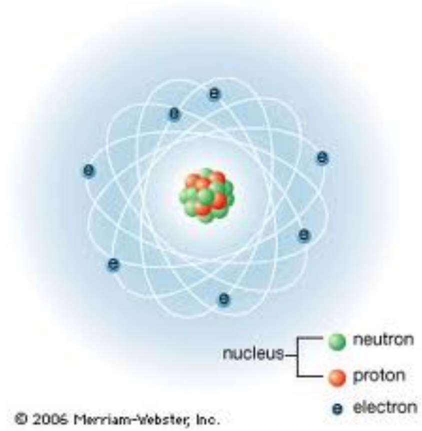
1898



1911



1932



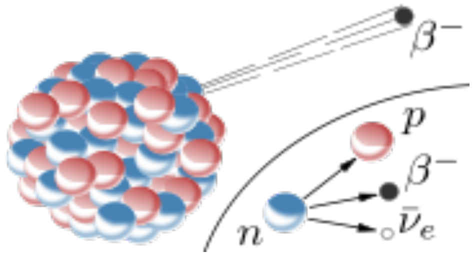
$$ {}^{A}_{Z}X_{N} $$

The presence of neutrons in the nucleus explains the phenomenon of isotopy and resolves some nuclear spin problems and the issue of e^- confinement

Origin of the β-decay electrons ?

1934: E. Fermi suggests the existence of a new force, the weak force, and derives a theory for β decay

Enrico Fermi



$$n \longrightarrow p + e^- + \nu_e$$

A neutron changes into a proton at the same time as an electron and Pauli's neutral particle ('neutrino'), are emitted

He submits his theory to Nature - but the paper is rejected because "it contained speculations which were too remote from reality".

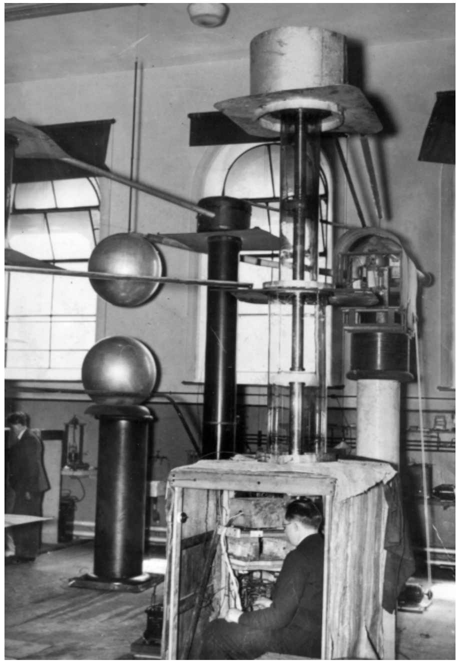
Accelerators to probe the nucleus

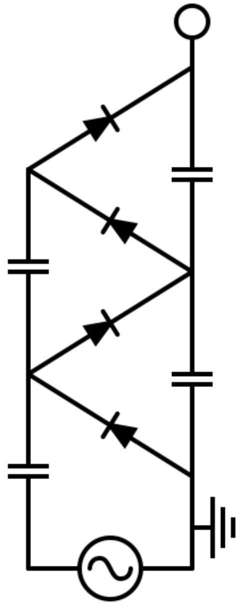
Ernest Walton, Ernest Rutherforf, John Cockroft

J. Cockroft and E. Walton build a machine capable of producing an accelerating voltage of 800 kV

Nature 129, February 1932, 242

Cockroft-Walton voltage multiplier



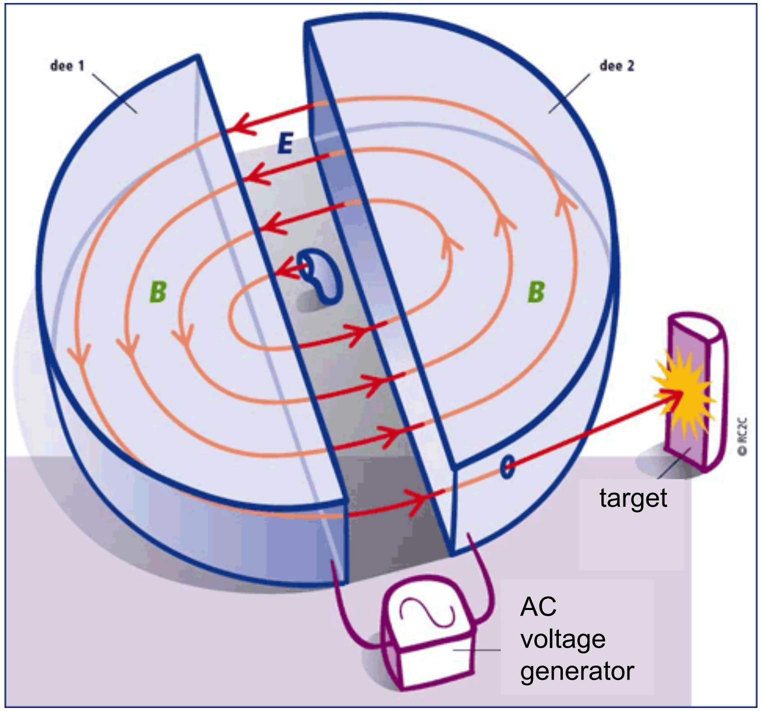


1932: Cockroft and Walton "split the atom"

Nature 129, April 1932, 649

First experimental confirmation of $E = mc^2$

The invention of the cyclotron



1931: E. Lawrence avoids using high voltages by using many times a moderate electric field to accelerate charges to a high energy (original idea by R. Wideroe, 1928)

1st cyclotron in 1931, V=1.8KV , Ø~12 cm acceleration of protons up to 80 keV

2nd cyclotron in 1932, V=1.8KV, Ø~27 cm acceleration of protons up to 1 MeV

1936: Ø~93 cm, acceleration of deuterons (8 MeV) and alpha particles (16 MeV)

The nuclear interaction

Strong attractive interaction (> electrostatic repulsion between protons) short range, repulsive at short distances and charge independent

Identical nuclear particles, drawn together by mutual interaction and surface tension - similar to the force, which binds water molecules within a liquid drop

W. Heisenberg, Congrès de Solvay 1933, from an original idea of G. Gamow (Proc. Roy. Soc. 126 (1930) 637)

Artificial radioactivity

1934 I. Curie and F. Joliot discovery of artificial radioactivity

$$^{27}_{13}Al + ^{4}_{2}He \rightarrow ^{30}_{15}P + n$$

$$^{30}_{15}P \rightarrow e^{+} + ^{30}_{14}Si + \nu$$

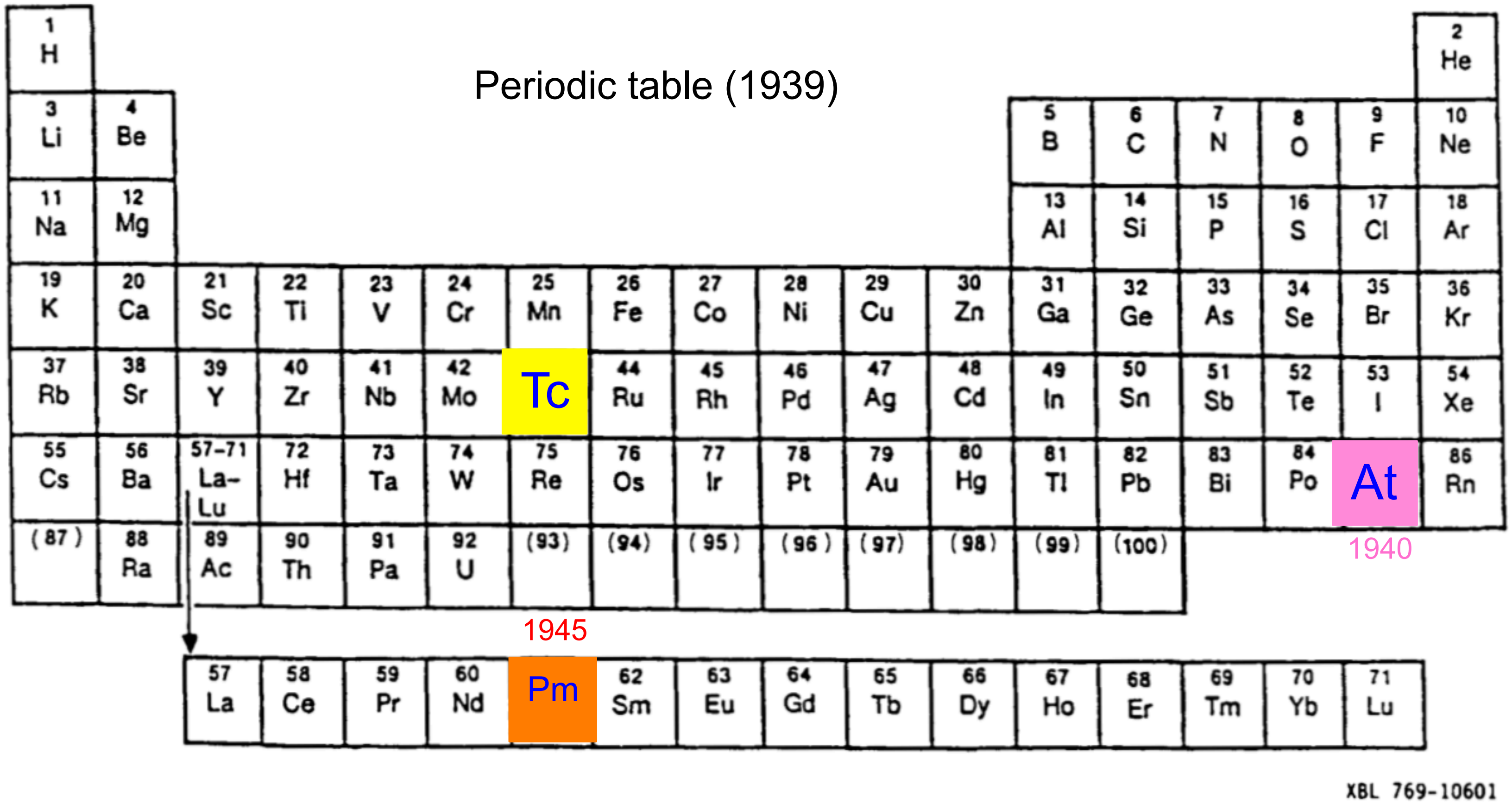
radio-phosphorus !

Irène Curie et
Frédéric Joliot

1936: John H. Lawrence is the first to use an artificial radio-element for therapeutic purposes: ^{32}P to treat leukaemia

Artificial elements

1937: E. Segrè and C. Perrier discover element Z=43, they call it technicium



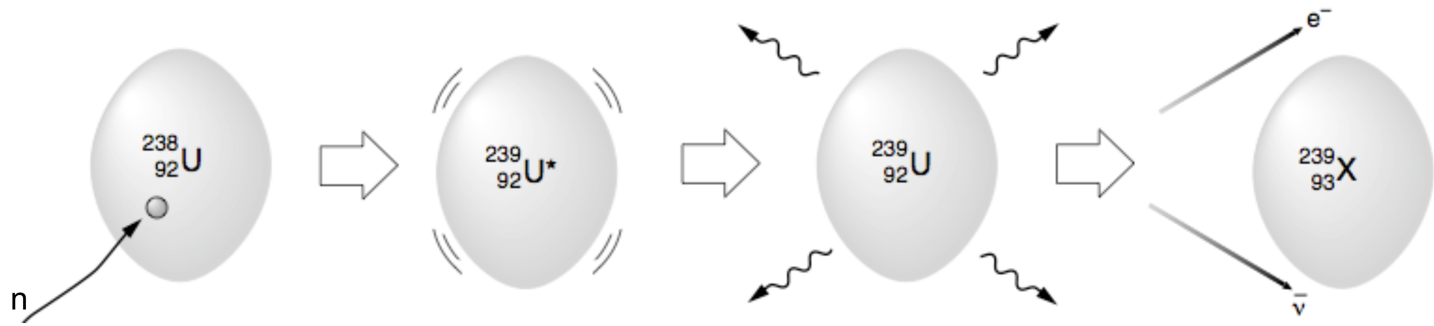
The era of the neutron

1934 E. Fermi proposes to bombard materials with neutrons

He demonstrates that nuclear transmutation occurs more readily with slow neutrons

His group identifies 40 new radio-isotopes in 3 years

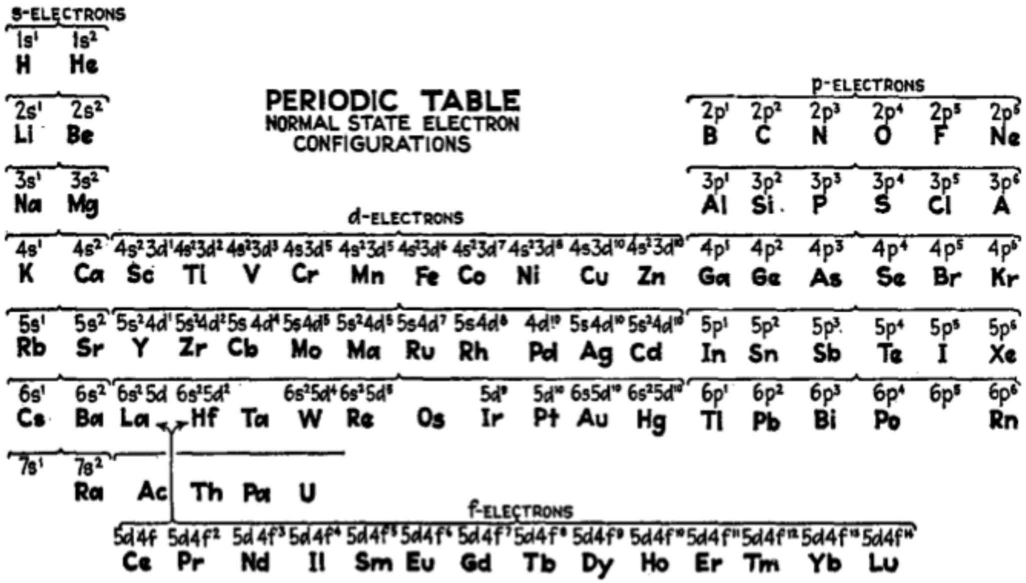
He proposes to irradiate heavy nuclei to synthesize transuranic elements and claims to have produced the elements Z=93 et 94 (Ausonium et Hesperium)



The quest for transuranic elements...

1935-1938: Otto Hahn, Lise Meitner and Fritz Strassmann discover a great number of new transuranium radio-isotopes (up to Z=96)

Irène Curie end Pavel Savitch claim to have produced a substance similar to Lanthanum (Actinium ?)



d

on

Lise Meitner and Otto Hahn (1918)

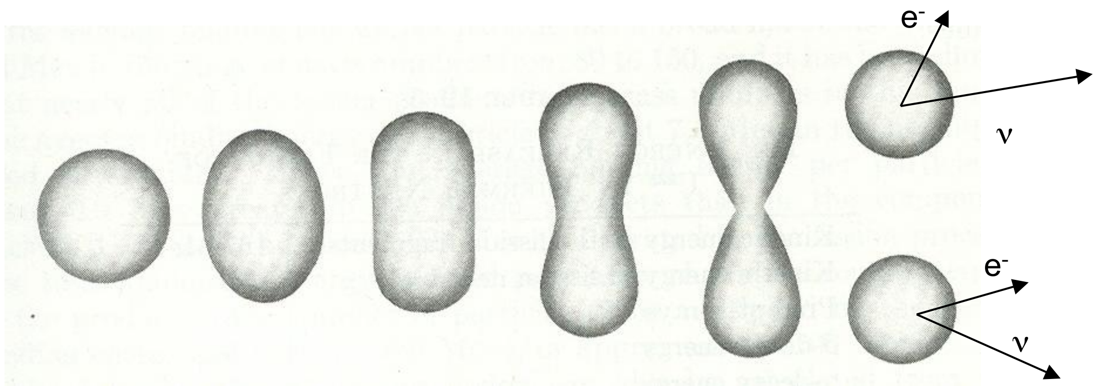
m and Cerium, what we called
horium. This is a difficult decision,
ear physics experiments.”

nd F. Strassmann, Naturwiss 27 (1939) 11

Fission

1939:, Together with her nephew Otto Frisch, L. Meitner gives an explanation for the observed phenomena: **fission** of uranium

L. Meitner and O. Frisch, Nautre 143 (1939) 239



This hypothesis is immediately confirmed by O. Frisch and by others (F. Joliot)

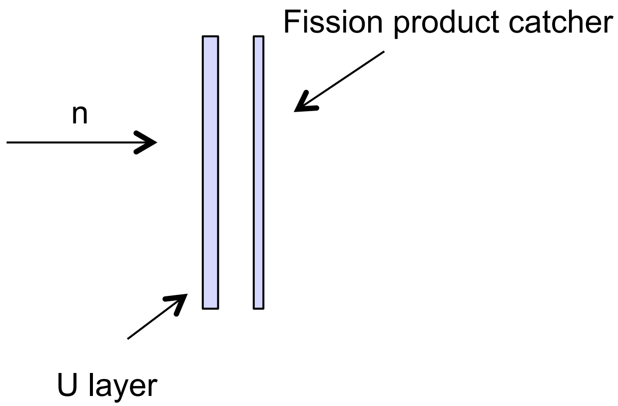
O. Frisch, Nature 143 (1939) 276

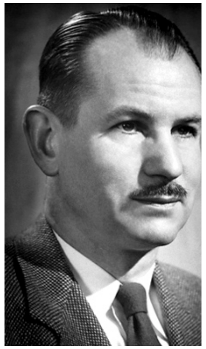
N. Bohr et J.A. Wheeler develop a theory of fission based on the liquid drop

N. Bohr et A. Wheeler, Phys. Rev. 56 (1939) 426

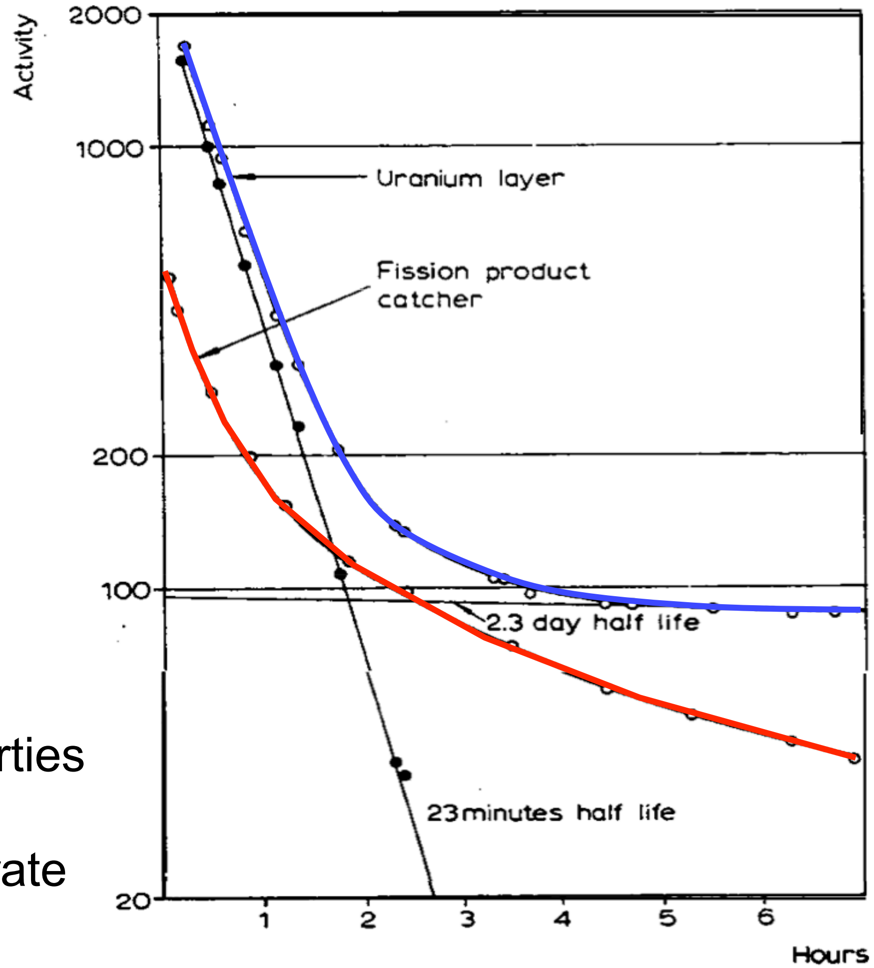
Transuranium elements are finally discovered

$$^{238}U_{92} + n \rightarrow {}^{239}U_{92} \xrightarrow{\beta} {}^{239}Np_{93}$$





E. McMillan



The new substance has none of the properties of Re but behaves like U

➔Chemical separation allows to demonstrate the growth from the ^{239}U activity

E. Mcmillan and P.H. Abelson, Phys. Rev. 57 (1940) 1185

1941: $^{238}U + {}^{2}H \rightarrow {}^{238}Np + 2n;\ {}^{238}Np \xrightarrow{\beta} {}^{238}Pu$ (~50 years)

G.T. Seaborg et al., Phys. Rev. 69, 366, not published until after the war

The actinide concept to go further

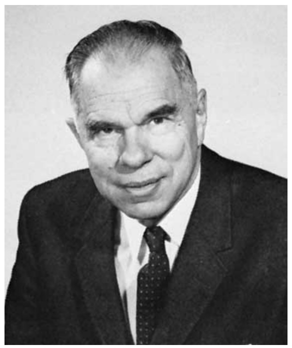
1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
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	86 Rn
87	88 Ra	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95	96								

Lanthanides	57 La	58 Ce	59 Pr	60 Nd	61	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
Actinides	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95	96							

1944
Americium (Z=95)
Curium (Z=96)

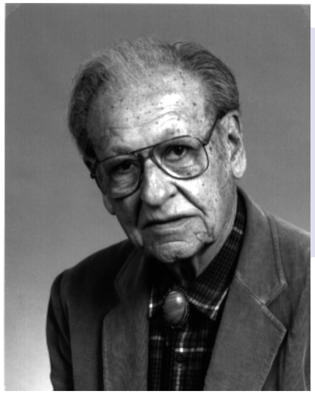
1949
Berkelium (Z=97)

1950
Californium (Z=98)



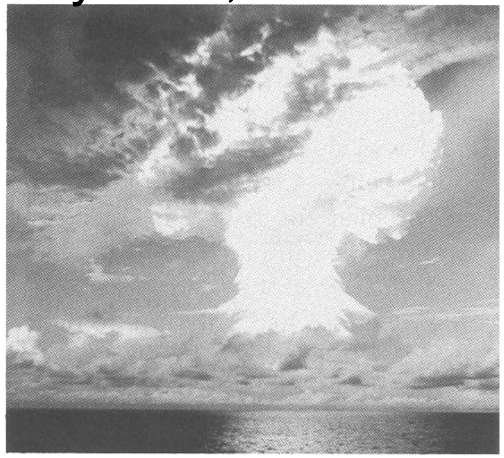
G.T. Seaborg

Discovery of Es (Z=99) & Fm (Z=100)



A. Ghiorso

Ivy Mike, 1/11/1952



^{255}Fm
β^-
^{253}Es
β^-
^{255}Es
β^-
^{253}Cf
β^-
^{255}Cf
β^-
β^-
β^-
$^{238}U(n,\gamma)$
$^{239}U(n,\gamma)$
$^{252}U(n,\gamma)$
$^{253}U(n,\gamma)$
$^{254}U(n,\gamma)$
^{255}U

Discovery of Md (Z=101)

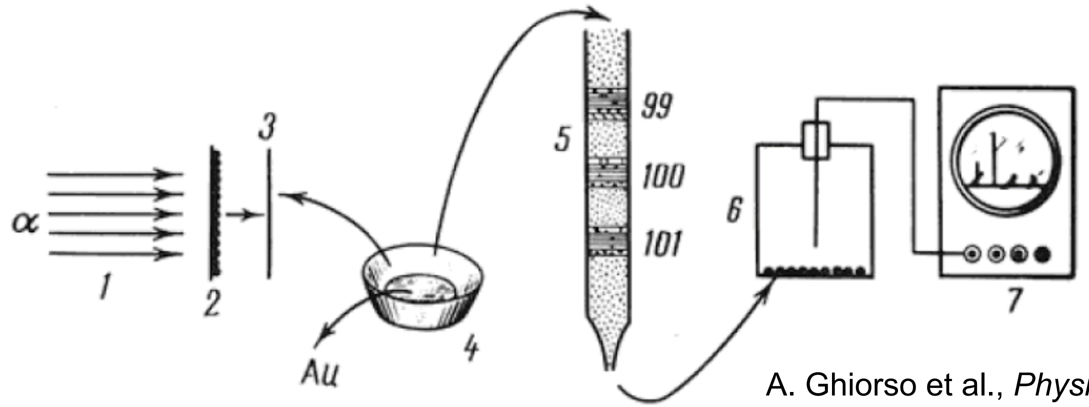
Last element to be identified by chemical separation

$^{253}Es(\alpha,n)^{256}Md$

target : ≈ 10^9 atoms produced in 1 year of irradiation

beam intensity : ~10^{14} p/s

New recoil technique



A. Ghiorso et al., *Physical Review*, 98 (1955) 1518

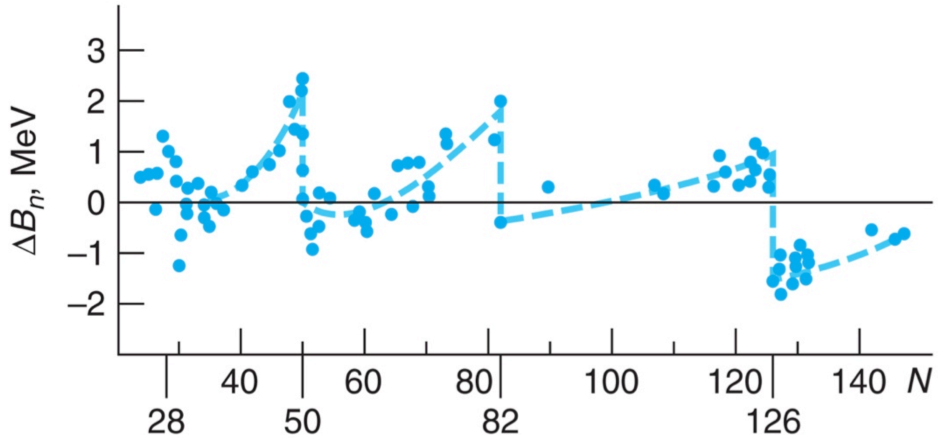
In the middle of the cold war, Ghiorso proposes the name of Mendelevium in honour of the Russian chemist

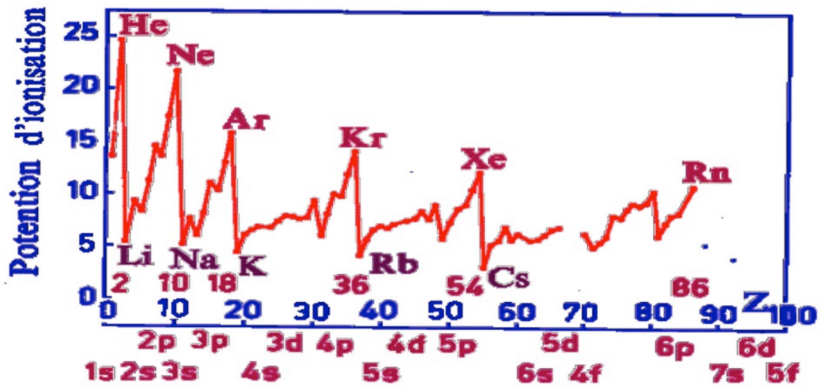
Magic numbers

Maria G. Mayer

M. Goeppert Mayer notices that nuclei with a number of neutrons and/or protons equal to 20, 28, 50, 82, 126 are relatively more abundant than their neighbours

The nuclei associated with magic numbers are also exceptionally bound and give rise to discontinuities with respect to the liquid drop energy



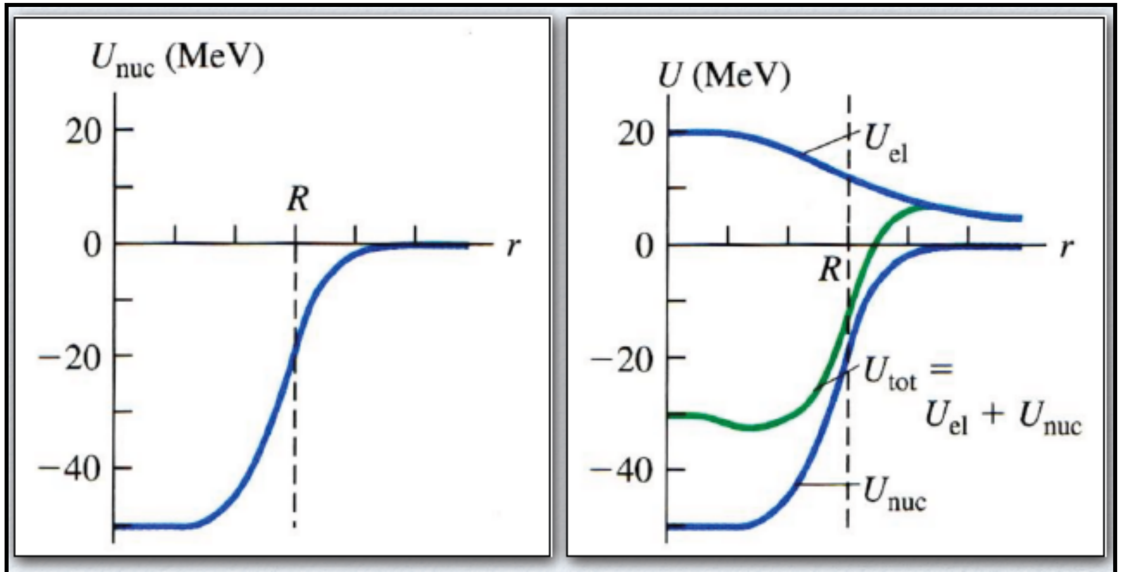


⇨ periodic structure of the nucleus ?

'On closed shells in nuclei', *M G. Mayer Phys. Rev. 74 (1948) 235*

Quantum mechanics doesn't give the correct answer ...

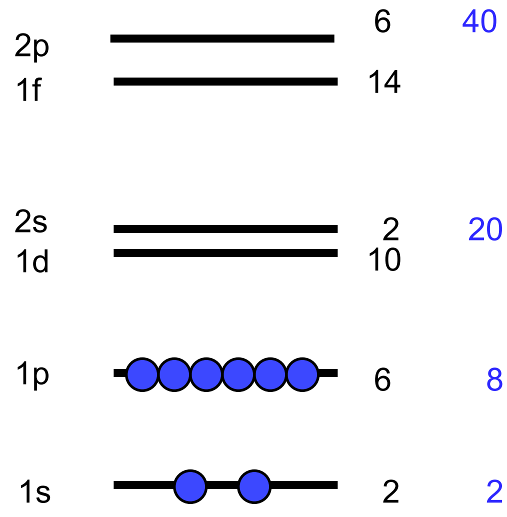
mean nuclear potential felt by nucleons



Strong force potential alone: as seen by neutrons

Strong + Coulomb potential: as seen by protons

energy levels



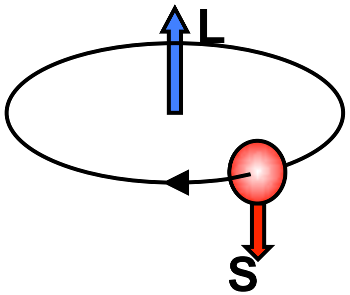
Total number of neutrons (or protons), which can be accommodated in each shell:

2, 8, 20, 40, 58, 92, 138

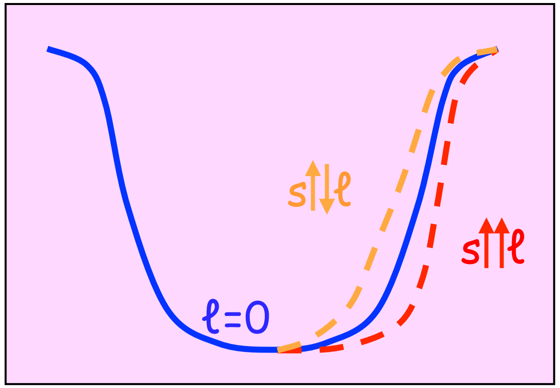
The question which solves the problem

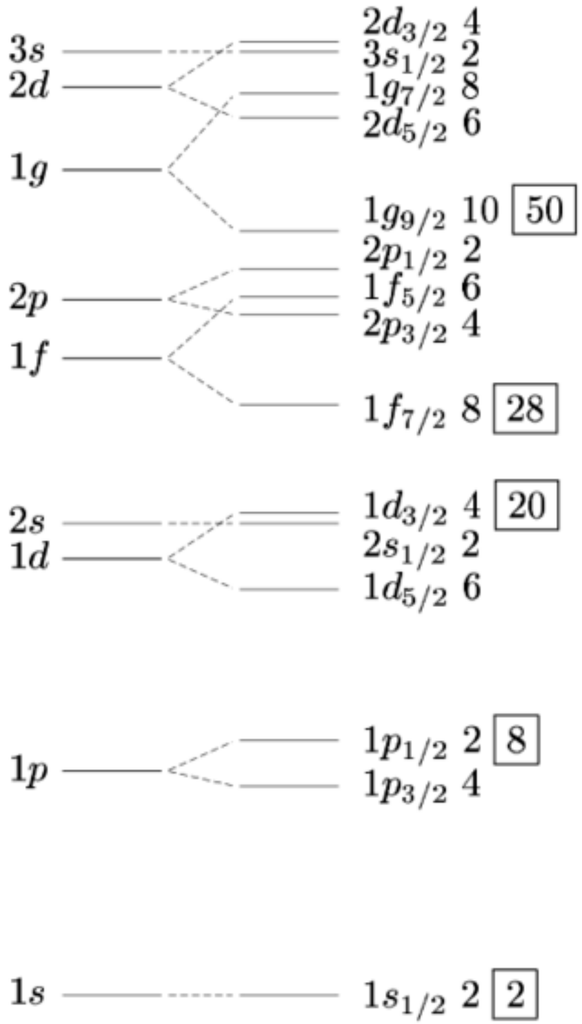
Thanks are due to Enrico Fermi for the remark, "Is there any indication of spin-orbit coupling?" which was the origin of this paper.

'On closed shells in nuclei. II',
M. G. Mayer Phys. Rev. 75 (1949) 1969



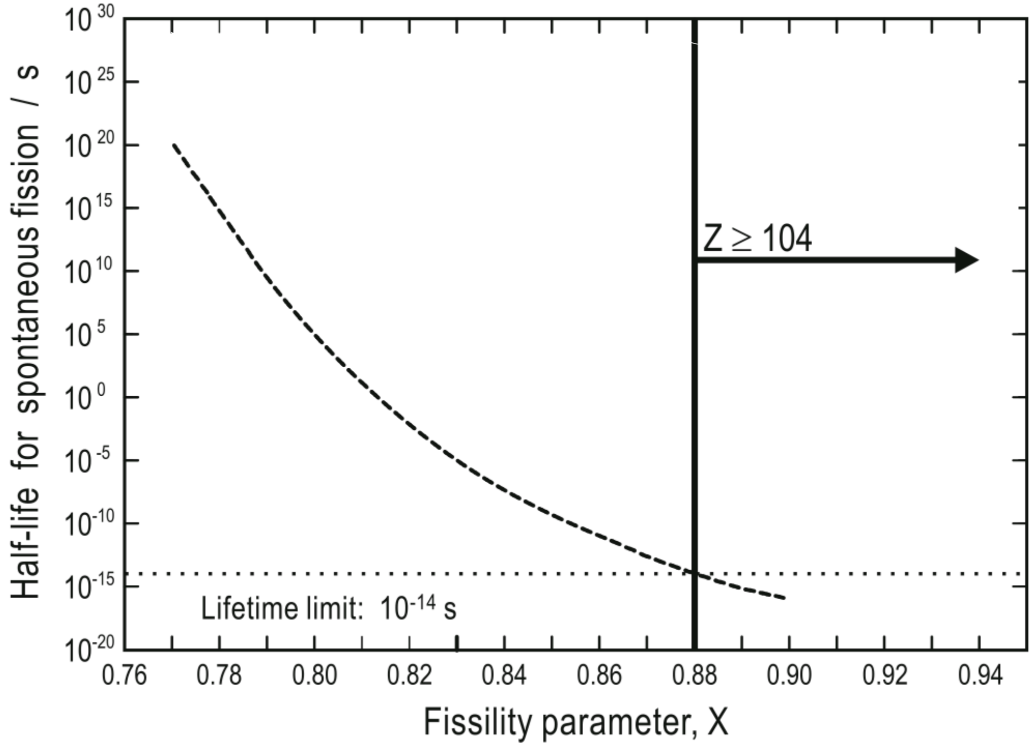
Hans Jensen

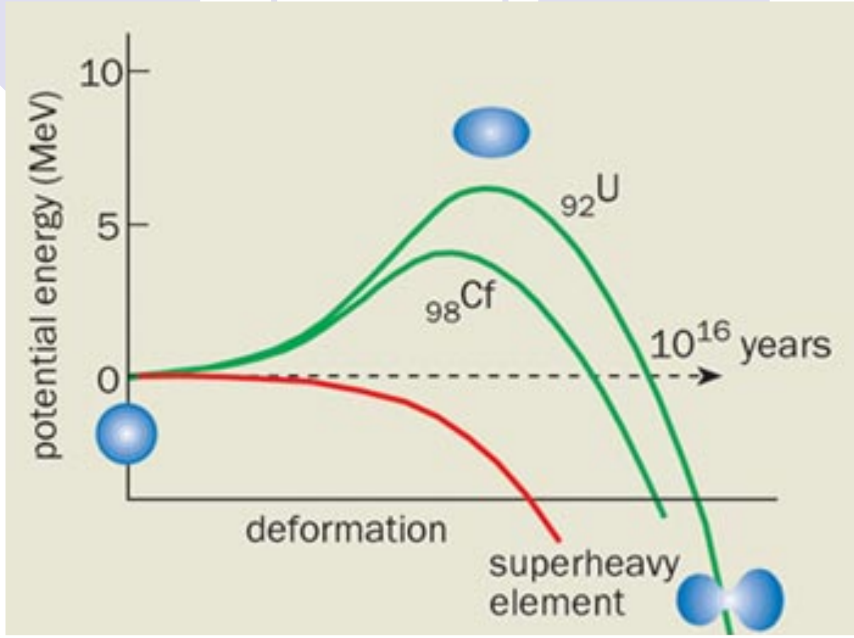




M.G. Mayer et H.D. Jensen 'Elementary Theory of Nuclear Shell Structure', 1955

Stabilisation of heavy nuclei





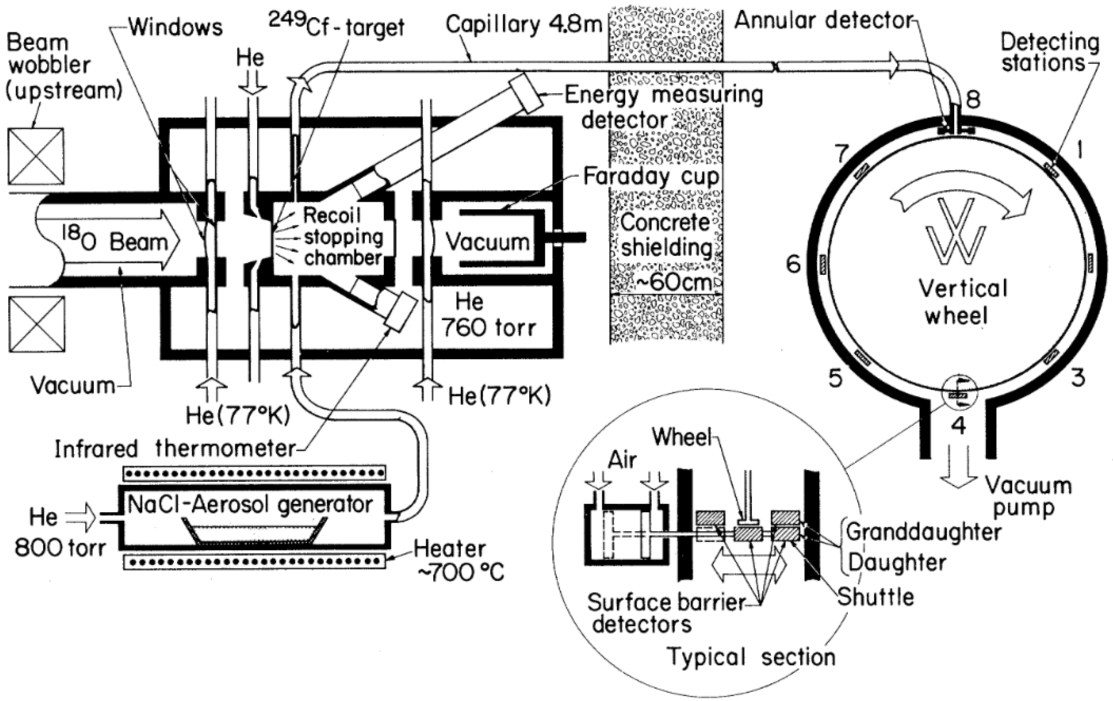
Next magic numbers (Island of stability):
Z=114, N=184

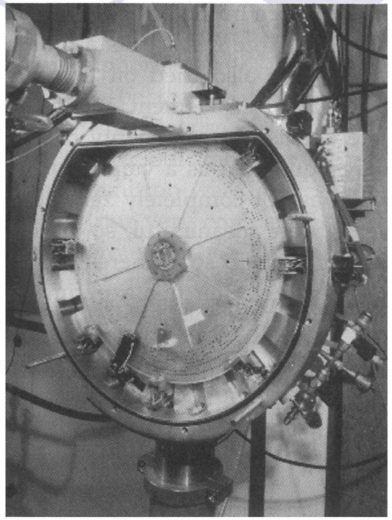
A. Sobiczewski, F.A. Gareev, B.N. Kalinkin
Physics Letters 22 (1966) 500
1966: V.M. Strutinsky; “Shell-correction” method

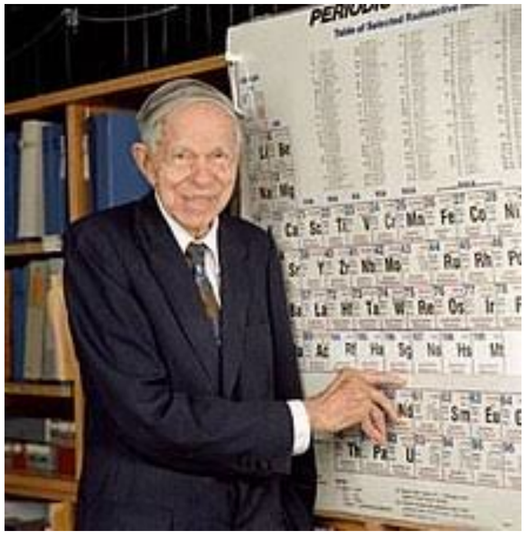
Z=102-106: Synthesis by hot fusion reactions and genetic correlations

$$^{249}Cf(^{18}O, 4n)^{263}106 \xrightarrow{\alpha} {}^{259}Rf \xrightarrow{\alpha} {}^{255}No$$

A. Ghiorso *et al.* Phys. Rev. Lett. 33 (1974) 1490

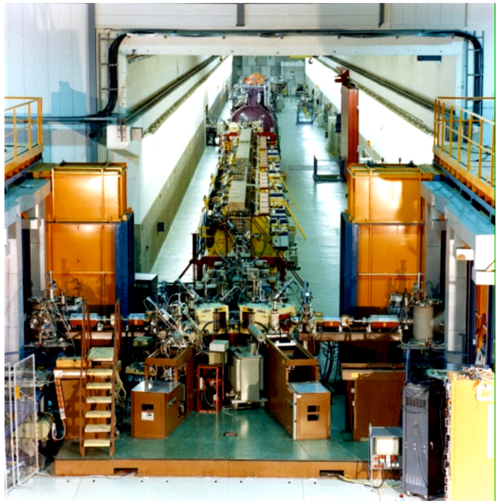


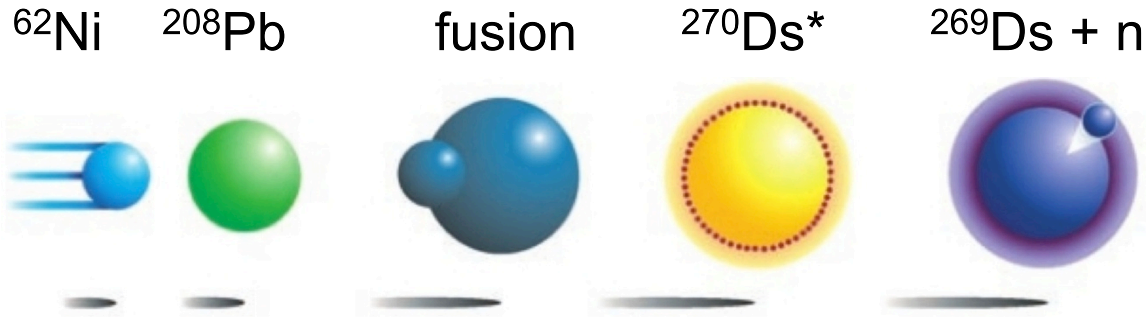




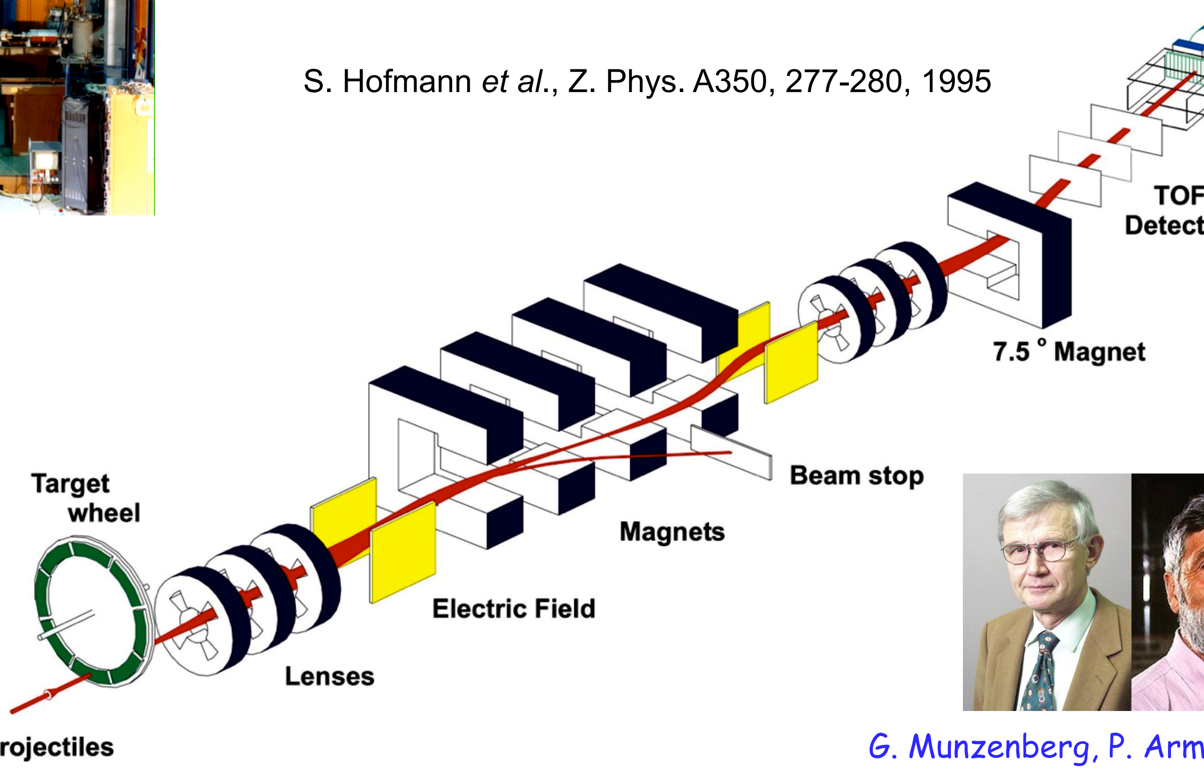
G.T. Seaborg (1994)

Cold fusion and new techniques to go further: Z=107 to 112 in GSI and finally 113 in Riken

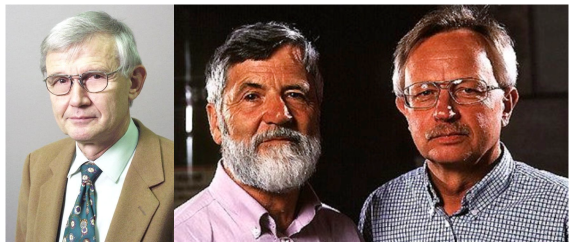




S. Hofmann *et al.*, Z. Phys. A350, 277-280, 1995

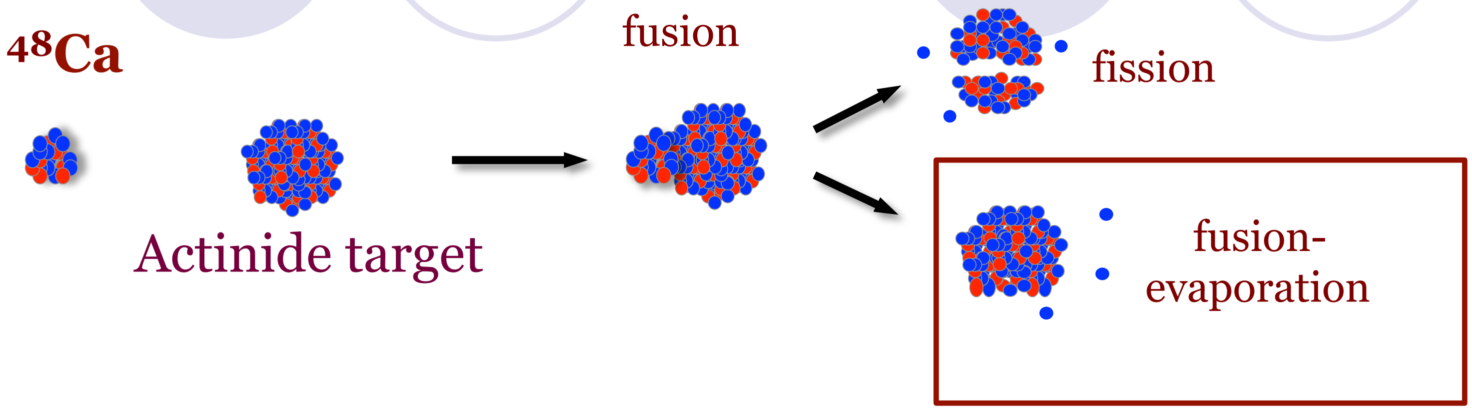


K. Morita

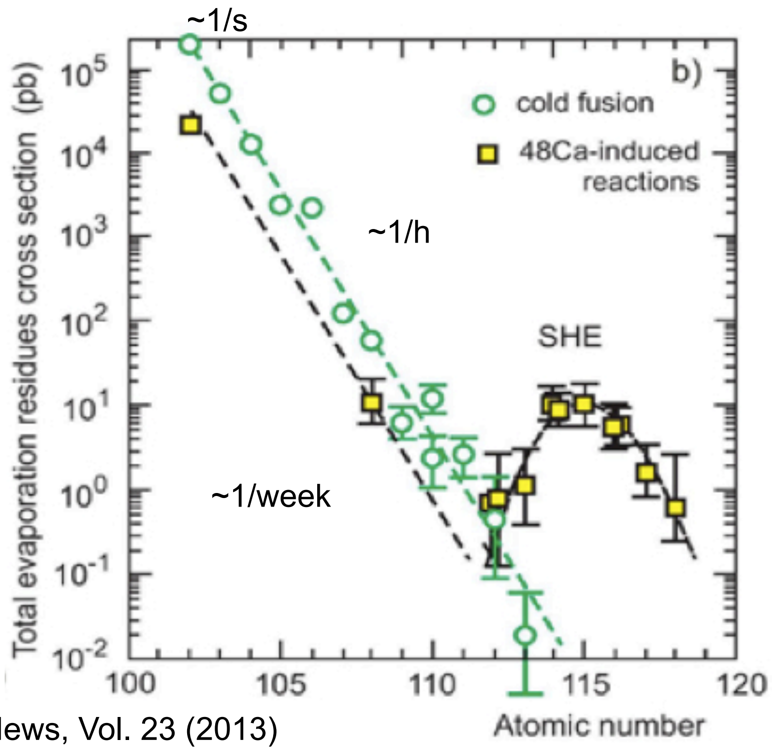


G. Munzenberg, P. Armbruster , S. Hofmann

Synthesis of the heaviest elements in Dubna



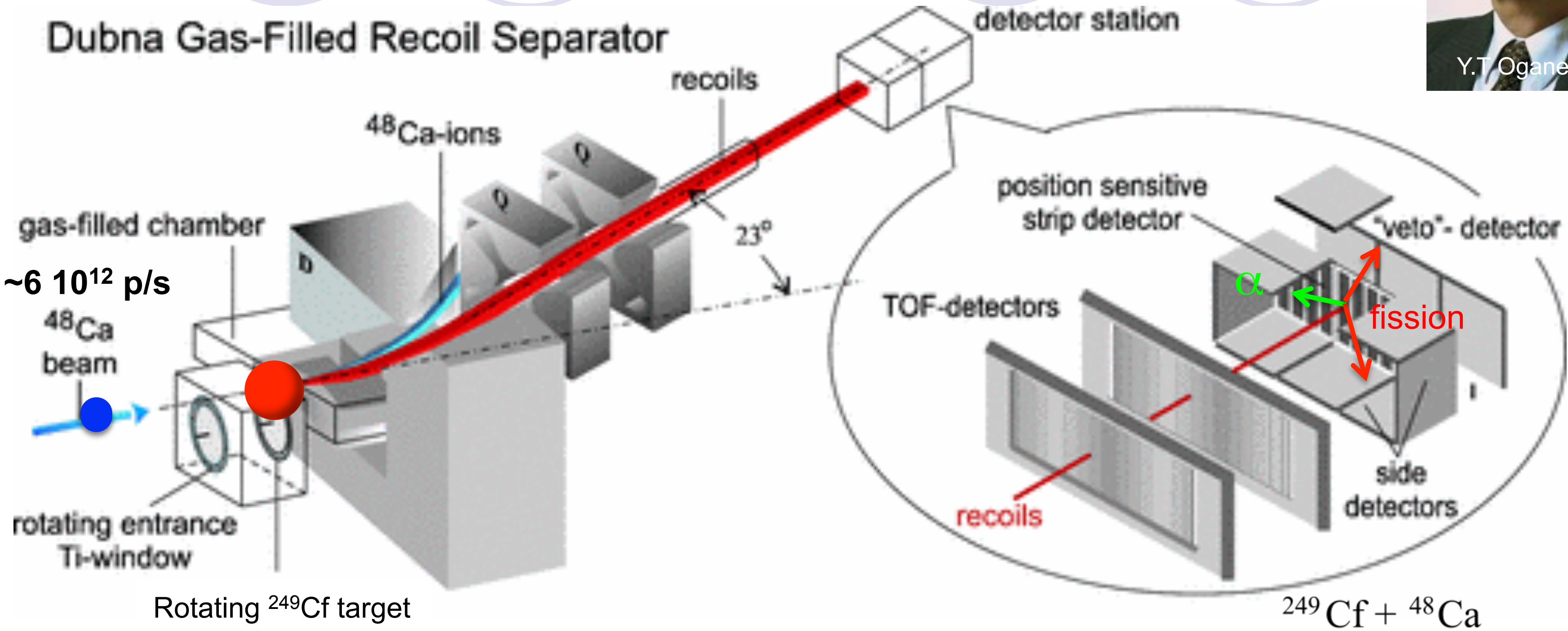
σ~1-10 pb !

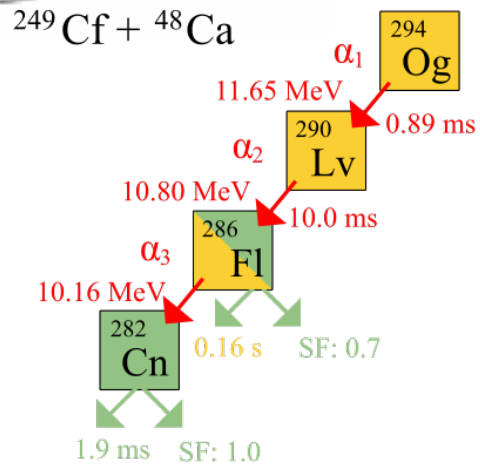


the

Y. Oganessian, Nuclear Physics News, Vol. 23 (2013)

The needle in the haystack



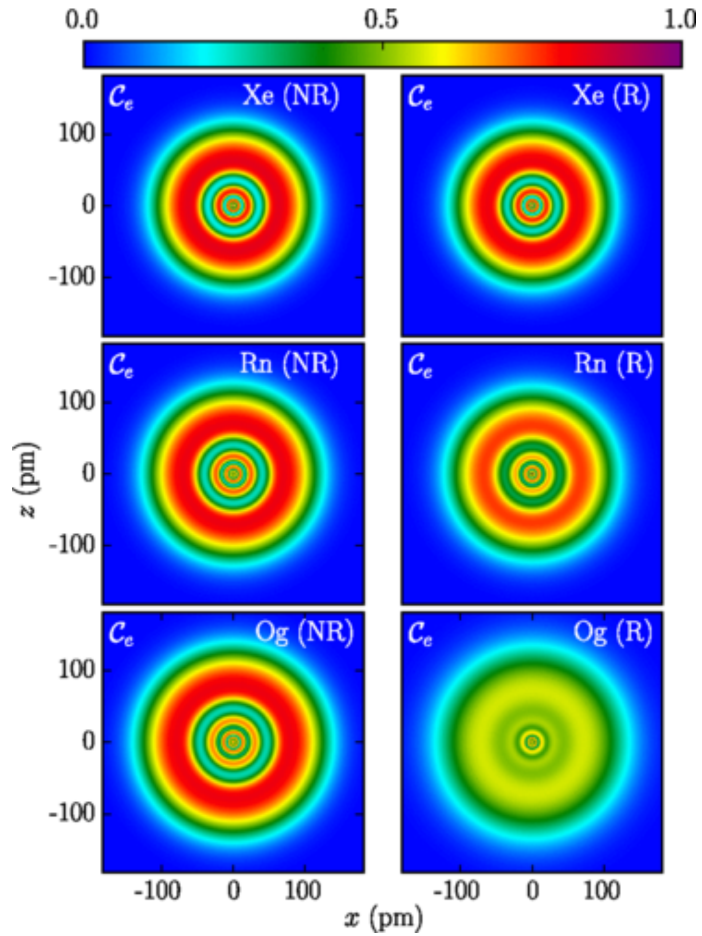


Verification by cross bombardments:

$^{48}Ca + ^{245}Cm \rightarrow ^{290}Lv + 3n$
$^{48}Ca + ^{242}Pu \rightarrow ^{286}Fl + 4n$
$^{48}Ca + ^{238}U \rightarrow ^{282}Cn + 4n$

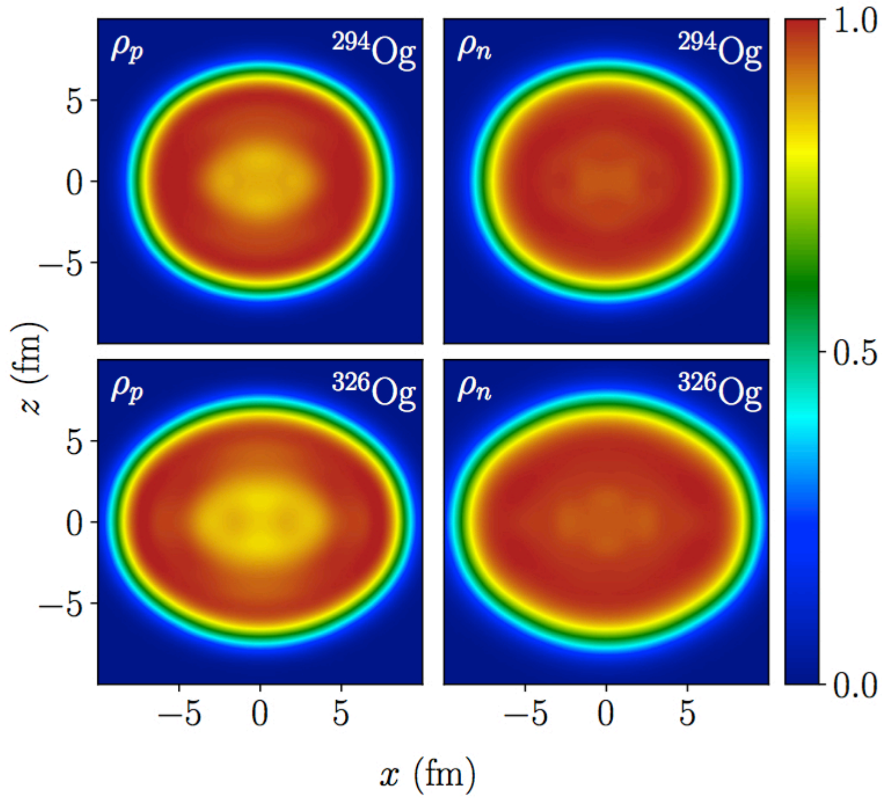
Intriguing properties

Uniform gas-like outer electronic structure



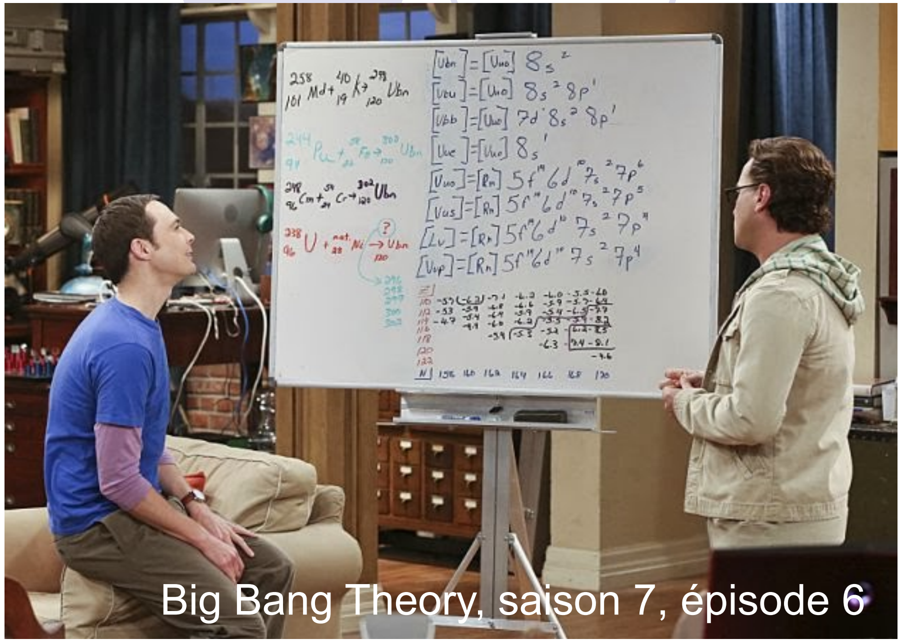
P. Jerabek et al., Phys. Rev. Lett. 120 (2018) 053001

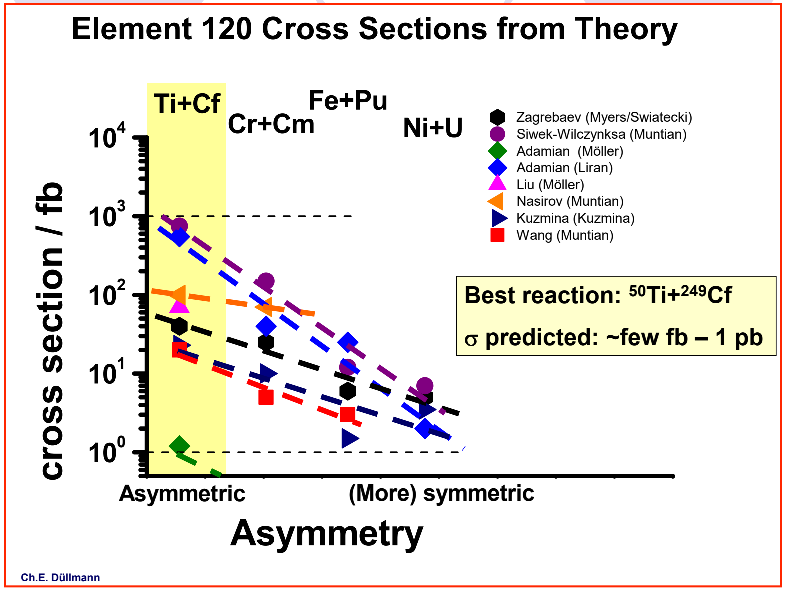
Hollow proton distribution

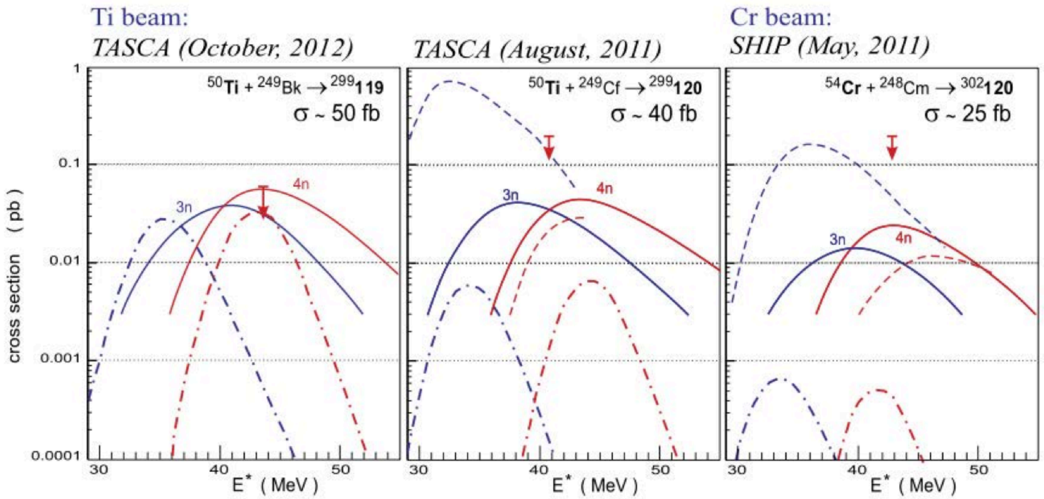


B. Schuetrumpf et al., Phys. Rev. C 96 (2017) 024306

What next ?







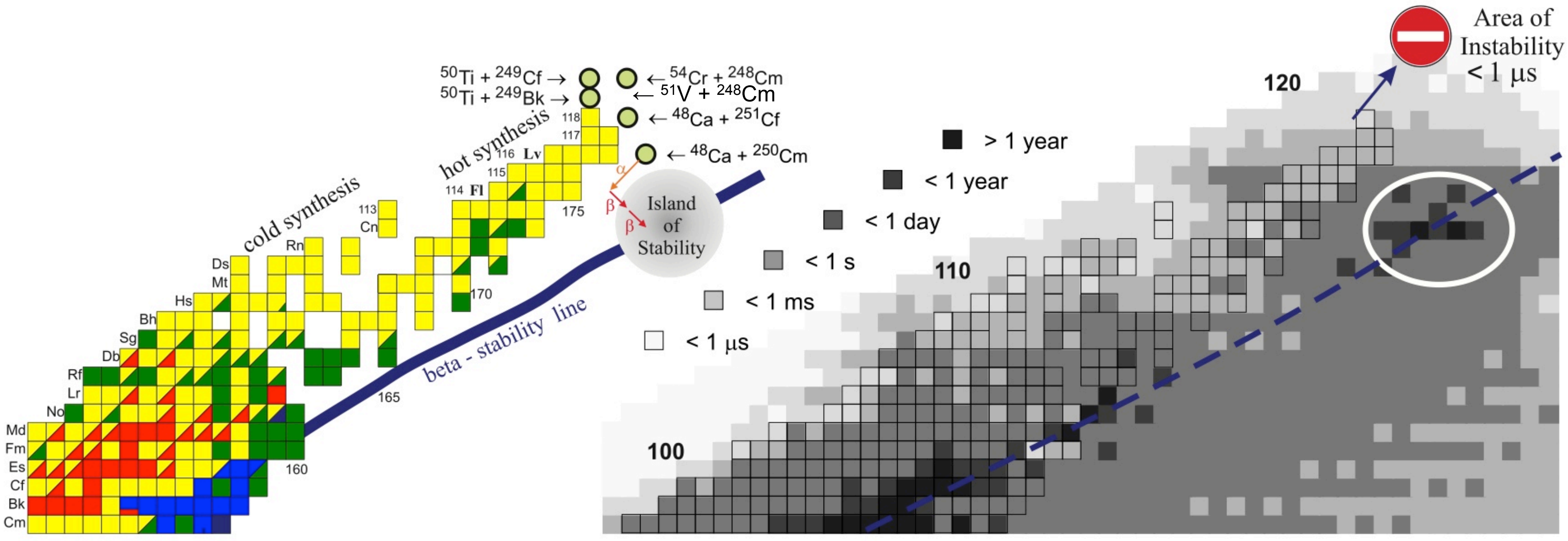
Currently in **RIKEN**:

$^{51}V+^{248}Cm \rightarrow ^{299}119$

New synthesis experiments will will soon start at **the Super Heavy Factory** in Dubna

Is there an end ?

V. Zagrebaev et al., Acta Phys. Pol. B 45 (2014) 291

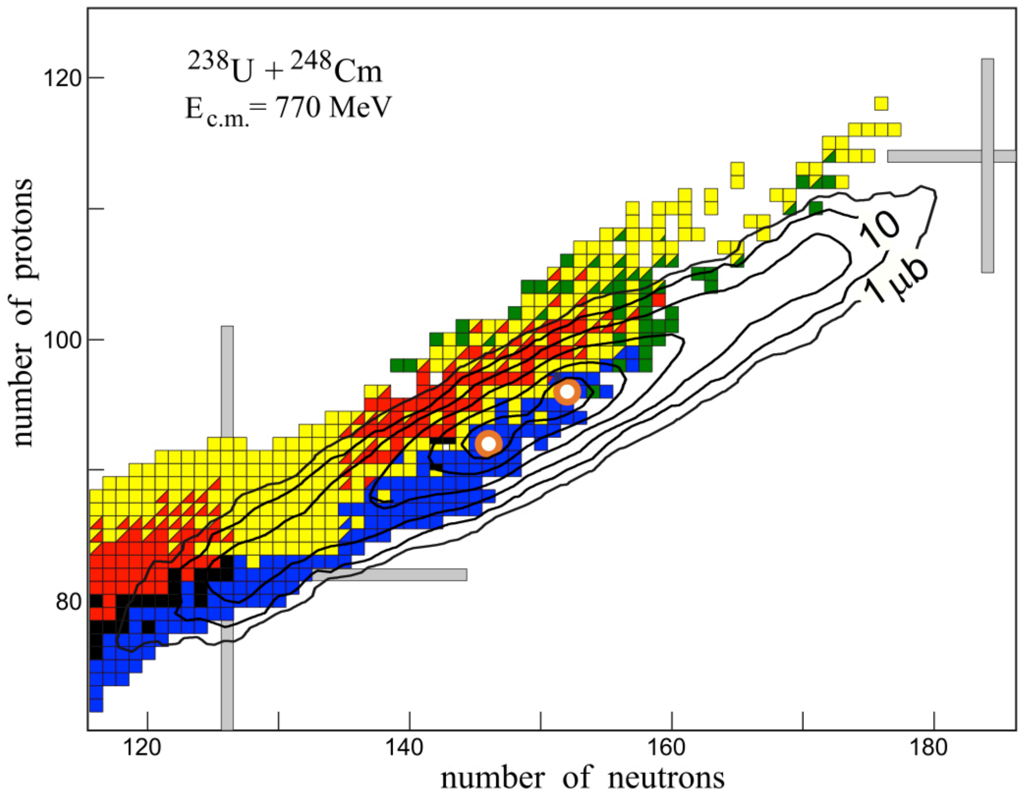


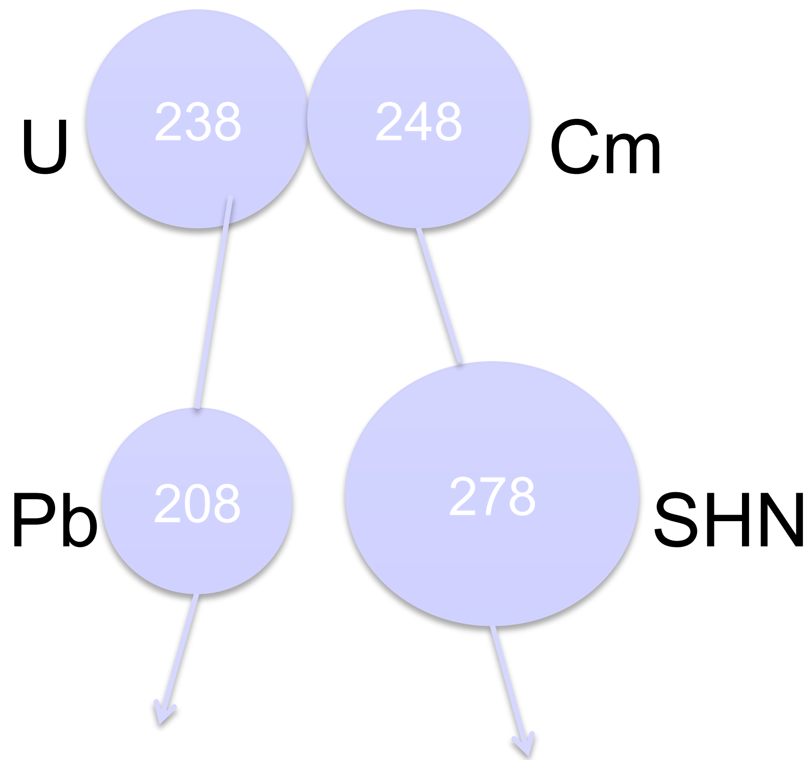
Decreasing lifetimes as Z increases

How to get more neutron rich ?

Multinucleon transfer

V.I. Zagrebaev, A.V Karpov and W. Greiner, EPJ Web of Conferences **86**, 00066 (2015)



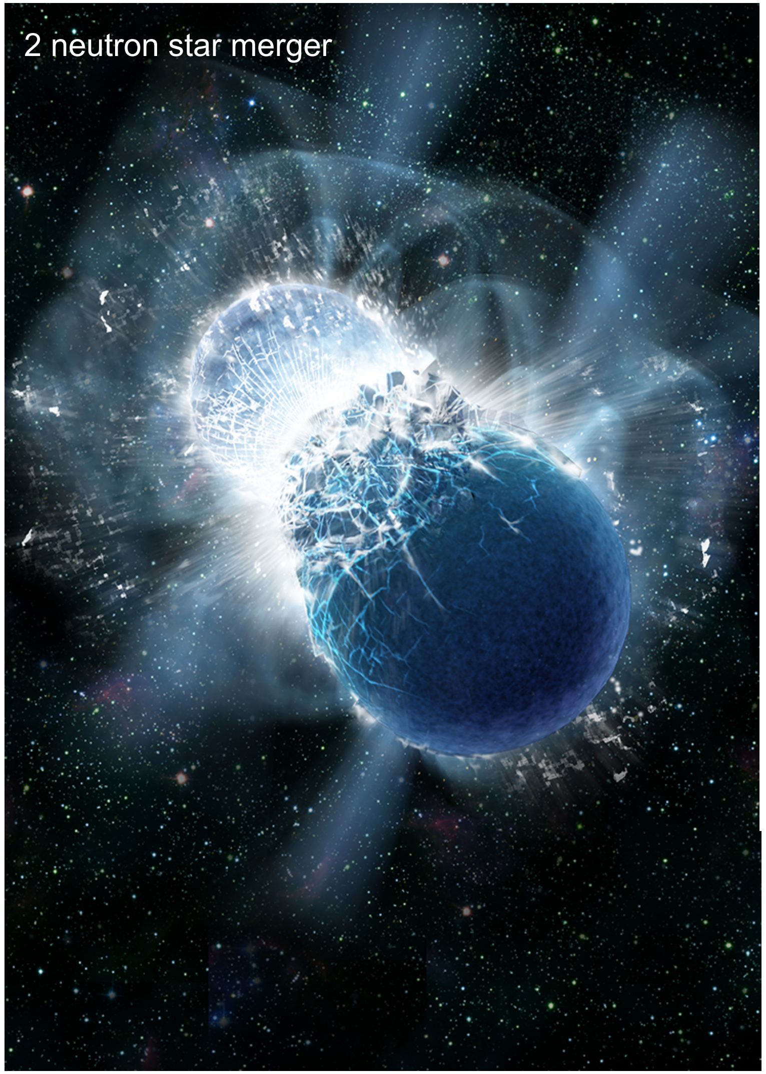


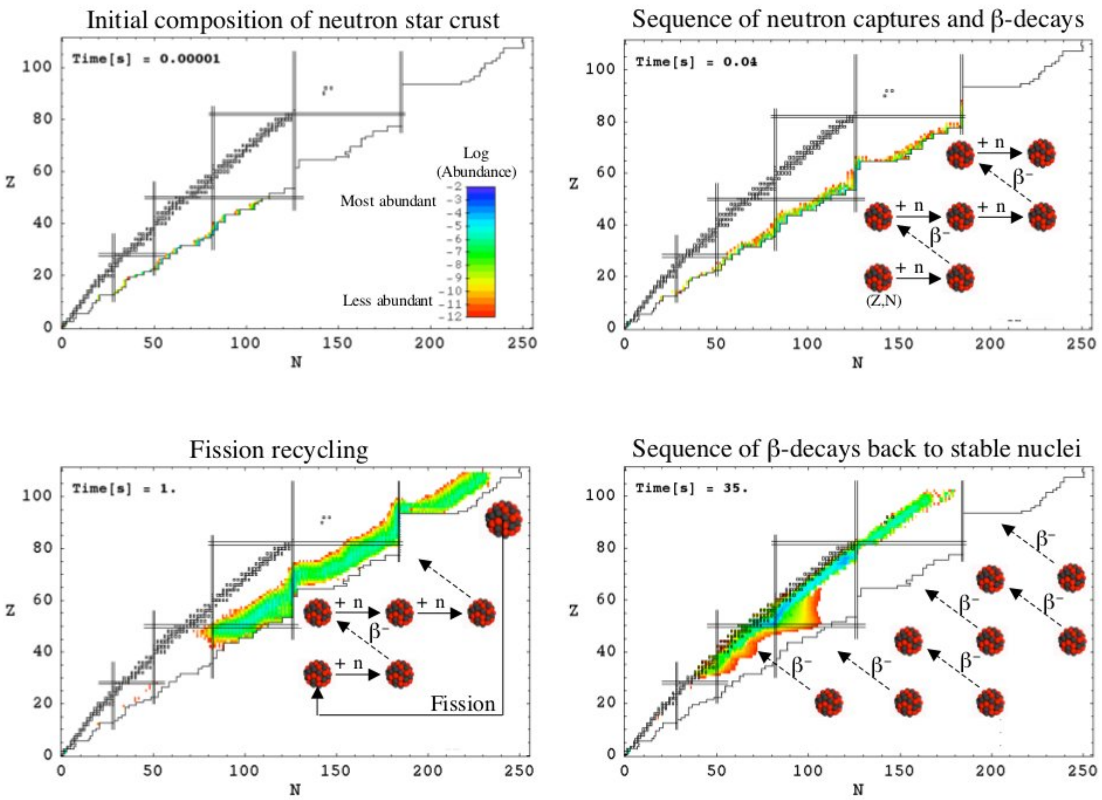
Encouraging experimental results

new projects are emerging

Are superheavy elements made in space ?

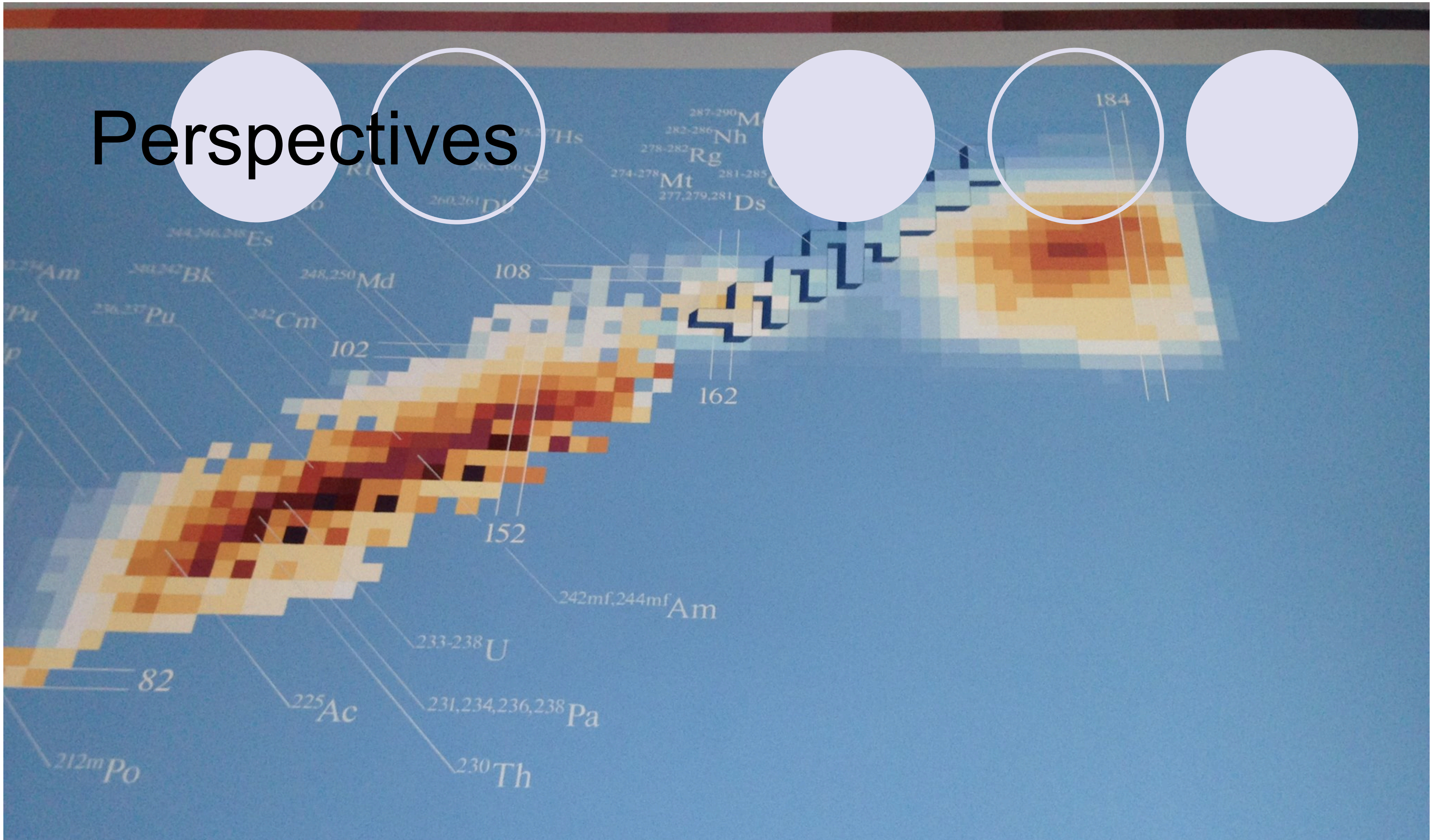
S. Goriely et al., Astrophysical Journal 738 (2011) L32





- Fission of superheavy nuclei dictates the distribution of elemental abundances
- Some superheavy nuclei may have long enough lifetimes to be observed today

Perspectives



We have entered into a new period, chemically and technologically:
the future will no doubt be full of surprises